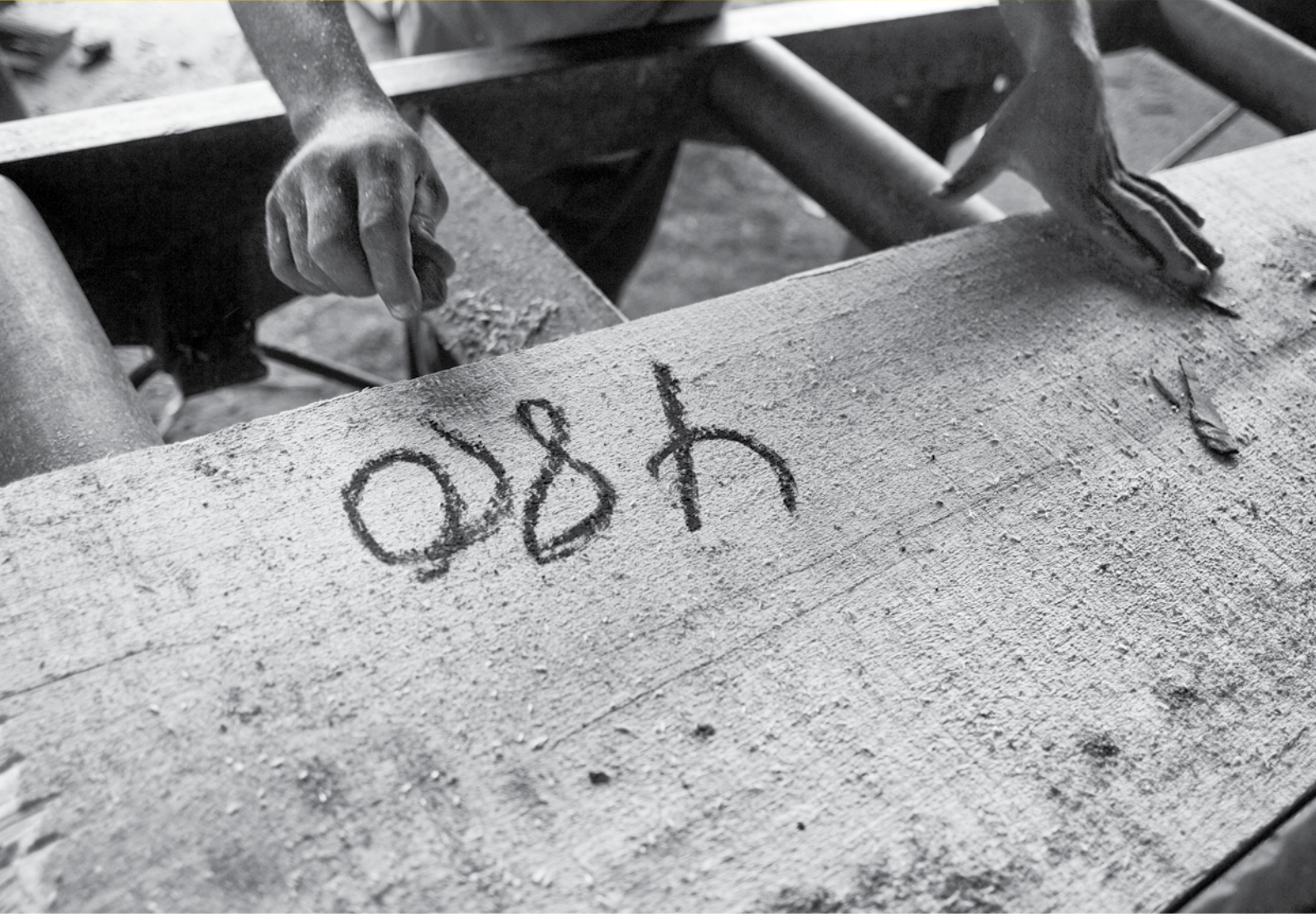


Rural structures in the tropics

DESIGN AND DEVELOPMENT

$$d = \sqrt{\frac{4 \times 57}{\pi}}$$

CTA

FAO FIAT PANIS

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Rural structures in the tropics

DESIGN AND DEVELOPMENT

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2011

About CTA

The Technical Centre for Agricultural and Rural Cooperation (CTA) was established in 1983 under the Lomé Convention between the ACP (African, Caribbean and Pacific) Group of States and the European Union Member States. Since 2000, it has operated within the framework of the ACP-EU Cotonou Agreement. CTA's tasks are to develop and provide products and services that improve access to information for agricultural and rural development, and to strengthen the capacity of ACP countries to acquire, process, produce and disseminate information in this area.

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Preface

There is a growing awareness of the need for better rural structures and services in many developing countries. For many years, rural buildings and structures in numerous countries have been built either traditionally with few improvements, or in an inadequate and often overly expensive way, guided by people with insufficient knowledge of the special technical, biological and socio-economic problems involved.

Rural buildings and structures have become an important part of integrated rural development programmes. As a large proportion of the food grain produced in Africa is stored on-farm, it is very important to develop effective storage methods and structures, especially for the modern, high-yielding grain varieties being adopted by farmers, which are more susceptible to pests than traditional types.

Improved management and breeding programmes to increase livestock production have also created a need for more appropriate animal housing.

The subject of rural structures and services needs to be included at all levels of the agricultural education system to assist the rural population still further in raising their standard of living. Specialists in rural structures and services need to have a thorough knowledge of farming systems, crop and livestock production systems and climate factors, as well as a genuine understanding of rural life and the farmer's social and economic situation. They should also be familiar with the full range of building materials and types of construction, from traditional indigenous to industrially produced, as they apply to rural structures. They must be able to select appropriate installations and equipment for rural buildings.

This knowledge will enable them to produce specifications, in cooperation with the farmer, for functional building designs that provide a good environment and durable construction, thereby contributing to efficient and economically sound farm operations. Further important tasks for specialists in rural structures and services are interpreting and explaining the drawings and technical documentation to farmers, as well as supervising the construction work. However, they should be aware of the need to consult other specialists in related fields where necessary.

This book is an effort by FAO to compile an up-to-date, comprehensive text on rural structures and services in the tropics, focusing on structures for small- to medium-scale farms and, to some extent, village-scale agricultural infrastructure. The earlier edition, entitled *Farm structures in tropical climates. A textbook for structural engineering and design*, was published in 1986, and was based on material developed as part of the FAO/SIDA Cooperative Programme: Rural Structures in East and South-East Africa. The programme was established to help member countries to develop functional, low-cost rural structures using locally sourced construction materials and skills wherever possible.

For over two decades, the earlier edition has been used as a standard textbook for teaching undergraduate and postgraduate courses on rural structures and services in universities throughout sub-Saharan Africa. As part of its normative programme on rural infrastructure development, the FAO Rural Infrastructure and Agro-Industries Division (AGS) commissioned a team of three professional engineers who participated in teaching courses on rural structures and services to review and rewrite the earlier edition, whilst examining the socio-economic and technological developments that have taken place over the past 25 years. This team, which worked during the period 2010–2011 under the direct supervision of former AGS Director, Professor Geoffrey C. Mrema, comprised Professor Lawrence O. Gumbe and lecturer Januarius O. Agullo from the University of Nairobi, Kenya, and Dr Hakgamalang J. Chepete from Botswana College of Agriculture.

We trust that this second edition will help to improve teaching – at all educational levels – on the subject of rural buildings in developing countries of the tropics and that it will assist professionals currently engaged in providing technical advice on rural structures and services, from either agricultural extension departments or non-governmental rural development organizations.

We also trust that this book will provide technical guidance in the context of disaster recovery and rehabilitation, for rebuilding the sound rural structures and related services that are key to development and economic sustainability.

While this book is intended primarily for teaching university- and college-level agricultural engineering students about rural structures and services, it is our hope that resources will be made available to produce textbooks based on this material for teaching at other educational levels. Although parts of the background material relate specifically to East and Southeast Africa, the book's principles apply to the whole of tropical Africa, Latin America and South Asia because, while building traditions may vary, the available materials are similar.

Acknowledgements

This book is based on the FAO publication *Farm structures in tropical climates*, published in 1986. The original material and documentation was produced by the FAO/SIDA Cooperative Programme: Rural Structures in East and South-East Asia. The lecturers underwent two six-month intensive training courses by the SIDA programme between 1981 and 1983.

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Chapter 1
Introduction

The subject of this book is rural structures and services in tropical regions. Although it has been written with a special focus on the situation in eastern and southern Africa, the principles apply to most of the tropics, albeit with some modifications to cater to local conditions. In many parts of Africa rural structures, including farm buildings, have been built using traditional methods and materials. However, rural development and globalization are bringing about significant changes in rural areas of Africa.

Whereas in the past it was common to find only small thatched and/or mud houses, nowadays brick-walled houses roofed with corrugated iron sheets and/or tiles are quite common in many rural areas of eastern and southern Africa. Some of these new structures are an improved traditional design constructed using industrial building materials. Others are replications of urban building designs and often fail to cater to the special technical, biological, physical and economic characteristics of rural areas, where in most cases agricultural production is combined with processing and dwelling.

There is therefore a growing need for improved rural structures in most parts of Africa. In urban areas, there are town/municipal engineers responsible for enforcing the building code, while in rural areas, rural development officers are normally called upon to provide technical advice on improving rural structures. Rural dwellers, who in most parts of Africa are either crop and/or livestock farmers, rely on the technical advice of agricultural extension workers who, in most countries, also serve as general rural development practitioners. Improved rural structures and services are becoming increasingly important parts of the rural development agenda.

Rural structures also play a major role in increasing agricultural productivity and overall production. Rural buildings are used not only for storing agricultural inputs such as fertilizers, but also for preserving agricultural outputs. In Africa this is particularly important because a significant percentage of grain production is stored on the farm for own consumption. It is therefore important to develop methods and structures for effective storage, especially for the modern high-yielding grain varieties, which tend to be more susceptible to pests than the traditional types.

Improved management and breeding programmes to increase livestock production have also created a need for improved livestock housing and services. For instance, in parts of eastern Africa many small-scale farmers have invested in intensive dairy projects where the dairy cows are zero-grazed. In addition, general development, which has led to improved standards of living for the rural population, has led to increased demand for durable, comfortable and healthy dwellings with clean water, sanitation facilities, telecommunications and community infrastructure. Most of these facilities would normally be owned by the individual farmer, while some may be communally owned.

All these rural structures and services play a significant role in increasing agricultural production, helping countries to achieve food security. These are some of the most important investments that rural dwellers will make in their lifetime. FAO projections show that, over the next 40 years, significant investment must be made in rural infrastructure if the world is to feed a global population of more than nine billion.

The general thinking on the future of rural areas, and countries in general, is reflected in the various policies of developing countries, such as: Vision 2030 in Kenya; Vision 2025 in Tanzania and Uganda; Growth, Employment and Redistribution (GEAR) in South Africa; Vision 2016 in Botswana; and Vision 2020 in Nigeria. All these policy statements include the primary objective of accelerating rural development.

As an example, the aim of Vision 2030 is to transform Kenya into a newly industrializing, "middle-income country providing a high quality life to all its citizens by the year 2030". The vision aspires to a country firmly interconnected through a network of roads, railways, ports and airports by the year 2030. According to the vision statement, it will no longer be possible to refer to any region of Kenya as "remote" as investments in the nation's infrastructure will be given the highest priority.

Increasing value and incomes in rural areas by transforming agriculture and making it more productive is a major objective of most planners and policy makers in developing countries, especially those in eastern and southern Africa. They all aim to raise incomes in crop, livestock, forestry and fishery production, as industrial production and the service sector expand. This will be achieved partially through processing, which will add value to agricultural produce before it reaches the market.

All countries of the region want agricultural producers to be competitive not only nationally, but

also regionally and globally. The aim is to accomplish this by means of an innovative, commercially oriented, modern style of agriculture that includes the crop, livestock, forestry and fishery sectors. Agricultural production should also be sustainable and every effort should be made to protect the environment.

The transformation of agriculture and other rural enterprises and livelihoods will require the planning, design, construction, operation and maintenance of a broad range of rural structures and infrastructure. Innovation is a key factor in the success of this endeavour because it will lead to the efficient and effective design and construction of rural structures. This is essential as there are major challenges, in particular limited financial resources.

The development of rural structures may be divided into four phases: planning; design; construction; operation and maintenance:

- **Planning:** This phase involves consideration of the various requirements and factors that affect the general layout and dimensions of the desired structures. It leads to the selection of one, or perhaps several, alternative types of structure that provide the best overall solution.

  The primary consideration is the structure's function. Secondary considerations include aesthetics, sociology, law, economics and the environment. In addition, structural and constructional requirements and limitations may affect the type of structure to be selected. Equipment and machinery to be installed in the structures also need to be factored in during the planning phase.
- **Design:** This phase involves the detailed consideration of the different options involved in the planning phase. It leads to the definition of the most suitable proportions, dimensions and details of the structural elements and connections required for constructing each option under consideration. Details of equipment and machinery to be installed in the structure also form part of the designs.
- **Construction:** This phase involves the procurement and transportation to the site of materials, equipment, machinery and personnel, as well as actual field erection. During this phase, some redesigning may be required due to unforeseen circumstances such as unavailability of specified materials or foundation problems.
- **Operation and maintenance**: During this period, the structure is in use. It requires planned and unplanned maintenance. Experience gained in this phase leads to the design of better structures in the future.

Engineers who specialize in designing rural buildings and services need to have a thorough knowledge of farming systems, crop and livestock production systems, climate factors and a genuine understanding of rural life and the farmer's social and economic situation. They should also be familiar with the full range of building materials and types of construction, from traditional indigenous to industrially produced, as applied to rural structures. They must be able to select appropriate installations and equipment for such buildings.

This knowledge will enable them to produce specifications, in cooperation with the farmer, for functional building designs that provide a good environment and durable construction, thereby contributing to efficient and economically sound farm operations. Further important tasks for the engineers responsible for rural structures and services are interpreting and explaining the drawings and technical documentation to farmers, as well as supervising construction work. However, engineers should be aware of the need to consult specialists in related fields where necessary.

This textbook is intended for the design and development of rural structures for agricultural production in the tropics. This single volume covers the basic procedures for planning, designing, constructing, operating and maintaining rural structures. Other topics include rural water supply, rural sanitation, rural energy and minor rural roads. In line with current and future requirements, the book presents modern methods of developing structures and infrastructure.

SCOPE OF THE TEXTBOOK

This textbook is intended as a resource for practitioners engaged in the planning, design, construction, operation and maintenance of rural structures and services in support of agricultural production. It focuses mainly on the structures and services required by smallholder farmers in rural areas of Africa. It is also designed to serve as a textbook for students enrolled in agriculture and engineering courses at colleges and universities.

The book is divided into four main parts. Part one deals with the fundamentals required by a professional responsible for providing technical advice on rural structures and services, such as graphical and geospatial techniques and the properties of construction materials. Part two deals with the principles of designing rural structures and services, including basic mechanics and structural design.

Part three deals with the elements of actual construction and building production. The final part, which is the largest, deals with the specifics of designing and constructing different types of rural structure (structures for livestock production, rural dwellings, structures for produce handling, conditioning and storage; rural infrastructure, such as rural roads, water and sanitation, and external services, such as fencing).

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Chapter 2
Planning farm and rural structures

INTRODUCTION

A major constraining factor in the design and construction of farm and rural structures in the tropics is the need to implement such projects in an environment where most farms are small and fragmented. Additional limiting factors include severe financial constraints and the need for agricultural mechanization and rural transformation. These challenges can be met, in part, by producing standard designs and case studies for target groups. These case studies can be modified thereafter to suit each individual need.

As buildings and other rural structures are fixed assets that have a relatively long lifespan and require a relatively large amount of resources to construct, it is important that they are planned and designed for efficient and profitable use throughout their life. Once a building is erected, however, it is expensive to make changes. A plan for an individual farm is influenced by a number of factors over which the farmer has no direct control, e.g. climate, soil fertility, government policies, state of knowledge about agricultural techniques and the value of inputs and outputs.

Functional planning is essential for the realization and achievement of the goals set. A good plan should provide an understanding of the situation and how it can be changed and thus assist farmers to see the problems, analyse them and be able to make sound decisions when choosing between alternative uses of their resources. While farm management planning helps farmers to choose the type and quantity of commodities to produce, advice from crop and livestock production specialists is required to help them decide how to produce them in an efficient way. When an enterprise requires buildings or other structures, the rural building specialist will suggest alternative designs for the efficient use of resources. The best plan for the whole farm operation is normally the result of interaction between the various farm planning disciplines.

Similarly, engineers can produce standard designs that are suitable for a large number of farms in an area, either as they are or with small modifications. However, the number of case studies and designs must be sufficient to allow all farmers to be given advice reflecting their individual situation, and which they are likely to adopt.

What is planning? An overview

The term 'planning' is a very general one. Its various definitions cover a wide range but do not provide a consensus. Various scholars have come up with different definitions, such as:

"…. Planning is the making of an orderly sequence of action that will lead to the achievement of stated goals" (Hall, 1974).

"…. Planning is an activity by which man in society endeavours to gain mastery over himself and shapes his collective future through conscious reasoned effort" (Friedmann, 1966).

The above definitions notwithstanding, there are also other schools of thought on planning. These include:

(i) Planning as a basic human activity

This looks at planning as a basic activity that pervades (informs every aspect of) human behaviour: "….a plan is any hierarchical process in the organism that can control the order in which a sequence of operations is to be performed".

Miller *et al.* (1960) concluded that each action is the result of a complex preliminary process, which they called a TOTE (Test Operate Test Exit) unit. This means that each action is preceded by an assessment of the situation and a visualization of the action to be undertaken (test); next the action is carried out (operated); its results are evaluated (test); then the sequence is concluded (exit); and a new one begun …

(ii) Planning as a rational choice

(a) This confines planning to matters of deliberate choice. A rational choice is one that meets certain standards of logic.

(b) In this case, planning becomes "a process for determining appropriate future actions through a sequence of choices" (Davidoff and Reiner, 1962).

(c) There is, however, a difference between rationality and planning as processes. Whereas both attempt to achieve a preferred and – through deliberate choice – comprehensive approach and link to action, planning can be distinguished by its emphasis on the future orientation of any decision.

(d) The weakness of this view of planning is its almost sole focus on choice, with only a vague link to action (if a group makes plans but does

not commit to implementing them, is this still planning?).

Such planning aims to apply the methods of rational choice for determining the best set of future actions to address novel problems in complex contexts. Furthermore, it is attended by the power and intention to allocate and commit often scarce social and economic resources (and to act as necessary) to implement the chosen strategy.

(iii) Planning as a control of future action
This definition embodies what could be seen as the antithesis of the narrowness of the above definition. It implies that planning does not exist when the process does not include implementation.

"…Planning may be seen as the ability to control the future consequences of present action. The more consequences of controls, the more one has succeeded in planning. The purpose is to make the future different from what it would have been without this intervention" (Wildavsky, 1973).

"… The problem is no longer how to make a decision more rational but how to improve the quality of the action" (Friedmann, 1966).

This view of planning is equally flawed. For instance, is it planning when someone pays the water bill? (Because this influences the future actions of the water company and commits resources to continued supply).

If so, then the definition of planning becomes so diluted that it may set standards so high that they become impossible to meet.

(iv) Planning as a spatial kind of problem-solving
Whereas the above definitions were process-oriented (addressing the 'what' and 'how' aspects of planning), this definition is more situational (addressing the specific realm in which planning activity occurs).

One opinion defines planning as problem-solving aimed at very particular kinds of problems referred to as 'wicked'. A wicked problem has no definitive formulation, no clear rules, no true or false answers (can only be better or worse) and no clear test for the solution. Each problem is unique but, at the same time, a symptom of another deeper, more extensive malady (disease, illness). Worse still, unlike the scientific experimenter, the problem-solving planner cannot afford mistakes.

Henry Hightower goes beyond wicked problems in defining planning, accommodating the planner's need to question values, institutions and given decision rules. He isolates the planning aspect, which uses rough, imprecise data, in contrast to the exact data used in science and engineering, and planning has an action orientation.

The weakness of this approach is that it is too inclusive; solving wicked problems is not restricted to planners but could also be applied to entrepreneurs, administrators and politicians.

(v) Planning is what planners do
This definition describes the contribution of planners, as technical experts, to public policy-making. This includes:

Defining the problem, stating the terms in which problems are solvable and comparing the importance of the (always) conflicting values inherent in any solution. Although this definition has the merit of being simple and obvious, the reality is that planners are not merely people who plan.

FORMS OF PLANNING

Regional planning

What is a region?
Essentially, it is a tract of land which, by virtue of geographical, political, economic, administrative, historical and other factors, or a combination of these, is distinguishable as a unit, a separate entity. This unit may be:

(i) geographical, e.g. lake district;
(ii) social/political, e.g. a state in Nigeria;
(iii) single-function area, e.g. coalfield;
(iv) a farming region, e.g. wheat fields;
(v) a river catchment area, e.g. Congo River Basin;
(vi) a metropolitan area, e.g. Johannesburg.

A clear delineation of regional units for land-use planning is still lacking. For instance, there is a dilemma concerning whether to adopt administrative or geographical/ecological units (e.g. cross-border resource management for Lake Victoria, Mara/Amboseli, etc.).

Regional planning seeks not to achieve any specific objective (though specific regional strategies do have their various objectives) but to regulate the relationship between human and environmental factors.

(i) Interregional – concerned with activity between central government and the regions and between one region and another;
(ii) Intraregional – between a region and the localities it contains.

Urban planning
Urban planning is the physical planning of concentrated human settlements designated as urban areas. It is a special case of planning that indicates that a certain degree of detail is required of the planner.

Urban planning requires the designation of an urban planning region with a base resident population not less than that stipulated in the policy document to indicate an official town or urban area. On a larger scale, it becomes city planning.

Urban plans are represented in the same way as physical plans but they normally include more detail, including:

- infrastructure network
- spatial organizational structures

- detailed action area plans
- density distribution
- zoning regulations for the areas
- location of functions in the urban system including population, industry, commerce, institutions, recreational facilities, utilities, natural resources, environmental action plans and other essential information thought to be important for the future growth of the urban region.

Urban plans are essential tools for town management, which need constant updating because of the complexity of urban regions.

Rural planning

A rural region, like an urban region, is another category of region for planning purposes. In developing countries in particular, rural areas tend to be home to as much as 80 percent of the country's population, and therefore urban planning becomes secondary to rural planning.

Rural planning is carried out in the national interest to improve living conditions, match agricultural production to demand and conserve natural resources. Many factors in the national or regional plans may directly influence the choice of production on farms and thus the requirements for buildings.

The aims of planning strategies in rural areas are based on political decisions. These may include:

1. Provision of support services such as extension education, market development, processing and credit.
2. Development of infrastructure such as roads, electricity and water supplies.
3. Self-help activities to develop community facilities.
4. Increased non-farm employment opportunities.

Rural plans try to define the best strategy for rural areas in order to mobilize their resources to produce the assets required for development in the regions. As rural regions are generally large, it is necessary to delimit subregions (i.e. through administrative boundaries), on which the plan will focus.

A rural plan therefore lays down rural region specifics:

- Land-use systems and activities (at policy level).
- Identification and definition of resource utilization policies.
- Linkages between the specific rural region and other regions.
- Local initiatives for administration and management of the region.
- Strategic environmental management for the region.
- Population management activities of the region.
- It is also important for the rural plan to show how the political structure of the region integrates with the larger regional political system.

Note that, in many developing countries, rural plans are often non-existent or very limited because all that exists is often a 'top-down' regional plan that only recognizes the rural areas as components in the larger regional plans, rather than as key actors in plan preparation. This model has often contributed to stagnating rural regions because 'top-down' systems often lead to poor identification of the most pressing needs at rural level. Later approaches, such as Participatory Rural Appraisal (PRA), Action Research (AR) and Participatory Approval (PA), are ways and means through which development actors have tried to make local levels active in achieving their planning priorities.

Infrastructure planning

Physical planning involves the distribution of goals, objects, functions and activities in space. The content of physical planning continues to change, yet the approach has been fairly consistent. Physical planning can be regarded as the nuts and bolts of the way the built environment is conceived. One of the components of physical planning includes infrastructure planning. The historic origins in many a region relate to a somewhat different tradition – that of municipal and civil engineering and public works. Today it is not unknown for these aspects to remain separately institutionalized in terms of recruitment, organization and statutory mandates.

Infrastructure planning involves planning for the provision of roads, water services, energy, health and education facilities and other utilities that are necessary for the effective functioning of communities. Their provision contributes greatly to rural transformation and improved standards of living for the population. Transport planning, in particular, interacts closely with land-use planning. Transport planning covers a range of geographic levels from the region to the street intersection or multimodal node, and also deals with the various modes of transportation – from air travel to bicycle routes – either separately or in combination. The two are interconnected in that land use generates travel demand, and access boosts the development potential of land. Transport planners follow much the same generic process as land-use planners.

An improved road network may, for example, make new urban markets accessible, thus making it feasible for farmers to go into vegetable or milk production. This in turn may require housing for animals and stores for produce and feed. It would therefore be advisable to investigate any plans for rural development in an area during the planning stages at an individual farm, or to implement an extension campaign promoting improved building designs in that area. Government policy is often an important factor in determining long-term market trends and thus the profitability of market production, and it is therefore of special importance when planning for production operations involving buildings.

Environmental planning

The broad objective of the planning process is to promote the welfare of citizens through the creation and maintenance of a better, healthier, more efficient and more attractive living environment. Economic forces in a free-market economy are not a reliable guide for directing urban activities towards the desired healthier life because they tend to maximize profits or individual wellbeing at the expense of societal wellbeing.

Moreover, human development activities, especially in low-technology areas, have tended to exploit rather than generate resources. Where exploitation continues unchecked, depletion will follow.

Environmental planning has become a necessary component of planning at all levels, to act as a check on market forces and to press for more health-oriented planning, more consideration for human social institutions, more awareness of resource conservation and more efficient utilization systems. Environmental planning covers a wide range of concerns, but essentially has the following main objectives:

- To minimize threats to human health and life by organizing activities in such a way as to reduce the spatial concentration of pollutants in our water by limiting dangerous and hazardous areas.
- To preserve resources for future use, e.g. minimizing soil erosion and deforestation.
- To achieve recreational goals such as preserving certain areas in their natural state.
- To minimize damage to the environment for its own sake rather than for humanity's sake, e.g. by preserving the habitat of a rare species that has no known or readily foreseeable use to us.

Environmental planning has previously been included in planning, but recently greater efforts have been made in this field because of impending major threats to the human population.

Economic planning and feasibility

All countries carry out economic plans to forecast how the economy will manage the scarce resources available to the population. Such plans may be yearly, two-yearly or five-yearly. Most nations have five-year plans.

Smaller regions of a country may also have economic plans for much the same reason as the country, but on a much smaller scale and in greater detail.

Economic plans are largely statistical, indicating sectors, financial expenditure and revenue and forecasts for the subsequent plan periods. They are largely policy-oriented. Economic plans are also carried out by smaller bodies, such as local authorities. In this case the plan will comprise an inventory of how the community earns a living and where it is heading in terms of resource stability.

Most community economic plans are divided into two segments: the export base and the secondary base. The export base is made up of those goods and services that the community exports to other towns or regions in order to bring in money. This will enable the community to grow. Secondary base businesses serve the local community. If the size of the community is small, the size of the local community may not grow much.

Feasibility

There are three golden rules in formulating a project:

(i) Ensure that all the factors necessary for its success are taken into account from the outset.
(ii) Carry out careful preinvestment studies.
(iii) Build in flexibility.

When the scope of the project has been determined, five main aspects must be taken into account:

(a) *Technical feasibility:* Have all the alternatives been considered? Is there a need for the project at all? For example, could better dry-farming techniques and moisture conservation increase output just as much as irrigation? Are the proposed methods, design and equipment the best for the purpose? Are the cost estimates realistic and can the successive phases of the project be carried out in the time allowed?
(b) *Economic viability:* Does the chosen technical solution offer the highest economic and social returns of all the technically and financially feasible alternatives?
(c) *Financial:* Are the necessary funds available? Will the project be able to meet its financial obligations when it is in operation? For example, will the farmer have sufficient income to cover repayments and interest on a loan?
(d) *Administration:* Will the administrative structure proposed for the project and its staff be adequate to keep the project on schedule and manage it efficiently? Will interdepartmental rivalries be an obstacle and, if so, can the proposed coordination machinery ensure an organized flow of decisions and the assignment of responsibilities within the chain of command?
(e) *Commercial:* What are the arrangements for buying materials for the project? Where will they come from? How will they be funded? How will the output of the project be sold?

Economic planning of the farm operation

Most textbooks on agricultural economics describe methods of economic planning for commercial farms in developed western countries, but very few deal with methods relevant to African agriculture, which is, and will for the foreseeable future be, dominated by smallholder farmers. Although the principles of economic theory may be relevant when reviewing African small-scale farms, their applications will undoubtedly differ from those used when reviewing large commercial farms.

Traditional applications assume, for example, that crops and livestock can be analysed separately, that the concept of farm size can be unequivocally defined, that the farmer makes all the decisions concerning farm operations, and that increasing cash income is the major objective. However, in most cases African agriculture is traditional and based on communal land ownership. In quite a number of cases this includes a multifamily situation in which two or more wives each have their own plots but also participate in joint enterprises and are subordinate to the husband's general decisions. This situation would make an approach to local community groups more relevant than emphasizing individual farms.

A multiple cropping system or a livestock-feed crop system may serve to reduce risk and result in a more uniform supply of food and cash, as well as family labour demand and, although the yields of the individual enterprises may be low, it may provide an acceptable overall result.

Money is the commonly used – and often the most convenient – medium of exchange in economic calculation. However, other units may occasionally be more relevant when small farms, with limited cash flow and strong non-monetary relations between production operations and the household, are analysed. Subsistence farmers may, for example, value the security of having their own maize production, so much so that they will produce enough for the household even if an alternative enterprise using the land and labour would generate more than enough cash to buy the maize at the market.

The principles of economic theory are valid whatever appropriate medium of exchange is used to specify the quantities, e.g. units of labour used to produce units of grain or meat. The difficulty or challenge, depending on the perspective, is to find a suitable alternative unit to use where the gains and losses are a mixture of money and non-money elements and to take into consideration farmers' personal beliefs so that the resulting plans reflect their individual goals and value system. There are usually a variety of reasons for reviewing the economic planning for the entire farming operation.

The plan will establish the resources available, as well as the limitations and restrictions that apply to the construction of a proposed building. A comprehensive economic plan for a farm, whether an actual farm or a case-study farm, may include the following steps:

1. Establishment of individual farmers' objectives, priorities and constraints for their farm operation. The objectives should preferably be quantified so that it can be determined whether they are being, or can be, achieved.
2. Analysis of financial resources, i.e. the farmer's assets as well as the cost and possibility of obtaining loans.
3. Listing of all available resources for the farming enterprises, quantifying them and describing their qualities, e.g. quantity and quality of land, water resources, tools and machines; roster of labour including a description of training and skills; existing buildings and evaluation of their serviceability; and the farmer's management skills.
4. Description of all factors in the physical, economic and administrative environment that directly influence the farming enterprises, but over which the farmer has no direct influence, e.g. laws and regulations, rural infrastructure, market for produce, availability of supplies, prices and market trends.
5. Individual analysis of each type of farm enterprise, whether crop or animal production, to determine

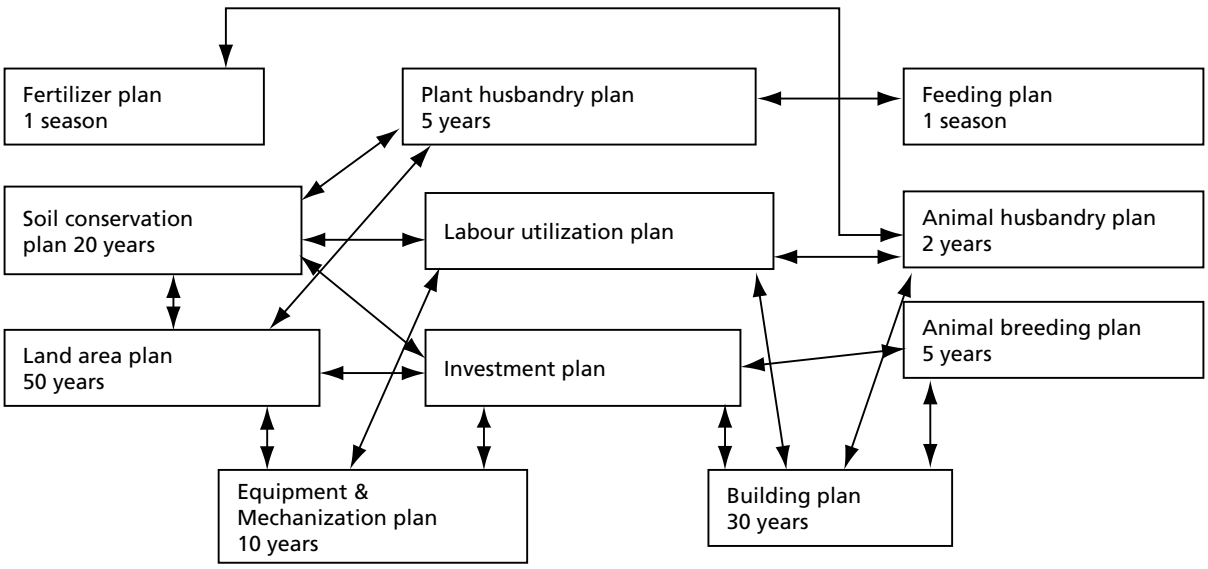


Figure 2.1 **Schedule of a sub-plan in a farming enterprise**

its allowance of total capital. Note that where multiple cropping is practiced, the mix of various crops grown together is considered to be one enterprise.

6. Determining the optimum mix of enterprises that satisfies the farmer's objectives and makes the best use of resources.

The resulting plan will be an expression of the farmer's intentions for the future development of the family farm. The plan will contain several interrelated subplans as shown in Figure 2.1.

Note that the subplans in the Figure 2.1 may interact in many more ways than have been illustrated. Many of these interrelationships are of great importance when trying to maximize the result of the total production at the farm, whether or not the product is sold. Optimization of each individual enterprise may not necessarily mean that the total farming enterprise is optimized.

If farmers already operate their farm according to a sound economic plan, a less ambitious approach, involving analysis of only the enterprise requiring a new or remodelled building and an investment appraisal, may suffice. A number of investment appraisal methods have been advocated for use in agriculture to give a rough indication of the merits of an investment. However, smallholders generally hesitate to risk cash for investment in fertilizer, pesticides and feed concentrate, as well as improved buildings and machinery, until enough food for the household is produced, a market with a cash economy is readily available and farmers are confident of their own technical, agricultural and economic skills. Money therefore, may not always be the most relevant unit to use in the calculations.

BOX 2.1
Building process in Kenya

The establishments that undertake planning and building in Kenya range from households to large state and non-state actors.

There are numerous laws that govern the building process. The laws that govern building in rural and urban Kenya include Local Government Act Cap 265, Physical Planning Act Cap 286, EMCA Act of 1999, Public Health Act Cap 242, Architect and Quantity Surveyors Registration Act, Cap 525 and Engineers Registration Act Cap 530. These laws provide the basis on which planning and building can be carried out in a systematic way. They provide for registration and professional development of key staff in the sector. Furthermore, the laws provide a basis for undertaking sustainable developments.

The key characteristics of planning and building in rural and urban Kenya are:

1. It is a process involving many stakeholders, principally regulators, developers, professionals and contractors.
2. Stakeholders are clustered and regulated by different legal and regulatory regimes.
3. It employs many labourers, especially in urban areas where it is the leading employer.

Planning and building process

Step 1 The developer (a household or corporation) identifies the project and the land on which the building will be constructed.

Step 2 The developer identifies a team of consultants (architects, quantity surveyors, surveyors, planners, environmental impact assessment experts, etc.) who manage the planning and building process. In rural areas, the master builder or 'fundi' is mostly responsible for management of the process.

Step 3 The design team carries out site investigations to determine the suitability of the site and the feasibility of the project.

Step 4 If the project is judged feasible, the design team applies to a local authority for planning approval.

Step 5 If planning approval is obtained, the design team prepares the design and submits it to a local authority for development approval.

Step 6 Upon approval, the design team appoints a contractor to build the project.

Step 7 Upon successful completion, the developer applies to a local authority for an occupancy certificate and registers the property with the Ministry of Lands.

These steps describe a process that is lengthy and involves several professionals, especially in urban areas. In rural Kenya, not all these steps are undertaken.

AN APPROACH TO BUILDING PLANNING

Once the building requirements have been established in the economic planning, it will be the task of the farm-building engineer to work out the functional and structural designs and deal with the farmstead plan. While there are laws, regulations and guidelines enacted by the central or local governments that govern the building and construction industry, most are only applicable to areas that have been designated as urban (townships, municipalities and cities). (see box 2.1 for Kenya). Rural areas are governed by County, District or Rural Councils with limited capacity to enforce such laws and regulations.

The planning process always starts with a list of available resources and restrictions and other background material. The major outline for the design is then sketched. The final design is developed by working from rough sketches towards increasingly detailed plans of the different parts of the building. Often, however, when some internal units such as farrowing pens have been designed and the required number established, the dimensions of the final building will be influenced by the pen size and number. The farmer will often impose restrictions on the design before the planning process begins. These should be critically evaluated and their effectiveness examined before they are accepted as part of the final design. It will be useful to discuss the extent of the proposed building and enterprise with an agricultural economist if the plan has not been based on an overall economic plan.

Standard solutions, promoted using demonstration structures and extension campaigns, will be the most important means of introducing improved building designs to small-scale farmers in rural areas for the foreseeable future. However, improved standard designs will be widely accepted by farmers only if they are based on a thorough understanding of the agricultural practices and human value systems prevalent in the local farming community and are developed to utilize locally available building materials and skills.

New ideas, materials and construction methods should be developed and introduced to complement the strengths of indigenous methods. Local builders will be valuable sources of information regarding indigenous building methods and effective channels through which innovation can be introduced. Close cooperation between builders and farmers will help the local community to deal with its own problems and to evolve solutions from indigenous methods and local resources that will have a good chance of becoming accepted.

Background information

An economic plan for the farming operation will provide much of the background information required by the farm-building engineer. As this is often missing, such information will have to be obtained by interviewing farmers and by studying similar farms in the area. Where the design is developed for a specific farm or farming enterprise, priority should be given to gathering as much information as possible from that farm or about that enterprise. All information should be critically evaluated prior to its acceptance as background material for the design of the proposed building or for a standard drawing.

When developing an economic plan, the farm-building engineer should obtain as much of the above information as possible, in addition to data relating to the following factors:

1. A comprehensive master plan of the farmstead.
2. For storage structures, data concerning the expected acreage and yield of the crop to be dried and stored, the length of the storage period, i.e. the amount of produce to be sold or consumed at the time of harvest.
3. For animal housing, the quantity and quality of animals currently owned and the possibility and time scale for increasing and improving the herd through a breeding programme should be considered.
4. Availability of building materials and construction skills at the farm or in the rural area concerned.
5. Laws and regulations applicable to the proposed building and the enforcement agencies involved.

Calculations

The standardized economic calculations used to determine the gross margin in a farm operation are often limited in scope and therefore a more detailed examination of the enterprise housed in the building may be of use. Knowing the expected production volume, additional data are calculated using the background information.

In the case of a building to be used for storage, the expected volume of the crop to be stored is determined, as well as the required handling capacity. In a multipurpose store where several different commodities are held, a schedule of the volumes and storage periods will be useful to determine the maximum storage requirement.

Analysing the activities

Activity analysis is a tool used for planning production in large, complex plants such as factories, large-scale grain stores and animal-production buildings, but it can also be a useful instrument in smaller projects, particularly for the inexperienced farm-building engineer.

Most production operations can be carried out in several ways involving various degrees of mechanization. By listing all conceivable methods in a comparable way, the most feasible method from a technical and economic standpoint can be chosen. This will ensure good care of produce and animals, as well as effective use of labour and machinery. Uniformity in handling improves efficiency, e.g. produce delivered

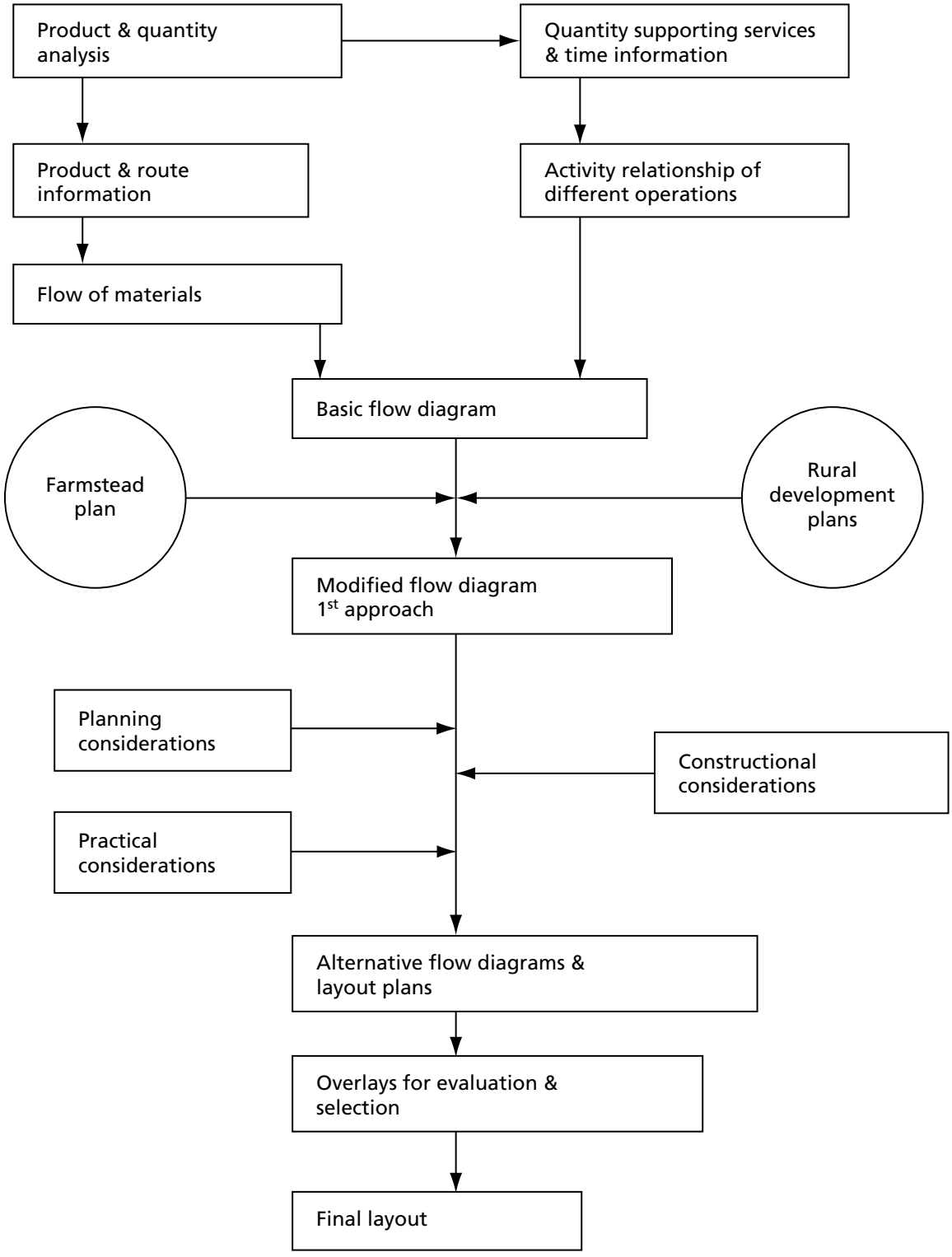


Figure 2.2 **Layout diagram of the planning procedure**

in bags to a store should be kept in bags within the store, particularly if it is to be delivered from the store in bags.

In animal housing projects, the handling operations for feed, animals, animal produce and manure are similarly analysed. Note that the analysis of handling operations for feed produced at the farm should include harvesting and transport from the field because these operations may determine the most appropriate storage and handling methods inside the building.

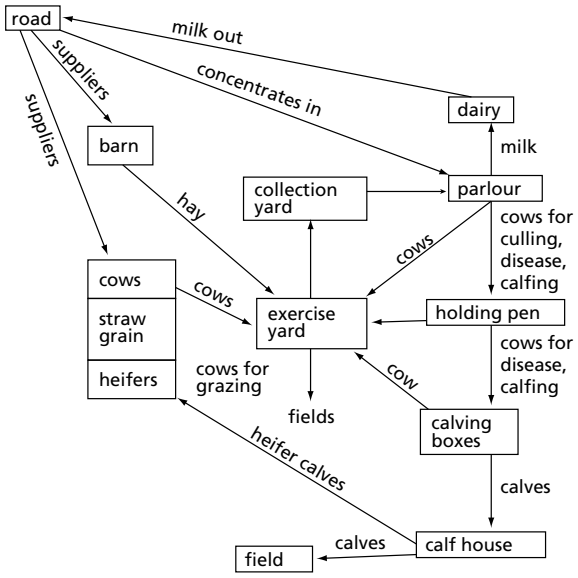


Figure 2.3 **Example of a material flow diagram for a dairy unit**

When all handling operations have been analysed, the result is summarized in a schedule of activities.

Labour efficiency is often an essential factor in small farm development. If farmers have a reasonable standard of living, cultural norms and social pressures may limit their willingness to invest in labour for a relatively low return, while labour-efficient methods allowing for a reasonable return on the labour invested may increase their willingness to produce a surplus.

Room schedule

This is a brief description of all rooms and spaces required for work, storage, communication, servicing of technical installations, etc. As variations in yield and other production factors are to be expected, an allowance is added to the spaces and the volumes. It would be uneconomical, however, to allow for the most extreme variations, particularly if a commodity to be stored is readily marketable and can be bought back at a reasonable price later.

The total space requirement is then obtained by simple addition. Also, partial sums indicate how the production operations can be divided into several houses.

Communication schedule

This describes the requirement and frequency of communication between the various rooms and spaces within the building and between the building and other structures at the farmstead. A schedule for movements between the farmstead, the fields and the market is also essential. It may also include quantities to be transported. Based on this information, the rooms between which there is frequent movement of goods and services can be placed close together for convenience and work efficiency when the building is being designed. The communication schedule is not always accounted for separately, but instead may be included in the schedule of activities.

Following the principle of working from the major outline of the project towards the details, the next step is to place the proposed building on the farmstead. Efficient communication within the farmstead is of great importance in creating functional and harmonious operations. The schedule of functions serves as a checklist when transportation is analysed. The room schedule provides information on the size of the building and the structural concept likely to be used.

A standard design can obviously not be shaped to fit a specific farmstead. Nevertheless, the group of farms for which the design is developed may have common features, which allows the designer to make recommendations concerning the location of the new building. Some structures have special requirements concerning where they can be constructed on the farmstead. A maize drying crib, for example, must be exposed to wind.

Where the plan includes the addition of a new building to an existing farmstead, alternative locations for the proposed building are sketched on the master plan or, better still, on transparent paper covering the master plan, and the communication routes are indicated by arrows between the buildings, the fields and the access road.

Considering all the planning factors and requirements, one of the proposed building locations is likely to have more advantages and fewer disadvantages than other alternatives. The transport routes to and from the building are then further studied and noted for use when the interior of the building is being planned.

Farmers will often have firm opinions about the location of the building from the start of the planning process. Their opinion should be critically analysed, but naturally it should be given considerable weight when the site is finally chosen.

Functional design of the building

Sketching alternative plan views of the building is mainly a matter of combining and coordinating the requirements that have been analysed in earlier steps. Some general guidelines are as follows:

1. Concentrate functions and spaces that are naturally connected to each other, but keep dirty activities separate from clean ones.
2. Communication lines should be as straight and simple as possible within the building and, to reduce the number of openings, they should be coordinated with those outside, as shown in the farmstead plan.
3. Avoid unused spaces and long communication corridors.
4. Provide for simple and efficient work. Imagine that you are working in the building.

5. Use as few handling methods as possible and choose methods that are known to be reliable, flexible and simple.
6. Provide a good environment for labourers and animals or produce.
7. Provide for future expansion.
8. Keep the plan as simple as possible within the limits of production requirements.

Finalization of sketching

After a number of sketches have been produced, they are carefully analysed to select the one that best reflects the farmer's objectives. However, because a farmer's objectives are usually complex and difficult to elicit, it is common to use more readily evaluated criteria such as total construction cost or cash expenditure. The selected building plan is then drawn to the correct scale, sections and elevations are sketched and, where applicable, the building is positioned on the master plan. In many cases, the results of earlier steps in the planning process, such as the activity schedule or room schedule, may have to be reviewed and adjusted as the work progresses.

Prior to being widely promoted, standard designs are often tested at a few typical farms. The construction phase and a period of use will often give rise to useful experience that may result in improvements to the design. Only if the designer is prepared to modify the design continuously as needed to adapt it to changing agricultural practices will it have a good chance of being successful in the long run.

A 'one of a kind design' intended for a specific farm can obviously not be tested in practice prior to its construction. Therefore the sketch, including a cost estimate, must be presented and carefully explained to farmers so that they understand the plan and feel confident that they can run an efficient and profitable production system in the building. Notwithstanding this, the farmer is likely to have objections and suggestions for alterations, which must be considered and worked into the final sketches. As an understanding of the operation and a positive attitude by all concerned are basic requirements for efficient production, farm labourers and members of the farmer's family who will be working in the building should also be given an opportunity to review the sketches.

Final design

When all sketches (farmstead plan, functional plan and structural concept) have been corrected, coordinated and approved by the farmer, the final building documents are prepared.

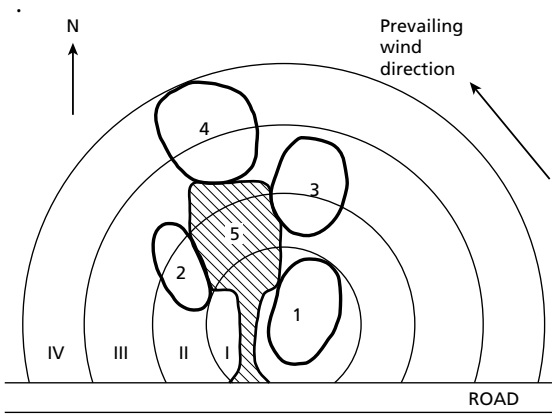
FARMSTEAD PLANNING

The farmstead forms the nucleus of the farm operation where a wide range of farming activities are undertaken. It normally includes the dwelling, animal shelters, storage structures, equipment shed, workshop and other structures. A carefully developed plan should provide a location for buildings and facilities that allows adequate space for convenient and efficient operation of all activities, while at the same time protecting the environment from such undesirable effects as odours, dust, noise, flies and heavy traffic. A wide range of factors, described in the 'Communication Schedule' section, should be considered when planning the location of buildings and services at the farmstead.

Although the immediate objective of these plans may be the inclusion of a new building in an existing farmstead, provision should be made for future expansion and the replacement of buildings. In this way a poorly laid out farmstead can be improved over the long term.

Zone planning

Zone planning can be a useful tool, but it is most effective when planning a new farmstead. The farmstead is divided into zones 10 metres to 30 metres wide by concentric circles, as shown in Figure 2.4.



1 Family living area including the dwelling
2 Implement and machinery storage, farm workshop
3 Grain and feed storage
4 Livestock buildings

Figure 2.4 **Zone planning in four zones**

Zone 1 at the centre of the farmstead is for family living, and should be protected from odour, dust, flies, etc. Clean, dry and quiet activities, such as implement sheds and small storage structures, can be placed in *Zone 2*. Larger grain stores, feed stores and small animal units are placed in *Zone 3*, whereas large-scale animal production is placed in *Zone 4* and beyond.

The advantage of zone planning is that it provides space for present farm operations, future expansion and a good living environment. However, in many African cultures the livestock has traditionally been placed at the centre of the farmstead. Thus the zone concept runs counter to tradition and may not be desirable.

Farmstead planning factors

Good *drainage*, both surface and subsurface, provides a dry farm courtyard and a stable foundation for buildings. A gentle slope across the site facilitates drainage, but a pronounced *slope* may make it difficult to site larger structures without undertaking extensive earthmoving work. *Adequate space* should be provided to allow for manoeuvring vehicles around the buildings and for the future expansion of farm operations.

Air movement is essential for cross-ventilation, but excessive wind can damage buildings. As wind will carry odours and noise, livestock buildings should be placed downwind from the family living area and neighbouring homes. Undesirable winds can be diverted and reduced by hedges and trees or fences with open construction. *Solar radiation* may adversely affect the environment within buildings. An orientation close to an east-west axis is generally recommended in the tropics.

An adequate supply of *clean water* is essential on any farm. When planning buildings for expanded livestock production, the volume of the water supply must be assessed. Where applicable, the supply pipe in a good building layout will be as short as possible. Similarly, the length of utility supply lines (e.g. *electric, gas)* should be kept to a minimum.

The *safety* of people and animals from fire and accident hazards should form part of the planning considerations. Children, especially, must be protected from the many dangers at a farmstead. It is often desirable to arrange for some *privacy* in the family living area by screening off the garden, outdoor meeting/ resting places, veranda and play area.

Measures should be taken for *security* against theft and vandalism. This includes an arrangement of buildings where the farmyard and the access driveway can be observed at all times, especially from the house. A neat and attractive farmstead is desirable and much can be achieved toward this end, at low cost, if the *appearance* is considered in the planning, and effective landscaping is utilized.

SAFETY AND FIRE PROTECTION

Measures to prevent fire outbreaks and to limit their effect must be included in the design of buildings. Fire prevention measures include the separation of buildings to prevent fire from spreading and to permit firefighting, and a farm or community pond as a source of water for extinguishing fires.

Fire resistance in materials and construction

The ability of a building to resist fire varies widely depending upon the construction materials and the manner in which they are used. Fire resistance is graded according to the period of time that a construction element is able to withstand standardized test conditions of temperature and loading.

Bare metal frameworks and light timber framing exhibit a low order of fire resistance and both types of construction fail to qualify for a grading of *one-hour fire resistance*, which in many countries is the lowest grade recognized. In contrast, most masonry walls have good fire-resistance ratings.

Timber framing can be improved with the use of fire-retardant treatments or fire-resistant coverings such as gypsum plaster or plasterboard. Steel columns can be protected with plaster or concrete coatings, while steel roof trusses are best protected with suspended ceilings of gypsum plaster or plasterboard.

Classification of fire hazards

Some types of activities and installations in farm buildings constitute special fire hazards. Wherever practical they should be isolated in a room of fireproof construction or in a separate building away from other buildings. A list of special fire hazards includes:

1. Flammable, highly combustible or explosive materials in excess of very small quantities, e.g. liquid and gas fuel, ammonium nitrate fertilizer, hay and bedding.
2. Hot-air grain drying and dust from grain handling may be explosive in high concentrations.
3. Furnaces and heating equipment; poultry brooder; fireplaces.
4. Farm workshop (especially welding) and garage for vehicles.
5. Electrical installations; continuously running mechanical equipment.

In addition, lightning, children playing with fire, smoking and lanterns are potential sources of fire outbreaks. Thatched roofs are highly combustible and prone to violent fires.

Fire separation

Fire spreads mainly by windborne embers and by radiation. Buildings can be designed to resist these conditions by observing the following recommendations:

1. Adequate separation of buildings by a minimum of 6 metres to 8 metres, but preferably 15 metres to 20 metres, particularly where buildings are large or contain special fire hazards. A minimum distance may be specified in the building code.
2. Construction using fire-resistant facing and roofing materials.
3. Avoidance of roof openings and low roof slopes, which can be more easily ignited by embers.
4. Use of fire-resistant walls that divide a large building into smaller fire compartments. To be effective, such walls must go all the way up through the building to the roof and any openings in the walls must be sealed by a fireproof door.

Evacuation and fire extinguishers

In the event of a fire outbreak, all personnel should be able to evacuate a building within a few minutes, and animals within 10 to 15 minutes. Equipment, alleys and

doors should be designed to facilitate evacuation. Smoke and panic will delay evacuation during a real fire, so evacuation during a fire drill must be much faster.

In animal buildings, exit doors leading to a clear passage, preferably a collecting yard, should have a minimum width of 1.5 metres for cattle and 1 metre for small animals so that two animals can pass at the same time. Buildings with a floor area exceeding 200 m² should have at least two exit doors as widely separated as possible. The travel distance to the nearest exit door should not exceed 15 metres in any part of the building.

Fire extinguishers of the correct type should be available in all buildings, in particular where there are fire-hazardous activities or materials. Water is commonly used for firefighting, but sand or sandy soils are effective for some types of fire. Dry powder or foam extinguishers are best for petrol, diesel, oil and electrical fires. Regardless of type, fire extinguishers require periodic inspection to ensure that they operate properly in an emergency.

Bushfire

The dry season or any period of prolonged drought brings with it a constant fire hazard. Fanned by strong winds and intensified by heatwave conditions, a large bushfire is generally uncontrollable.

Firebreaks are an essential feature of rural fire protection and should be completed before the fire season starts. It is desirable to completely surround the homestead with major firebreaks at least 10 metres wide. Breaks can be prepared by ploughing, mowing, grazing, green cropping or, with great caution, by burning, and may include any watercourse, road or other normal break that can be extended in width or length.

Shelter belts or even large trees are useful in deflecting wind-borne burning debris. For further protection, all flammable rubbish and long, dry grass should be removed from the surroundings of the buildings and any openings, such as windows, doors and ventilators, covered with insect screens to prevent wind-borne embers from entering the building and starting a fire

PROJECT PLANNING AND EVALUATION TECHNIQUES

Project planning

Project planning is customarily defined as strategic, tactical, or operational. Strategic planning is generally for five years or more; tactical can be for one to five years and operational normally covers six months to one year.

Project planning means determining what needs to be done, by whom, and by when, in order to fulfil assigned responsibilities. There are nine major components of the project planning phase:

- *Objective:* a goal, target, or quota to be achieved by a certain time.
- *Programme:* the strategy to be followed and major actions to be taken in order to achieve or exceed objectives.
- *Schedule:* a plan showing when individual or group activities or tasks will be started and/or completed.
- *Budget:* planned expenditures required to achieve or exceed objectives.
- *Forecast:* a projection of what will happen by a certain time.
- *Organization:* design of the number and kinds of positions, along with corresponding duties and responsibilities, required to achieve or exceed objectives.
- *Procedure:* a detailed method for carrying out a policy.
- *Standard:* a level of individual or group performance defined as adequate or acceptable.

Project evaluation and techniques

Project evaluation is a management tool. It is a time-bound exercise that attempts to assess systematically and objectively the relevance, performance and success of ongoing and completed projects. Evaluation is undertaken selectively to answer specific questions to guide decision-makers and/or project managers and to provide information on whether underlying theories and assumptions used in project development were valid, what worked and what did not work, and why. Evaluation commonly aims to determine the relevance, efficiency, effectiveness, impact and sustainability of a project.

The main objectives of project evaluation are:

(i) To inform decisions on operations, policy, or strategy related to ongoing or future project interventions.
(ii) To demonstrate accountability to decision-makers.
(iii) Improved decision-making and accountability are expected to lead to better results and more efficient use of resources.

Other objectives of project evaluation include:

(i) To enable corporate learning and contribute to the body of knowledge on what works and what does not work, and why.
(ii) To verify/improve project quality and management.
(iii) To identify successful strategies for extension/expansion/replication.
(iv) To modify unsuccessful strategies.
(v) To measure effects/benefits of projects and project interventions.
(vi) To give stakeholders the opportunity to have a say in project output and quality.
(vii) To justify/validate projects to donors, partners and other constituencies.

Evaluation is often construed as part of a larger managerial or administrative process. Sometimes this is referred to as the *planning-evaluation cycle*. The distinctions between planning and evaluation are not always clear; this cycle is described in many different ways, with various phases claimed by both planners and evaluators. Usually, the first stage of such a cycle is the planning phase.

Project evaluation involves a needs assessment, which entails assessing the use of methodologies that help in conceptualization and detailing and the application of skills to help assess alternatives and make the best choice.

Methodology

The evaluation phase also involves a sequence of stages that typically includes: the *formulation* of the major objectives, goals and hypotheses of the programme or technology; the *conceptualization* and operationalization of the major components of the evaluation – the programme, participants, setting and measures; the *design* of the evaluation, *detailing* how these components will be coordinated; the *analysis* of the information, both qualitative and quantitative; and the *utilization* of the evaluation results. Different means of evaluation include:

- *Self-evaluation:* This involves an organization or project holding up a mirror to itself and assessing how it is doing, as a way of learning and improving practices.
- *Participatory evaluation:* Participatory evaluation provides for active involvement in the evaluation process of those with a stake in the programme: providers, partners, customers (beneficiaries) and any other interested parties.
  Participation typically takes place throughout all phases of the evaluation: planning and design; gathering and analysing the data; identifying the evaluation findings, conclusions, and recommendations; disseminating results; and preparing an action plan to improve programme performance.
- *Rapid participatory appraisal/assessment:* Originally used in rural areas, the same methodology can, in fact, be applied in most communities. It is semistructured and carried out by an interdisciplinary team over a short time.
- *External evaluation:* This is an evaluation conducted by a carefully chosen outsider or outside team.

Project evaluation involves:

(i) Looking at what the project or the organization intended to achieve. What difference did it want to make? What impact did it want to make?
(ii) Assessing its progress towards what it wanted to achieve and its impact targets.
(iii) Looking at the strategy of the project.
(iv) Looking at how it worked.

The main questions in an evaluation should address:

(a) Effectiveness: Is the project or programme achieving satisfactory progress toward its stated objectives? The objectives describe specifically what the project is intended to accomplish. Accomplishments on this level are sometimes referred to as project outputs (what was done), and are assumed to be linked to provision of inputs (human, financial and material resources contributed to achieve the objectives).

(b) Efficiency: Are the effects being achieved at an acceptable cost, compared with alternative approaches to accomplishing the same objectives? The project may achieve its objectives at lower cost or achieve more at the same cost. This involves considering institutional, technical and other arrangements as well as financial management. What is the cost-effectiveness of the project?

(c) Relevance: Are the project objectives still relevant? What is the value of the project in relation to other priority needs and efforts? Is the problem addressed still a major problem? Are the project activities relevant to the national strategy and plausibly linked to attainment of the intended effects?

(d) Impact: What are the results of the project? What are the social, economic, technical, environmental and other effects on individuals, communities, and institutions? Impacts can be immediate or long-term, intended or unintended, positive or negative, macro (sector) or micro (household).

(e) Sustainability: Is the activity likely to continue after donor funding, or after a special effort, such as a campaign, ends? Two key aspects of sustainability for social development programmes are social-institutional and economic (for economic development projects, environmental sustainability is a third consideration). Do the beneficiaries accept the programme, and is the host institution developing the capacity and motivation to administer it? Do they 'own' the programme? Can the activity become partially self-sustaining financially?

ENVIRONMENTAL MANAGEMENT

The environment consists of the land, air and water on the planet Earth. It encompasses all living and non-living things occurring naturally on Earth or any region thereof. The built environment on Earth comprises the areas and components that are strongly influenced by humans. A geographical area is regarded as a natural environment if the human impact on it is kept below a certain limited level.

The construction and operation of rural structures and infrastructure have the potential to introduce pollution into the environment. Pollution is the introduction of contaminating substances into the environment that lead to its degradation.

Environmental management is management of the interaction of modern human societies with, and their impact upon, the environment. The aim of management is to limit environmental pollution and degradation. In line with all management functions, effective management tools, standards and systems are required. These include the environmental management standards, systems and protocols that that have been set up to reduce the environmental impact, measured against objective criteria.

There are various international and national standards for environmental management. The ISO 14001 standard is the most widely used standard for environmental risk management and is closely aligned to the European Eco-Management and Audit Scheme (EMAS). As a common auditing standard, the ISO 19011 standard explains how to combine this with quality management.

In the tropics, various statutory agencies exist to enforce environmental standards. These include the National Environment Management Council (NEMC) of Tanzania, the Bangladesh Environment Conservation Act (BECA), the Environmental Management Authority (EMA) of Trinidad and Tobago, the Environmental Protection Agency (EPA) of Guyana, the Philippines Department of Environment and Natural Resources, the Federal Environmental Protection Agency of Nigeria.

In most countries, there is a legal requirement to conduct an Environmental Impact Assessment (EIA) before any construction project is given a license to proceed. The EIA is an assessment of the possible impact – positive or negative – that a proposed project may have on the environment, together consisting of the natural, social and economic aspects. The purpose of the assessment is to ensure that decision-makers consider the ensuing environmental impacts to decide whether or not to proceed with the project. The International Association for Impact Assessment (IAIA) defines an environmental impact assessment as "the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made."

For ongoing enterprises an annual Environmental Audit is a legal requirement in many countries. Environmental audits are intended to quantify environmental performance and environmental position. In this way they perform a function analogous to financial audits. An environmental audit report ideally contains a statement of environmental performance and environmental position, and may also aim to define what needs to be done to sustain or improve on these performance and position indicators.

WORKING PROJECT

You have visited a village in a rural part of your country. A wide range of farming activities take place in the village, including livestock keeping, chicken rearing and small-scale processing of products and animal feeds. There are also buildings scattered all over the homestead.

1. Illustrate how you would go about reorganizing the existing farmstead in preparation for future expansion.
2. With the aid of sketches, present a plan and elevations of a simple rural farm building

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Chapter 3
Graphical techniques

INTRODUCTION

Graphics are essential for planning buildings, completing engineering designs, estimating quantities of materials and relative costs and, lastly, communicating to the builder all the information that the designer has formulated.

Computing, drafting, typing and printing technologies have changed dramatically since the early 1980s. Slide rules have been replaced by calculators and computers. Drawing tables, pencils, pens, T-squares and erasers have been replaced by computers. Various computer hardware systems have been developed to process high-quality graphics at very high speeds and to keep project costs to a minimum. These technologies are known as computer-aided design and drafting (CADD).

Computer-aided design and drafting (CADD)

CADD is an electronic tool for preparing quick and accurate drawings with the aid of a computer instead of the traditional tools (pencils, ink, rulers and paper). Unlike the traditional methods of preparing drawings on a drawing board, CADD enables high-precision drawings to be created on a computer.

CADD software has generally replaced the traditional drawing board in drafting offices. In the 1990s, CADD was used only for specific high-precision engineering applications. This was a result of the high price of CADD software, which made it accessible to only a few professionals. However, as prices have fallen there has been a significant increase in the use of CADD software and it is now widely used by most professionals.

CADD software can be used to produce two-dimensional (2D) drawings directly or to build a three-dimensional (3D) model of a project, from which the software can extract 2D drawings that will be printed on paper. Some CADD software also includes modules for rendering realistic images.

Much more can be achieved using CADD than with the traditional drawing board. Some of the major capabilities are: presentations, flexibility in editing, units and accuracy levels, storage and access for drawings, sharing CADD drawings, project reporting, engineering analysis, computer-aided manufacturing (CAM), design and add-on programmes.

Using CADD to produce a building drawing has the following advantages:

- The drawings are clean, neat and highly presentable.
- The drawings can be subdivided into smaller parts that can be reused or worked on by several people.
- Updating drawings is much faster than with hand-drawn plans that would have to be redrawn.
- Drawings can be presented in different formats, thereby facilitating transfer from one system to another.
- Several integrated tools are used to check drawings for errors.
- It is possible to work with real world units – the CADD system performs scaling automatically to fit any size of paper.

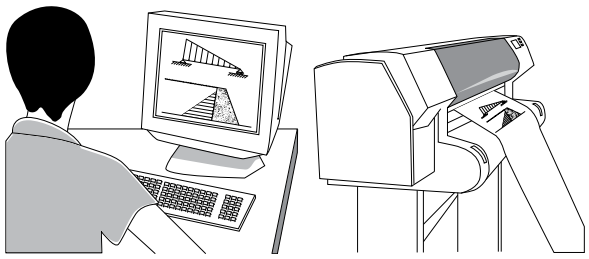


Figure 3.1 **A modern drafting office**

It should also be noted that current CADD systems are moving away from traditional drawing-oriented solutions towards fully featured architectural solutions (i.e. building information processing), which can be used not only to design a project, but also to manage the enormous quantities of information (such as materials, prices or utilization) that go into an architectural project.

CADD hardware and software

The main components of a CADD system are the hardware and the software. The CADD hardware refers to the electronic and electromechanical parts of the system. The hardware include: system unit, central processing unit, memory, hard disk, floppy disk, CD-ROM, external storage devices, monitor, printers and plotters, keyboard, digitizer and mouse.

The CADD software refers to the instructions that tell the hardware via the operating system how to perform specific tasks. A CADD programme contains

hundreds of functions to perform specific drawing tasks such as drawing objects, editing objects, data management, data storage and data output.

The CADD programme usually implements a user interface to enable the user and the computer to communicate efficiently. Most CADD applications provide a graphical user interface (GUI) for this purpose. Using the GUI, the user may communicate with the computer via menu bar, command line, tool buttons, dialogue boxes and the model space. These can be used to directly or indirectly call functions implemented in the drawing module, which supplies the user with tools to:

- draw lines
- select line types;
- draw flexible curves;
- draw arcs and circles;
- draw ellipses and elliptical arcs;
- add text to drawings;
- manipulate text styles;
- add dimensions to drawings;
- set dimension styles;
- add hatch patterns to drawings;
- draw symbols;
- draw arrows.

For a given single task, several functions are executed behind the scenes that then results into the final drawing, which is basically a grouping of individual components (lines, arcs, circles, ellipses, polylines, text, dimensions, pointers, symbols, borders and patterns). Performing the same tasks with the traditional drawing board would involve use of several instruments, which is time consuming and inaccurate. With a CADD system, all these are automated and can be performed efficiently.

The edit module in CADD programmes provides great flexibility in changing drawings. If the editing functions of CADD were not available, then it would probably take the same time to complete a drawing as it would on a drawing board. However, with editing capabilities inbuilt, CADD becomes a dynamic tool that results in significant time savings. Changes that may look extremely difficult on a drawing board can be easily accomplished with CADD. For example, even for major changes redrawing is not necessary because diagrams can be manipulated in a number of ways to rearrange existing pieces of the drawing to fit the new shape. The basic editing capabilities include erasing, moving, rotating, mirroring, scaling, copying and changing the appearance of drawing objects.

Drawings created in CADD can be stored in the computer hard drive as memory blocks called files. The user can name the files as desired, though the operating system may impose some restrictions on the use of specific characters and symbols. This is important as it enables the files to be accessed when required in the future. For example, if some work on a specific file is to be postponed to another time. Also, modifications can be made to the files for use in another project. Such a file can be renamed leaving the original file intact.

The files dealt with in a given drawing office can run into hundreds. Thus, it is important that proper file management be put in place. This is made easy by the computer as it allow files to be stored in directories and subdirectories. Files organized in this manner are easier to trace when required.

CADD design applications

The CADD system, as the acronym suggests, should have a design component inbuild. But this is not the case most of the times. Many CADD programmes have only the drafting component even if they bare the name CADD. However, mild design can be carried out with these systems. A CADD programme can only be called a design programme, if it has capabilites to solve problems and perform analyses.

Where a CADD system has design capabilities, the programme is usually based on a number of principles that will vary from product to product. The product can be based on performing calculations; it may employ comparison and logic; use a database or another form of artificial intelligence or combination of everything.

The following are some examples of design programmes:

1. *Calculation programmes:* These are extremely effective in solving complex mathematical problems.
2. *Intelligent CAD systems:* These are based on logic and comparison and have a number of applications in product design, mechanical design, spatial planning, etc.
3. *Knowledge-based CAD systems*: These are also known as expert systems. They make use of information gathered from previous projects (or parameters defined by the programmer) and use it for new design proposals.

PROJECTIONS

Projections are often useful in presenting a proposed building to someone who is not familiar with a presentation in the form of plans, sections and elevation drawings. Isometric or oblique projections are useful for presenting a pictorial, although slightly distorted, view of a structure. The axonometric projection is best suited to showing the interior of rooms with their furniture, equipment or machinery. The two-point perspective, which is a little more complicated to construct on a drawing board, can be generated easily using CADD and gives a true pictorial view of a building as it will appear when standing at about the same level as the building and at some distance.

All types of projection can be constructed to scale, but they become really useful to the building designer once the technique is so familiar that most of the details

in the drawing, and eventually even the major contours of the picture, can be drawn freehand.

Isometric projection

With isometric projection, horizontal lines of both the front view and the side view of the building are drawn 30° from the horizontal using dimensions to scale. Vertical lines remain vertical and the same scale is used. Simple 2D functions can be used and lines drawn at specific angles to complete an isometric drawing. Polar coordinates are particularly helpful for measuring distances along an angle.

Oblique projection

An oblique projection starts with a front view of the building. The horizontal lines in the adjacent side are then drawn at an angle, usually 30° or 45°, from the horizontal. The dimensions on the adjacent side are made equal to 0.8 of the full size if 30° is used, or 0.5 if 45° is used.

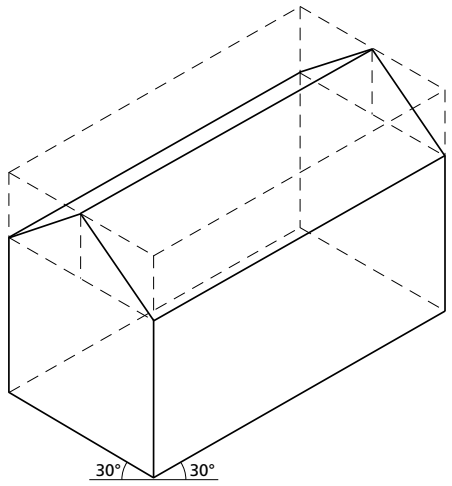


Figure 3.2a **Isometric**

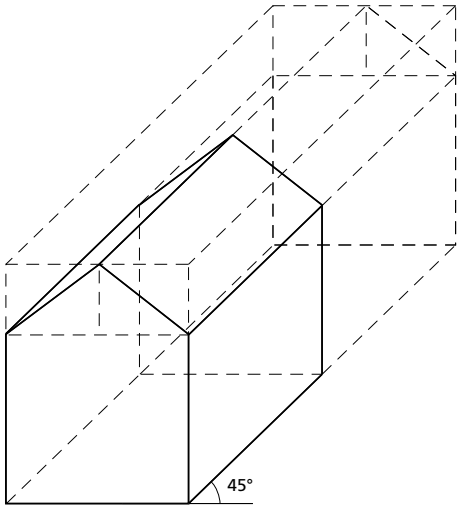


Figure 3.2b **Oblique projections**

Axonometric projection

In an axonometric projection, the plan view of the building is drawn with its side inclined from the horizontal at any angle. Usually 30°, 45° or 60° is chosen because these are the angles of a set square. All vertical lines of the building remain vertical and are drawn to the scale of the plan view.

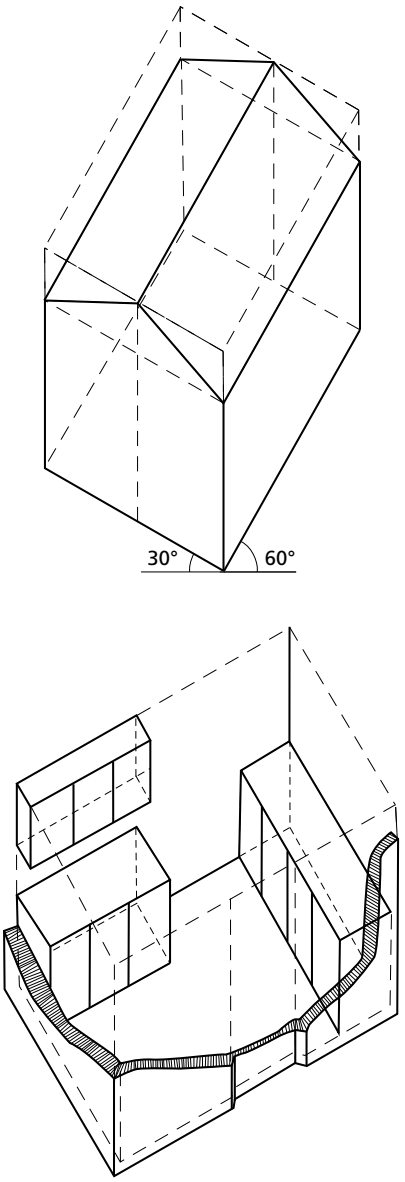


Figure 3.3 **Axonometric projection**

PERSPECTIVE

The different technical terms used in perspective drawing can be explained by imagining that you are standing in front of a window looking out at a building from an angle where the two sides of the building are visible. If you then trace on the window pane what is seen through the glass, this gives the outline of the building. This results in a perspective drawing of the

building and, if the glass could be removed and laid on the drafting table, the drawing would look like a perspective drawing made on paper.

The station point is the viewing point, supposedly occupied by the eye of the observer. The viewing point is also determined by the eye level, usually assumed to be 1.7 metres above ground level. Looking across a large body of water or a plain, the sky and water/ground appear to meet in the distance, on the horizon line. This must always be considered to be present, even when hidden by intervening objects. The horizon line is at eye level.

When standing and looking down a straight road, the edges of the road appear to meet at a point called the vanishing point, which is on the horizon line and therefore also at eye level. Similarly, the parallel horizontal lines of a building appear to meet at vanishing points, one for each visual side.

The outline of the building is brought to the window by your vision of the building, along the vision rays. The picture is traced on the window pane, which is called the picture plane.

As the technique with a window pane obviously cannot be used for a proposed, but still non-existent building, the perspective has to be constructed from available documentation. A perspective drawing of a building can be constructed using the plan view or, if several buildings are to be included, the site plan may be more suitable. In addition you need elevations of all visual sides of the building(s), i.e. in the case of one building the front elevation and one end elevation.

THREE-DIMENSION DRAWING AND MODELLING IN CADD

The isometric, oblique and perspective views of objects can be easily, accurately and efficiently drawn in CADD. CADD also provides a great deal of flexibility in terms of editing and display compared to the drawing board.

Two methods can be used to draw 3D object. The drawings can be done using 2D functions or 3D functions. The 2D approach enables the designer to draw 3D objects in the traditional drawing board style in which drawing tools such as lines, arcs and ready to use 2D objects can be joined together to come up with the desired drawing. The 2D approach is quick way to draw simple isometric and oblique views. However, 3D objects drawn in this manner are static just as they are in traditional drawing board.

The inclusion 3D modules within a CADD system greatly enhances it 3D drawing capabilities including ability to perform 3D modelling and the ability to derive the 3D models from their 2D drawing views. The 3D capabilities enable the designer to create 3D models that are virtually realistic as the actual objects and can even be made better by rendering programmes. The models developed can be rotated on the screen, displaying views from different angles. This is advantageous when the designer need to view the model at different angles so as to make necessary adjustment and during presentations to the clients, who are then able to view the end product in a virtual world and suggest changes if desired. The 3D models developed can be wire-frame, surface or solid

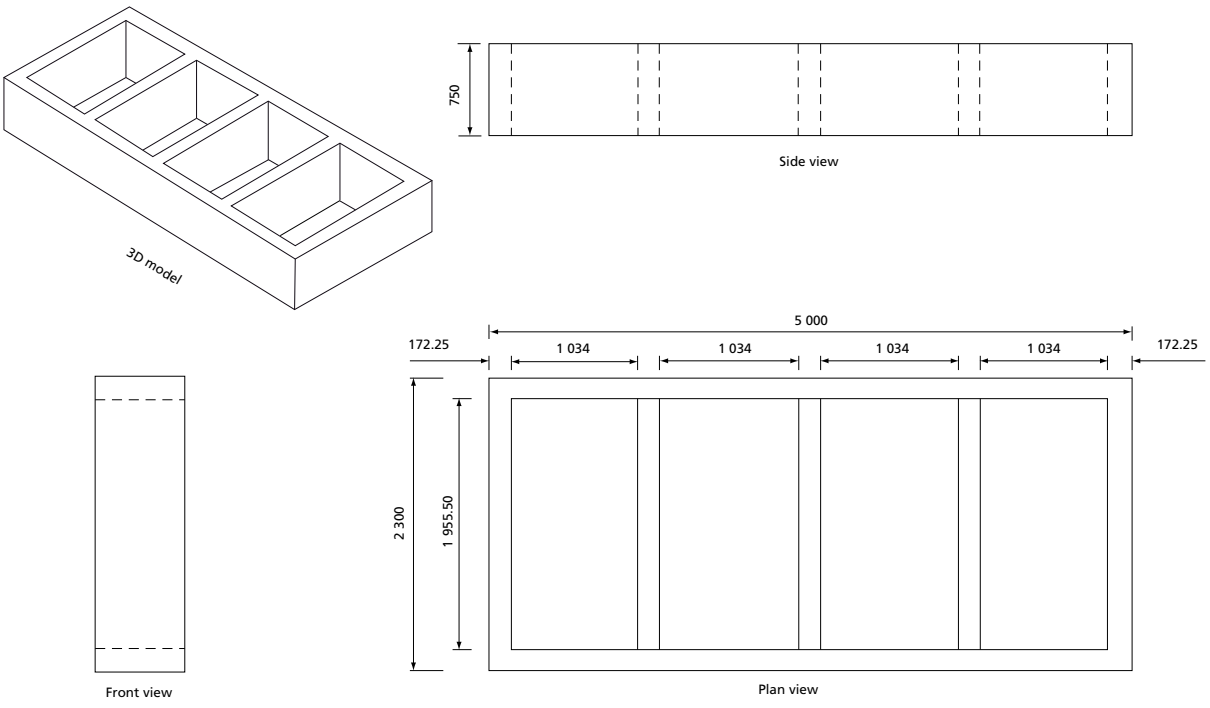


Figure 3.4 **Three-dimensional modelling**

models. Figure 3.4 shows a 2D drawing together with its 3D model developed within a CADD system.

PRINTING AND PLOTTING PROCESS

CADD drawings are printed using a printer or a plotter. The printing process is as simple as selecting the print or plot function from the menu. This action sends data from the computer to a printer or plotter, which produces the final drawing. The drawings are neat, clean and – depending on the quality of the printer – highly accurate.



Figure 3.5 **A plotter in use**

A number of parameters can be specified to control the size and quality of a plot. A drawing can be plotted to any size by applying an appropriate scale factor. Line thicknesses and colours can be specified for different drawing objects. A number of other adjustments can also be made, including rotating a plot, printing only selected areas of a drawing, or using specific fonts for text and dimensions.

The following are the most important considerations for plotting:

- selecting a scale for drawings;
- composing a drawing layout;
- selecting text and dimension heights;
- choosing pen colours and line weights.

Selecting a scale for drawings

When working on a drawing board, a specific scale can be used to draw diagrams. For example, when a plan of a building or a township has to be drawn, the size of the diagrams can be reduced to 1/100 or 1/1000 of the actual size, i.e. using a scale of 1:100 or 1:1000. When a diagram of a small machine part has to be made, it is drawn many times larger than its actual size. CADD uses the same principle to scale drawings but takes a different approach.

Standard paper sizes used for plotting

As building drawings include many details, they should be large enough to be accurately executed and easily read. The standard formats from the A-series should be used for all drawings for a building. However, several detailed drawings may be put on one sheet. The A-series includes the following sizes:

A0	841 × 1189 mm
A1	594 × 841 mm
A2	420 × 594 mm
A3	297 × 420 mm
A4	210 × 297 mm

If the building plans tend to be very long, one of the following alternative sizes may be useful:

A10	594 × 1189 mm
A20	420 × 1189 mm
A21	420 × 841 mm
A31	297 × 841 mm
A32	297 × 594 mm

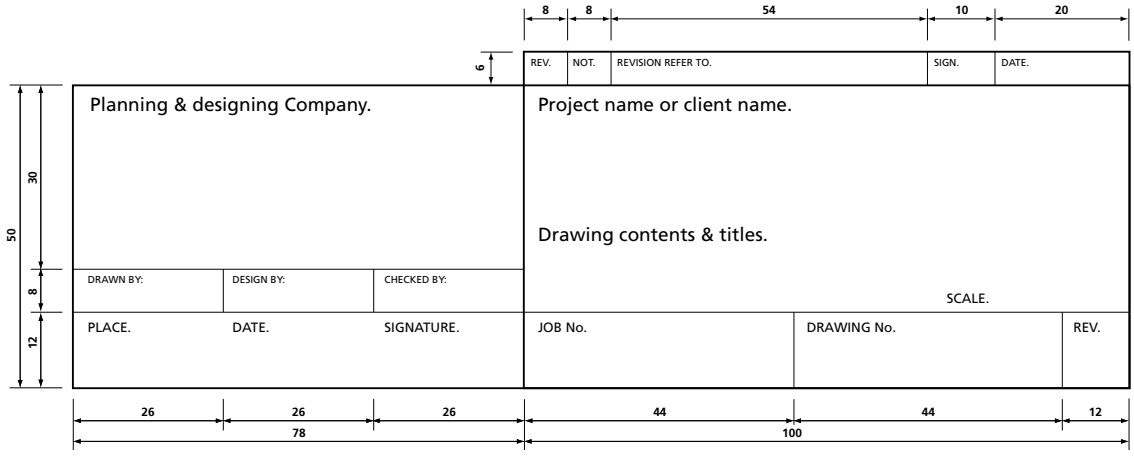


Figure 3.6 **Title box with revision table**

If possible, only one format should be used for all drawings in a project, or alternatively all drawings should be of equal height. The formats A0, A10 and A20 are difficult to handle and should therefore be avoided. It is better to use a smaller scale or divide the figure into more drawings.

CADD provides a number of special functions to compose a drawing layout. Diagrams can be arranged on a sheet as required and any scale factor can be applied. The drawing can then be plotted on the best fitting standard paper size.

Title box

All drawings must have a title box, as shown in Figure 3.6.

Note that the lines indicating the dimension limits do not touch the figure.

Architectural symbols

These are graphical representations of different features that appear on blueprint plans or elevation drawings of buildings. The graphics themselves can vary in appearance from one plan to another, but can usually be distinguished fairly easily by anyone with a basic understanding of their meaning.

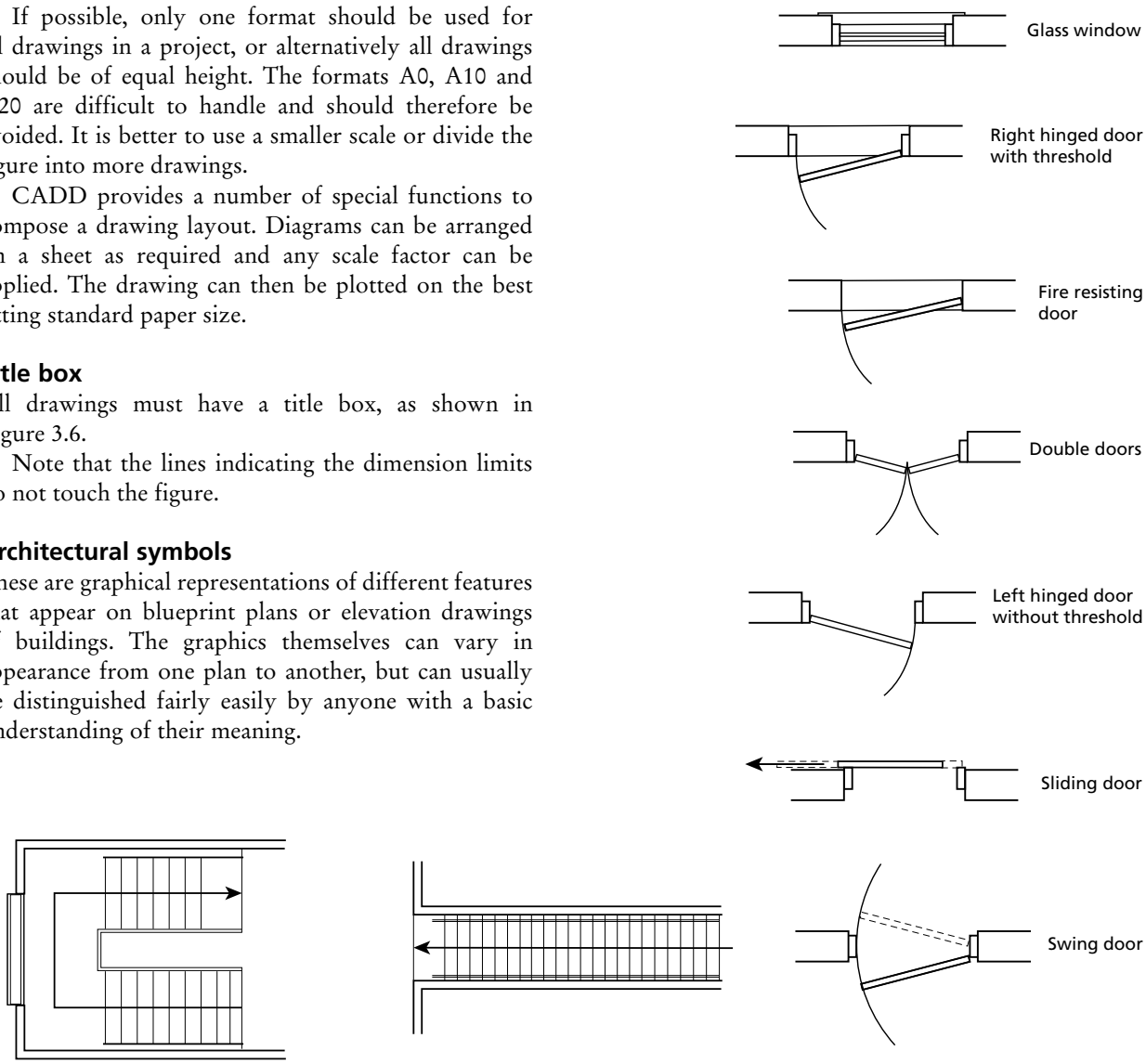


Figure 3.7 **Architectural symbols**



Figure 3.8 **Symbols for installations in buildings**

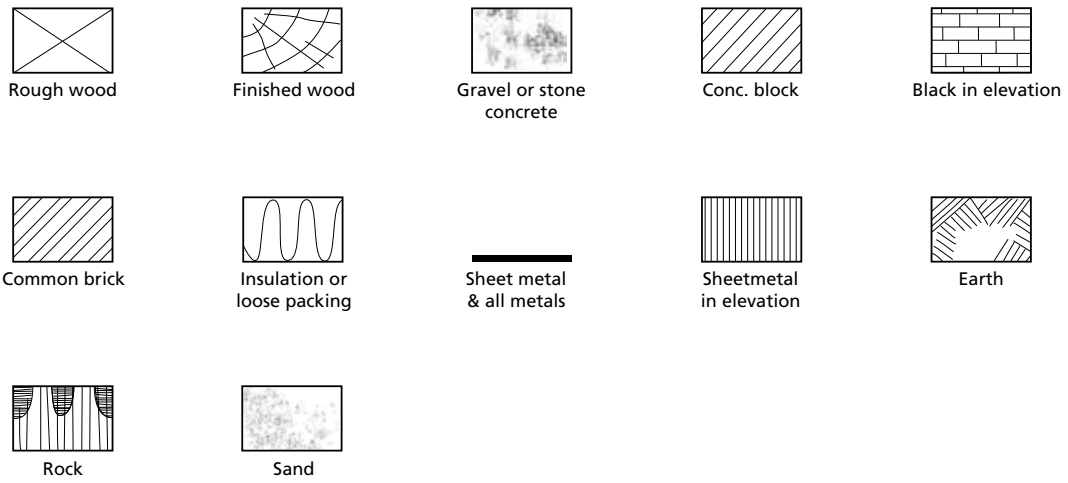


Figure 3.9 **Symbols for materials**

DOCUMENTATION FOR A BUILDING PROJECT

A building project normally requires several types of drawing that will be discussed in sequence in this section. In small- and medium-sized projects, two or three drawings may be combined into one, whereas in large projects each title listed may require several drawings. It is not advisable to include so much information in one drawing that interpretation becomes difficult.

Site plan

Scale 1:1000, 1:500 or 1:200

The location of the building in relation to its surroundings, including:

- existing buildings, roads, footpaths and gravelled or paved areas;
- the topography of the site with both existing and finished levels;
- plantings, fences, walls, gates, etc.;
- north point and prevailing wind direction;
- the extent of earthworks including cutting, filling and retaining walls.

Plan of external service runs

Scale 1:500, or 1:200

The layout of external service runs including:

- electricity and telephone;
- well or other source of water;
- drainage (run-off rainwater, groundwater);
- drainage (wastewater, urine, manure);
- sanitation (septic tank, infiltration).

External service runs are often included in the site plan or the foundation plan.

Foundation plan

Scale 1:200, 1:100 or 1:50

- Earthwork for foundation;
- drainage;
- footings and foundation.

Plan view

Scale 1:200, 1:100 or 1:50

- Outer walls;
- load-bearing walls;
- partitions;
- main openings in walls and partitions (doors and windows);
- door siting;
- stairs in outline;
- fixed equipment, cupboards and furniture;
- sanitary fittings;
- major dimensions and positions of rooms, openings and wall breaks;
- section and detail indications;
- room names;
- grid and column references (where applicable);
- in multistorey buildings a plan is required for each floor.

Section

Scale 1:100 or 1:50

- Structural system for the building;
- major dimensions of heights, levels and roof slopes;
- annotations on materials for walls, ceiling, roof and floor;
- foundation (if not in a separate foundation plan).

Elevation
Scale 1:200, 1:100 or 1:50
- Doors;
- windows;
- miscellaneous external components;
- shading and hatching for the texture of facing surfaces (optional);
- dimensions of all projections from the building, including roof overhangs.

Details
Scale 1:20, 1:10, 1:5, 1:2 or 1:1
The information that builders need for each element of the building they are to construct may be classified as follows:
- What has to be installed or erected, including information about its nature and the physical dimensions.
- Where it is to be placed, requiring both graphical and dimensional information regarding its location.
- How it is to be placed or fixed in relation to adjacent elements.

The designer must include all details necessary for the builder to complete all elements of the building. When standard practice, general specifications or building codes are not followed, it is particularly important to include complete detail drawings, annotations and specifications.

Where prefabricated elements are used, for example windows, a specification rather than a detail drawing is adequate. This allows the builder to choose the least expensive alternative that meets the specification.

Where machinery and equipment require special foundations, supports, openings and cavities, the required detail drawings will, in most cases, be supplied by the manufacturer.

Often there is no need to produce detail drawings specifically for each project. An established drawing office will have detail drawings covering the most frequent requirements, which may be affixed to current projects.

Plan of electrical installations
Scale 1:200, 1:100 or 1:50
- Incoming power supply and all wire locations;
- main switch, fuses and meter;
- location of machinery and switches;
- location of lighting points and switches, both internal and external;
- sockets;
- annotations and dimensions.

Plan of water and sanitary installations
Scale 1:200, 1:100 or 1:50
- Pump, pressure tank, storage tank;
- water heater;
- water pipe locations;
- tapping points, valves and control equipment;
- wastewater pipe location;
- wastewater drains and sanitary installations;
- annotations, dimensions, levels and slopes.

List of drawings
Where there are several drawings for a building project, the loss or omission of a single drawing can be avoided by listing all of them on an A4 sheet. Information on the latest revisions ensures that all drawings are up to date.

Technical specifications
The technical specifications should set out quality standards for materials and workmanship for the building elements that have been described in the drawings. Where general specifications are available they are commonly referred to and only variations are specified in the technical specifications.

However, in drawings for small- and medium-sized farm building projects, there is a tendency to include directly on the drawings much of the information normally given in the specifications.

As a basic rule, information should be given only once, either in the specifications, or on the drawing. Otherwise there is a risk that one occurrence will be forgotten in a revision and thus cause confusion.

Functional and management instructions
Frequently information has to be transferred to the person using a structure to enable him or her to utilize it in the most efficient way, or the way intended by the designer. In a pig house, for example, different types of pen are intended for pigs of different ages. Alleys and door swings may have been designed to facilitate the handling of pigs during transfer between pens. In a grain store, the walls may have been designed to resist the pressure from grains stored in bulk to a specified depth.

Bill of quantities
The bill of quantities contains a list of all building materials required and is necessary to make a detailed cost estimate and a delivery plan. It cannot be produced, however, until the detailed working drawings and specifications have been completed. Bills of quantities are further discussed in Chapter 9 of this text.

Cost estimate
The client will require a cost estimate to determine whether or not the building should be constructed. Clients need to know whether the proposed design is within their financial means and/or whether the returns on the intended use of the building justify the investment.

	Activities	Month n.														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Prepare working drawings															
2	Prepare bills of quantities															
3	Tendering															
4	Site clearing & excavation															
5	Building operations															
6	Delivery of feed and animals															
7	Commencing farrowing							*	→							
8	Commencing sale of pigs															* →

Figure 3.10 **Time schedule**

Time schedule

A simple progress chart, as shown in Figure 3.10, will considerably facilitate the planning of building operations and subsequent activities.

Farmers may obtain information concerning when they and any farm labourers will be involved in construction operations, when animals and feed should be delivered, when a breeding programme should be started, or the latest starting date for the construction of a grain store to be completed before harvest. This is the type of information needed to enable the returns on the investment to be realized as early as possible. A contractor will require a more detailed chart for the actual construction operations to ensure the economical use of labour, materials and equipment.

MODEL BUILDINGS

Even people with a good basic education will need considerable experience to be able to envisage fully a building from a set of drawings. The rural building engineer will therefore soon learn that the average rural dweller not only finds it very difficult to understand simple plan view and section drawings, but may even find it hard to interpret fully rendered perspectives. However, the fact that a model, unlike drawings, is three-dimensional and thus can be viewed from all sides brings more realism to the presentation and usually results in better communication and transfer of ideas.

There are three types of model in common use for the presentation of rural building projects:

- Three-dimensional maps or site plans are used to present development plans for large areas or the addition of a new building on an old site with existing structures. These models have contours to show the topography, while structures are rendered in simple block form with cardboard or solid wood, usually with no attempt to show detail.
- Basic study models are used to examine the relationships and forms of rooms and spaces in proposed buildings. They are often built of cardboard or are computer-generated using 3D graphics, and there is usually little attempt to show details, although furnishings and equipment may be indicated. Windows and door openings are shown with dark-coloured areas or left open. Contours are shown only if they are of importance for the building layout.
- Fully developed models may be used in extension campaigns, for public exhibition, etc. These models show details to scale and represent as accurately as possible the actual materials and colours. Part of the roof is left out or made removable in models aiming to show the interior of a building and, with current CADD software, it is even possible to make a virtual tour of the building.

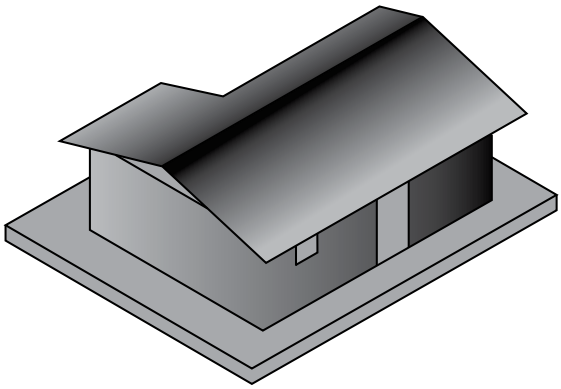


Figure 3.11 **Computer-generated 3D model**

Physical model

Where the model is to be physically built, a sturdy base for the model, made of either plywood or particle board, not only facilitates handling but also helps to protect the model. For models to be displayed in public, it is

advisable to have well-finished borders, preferably in hardwood and, although expensive, an acrylic plastic (plexiglass) cover. During transport, a plywood box without a bottom, fixed to the base of the model with screws, will provide sufficient protection if handled with care. Otherwise, where appropriate, a full virtual tour of a building project can be shown to the public directly from a computer using an electronic projector.

The size of the model is determined by the scale to which it is made and the size of the actual project. While detail is easier to include in a model made to a large scale, too much detail may distract from the main outlines and essential features. If the model is too large it will be more costly and difficult to transport. Basic study models are often made to a scale of 1:50 or 1:100 to allow for coordination with the drawings, while fully developed models of small structures may be made to a scale of 1:20 or even larger. Whatever scale is used for the model, it is desirable to include some familiar objects, such as people or cars, to the same scale as the model to give the observer an idea of the size of the actual structure.

The construction of contours and elevations requires access to a map or a site plan with contour lines to the same scale as that used in the model. One way of showing contours is to build up a model with layers of cardboard or styrofoam sheets of a thickness equal to the scale of the real difference in height between contour lines. Employing one piece of cardboard for each contour line, trace the line onto the cardboard using carbon paper, cut out the contour, place it on the model and secure it with glue. The contours can either be left as they are, giving sharp, distinct lines, or be smoothed to a more natural slope using sandpaper or filler.

For more elaborate models the landscaping may be represented by painting. Trees and bushes can be made from pieces of sponge or steel wool on twigs or toothpicks. Coloured sawdust can be used for grass and fine sand for gravel. If available, model railroad supplies and other hobby materials can be useful.

Although the same materials employed in the actual building, or close simulations, are used for the most elaborate models, cardboard (or for models made to a large scale, plywood) is usually easier to work with and can be finished by painting to represent most types of material. Cardboard or plywood of the right scale thickness for use as walls is often unavailable, but it will make no difference as long as the overall scale and dimensions of the building are maintained.

Round wooden posts commonly used in farm buildings for post-and-beam or pole construction can be conveniently made from twigs or hardwood sticks. Any finish on the walls to represent openings or materials should be applied before the model is assembled. Neat, clean-cut lines are easier to achieve in this way. While a plain cardboard roof is adequate for most purposes, corrugated paper painted in a suitable colour may be used to represent corrugated roofing materials, and thin grass glued to the cardboard can be used to represent thatch.

The strength and rigidity of models can be increased by bracing the walls with square pieces of cardboard in positions where they will not be seen in the finished model. Bracing is particularly important in models that are going to be painted, as paint tends to warp cardboard and sheet wood if applied over large areas. Regardless of the material being represented, colours should be subdued and have a matt, not glossy, finish. Distemper or water colour is best for use on cardboard and unsealed wood, but care must be taken to remove excess glue, as this will seal the surface and cause the colour to peel off.

A photograph of the model may be used in cases where it is not feasible to transport the model, or when photos need to be included in information material but the actual building has not yet been completed. Models often appear more realistic when photographed, particularly in black and white because of the better contrast, but adequate lighting from a direction that produces a plausible pattern of sun and shade on the building should be used. Outdoor photography allows the sky or terrain to be incorporated as a background in the photograph of the model.

Computer-generated models

These models can be built directly using 3D CADD software or from the 2D drawings of the building. Once the model is complete, the addition of features to the model from the material library can achieve a realistic model picture. The quality of the model can be further improved by the use of rendering software. If the CADD software allows, the developed model can be used to simulate different conditions that may be experienced in the real building. For example, the building may be oriented in different directions and the effect of environmental factors such as wind and solar radiation can be studied to achieve the optimum design conditions.

REVIEW QUESTIONS

1. What are the advantages of CADD over manual drafting?
2. Outline some of the capabilities of a CADD system.
3. Describe the components of a CADD system.
4. How can a designer benefit from the 3D capabilities of a CADD system?
5. What are the advantages of developing a computer-generated model over a physical model of a building project?

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Chapter 4
Geospatial techniques

INTRODUCTION

Geospatial technology is an integration of various technologies in the mapping, visualization and recording of phenomena in the Earth system and space. Down through history humankind has been attempting to fully understand and document the Earth, and this has driven innovation in geospatial science to the current state of the art.

Geospatial technology encompasses the following specialist areas:

1. *Engineering survey*: This involves the preparation of maps and plans for planning and designing structures, as well as ensuring that they are constructed in accordance with the required dimensions and tolerances.
2. *Geographic Information Systems*: This involves collecting and manipulating geographic information and presenting it in the required form.
3. *Cartography*: This is the accurate and precise production of maps or plans and the representation of the information in two or three dimensions.
4. *Photogrammetry*: This involves obtaining information from photographic images in order to produce a plan of an area.
5. *Hydrographic survey*: This involves measuring and mapping the Earth's surface that is covered by water.

In the development of rural structures, the engineering survey is most important because it allows:

1. Investigation of land using manual or computer-based measuring instruments and geographical knowledge to work out the best position for constructing buildings, bridges, tunnels, water channels, fences and roads.
2. Production of plans that form the basis for the design of rural structures.
3. Setting out a site so that a structure is built in the correct position and to the correct size.
4. Monitoring the construction process to make sure that the structure remains in the right position, and recording the final position of the structure.
5. Provision of control points by which the future movement of structures, such as roads, water dams, channels and bridges, can be monitored.

In large and complicated projects, it is necessary to engage the services of a geospatial expert, also known as a surveyor. In small buildings or infrastructure projects, and other professional, such as an engineer, may perform the geospatial tasks.

At different times in history, a variety of tools have been developed and used for land measurement, plan production and setting out buildings. These range from pacing methods to hand-held instruments. The various methods are discussed in the section 'Survey of a building site'.

SURVEY OF A BUILDING SITE

A simple survey of a building site provides accurate information needed to locate a building in relation to other structures or natural features. Data from the survey are then used for drawing a map of the site, including contours and drainage lines if needed. Once located, the building foundation must be squared and leveled. This section covers the various procedures involved.

Distances

Steel tapes or surveyor's chains are used for measuring distances when stations are far apart and the tape or chain must be dragged repeatedly. Linen or fiberglass tapes are more suitable for measuring shorter distances such as offsets when making a chain survey or laying out a foundation. To obtain accurate results, a chaining crew must first practice tensioning the chain or tape so that the tension will be equal for each measurement.

Range poles are 2 to 3 metres metal or wooden poles painted with red and white stripes, and are used for sighting along the line to be measured.

Land arrows come in sets of 10 and are set out by the lead person in a chaining crew and picked up by the following person. The number picked up provides a check on the number of lengths chained.

A field book is used for drawing sketches and recording measurements.

When measuring for maps or site plans, horizontal distances are required. Thus, when chaining on sloping land, stepping will be necessary. This procedure allows the tape or chain to be kept level, as checked with a hand or line level, while the point on the ground under the high end of the tape is located with a plumb-bob, as shown in Figure 4.1.

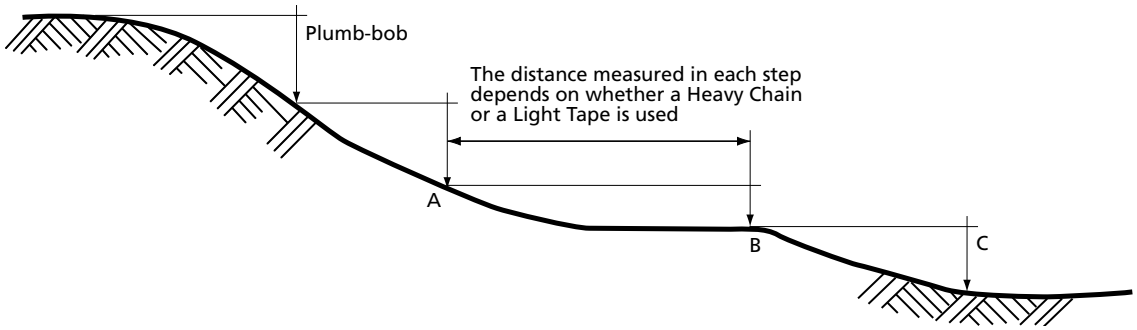


Figure 4.1 **Stepping on sloping ground**

Angles

There are several types of tripod-mounted levels available, some of which are equipped with horizontal rings allowing them to be used for measuring or setting out horizontal angles. Theodolites are designed to measure or set out both horizontal and vertical angles. Although these surveying instruments provide the most accurate means of measuring angles, they are expensive and rather delicate. Fortunately much of the surveying of rural building sites involves only distances, 90° angles and contours that can be measured or set out with fairly simple equipment.

One simple yet accurate means of setting out the 90° corners of a building foundation makes use of the Pythagorean Theorem, or the 3–4–5 Rule (or any multiple of the same).

Starting at the corner of the foundation site, a line is stretched representing one side of the foundation. A distance of 4 metres (m) along the line is marked. Then another line is stretched from the corner at approximately 90°, and 3 m is measured along this line. When using the tape between the 4-m and the 3-m marks, the second line is swung slightly until exactly 5 m is measured between the marks. The first two lines then form a 90° angle.

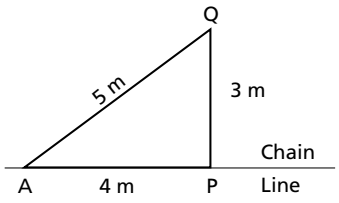


Figure 4.2a **The 3–4–5 Rule**

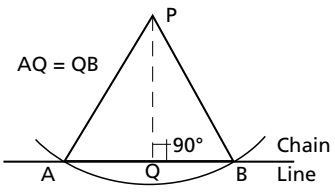


Figure 4.2b **Erecting a perpendicular**

Figure 4.2 illustrates this procedure, as well as the method of swinging an arc to erect a perpendicular.

Two simple instruments for setting out right angles are the cross-stave and the optical square (Figure 4.3). Either can be mounted at eye level on a range rod at the corner where the angle is to be set out. The instrument is then turned carefully until one line of the right angle can be sighted. The second line can then be swung slightly until it can also be sighted.

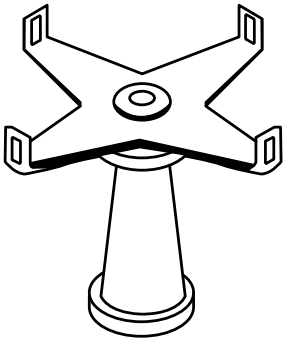


Figure 4.3a **Cross-stave**

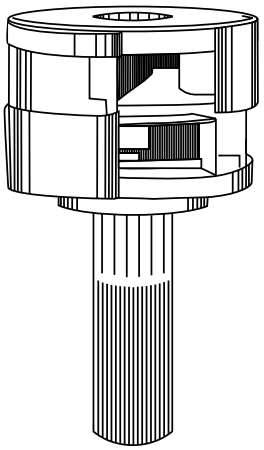


Figure 4.3b **Optical square**

Vertical alignment

A surveyor's plumbline consists of a sturdy cord, a distance bar and a conically shaped plumb-bob with a hardened steel point. It is used for positioning surveying instruments or when stepping with a tape or chain. It may also be used to check the vertical alignment of foundations, walls and posts. A simple plumbline for these jobs can be made from string and a stone (see Figure 4.4).

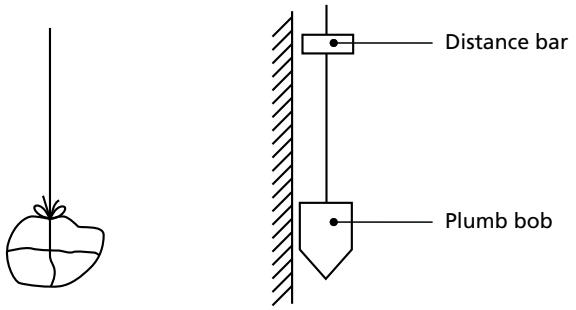


Figure 4.4 **Plumb bobs**

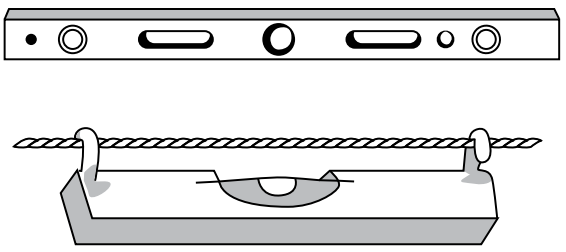
Leveling

Just as in the case of angle measurement, there is a wide variety of surveying instruments used for leveling. Most are designed for accuracy and are rather expensive. Although built for use in the field or on a building site, as with any precision instrument they require careful handling and regular attention to ensure good service.

Fortunately, there are several rather simple devices that may be used for leveling foundations, running contours or aiding in step-chaining.

Builder's levels are made of wood, plastic or aluminium and are available in several lengths, 1 metre being a convenient size. The bubble tubes are graded for sensitivity to suit the work. Most are now made of plastic and filled with fluorescent liquid – an aid in poor light. see Figure 4.5.

Line levels are designed to hang on a tightly stretched line. Both of these types are useful in foundation construction work.

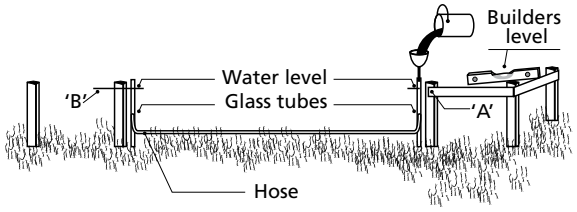


Alluminium line and surface level

Figure 4.5 **Builder's level and line level**

Hand levels and Abney levels are both hand-held instruments incorporating a spirit bubble tube and a split-image mirror. When they are held to the eye and the bubble centred, the viewer is looking at a point exactly at eye level. They are useful for keeping a chain or tape horizontal when stepping, and for doing simple contouring. The accuracy of work with either of these levels may be improved somewhat by placing the level on a rod of known length, still keeping the instrument approximately at eye level. As they have either a low-power scope or no telescope, they are only suitable for distances of up to approximately 30 metres.

For levelling the lines used in laying out a foundation, a builder's water level is a simple, inexpensive device that provides a satisfactory degree of accuracy. It consists of a length of rubber or plastic tubing, at each end of which there is a transparent sight-tube of glass or plastic. It works well over a distance of about 30 m and is particularly useful for transferring levels around corners, from outside a building to inside, or around obstacles where the two levelling points are not intervisible. It is also a useful tool for obtaining the slope in pipe runs. See Figure 4.6 for the method of use.



1 Set corner profiles at one corner as at right
2 Place hose as shown
3 Fill with water until water level is at top of corner profile A
4 Mark water level at opposite end B and set profile to mark

Figure 4.6 **Setting out corner profiles**

Chain surveying

In a chain survey, the area to be surveyed is enclosed by one or more triangles, the sides of which are measured and recorded. Then the perpendicular distance from the side of a triangle to each point of detail, such as trees, buildings or boundaries, is measured. From this information, a detailed plan of the site can be drawn to scale. A proposed structure may then be superimposed on the plan and its location transferred to the actual land site.

The following step-by-step procedure is used in a chain survey:

1. Make a preliminary survey by walking around the site, deciding where to put stations and where the main survey lines should be arranged. Stations should be selected so that they are intervisible and the lines laid out so that obstacles

are avoided. Make a sketch of the site in the fieldbook (Figure 4.7a).

2. Set the range poles, chain the triangle sides and record the distances.
3. Measure the perpendicular offsets from the chain lines to the details of the site. This will be easier to do if the chain lines have been arranged so that offsets can be kept as short as possible. Record the measurements in the field book (Figure 4.7b). Each page should record offsets along one chain line. Entries start from the bottom of the page and details are entered to the left or right of the centre column where distances along the chain line are noted. Not all details are measured by perpendicular offsets. Sometimes it is more accurate and convenient to use pairs of inclined offsets which, together with a portion of the chain, form acute-angled triangles. Note the top corner of the house in Figure 4.7b.
4. If contour lines need to be included on the map or site plan, the next step will be to measure levels with a levelling instrument and a staff.

   The grid method is most commonly used for construction projects, provided the ground does not slope too steeply. The grid is pegged out on the site in the position considered most suitable, and levels are taken at points where lines intersect. Sides of squares may be 5 m to 30 m, according to the degree of accuracy required. If the area is reasonably small, staff readings may be recorded near to each point on a sketch or drawing similar to that shown in Figure 4.7c. Alternatively, staff readings may be recorded in a field book. Each point has a reference letter and number.

   If all points on the site are within range of the levelling instrument and, providing the staff at each point can be seen through the telescope, the instrument should preferably be set up near the middle of the site so that all readings can be taken from one position. The first staff reading is made on an ordnance benchmark (OBM), if one is available in the near vicinity, or alternatively on a site datum, which may be assumed to be at a reduced level of 10 m, or any other convenient height.

   It is normal practice to leave a number of selected and carefully driven pegs in position on the site to assist in the work of setting out when development work commences.

   From the spot levels obtained by this grid method, the contours can be drawn, the volume of earth to be excavated can be calculated and the average level of the grid can be determined.
5. Make a map or site plan. Start by making a scale drawing showing the main surveying lines. Then plot the offsets to buildings and other features in the same order as they were recorded in the field book.

   If contour lines are to be included, start by drawing the grid to the scale of the drawing. The contour lines may then be indicated by interpolation. Contour points are plotted on each line between each pair of spot levels in the grid, assuming the ground has a fairly constant slope. A smooth curve is then drawn to link up points of the same height. Note that contour lines may not cross, but they may approach closely at points where the gradient of the ground surface is steep.

To produce the final map or site plan, cover the preliminary drawing with tracing paper and draw the final plan, omitting the survey lines, offset lines and grid.

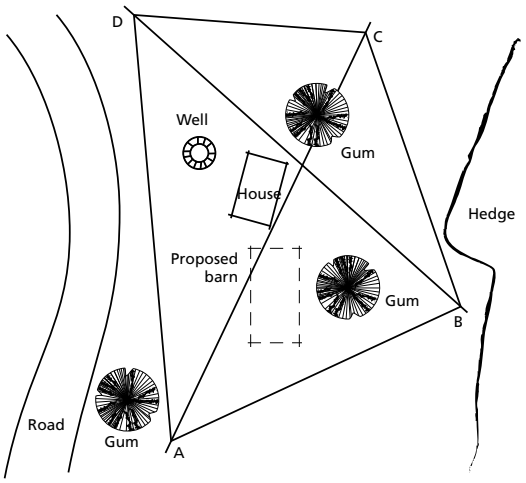


Figure 4.7a **Field book sketch of the site with stations and main survey lines**

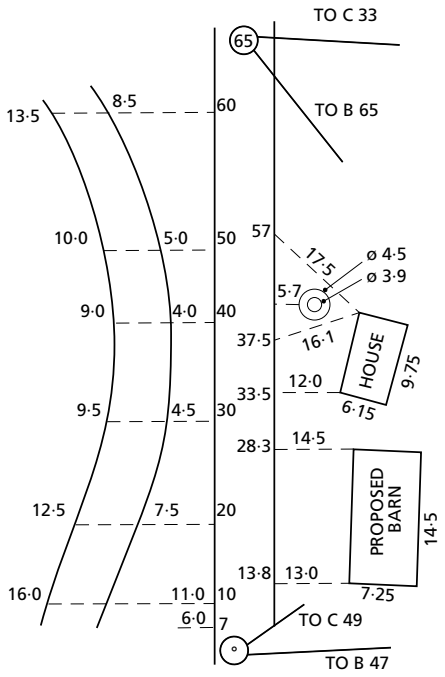


Figure 4.7b **Field book recordings of offsets along chain line A–D**

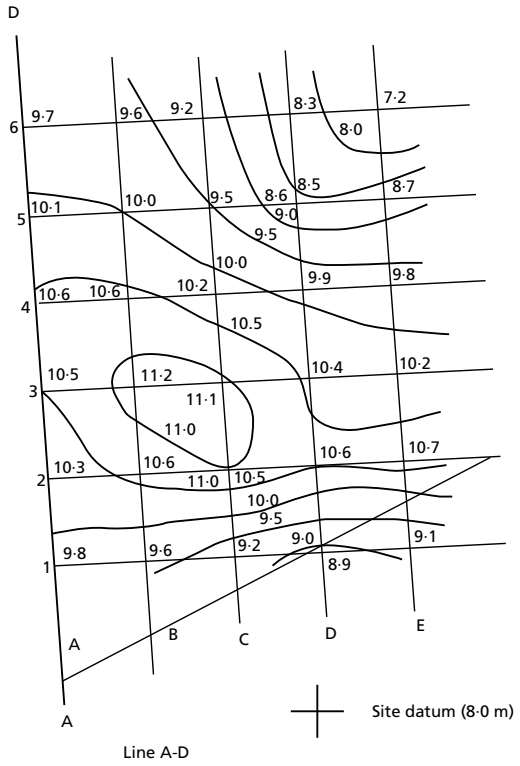


Figure 4.7c **Site plan made up to scale from field book recordings**

Setting out the building work

Before a decision about the final site of a building can be made, a number of factors need to be taken into account. Consideration must be given to local authority and planning regulations, to functional requirements, orientation, view, prevailing wind, noise, shelter, water supply, access, slope of ground, privacy and the type of soil on which to build.

Orientation can be important – perhaps the best position for comfort is an east–west alignment. This arrangement eliminates much glare by confining the sun's rays to the end walls. It also allows cross-ventilation – crucial when humidity is high.

To set out a building there needs to be a base line (one side of the building) and a fixed point on the line, usually one corner of the building. At this point, as at all other corners, a peg is first driven and then a nail is driven into the top of the peg to mark the exact position of the corner.

The distance from one peg to the next is carefully measured with a steel tape, and the peg and nail firmly driven. Depending on the size and nature of the building, the correct position of all other lines and pegs in relation to the base line and to each other may be obtained by means of:

- a levelling instrument fitted with a horizontal circle;
- a cross-stave or optical square;
- a flexible tape, using the 3–4–5 method;
- a builder's square (see Figure 4.8).

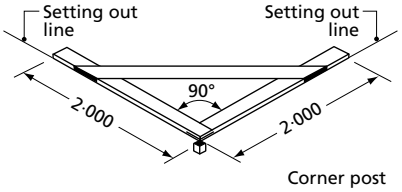


Figure 4.8 **Builder's square**

Having obtained the direction of all lines, measured all distances and driven pegs and nails at the points, the accuracy of the setting-out may be checked by measuring the overall horizontal distances in both directions. Pairs of lines should be exactly equal.

Check again the accuracy of the setting-out by measuring the diagonals of the rectangle. For buildings with sides between 5 m and 20 m long, the length of the diagonals *A* and *B* in Figure 4.9 should not differ by more than 0.5 percent. If adjustments are necessary subsequent to this check, it is advisable to keep the two longest parallel sides fixed and to make the required adjustments on the short sides.

Finally, check the drawing against the setting-out to ensure that lines and corners are in their correct positions and that dimensions are correct.

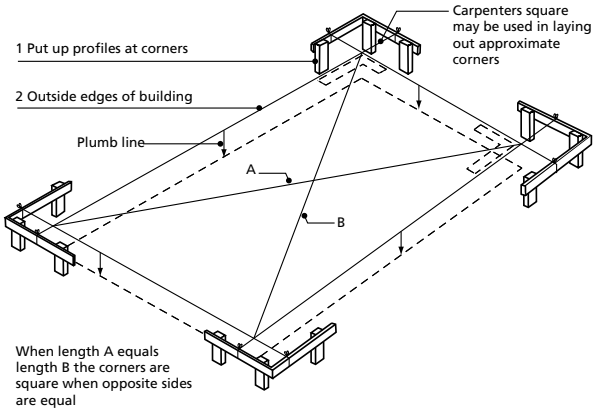


Figure 4.9 **Corner profiles and checking for accuracy**

When the setting-out and checking have been completed, timber profiles are erected. Profiles consist of horizontal rails supported by vertical pegs set up clear of the excavation. Inside and outside faces of the wall and the width of the foundation are marked on the horizontal rail by means of fine nails or saw cuts. Strings are later stretched between these nails or saw cuts on opposite rails to guide the workers during trench excavation and footing and foundation wall construction.

Ideally, profiles should be set up for all corners and internal walls. The profile shown at A in Figure 4.10 should be located at A1, if the foundation area is to be excavated.

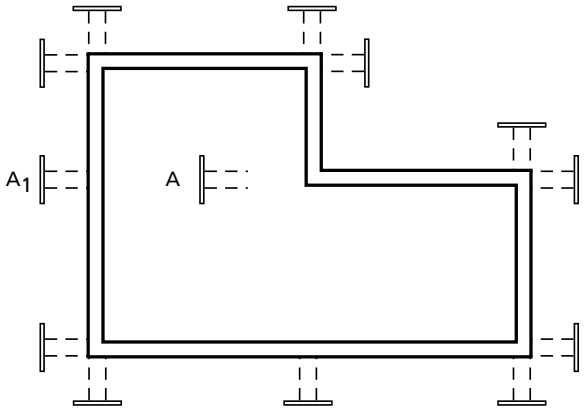


Figure 4.10 **Plan of walls and profiles**

Excavation depth control

When any building work is to be done, it is usually necessary to excavate at least a foundation trench. In many cases, if concrete is to be used, some excavation is required in order to make the floor finish at the level required. In addition, it may be necessary to finish a surface such as a roadway or ditch bottom to an even gradient. In all these cases it is necessary to control the depth of the excavation to ensure that the correct amount of soil is removed.

Sight rails

Sight rails are made either across the line of an excavation, such as a trench, as shown in Figure 4.11, or alongside an area such as a roadway or floor. If the

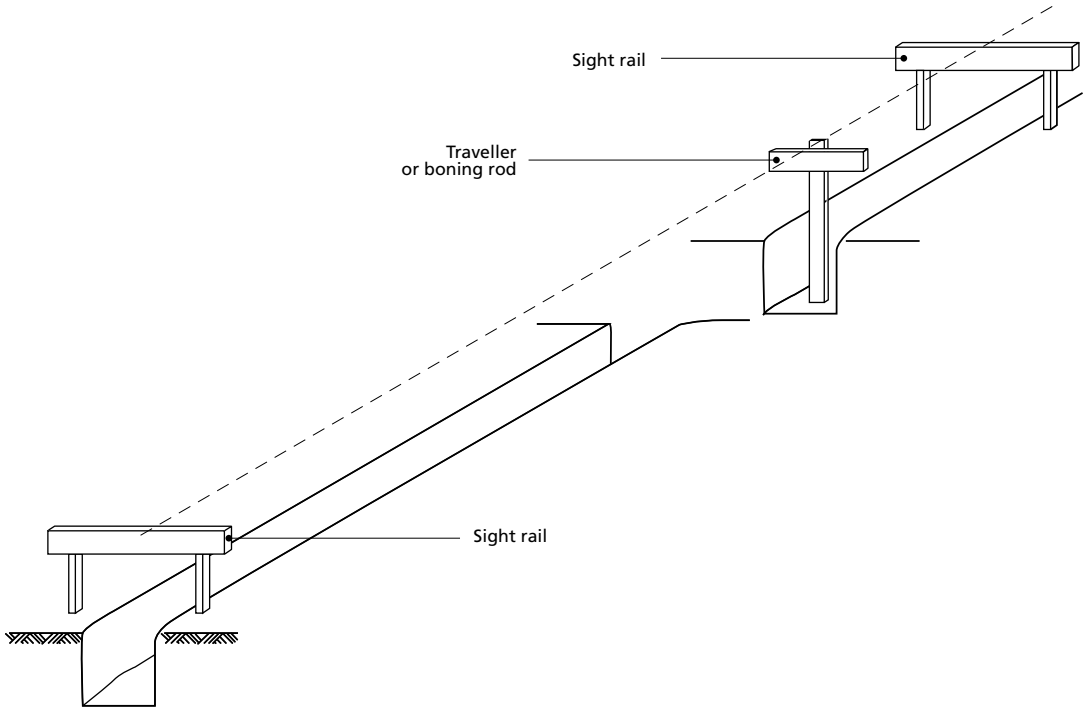


Figure 4.11 **Sight rails and traveller for boning**

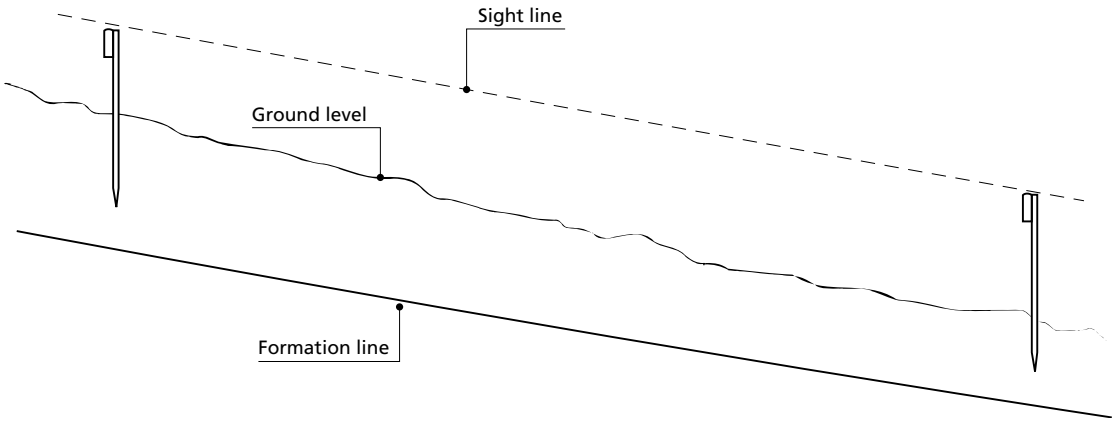


Figure 4.12 **Section between two sight rails on a gradient**

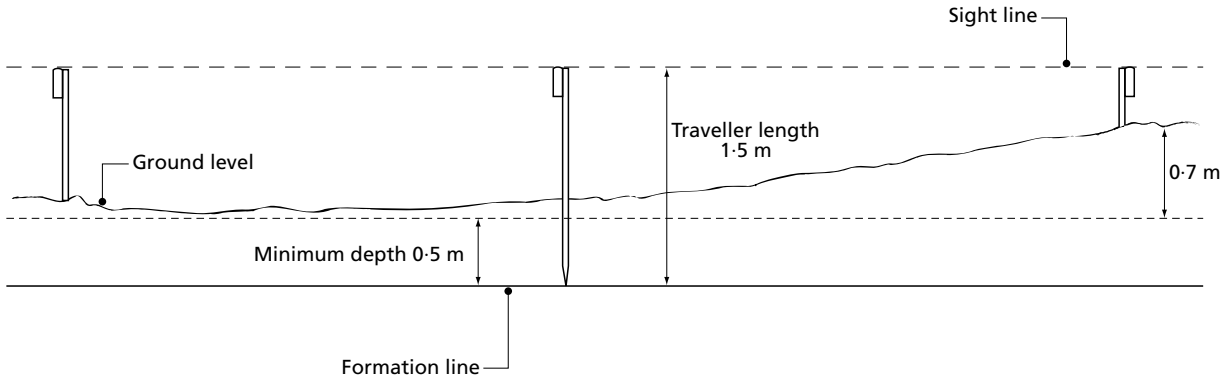


Figure 4.13 **Section showing level excavation**

excavation is to be level, then the tops of the crosspieces must all be at the same height. If there is a gradient to the excavation, however, the tops of the sight rails should be set at heights so that they fall on the same gradient (see Figure 4.12).

On a small building site it may be possible to use a long straight-edge with a spirit level to ensure that the sight rails are level. However, with longer excavations or where a gradient is required, it may be necessary to use a tape and level to achieve the appropriate fall from one sight rail to another.

Traveller

A traveller, also known as a 'boning rod', is T-shaped and normally wooden. The overall length is the same as the distance from the sight rail down to the excavation depth required, as shown in Figure 4.11. It can be an advantage, therefore, to set up the sight rails at a known height above the excavation. For example, a level excavation will normally be specified as having a minimum depth. If a trench is required with a minimum depth of, say, 0.5 m and the ground rises along the length of the trench by 0.7 m, then the first profile must be set high enough for the second to be above the ground, and a traveller of 1.5 m may be used. The first profile will then be 1 m above the ground. See Figure 4.13.

As the excavation progresses, the depth can be checked by looking across from the top of one profile to another. As long as the traveller crosspiece can be seen, the excavation is not deep enough and should be continued until the crosspiece is just invisible.

Volume of earth to be removed

The labour and expense involved in moving soil can be substantial. Careful planning and volume estimation will minimize the amount that needs to be moved.

When the land is essentially level, the volume to be removed from an excavation can be estimated by multiplying the cross-section area of the excavation by the length.

Often, however, the land has a considerable slope and must be levelled before construction can begin. Sometimes the soil will need to be removed from the site but, in many cases, soil removed from the building site can be used for fill in an adjacent area. It is rather more difficult to estimate how much to 'cut' to ensure that the soil removed just equals the 'fill' required to give a level site. Several approaches are explained in surveying books, but a graphical method using the information from the site contour map should be satisfactory for rural building construction.

A scale drawing of the building foundation is made and the contours superimposed on it (Figure 4.14a). A line is drawn through the centre of the building plan and a section constructed using the values obtained from the intersections of the contour lines and the section line (Figure 4.14b).

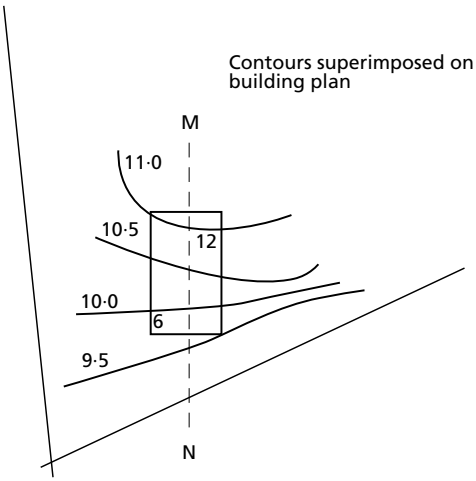


Figure 4.14a **Contours for establishing a cut and fill line**

A horizontal line is then drawn that is estimated to produce equal areas for cut and fill. The elevation of the line indicates an optimum elevation for the building. The approximate volume to be moved is given by the equation:

$V = ½\ hbw$
$= ½ \times 0.6 \times 6 \times 6$
$= 10.8\ m^3$

where
h= height above line
b = base of cut area
w = width of cut area

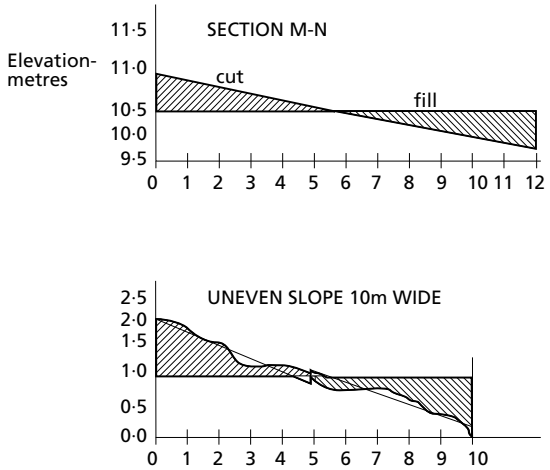


Figure 4.14b–c **Estimating cut and fill**

If the slope is not as uniform as illustrated in Figure 4.14b, the slope line must be averaged as shown in Figure 4.14c. In this example the volume to be moved is estimated to be 45.6 m^3.

$V = ½\ hbw$
$= ½ \times 1.9 \times 4.8 \times 10$
$= 45.6\ m^3$

When excavated, the volume of firm soil will increase by approximately 20 percent. If this soil is used for fill, it must either be allowed to settle for some time or be compacted to reduce it to the original volume before any construction work can begin. In addition, African soils are generally prone to settlement and erosion. Problems may be experienced in wet areas at the edge of the fill if it is not adequately stabilized with vegetation or a retaining wall. Therefore the 'cut and fill' technique should be avoided and, if used, a reinforced concrete footing may be required.

MODERN GEOSPATIAL TECHNOLOGIES

Modern scientific advances in information technology have resulted in the development of the following areas of geospatial science:

1. Remote sensing
2. Global Positioning System (GPS)
3. Geographic Information Systems (GIS)
4. Digital mapping

These technologies are important in the positioning, mapping and design of rural structures and infrastructure.

Remote sensing

Remote sensing involves the detection and measurement of radiation/reflectance of different wavelengths reflected or transmitted from distant bodies. It is the science and art of identifying, observing and measuring objects without coming into direct contact with them.

Global Positioning System (GPS)

The GPS is a system of 24 satellites owned and managed by the United States Air Force. The satellites orbit the Earth continuously and transmit radio signals that are tracked by GPS receivers on the Earth's surface to compute their three-dimensional position in an Earth-fixed coordinate frame/system. With the three-dimensional coordinates computed, the position of the receiver is defined uniquely in the three-dimensional coordinate frame.

The GPS infrastructure is composed of three segments (see Figure 4.15):

1. **Space segment**: This comprises a constellation of 24 satellites that broadcast electromagnetic signals to the GPS receivers on Earth. They also receive commands from the ground control stations.
2. **Control segment**: This monitors the space segment and sends commands to the satellites. It computes the satellite orbit data and uploads them to satellites for transmission to receivers. It also monitors the satellite clocks for synchronization and general satellite health.
3. **User segment**: This comprises satellite receivers sited on the Earth surface, including the air and the sea. The receivers record and interpret the electromagnetic signals broadcast by the satellites and compute the position to varying degrees of accuracy depending on the type of the receiver and the physical conditions.

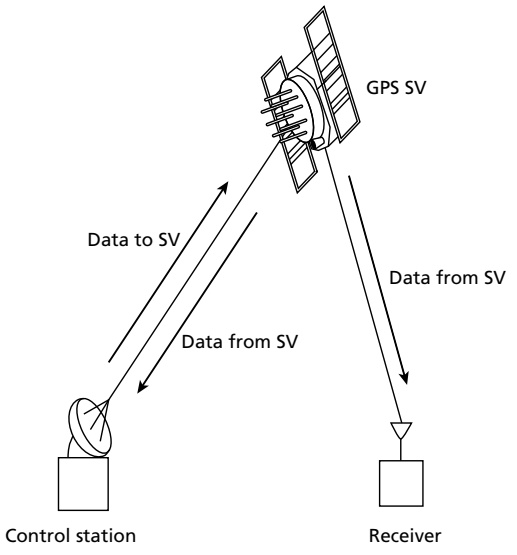


Figure 4.15 **GPS segments**

The computation of three-dimensional coordinates of points in the Earth space allows the mapping of features in a given reference system. The mapping accuracy varies according to the type of the GPS receiver used. Hand held receivers are less accurate as compared to geodetic receivers.

Principle of GPS positioning

The GPS can be explained by a simple resection process where ranges/distances/vectors are measured from a user's GPS receiver to the orbiting satellites 20 200 km above the Earth surface.

Consider a satellite S, at a single epoch (instant of GPS time system) being tracked by a GPS receiver *GR*, on the Earth surface (Figure 4.16a). The Geocentre, as shown, is the centre of the Earth with coordinates X,Y,Z (0,0,0).

The space co-ordinates of the satellite, relative to the earth centre can be determined from the ephemeris (orbit data) broadcast. The vector *r*, the geocentric co-ordinates of the satellite are therefore known. The vector/range *R*, from the receiver to satellite is normally measured by the receiver from the signals from the satellite. This is achieved by multiplying the GPS signal travel time from the satellite to the receiver and the velocity of the GPS signal.

The vector ρ, is the geocentric co-ordinate of the receiver at ground station whose values are unknown. The unknowns in this case are the three Cartesian coordinates (X, Y, Z). The solution of the three co-ordinates requires at least three equations. Given that every measured vector to a satellite produces one equation and there are three unknowns, observations to at least three satellites as shown in Figure 4.16b are required.

Using the three vector/ranges equations, the solution is computed as indicated by the following equation:

$$R_r^s = \sqrt{(X_s - X_r)^2 + (Y_s - Y_r)^2 + (Z_s - Z_r)^2}$$

where R_r^s is the range between the satellite and the receiver, (X_r, Y_r, Z_r) are the coordinates of the receiver and (X_s, Y_s, Z_s) are the coordinates of the satellite.

When the system is using code pseudo-ranges for range measurements, additional unknown, the GPS time exists, increasing the total number of unknowns to four. Thus measurements to at least four satellites are necessary (see Figure 4.16c). With carrier phase measurement, an additional unknown, the ambiguity number, is introduced. Here again, the solution will require at least four satellites. Whichever the case, any GPS measurements therefore requires observations to at least four satellites for observation positions to be determined. In this case the position of the receiver is obtained as X, Y, Z, t, where t is the time.

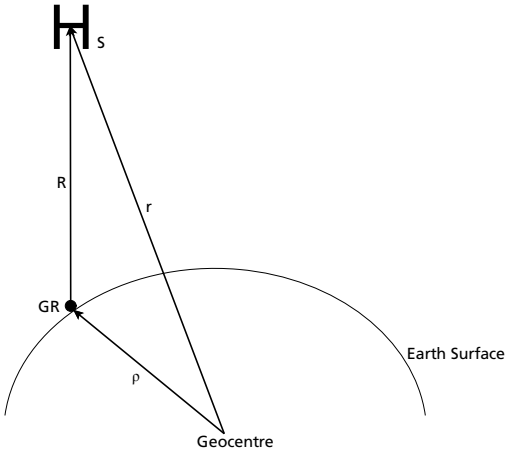


Figure 4.16a **One satellite tracking**

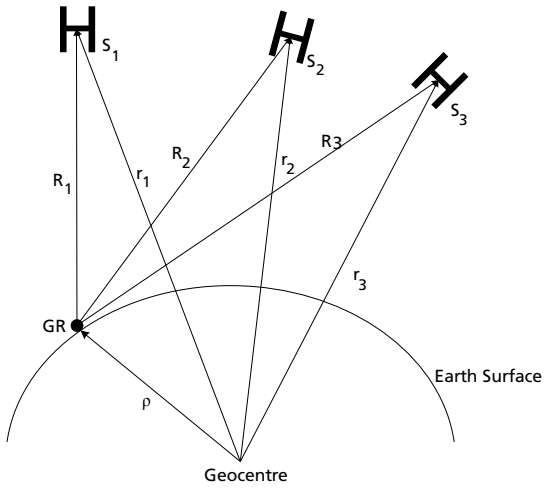


Figure 4.16b **Three satellite tracking**

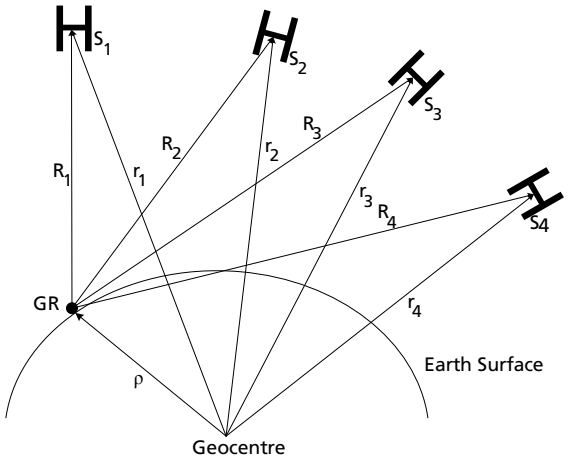


Figure 4.16c **Four satellite tracking**

Figure 4.16 **GPS positioning principles**

Geographic Information Systems (GIS)

This is the merging of cartography and database technology. It refers to a set of systems that captures, stores, analyses, manages and presents data that are linked to location. Technically, a GIS is a system that includes mapping software combined with an application for remote sensing, land surveying, aerial photography, mathematics, photogrammetry, geography and software tools. Apart from supporting map drawing on demand, GIS is able to support decision-making because of its ability to match the spatial characteristics of the data (such as position and the topology of lines and polygons, i.e. how points are connected to each other) with other textual data. This auxiliary data about points, lines and polygons on a map forms part of the attribute data (see Figure 4.17).

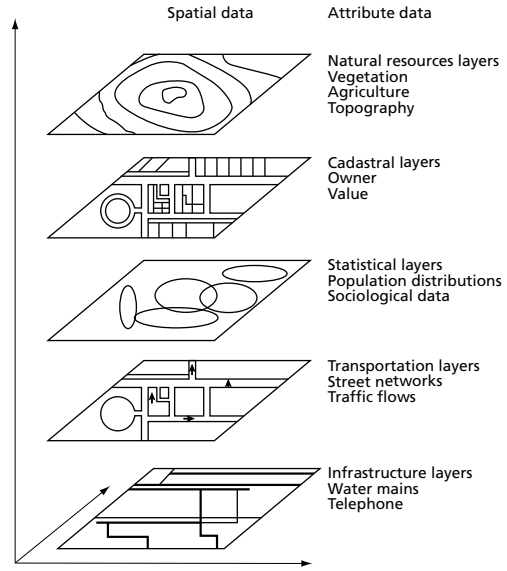


Figure 4.17 **The GIS concept incorporating spatial data layers and attribute data**

In a GIS database, each layer of a map may have a set of global attribute data specifying, for example, the origin of the data set, when it was last updated, the purported accuracy of the data and how it was captured. This is sometimes referred to as 'metadata'. However, attribute data for specific feature points in a map (or map layer) usually take the form of a text table. The definition of the text table normally differs for different features. For example, a tree may have attribute data linked to it concerning species, height, girth, etc., while the attribute data linked to a road segment will have different entries, such as width, date of construction or surface quality. The ability to access this additional data (hidden in attribute data tables) simply by pointing to the map feature on the computer screen makes GIS a powerful query tool.

Digital mapping

Digital mapping is the production of maps in electronic or computer-compatible formats. In digital mapping, the geographic location of terrain points in a given reference system is stored in an electronic medium in the form of letters or numbers (i.e. *X, Y, Z* or latitude, longitude and heights). Digital maps are compiled from aerial photographs and/or satellite imagery.

Photogrammetry is the art, science and technology of obtaining reliable information about physical objects and the environment through a process of recording, measuring and interpreting photographic images and patterns of recorded radiant energy and other phenomena.

Photographs are still the principal source of information, and included within the domain of photogrammetry are two distinct processes: (1) metric photogrammetry and (2) interpretive photogrammetry. Metric photogrammetry involves making precise measurements from photographs to determine the relative location of points. This enables angles, distances, areas, elevations, sizes and shapes to be determined. The most common application of metric photogrammetry is the preparation of planimetric or topographic maps from aerial photographs.

The principle of metric photogrammetry is to conduct measurements on a pair of photographs (stereo-pair) with an overlap area that appears in both photographs (see Figure 4.18). Through mechanical or computational means, the position and orientation of the two cameras are determined in a model, which includes the photographed terrain in its three-dimensional (scaled) visualization. The horizontal (planimetric) and vertical (height) coordinates can be scaled off this virtual model (viewed stereoscopically through special optics).

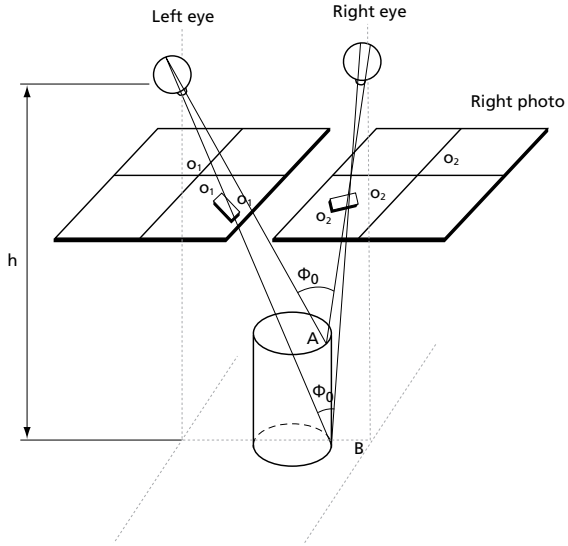


Figure 4.18 **Stereoscopic reconstruction of terrain objects using overlapping aerial photos**

Some of the most significant advances in photogrammetry have been to transform the process of making maps using labour-intensive, analogue photogrammetric techniques into modern, automatic digital photogrammetric procedures, where the photographic image is stored in a computer rather than in the form of a plate or negative. Although airborne cameras are still used to make the initial image, in the near future high resolution satellite images will be used increasingly for small-scale maps. These images have a resolution finer than 1 metre.

REVIEW QUESTIONS

1. Name five or more necessary types of surveying equipment that a rural farm or rural area surveyor must own or possess, preferably stating the importance of each alongside its name.
2. When setting out farm structures, which factors should be considered when deciding which equipment to acquire for use in the particular set-up?
3. In which instances in rural farm surveying does older equipment still prevail over modern surveying equipment?
4. Compare instances in rural surveying where modern surveying equipment would be preferred over older equipment?
5. Modern GPS technology has revolutionized the surveying industry. What positive changes has it brought to the process of managing rural farms?
6. What are the main challenges facing rural surveyors and field technicians with regard to adaptation of modern surveying technology?
7. Briefly describe three modern geospatial techniques.
8. Briefly discuss four uses of modern geospatial techniques.

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Chapter 5
Construction materials

INTRODUCTION

A wide range of building materials is available for the construction of rural buildings and structures. The proper selection of materials to be used in a particular building or structure can influence the original cost, maintenance, ease of cleaning, durability and, of course, appearance.

Several factors need to be considered when choosing the materials for a construction job, including:

1. Type and function of the building or structure and the specific characteristics required of the materials used, i.e. great strength, water resistance, wear resistance, attractive appearance, etc.
2. Economic aspects of the building/structure in terms of original investment and annual cost of maintenance.
3. Availability of materials in the area.
4. Availability of the skilled labour required to install some types of material.
5. Quality and durability of different types of material.
6. Transportation costs.
7. Selection of materials with compatible properties, dimensions and means of installation.
8. Cultural acceptability or personal preference.

WOOD

Wood is a commonly used construction material in many parts of the world because of its reasonable cost, ease of working, attractive appearance and adequate life if protected from moisture and insects. However, forests are a valuable natural resource that must be conserved, particularly in areas with marginal rainfall. As good a material as wood may be, there are regions where other materials should be considered first, simply on a conservation basis.

Wood for building is available from many different species with widely varying characteristics. Some species are used in the form of small poles for light construction, while other species are allowed to mature so that timber (*lumber* in many countries) may be sawn from the large logs. The species that produce small, inexpensive poles in rather short growing periods often grow in the fringes of agricultural land and can be used without danger to the ecology of the region.

The various species of wood have a number of physical characteristics that will be discussed in relation to their use in building construction.

Hardwoods versus softwoods

Wood cut from deciduous trees (which drop their leaves sometime during the year) is considered to be hardwood, while that cut from coniferous (needle-bearing) trees is considered to be softwood. However, this classification does not accurately reflect whether the wood itself is soft or hard. In this book, hardwood will be used to classify wood with hard characteristics.

Wood characteristics

Strength in wood is its ability to resist breaking when it is used in beams and columns. Not only is strength related to the species, but also to moisture content (MC) and defects. Strength is also quite closely related to density.

Hardness is the resistance to denting and wear. While hardwoods are more difficult to work, they are required for tools, tool handles, flooring and other applications subject to wear, or where a high polish is desired.

Woods that are stiff resist deflection or bending when loaded. Stiff woods are not necessarily very strong. They may resist bending up to a point and then break suddenly.

Tough woods will deflect considerably before breaking. Even after fracturing, the fibres tend to hang together and resist separation. Tough woods are resistant to shock loading.

Warping is the twisting, bending or bowing distortions shown by some woods. The method of sawing and curing affects the amount of warping, but some species are much more prone to warping than others.

Nail-holding resistance for hardwoods is greater than for softer woods. However, woods that are so hard that they tend to split when nailed, lose much of their holding ability. Preboring to 75 percent of the nail size avoids splitting.

The workability, such as sawing, shaping and nailing, is better for soft, low-density woods than for hardwoods, but usually they cannot be given a high polish.

Natural-decay resistance is particularly important in the warm, humid regions of east and southeast Africa. A wide range of resistance is shown by different species. However, for all species, the heartwood (the darker centre area of the tree) is more resistant than the sapwood (the lighter outer area of the tree). In addition to selection for natural-decay resistance, wood

preservatives should be considered where contact with the ground is likely.

Paint-holding ability differs between woods and, as a general rule, this should be considered when selecting materials.

Defects in wood

Defects to watch for when selecting timber are:

Brittle heart, found near the centre of many tropical trees, makes the wood break with a brittle fracture.

Wide growth rings indicate rapid growth resulting in thin-walled fibres with consequent loss of density and strength.

Fissures include checks, splits, shakes and resin pockets. Knots are the part of a branch that has become enclosed in a growing tree. Dead knots are often loose and therefore reduce the effective area that can take tensile stress. Knots can also deflect the fibres, thereby reducing strength in tension.

Decay, which results from moisture levels between 21 percent and 25 percent in the presence of air, reduces the strength of the wood and spoils its appearance.

Insect damage caused by borers or termites.

The fungi that feed on wood can be divided into three main categories: staining fungi, moulds and decay fungi. Most fungi thrive under moist conditions. Staining fungi live mainly on the sapwood but they may penetrate deeply into the wood and spoil the timber's attractive appearance. Moulds do not penetrate below the surface and do not seem to affect the strength of the wood, but they look unsightly. Decay fungi eat the cell walls of the wood. This causes the tree to lose its strength and often reduces it to a crumbling, rotting mass. These decay fungi never attack timber that is seasoned to a moisture content of less than 20 percent and kept well ventilated and dry.

The main species of borer that attack tropical woods are the pinhole borer and the *Lyctus*, or powderpost beetle. The pinhole borer attacks newly felled logs and sometimes standing trees. The attack can occur within hours of felling. The beetles do not normally continue to operate in seasoned timber. The powderpost beetle attacks seasoned tropical hardwoods – particularly those that contain starch on which the larvae feed. Timber is sometimes sprayed in the yard to protect it until it is transported.

Termites are normally of two kinds: the dry wood types that are able to fly and the subterranean type. Termites usually operate under cover and it is only after the first signs of damage appear that the full extent is realized. Flying termites usually enter the end-grain of untreated timber and build up a colony from inside, finally devouring all the interior wood and leaving only a thin skin behind. Some subterranean termites, white ants, operate from a central colony and travel in search of food. Their nests or hills sometimes achieve great size and house millions of ants. While no timber is completely immune to attack from ants or other insects, there are great variations among the species. The density of the timber is no guide to its resistance to termite damage, as some of the lighter timbers are more immune than heavier varieties.

Weathering is the disintegration of wood caused by alternate shrinkage and swelling as a result of rain, rapid changes in temperature, humidity and the action of sunlight. Painting, when properly carried out, does much to prevent weathering. The paint must be of exterior quality, however, and applied according to the maker's instructions.

POLES AND TIMBER

Wooden poles

In farm buildings and rural structures, wood is often used in the form in which it has grown, i.e. round poles. In some areas where enough trees are grown on the farm or in local forests, wooden poles can be obtained at very low cost. These poles have many uses in small building construction, such as columns for the load-bearing structure, rafters, trusses and purlins. Sticks and thin poles are often used as wall material or as a framework in mud walls.

Where straight poles are selected for construction, it is as easy to work with round timber as with sawn timber. However, somewhat crooked poles can also be used if they are turned and twisted and put into positions in which the effects of the bends are unimportant.

Round timber can generally be considered stronger than sawn timber of the same section area because the fibres in round timber are intact. The pole is normally tapered and therefore the smallest section, the top end, must be used in the calculation of compressive and tensile strength.

A great number of species can be considered when selecting poles for construction, but only a limited number are available on the commercial market. Some species are more suitable for silviculture (growing on farms) and silvipasture (growing on pastures) than others, but must always be selected to suit local climatic and soil conditions. Generally there are several species suitable for each location that are fast and straight-growing, and produce strong and durable timber. In addition to building poles or timber, some species will produce fodder for animals, fruit, fuelwood, etc.

Many species of eucalyptus, from which gum poles are obtained, are very fast and straight-growing hardwoods. However, they warp and split easily. Dimensions suitable for building construction are obtained by harvesting the still immature trees. Gum poles provide a strong and durable material if chemically treated.

In high-altitude areas, several species of acacia produce good building poles. *Acacia melanoxylon* (Australian blackwood) is very resistant to attack by termites, but grows more slowly than eucalyptus. In low- to medium-altitude areas with sandy soils and low rainfall, *Casuarina* produces straight and durable poles.

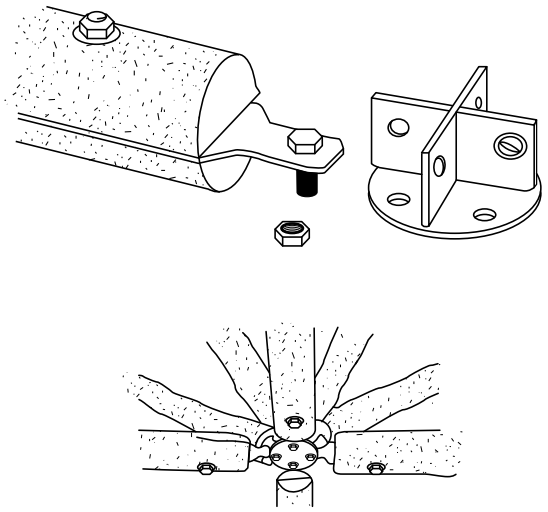


Figure 5.1 **Pole connectors**

Cedar posts for fencing are obtained by splitting large logs. The posts are durable and resistant to rot and attack by termites. They are also suitable for wall posts in the construction of buildings.

In coastal areas, mangrove poles are widely used for posts in walls and trusses in roofs.

Unprocessed round wood material can be joined by being nailed or tied with string or wire. A special connector has been developed to join round wood in trusses where several members may have to be connected at each point.

Sawing timber

The rate at which a tree grows varies with the season. The resulting growth rings of alternate high and low density form the grain in the sawn timber (lumber). The method of sawing has a considerable effect on the appearance, resistance to warping, shrinking, paint-holding ability and wear resistance of the final piece.

There are several methods of sawing a log into boards and planks, giving different relationships between the growth rings and the surface, i.e. more or less parallel to the surface in plain sawn timber and at right angles in radial sawn timber.

Radially sawn boards shrink less, are less liable to cup and twist and are easier to season. Unfortunately, cutting methods that produce a high proportion of quarter-sawn timber are wasteful and therefore only used to produce material for high-class joinery work (see Figures 5.2 and 5.3).

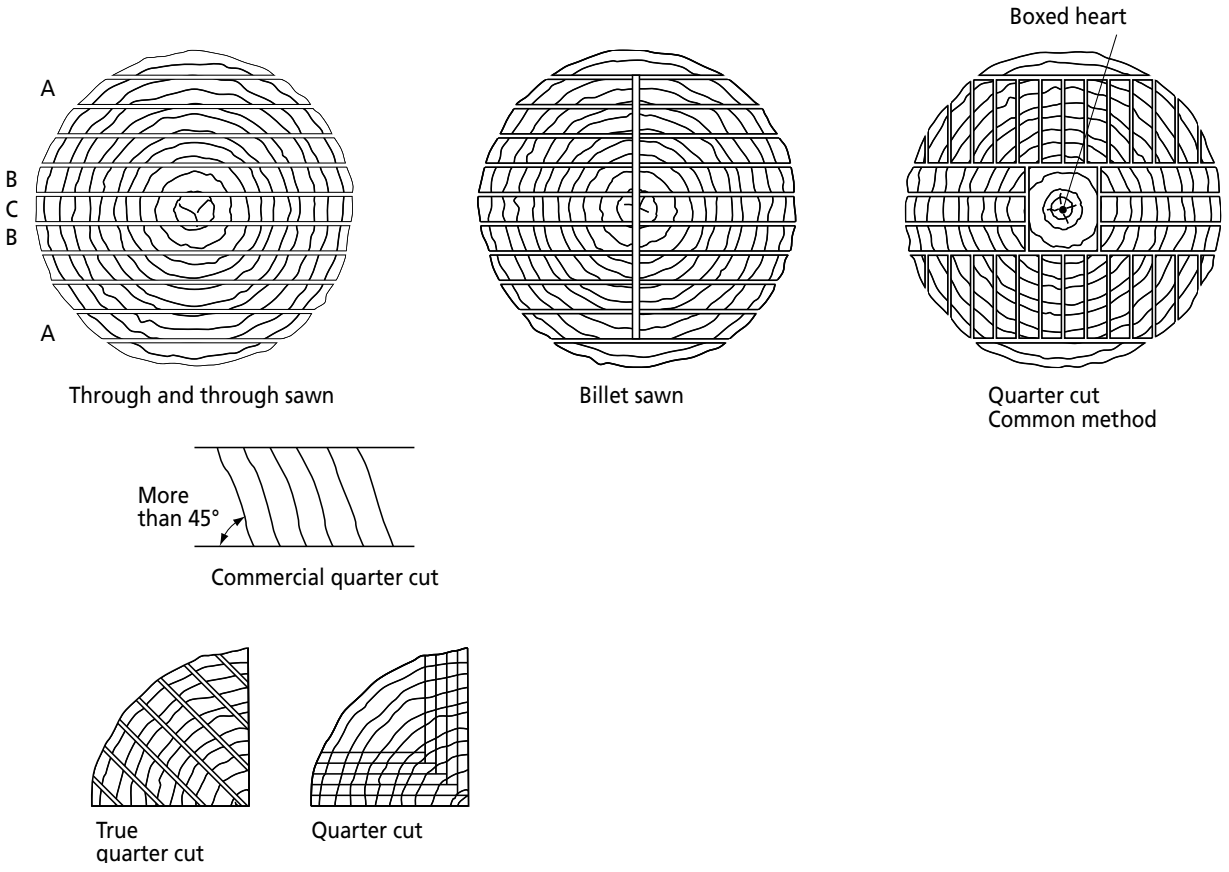


Figure 5.2 **Methods of sawing timber**

Offcuts

A tree is tapered and cylindrical, whereas boards and planks are rectangular. This results in the outer pieces with tapered edges and less than full dimensions throughout the length. Such pieces, called offcuts, can sometimes be obtained at low cost and used for rough building.

Seasoning of timber

The strength, stiffness and dimensional stability of wood are related to its moisture content. Hence, if wood is dried (seasoned) before use, not only can higher strength values be used in a design, but a more durable structure will result. In developing countries, most timber is not seasoned and it is sold in what is called its 'green' state.

Timber must be stacked, supported and sometimes restrained so as to minimize distortion during seasoning. If drying is too rapid, the outer parts, in particular the unprotected ends, shrink before the interior does, and this leads to surface checking and splitting, as well as the possible extension of ring and heart shakes. Some timber species are more difficult to season satisfactorily than others.

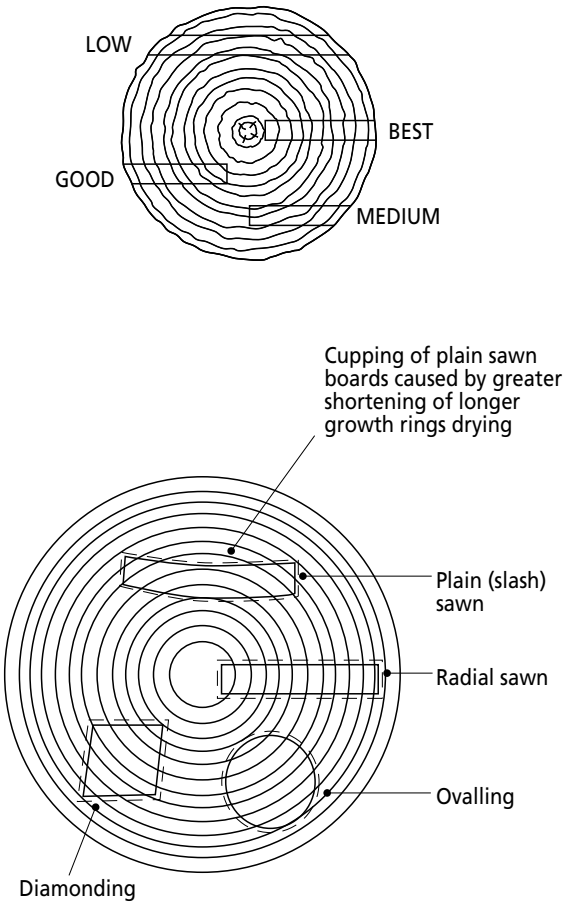


Figure 5.3 **Effects of cupping and shrinkage of different methods of sawing**

Air seasoning

Timber should be protected from rain and from the ground. It should therefore be stacked so that air can circulate freely around all surfaces, reducing the risk of twisting and cupping, as well as minimizing attacks by fungi and insects. In favourable conditions, thin softwoods can be air-seasoned in weeks but in unfavourable conditions some hardwoods require a year or more.

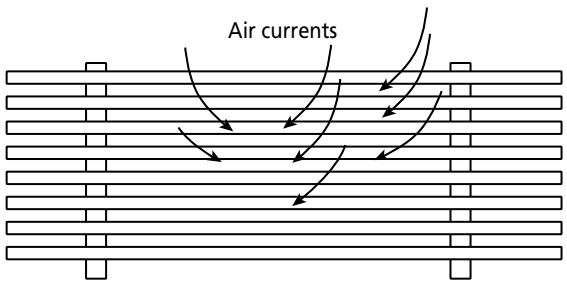


Figure 5.4 **Air-drying of timber**

Artificial seasoning

Artificial seasoning can be either moderate or rapid, depending on the temperature of the air injected into the chamber where the timber is piled, and on the rate at which the air is circulated and extracted from the chamber. This method is expensive and can only be applied on small quantities of timber. Timber can be artificially seasoned from the green condition, but often hot-air seasoning is used only at a later stage, after most of the moisture has been removed by air seasoning.

Smoke seasoning is a moderate process and involves placing the timber over a bonfire. It can take a month or two, depending on the size and type of wood being seasoned. This method is considered to be both a seasoning and a treatment method for timber. Presumably it protects the timber against pest attacks and increases durability. However, it is not very reliable and can lead to splitting of the timber because of the lack of control over the heat from the bonfire.

Care of seasoned timber

Timber should be protected from moisture on the building site. Close piling and covering with tarpaulins delays the absorption of atmospheric moisture, particularly in the interior of the pile.

Grades and sizes for timber

Grades

Grades are established by various government agencies. Even within a single country, more than one grading system may be in use. While the grade may not be important for small construction jobs, in large projects

where materials are bought by specification, it is important to indicate the required grade.

Grades that provide specific information in structural design are most useful. The grade standard established by the Kenya Bureau of Standards, shown in Table 5.1, is a good example.

TABLE 5.1
Timber grades and application

Grade	Applications
F	Furniture, high-class joinery
GJ	General joinery
S-75	Structural grade, having a value of 75% of basic stress
S-50	Structural grade, having a value of 50% of basic stress
C	A general construction grade for non-stressed construction
L	A low grade for low quality work

It is the S-75 and S-50 grades that are significant in building construction, as will be seen in later sections.

Sizes

Timber in eastern and southeastern Africa is available in a number of *Système Internationale* (SI) metric sizes, but not all are available in all localities. The dimension indicates actual size as sawn. Smoothing will reduce the timber to less than dimension size.

Timber measurement for trade

Even though timber is normally sold by length (running metre or foot), the price may be calculated per cubic metre when sold in large quantities. Basic lengths are between 1.8 metres and 6.3 metres, although pieces longer than about 5.1 metres are scarce and costly. Timber normally comes in running lengths, that is to say, not sorted by length.

Strength of wood

Building materials of any type that are under load are said to be subjected to fibre stress. The safe fibre stress for a material is the load that the material will safely resist. Wood, like other materials, has safe fibre stress values given in N/mm² that have been determined by destructive testing to obtain first an ultimate stress, and then, by the use of various correction and safety factors, the safe fibre stress to be used for designing a structure.

Table 5.2 lists basic working-stress values for several types of loadings in five strength groups. Table 5.3 divides some representative species into the strength groups used in Table 5.2.

TABLE 5.3
Some representative timbers grouped according to strength and density

Group	Latin name	Common name
1	*Pinus radiata* (12 years)	Young pine
	Polyscias kikuyuensis	Mutati
2	*Cordia abyssinica*	Muringa
	Pinus patula (17 years)*	Pine
	Pinus radiata (17 years)	Pine
	*Cupressus lusitanica***	East African cypress
3	*Podocarpus*	Podo/musengera
	Juniperus procera	African pencil cedar/mutarakwa
	Octea usambarensis	East African camphorwood/muzaiti
	Acacia melanoxylon	Australian blackwood
	Grevillia robusta	Grevillea/silky oak
	*Vitex keniensis**	Vitex/muhuru/meru oak
	Pterocarpus angolensis	Muninga
	Khay anthot heca	African mahogany
	Eucalyptus regnans	Australian mountain ash
4	*Cassipourea malosana*	Pillarwood/musaisi
	Dombeya goezenii	Mueko
	Eucalyptus saligna	Saligna gum/Sydney blue gum
	*Premna maxima**	
	Afzelia quanensis	Afzelia
5	*Olea hochstetteri*	East African olive/musharagi

* One group lower in compression perpendicular to grain
** One group lower in joint shear

There are dozens more tree species found in eastern and southern Africa, many of which are used only in very local areas. In order to obtain approximate working-stress data for these indigenous species, their densities may be used to place them in the proper group in Table 5.2. If the density is not known, a good

TABLE 5.2
Guide to basic working-stress values and modulus of elasticity for timber

Strength group	Strength rating	Density green	Density 12% MC	Maximum bending strength and tension parallel to grain	Modulus of elasticity	Maximum compression strength		Maximum shearing strength	
						Parallel to grain	Perpendicular to grain	Beams	Joints
		kg/m³	*kg/m³*	*N/mm²*	*kN/mm²*	*N/mm²*	*N/mm²*	*N/mm²*	*N/mm²*
1	Weak	< 520	< 400	10	4.0	2.5	0.6	1.0	0.4
2	Fairly strong	521–650	401–500	15	6.0	10.0	1.2	1.3	1.6
3	Strong	651–830	501–640	20	7.5	13.0	2.0	1.9	2.4
4	Very strong	831–1 040	641–800	30	9.0	20.0	3.2	2.4	3.5
5	Exceptionally strong	> 1 041	> 801	50	10.5	29.0	5.0	3.2	4.1

approximation can be found quite easily. A bucket, a graduated cylinder (millilitres) and an accurate scale for weighing a sample of the wood will be needed. The procedure is as follows:

1. Weigh the sample.
2. Place the bucket on a level surface and fill to the rim with water.
3. Carefully submerge the sample and then remove.
4. Refill the bucket from the graduated cylinder, noting the amount of water needed to refill the bucket.
5. Density = weight / volume = kg/m³
6. Place the species in the appropriate group using the appropriate density column for a green or dry sample (see Table 5.2, column 3 or 4).

Table 5.2 lists basic working-stress values. For design purposes, these should be adjusted for a number of different variables, including: grade, moisture content, duration of load, exposure and use of the structure.

Factors that affect timber strength include:

1. *Sloping grain*

As timber is a material with maximum mechanical properties in the direction of the grain, any load not applied in this direction will be resisted by lower strength and stiffness characteristics. The effect of a sloping grain on the strength of beams must be considered in the design. For example, lowering the grain slope from 1 in 20 to 1 in 8 reduces the strength of timber by over 50 percent. The reduction in strength resulting from the sloping grain (deviation) may be calculated from the relationship.

$$N = \frac{PQ}{P\sin\theta + Q\cos\theta} \tag{5.1}$$

where N is the strength at angle θ from the fibre direction; P is the strength parallel to the grain (θ = 0°) and Q is the strength perpendicular to the grain (θ = 90°).

2. *Moisture*

When moisture decreases below the fibre saturation point, it begins to affect the mechanical properties of wood. A decrease in moisture content increases the strength of wood because the cell walls become more compact. Cell walls are compacted because, with the loss of moisture, the mass of wood substance contained in a certain volume increases.

Given any mechanical property at standard values of moisture content, it is possible to predict the values of that property at any moisture content using Equation 5.2:

$$P_x = P_{12}\left(\frac{P_{12}}{P_g}\right)^{-\left(\frac{M_X - 12}{M_P - 12}\right)} \tag{5.2}$$

where P_x is the mechanical property at a given moisture content, for example, tensile strength at 8% MC; P_{12} is the property at 12% MC; P_g is the property value in green condition; M_x is the MC at which property is desired and M_p is the moisture content at the intersection of a horizontal line representing the strength of greenwood and an inclined line representing the logarithm of the strength/MC relationship for dry wood. It is usually taken to be 25% MC.

Owing to the effect of moisture, mechanical properties are determined in green condition (above fibre saturation) or in air-dry conditions (12% MC). This makes it possible to have comparable results. Correction factors are used to adjust moisture content to these two standard values.

3. *Density*

Density is a measure of the wood substance contained in a given volume. The substance of which wood is composed has a specific gravity of about 1.5, yet wood floats on water. This would indicate that wood contains numerous cell cavities and pores. As the strength of timber is a function of the wood material present, density is a good indicator of strength, and the relationship is given by Equation 5.3:

$$\frac{S}{S'} = \frac{g^n}{g'} \tag{5.3}$$

where S and S' are values of strength corresponding to densities g and g' and n is an index with a value in the range 1.25 to 2.50.

4. *Temperature*

The influence of temperature can be analyzed at two levels:

(i) Reversible effects

In general, the mechanical properties of wood decrease when heated and increase when cooled. At constant MC and below 150 °C, the relationship between mechanical properties and temperature is approximately linear. At temperatures below 100 °C, the immediate effect is essentially reversible, i.e. the property will return to the value at the original temperature if the change is rapid.

(ii) Irreversible effects

This occurs at high temperatures. This permanent effect results in degradation of the wood substance, which results in the loss of weight and strength. However, wood will not often reach the daily extremes in temperature of the air around it in ordinary construction. Long-term effects should therefore be based on the accumulated temperature experience of critical structural parts.

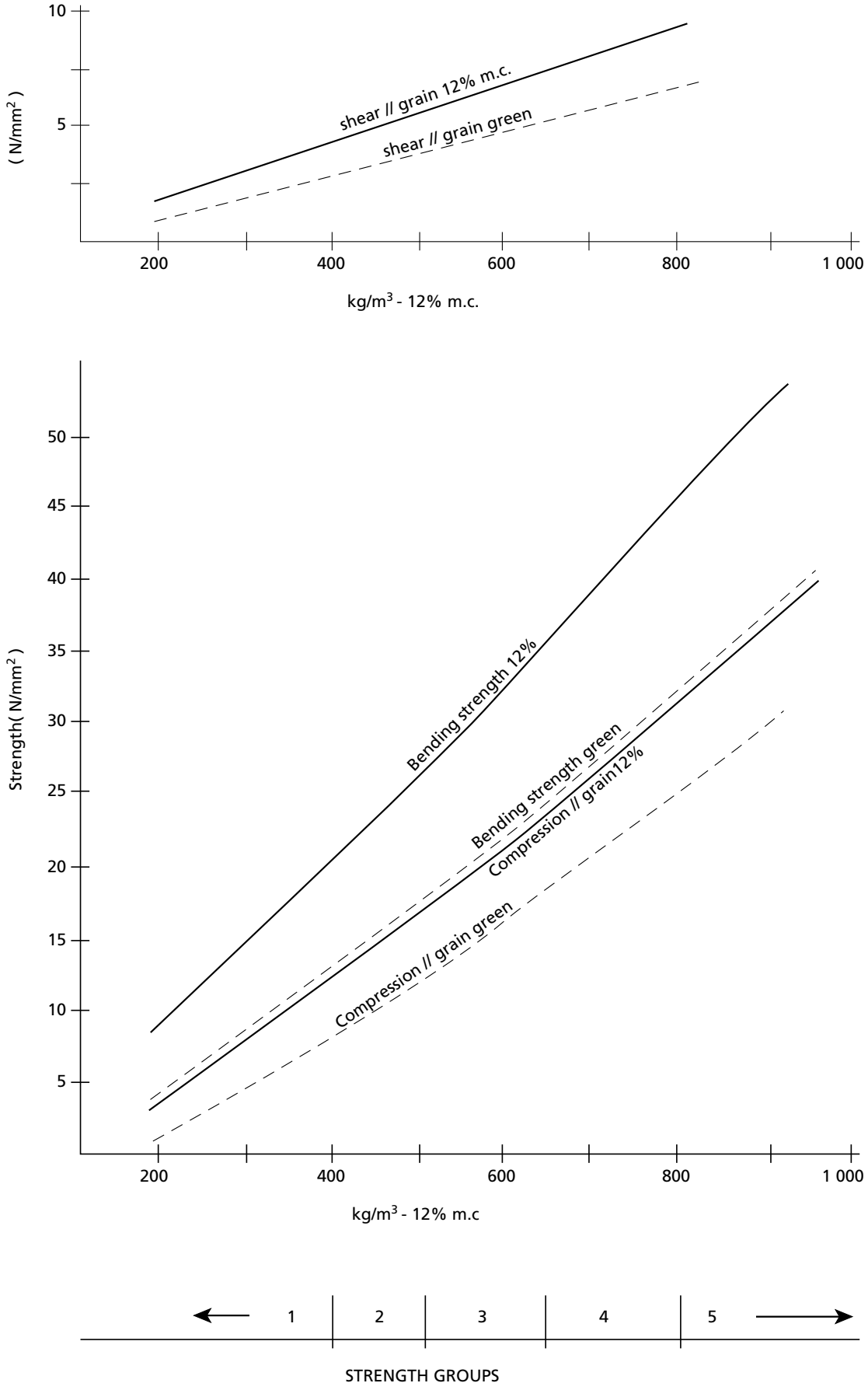


Figure 5.5 **Basic working stresses for timber**

(iii) *Time under load*

Static strength tests are typically conducted at a rate of loading to attain maximum load in about 5 minutes. Higher-strength values are obtained for wood loaded at more rapid rates, and lower values are obtained at slower rates. For example, the load required to produce failure in a wood member in 1 second is approximately 10 percent higher than that obtained in a standard strength test.

Grades

As an example, the Kenya Forest Department recommends that the following grades should be used:

Grade 1	75% of basic working-stress value
Grade 2	50% of basic working-stress value
Grade 3	35% of basic working-stress value
Grade 4	15% of basic working-stress value

Moisture

Table values need to be reduced when timber is installed green and will remain wet and uncured continuously. Use Figure 5.5 to find a suitable stress value for green wood corresponding to the dry value in Table 5.2.

Exposure

Timbers exposed to severe weather and decay hazards should be designed using a 25 percent stress-value decrease, particularly for columns and for bearing points.

TIMBER PRESERVATION

The main structural softwood timbers of eastern and southeastern Africa are not naturally durable. If used in conditions subject to fungal, insect or termite attack, they will fail after some time. To avoid this, the timber used in permanent structures should be treated with a preservative.

Effective preservation depends on the preservative and how it is applied. An effective preservative should be poisonous to fungi and insects, permanent, able to penetrate sufficiently, cheap and readily available. It should not corrode metal fastenings, nor should the timber be rendered more flammable by its use. It is sometimes desirable to have a preservative-treated surface that can be painted.

If a structure is correctly designed and built, and the moisture content of its timber does not exceed 20 percent, then a preservative treatment is generally unnecessary for protection against fungal attack. However, where the above conditions are not present, there will be a risk of fungal decay, and proper preservation is recommended.

Wood preservatives

Creosote is an effective general-purpose preservative that is cheap and widely used for exterior work and, to a lesser degree, indoors. It is a black to brownish oil produced by the distillation of coal tar and, while it has many of the properties required of a preservative, it increases flammability, is subject to evaporation, and creosoted wood cannot be painted. It should not be used on interiors where the characteristic smell would be objectionable. Unfortunately, creosote has been found to be a carcinogen and must be used with caution.

Coal tar is not as effective a preservative as the creosote produced from it. Tar is less poisonous, does not penetrate the timber because of its viscosity, is blacker than creosote and is unsuitable for interior wood work.

Unleachable metallic salts are based mostly on copper salts. A combination of copper/chrome/arsenate is used. The copper and arsenical salts are toxic preservatives that are rendered non-leaching (cannot be washed out) by the chrome salt, which acts as a fixing agent. The timber is impregnated using a 'vacuum-pressure' process. Preservation by metallic salt is being used increasingly because the treated surfaces are odourless and can be painted or glued.

Water-soluble preservatives are not satisfactory for exterior use as they are liable to be washed out of the timber by rain.

By contrast, they are very suitable for interior work as they are comparatively odourless and colourless and the timber can be painted.

Used engine oil can often be obtained free of charge, at least in small quantities. The oil contains many residual products from combustion and some of them act as preservatives, but it is not nearly as effective as commercial preservatives. It can be thinned with diesel fuel for better penetration. The combination of 40 litres of used engine oil and 1 litre of Dieldrin is a viable alternative in rural construction.

Methods of wood preservation

There are two categories of timber preservation methods:

Non-pressure methods

These are applicable for both green and dried timber (less than 30 percent MC) and include:

1. Soaking (steeping), used for small quantities of timber.
2. Hot and cold soaking: the tank with the preservative and timber is heated to nearly boiling point for 1-2 hours and allowed to cool. During the heating period, the air in the cells expands and some is expelled. When cooling, a partial vacuum develops in the cells and liquid is absorbed.
3. Steam and cold quenching.
4. Superficial methods such as painting and spraying.

To make non-pressure methods more effective, storage in a closed environment is recommended.

Pressure methods

The treatment in pressure processes is carried out in steel cylinders, or 'retorts'. Most units conform to size limits of 2–3 metres in diameter and up to 46 metres or more in length, and are built to withstand working pressures of up to 1 720 kPa. The wood is loaded on special tram cars and moved into the retort, which is then closed and filled with the preservative.

Pressure forces preservatives into the wood until the desired amount has been absorbed. Three processes – full-cell, modified full-cell and empty-cell – are commonly used. These processes are distinguished by the sequence in which vacuum and pressure are applied to the retort. The terms 'empty' and 'full' refer to the level of preservative retained in the wood cells.

The full-cell process achieves a high level of preservative retention in the wood cells, but less penetration than the empty-cell process. On the other hand, the empty-cell process achieves relatively deep penetration with less preservative retention than the full-cell process.

1. *Full-cell process*

The Bethel full-cell process is generally used with water-based preservatives, especially for timber that is difficult to treat and also requires high retention. The full-cell process steps are listed below:

- The wood is sealed in the treatment cylinder and an initial vacuum is applied for approximately 30 minutes to remove as much air as possible from the wood and from the cylinder.
- The preservative, either heated or at ambient temperature depending on the system, enters the cylinder without breaking the vacuum.
- After the cylinder is filled, the cylinder is pressurized until no more preservative will enter the wood, or until the desired preservative retention is obtained.
- At the end of the pressure period, the pressure is released and the preservative is removed from the cylinder.
- A final vacuum may be applied to remove excess preservative that would otherwise drip from the wood.

2. *Empty-cell process*

The empty-cell process results in deep penetration of the preservative with a relatively low net preservative retention level. If oil preservatives are used, the empty-cell process will most probably be used, provided it will yield the desired retention level. The Rueping process and the Lowry process are the two most commonly used empty-cell processes. Both use compressed air to drive out a portion of the preservative absorbed during the pressure period.

(i) Rueping process

In the Rueping process, compressed air is forced into the treatment cylinder containing the charge of wood, in order to fill the wood cells with air prior to preservative injection. Pressurization times vary with wood species. For some species, only a few minutes of pressurization are required, while more resistant species may require pressure periods of 30-60 minutes. Air pressures used typically range from 172 kPa to 690 kPa, depending on the net preservative retention desired and the resistance of the wood.

After the initial pressurization period, preservative is pumped into the cylinder. As the preservative enters the treatment cylinder, the air escapes into an equalizing, or Rueping, tank at a rate that maintains the pressure within the cylinder. When the treatment cylinder is filled with preservative, the pressure is raised above the initial air pressure and maintained until the wood will take no more preservative, or until enough has been absorbed to leave the desired preservative retention level after the final vacuum. After the pressure period, the preservative is removed from the cylinder and surplus preservative is removed from the wood with a final vacuum. This final vacuum may recover 20–60 percent of the gross amount of preservative injected. The retort then is unloaded, and the treated wood stored.

(ii) Lowry process

The Lowry process is an empty-cell process without the initial air pressure. Preservative is pumped into the treatment cylinder without either an initial air pressurization or vacuum, trapping the air that is already in the wood. After the cylinder is filled with the preservative, pressure is applied and the remainder of the process is identical to the Rueping process. The advantage of the Lowry process is that full-cell equipment can be used without the accessories required for the Rueping process, such as an air compressor, an extra tank for the preservative, or a pump to force the preservative into the cylinder against the air pressure. However, both processes are used widely and successfully.

MANUFACTURED BUILDING BOARDS

There are a number of building boards made from wood veneers or the waste products of the timber industry that are convenient and economical materials to use in building construction. In general, they offer excellent bracing for the building frame, together with labour savings because they are available in large sizes requiring a minimum of fitting.

Some manufactured boards are designed with specific characteristics, such as fire resistance, ease of cleaning, high insulation value or resistance to weathering.

Plywood

Plywood is produced by gluing together three to seven veneers that have been peeled from logs. The grain of each successive veneer is angled at 90° from the previous one, resulting in a board that has considerable strength and rigidity in all directions. Waterproof glue is most commonly used, giving a product that is highly resistant to moisture. Waterproof glue panels should always be chosen for farm buildings. As the wood itself is not waterproof, the panels are still subject to swelling and shrinkage from moisture changes.

Grades of plywood

Plywood is generally given four to five grades, based on the appearance of the surface veneers. Each panel has a double-letter grade to indicate the grade of the face of the panel and the back of the panel. The top-grade surface is generally free enough from defects to be finished naturally, while the second-best grade is good for painting. Lower grades are used for structural applications where appearance is of little importance. Theoretically, between 10 and 15 different grade combinations are possible. In practice, only a few tend to be available from timber merchants.

Sizes of plywood panel

As an example of a standard used in the region, the Kenya Bureau of Standards provides a standard with 12 panel sizes and 9 different thicknesses. Combining grades, panel sizes and thicknesses, there are numerous permutations, but only a few will be manufactured. The most common panel size is 2 400 by 1 200 mm, in thicknesses of 9 mm, 12 mm, 15 mm and 19 mm.

Plywood for structural members

Plywood panels are made from many different species of wood and have a wide range of strengths and stiffnesses. Specific strength characteristics for plywood can be provided by either the manufacturer or a trade association that publishes grade standards to which manufacturers adhere. In general, plywood panels should equal or exceed the strengths shown in Table 5.4.

TABLE 5.4
Safe spans for plywood panels parallel to the grain of the plys

	Load	
	167 Pa	4 790 Pa
Thickness	(170 kg/m²)	(490 kg/m²)
9 mm	400 mm	-
12 mm	600 mm	-
15 mm	770 mm	300 mm
19 mm	925 mm	400 mm

Other manufactured boards

Blockboards and laminboards are made of strips of wood between 8 mm and 25 mm wide, glued together and covered with one or more veneers on each side. At least one pair of corresponding veneers will have the grain at right angles to the grain of the core. If the finish grain is to run parallel with the core, there must be at least two veneers per side.

The same 12 panel sizes listed for plywood are also listed for blockboard. However, the thicknesses are greater, ranging from 15 mm to 50 mm, in 5 mm increments. The same appearance, grades and types of glue listed for plywood also apply to blockboards. Blockboard panels are often used for doors.

Particleboards are formed by pressing chips or flakes of wood between pairs of heated platens so that the particles lie in random fashion with their longer dimensions parallel to the surface of the board. The chips are bonded with thermosetting synthetic resins. Depending on the size of the particles, these boards are variously known as *particleboard, chipboard or waferboard*. Strength and rigidity generally increase with density, but that alone is not a measure of quality, as moisture resistance varies considerably and most particleboards should not be used in moist locations.

Softboards are made from uncompressed woodchips or sugarcane fibres mixed with water and glue or resins, giving a density of less than 350 kg/m³. They are inexpensive and can be used for wall or ceiling surfaces that are not subject to high-moisture conditions.

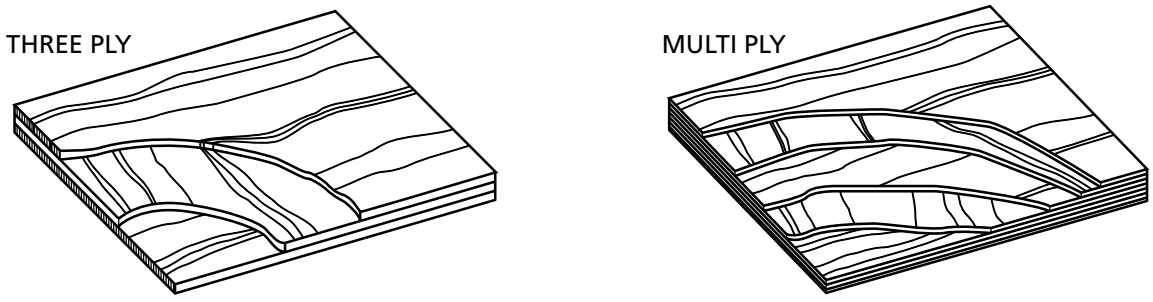


Figure 5.6 **Plywood**

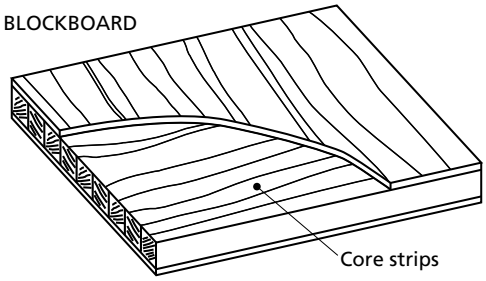


Figure 5.7a **Blockboard**

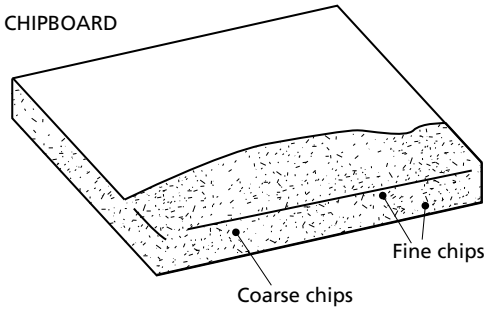


Figure 5.7b **Particleboard**

Softboards have little resistance to rupture and must be supported frequently (300–400 mm) when installed. The 2 400 mm by 1 200 mm size is most common in thicknesses of 6.4 mm to 25 mm.

Mediumboards, with a density ranging from 350 kg/m³ to 800 kg/m³, are used for panelling, in particular those with a density at the higher end of the range. The most common size is 2 400 mm by 1 200 mm, and thicknesses range from 6.4 mm to 19.0 mm.

Hardboards are made of wood fibres compressed to more than 800 kg/m³. They are usually smooth on one surface and textured on the other. The most common size is 2 400 mm by 1 200 mm size in thicknesses of 3–12.7 mm. An oil-treated grade labelled 'tempered' has good resistance to moisture.

OTHER WOOD PRODUCTS

Woodwool slabs consist of long wood shavings, mixed with cement, and formed into slabs 25–100 mm thick with a high proportion of thermal insulating voids. Although combustible, they are not easily ignited and provide good sound absorption.

Shingles are cut from clear rot-free timber logs. They are made about 2 mm thick at the top end and 10 mm thick at the bottom, and usually about 400 mm long. Some woods need treatment with preservatives before being used as roofing shingles, whereas others will last 10–15 years without treatment.

Sawdust is a by-product from sawmills. It is a good natural insulating material, and also a good bedding material for use in animal housing.

Wicker made from shrubs, bushes and trees is used either directly, for fencing or wall cladding, or sealed by smearing on mud, plaster, etc.

OTHER ORGANIC MATERIALS

Bamboo

Bamboo is a perennial grass with over 550 species, found in tropical, subtropical and temperate zones. It contains a large percentage of fibre, which has high-tensile, bending and straining capacity.

However, bamboos have some shortcomings that limit their application. The low durability of bamboo is one of its most serious defects, along with its flammability and tendency to split easily. This usually prevents the use of nails. Cutting a notch or a mortise in a bamboo drastically reduces its ultimate strength. The remedy is the use of nodes as places of support and joints, and the use of lashing materials (strings) in place of nails. Dry bamboo is extremely susceptible to fire, but it can be covered or treated with a fire-retardant material.

The strength properties of bamboo vary widely with species, growing conditions, position within the culm, seasoning and moisture content. Generally bamboo is as strong as timber in compression and very much stronger in tension. However, bamboo is weak in shear, with only about 8 percent of compressive strength, whereas timber normally has 20–30 percent. It is used mainly in building construction, for wall poles, frames, roof construction, roofing and water pipes and, after splitting, to form flattened boards or woven wall, floor and ceiling panels.

New stalks of bamboo are formed annually in clumps growing out of the spreading roots. The individual bamboo shoots complete their growth within a period of 4–6 months in the first growing season. A strengthening process takes place during the subsequent 2–3 years, and the culm reaches maturity after the fifth or sixth year, or even later depending on the species. It must be cut before blooming because it looses its resistance and dies after blooming. Some bamboos grow to 35 metres in height, while others are no more than shrubs. Diameters vary from 10 mm to 300 mm.

Bamboo without proper seasoning and preservative treatment will rot and be attacked by insects, particularly if used in moist locations, such as in earth foundations.

Bamboo joints

As nailing causes splitting and notching, drastically reducing the strength of a bamboo culm, lashes are generally used as binding elements for framing. They may be split from the bamboo itself, or made from vines, reeds or the bark of certain trees. Soft galvanized wire is also used for binding. Bamboo can be kept from splitting when bending by boiling or steaming it first, then bending it while hot.

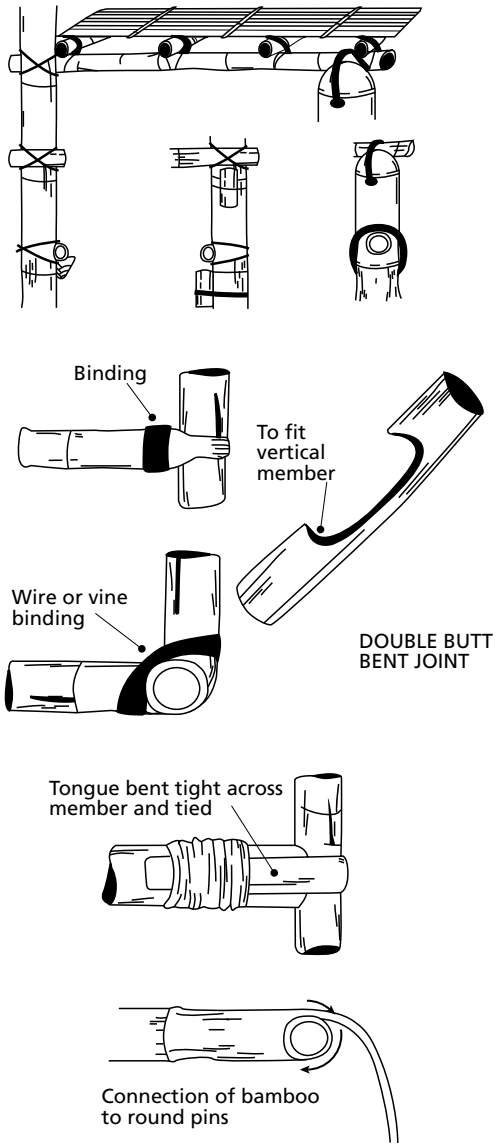


Figure 5.8 **Lashing bamboo joints**

Several methods can be used for splitting bamboo culms. The edges of the strips can be razor sharp and should be handled carefully (see Figure 5.9).

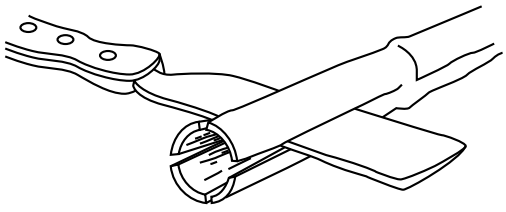


Figure 5.9a **Make four cuts in the upper end of the culm with a splitting knife**

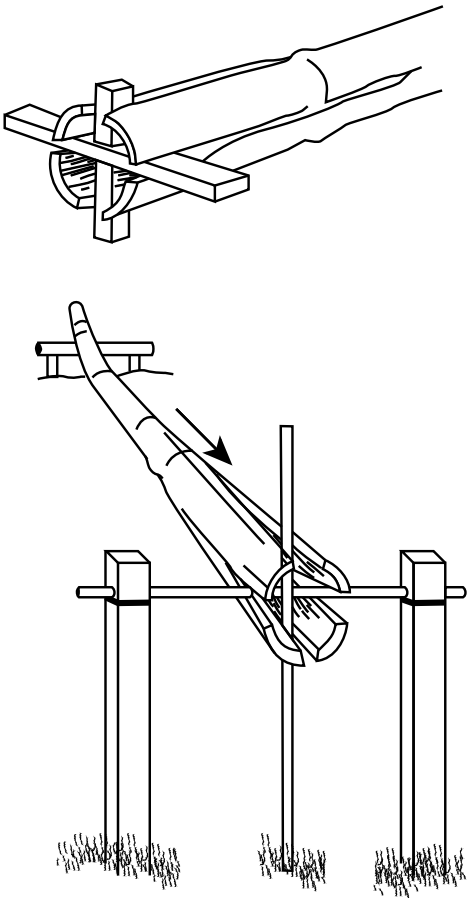


Figure 5.9b **Split the culm the rest of the way by driving a hardwood cross along the cuts**

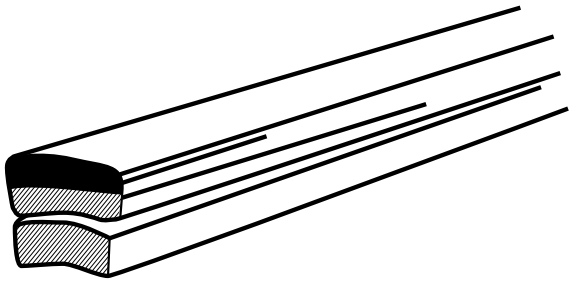


Figure 5.9c **Use a knife to split the harder outer strip from the soft, pithy inner strip, which is usually discarded**

Bamboo preservation

Immediately after cutting, the freshly cut lower end of the culm should be dusted with insecticide. The bamboo is then air seasoned for 4–8 weeks, depending on the ambient humidity. Bamboo should be stacked well off the ground so that air can circulate freely. When the culms have dried as much as conditions permit,

they should be trimmed and all cut surfaces should be dusted with insecticide immediately. The seasoning is finished in a well ventilated shelter where the culms are protected from rain and dew.

If the bamboo is to be stored for a long time, stacks and storage shelves should be treated with an insecticide every 6 months. Bamboo that has already been attacked by insects, fungus or rot should never be used for construction. Culms that have fissures, cracks or cuts in the surface should also be rejected.

Natural fibres

Natural fibres have been used for building since ancient times. Fibrous materials can be used by themselves as roofing material or for walls and mats. Natural fibres can also be combined with hydraulic-setting binders to make various types of roofing board, wall board, block and shingle. Animal hair is often used for reinforcing plaster.

Thatch

Thatch, whether made of grass, reeds, palm or banana leaves, is susceptible to decay caused by fungi and insects, and to destruction by fire. Preservative treatment is desirable but expensive. A treatment combining copper sulphate, sodium chromate and acetic acid reduces attack by rot and may considerably increase the life span of a thatched roof (see Chapter 8).

Grass

The use of thatched roofs is common in many countries, and suitable grass can be found almost everywhere. When well laid and maintained, it can last for 10–20 years or longer.

A good-quality thatching grass must be fibrous and tough, with a minimum length of 1 metre. It should also have thin stems without hollows, a low content of easily digestible nutrients and the ability to withstand repeated wetting without decaying.

An annual treatment with a mixture of the following chemicals will improve the fire-resistance of a thatched roof, and also give some protection against decay: 14 kg ammonium sulphate, 7 kg ammonium carbonate, 3.5 kg borax, 3.5 kg boric acid, 7 kg alum and 200 kg water.

Reeds

Reeds must be dry before use as a building material, and can be impregnated or sprayed with copper-chrome preservatives to prevent rotting. Ammonium phosphate and ammonium sulphate are used to protect the reeds against fire (see Chapter 8).

Reeds can be woven into mats for use as wall or ceiling panels, shade roofs, etc. The mats can be plastered easily. In tropical areas, thatch from untreated reeds may last only 1 year but, if well laid, treated and maintained, it can last 5–10 years.

Sisal stems

Before dying, at 7–12 years of age, the sisal plant forms a pole shoot to carry the flowers. The pole may reach a height of 6 metres or more and has a fibrous circumference, which makes it tough, but the inner parts are quite soft. Sisal poles have limited structural strength and durability, but are sometimes used for wall cladding in semi-open structures, such as maize cribs. The poles can be split and are joined in the same way as bamboo.

Sisal fibre

Sisal fibre is one of the strongest natural fibres. It has traditionally been used as reinforcement in gypsum plaster sheets. Sisal fibres have the ability to withstand degradation from bacteriological attack better than other organic fibres, but are attacked by the alkalinity of cement. However, research has been carried out to make sisal fibre, like other natural fibre composites, into a reliable cement reinforcement for long-term use in exposed situations. Refer to the section on fibre-reinforced concrete.

Coir waste

Coir is a by-product of coconuts. The husk is used for making coir mats, cushions and as fuel. It can be mixed with cement, glue or resins, either to produce low-density boards with good insulating and sound-absorption properties, or to be compressed to make building boards. It is also used as reinforcement in cement for making roofing sheets.

Elephant grass

Elephant grass is a tall plant similar to bamboo, but with the difference that the stem is not hollow. The fibres of the grass can be used to partly or wholly replace the asbestos in net and corrugated roofing sheets. However, the sheets are more brittle and have a slightly lower strength than asbestos-cement sheets.

Straw

Baled straw, if supported by a framework of wooden poles, can be used to construct temporary walls. Straw has also been used as raw material for manufactured building boards. Straw and split bamboo can be cement-plastered to permanent structures, such as vaults and domes, at low cost.

NATURAL STONE PRODUCTS

Natural stones are strong in compression and are generally extremely durable, although deterioration may result from the action of soluble salts, wetting and drying, or thermal movement. According to the manner of their geological formation, all stones used in building fall into one of three classes: *igneous, sedimentary* or *metamorphic.*

Igneous rocks are mostly very hard and difficult to cut to size and shape. However, they are very durable.

Sedimentary rocks, such as sandstone and limestone, are used extensively for building. They are not difficult to work, yet are quite durable. Coral stone is found in coastal areas, where chips or small stones are used in mud walls. Coral stone is also cut into blocks and, although not very strong, can be used in foundations and walls in multistorey houses.

Metamorphic stones consist of older stones that have been subjected to intense heat and pressure, causing structural change. Thus clay becomes slate, limestone becomes marble and sandstone becomes quartzite. Slate develops cleavage planes during formation. Roofing slates are split along these planes. They make very durable roof surfaces, but require strong frames because of their weight.

At the building site, the stones can be dressed to obtain a smooth surface. Often only the side(s) that will be visible are dressed.

Stones may also be used in the forms and sizes in which they naturally occur, and be embedded in mortar for foundation and wall construction. Stones are also crushed and sorted for size and use. Small crushed stones are used in making concrete. Large sizes are used as hardcore for filling purposes.

EARTH AS A BUILDING MATERIAL

Earth is one of the oldest materials used for building construction in rural areas. The advantages of earth as a building material are:

1. It is resistant to fire.
2. It is cheaper than most alternative wall materials, and is readily available at most building sites.
3. It has a very high thermal capacity, which enables it to keep the inside of a building cool when it is hot outside and *vice versa*.
4. It absorbs noise well.
5. It is easy to work using simple tools and skills.

These qualities encourage and facilitate self-help and community participation in house building.

Despite its good qualities, earth has the following drawbacks as a building material:

1. It has low resistance to water penetration, resulting in crumbling and structural failure.
2. It has a very high shrinkage/swelling ratio, resulting in major structural cracks when exposed to changing weather conditions.
3. It has low resistance to abrasion, and requires frequent repairs and maintenance when used in building construction.

However, there are several ways to overcome most of these weaknesses that make earth a suitable building material for many purposes.

Soil classification

Soil and earth are synonymous when used in relation to building construction. The term 'soil' refers to subsoil, and should not be confused with the geological or agricultural definition of soil, which includes the weathered organic material in topsoil. Topsoil is generally removed before any engineering works are carried out, or before soil is excavated for use as a building material. Mud is the mixture of one or more types of soil with water.

There are several ways in which soil may be classified: by geological origin, by mineral content (chemical composition), by particle size or by consistency (mainly related to its moisture content).

Particle size

Soils are grouped and named according to their particle size, as shown in Table 5.5.

Grading

The soil materials in Table 5.6 seldom occur separately, and this necessitates a further classification according to the percentage of each contained in the soil. This is shown in the soil classification triangle, which shows, for example, that a sandy clay loam is defined as soil that contains 50–80 percent sand, 0–30 percent silt and 20–30 percent clay.

Only a few mixes can be used successfully for building construction in the state in which they are found. However, many mixes can be improved to make good building material by correcting the mix and/or adding stabilizers.

The clay fraction is of major importance in earth construction because it binds the larger particles together. However, soils with more than 30 percent clay tend to have very high shrinkage/swelling ratios which, together with their tendency to absorb moisture, may result in major cracks in the end product. High-clay soils require very high proportions of stabilizer or a combination of stabilizers.

Some soils produce unpredictable results, caused by undesirable chemical reactions with the stabilizer. Black cotton soil, a very dark coloured clay, is an example of such a soil. Generally speaking, soils that are good for building construction purposes are characterized by good grading, i.e. they contain a mix of different-sized particles similar to the ratios in Table 5.6, where all voids between larger particles are filled by smaller ones. Depending on use, the maximum size of coarse particles should be 4–20 mm.

Laterite soils, which are widely distributed throughout the tropical and subtropical regions, generally give very good results, especially if stabilized with cement or lime. Laterite soils are best described as highly weathered tropical soils containing varying proportions of iron and aluminium oxides, which are present in the form of clay minerals, usually together with large amounts of quartz. Their colours range from ochre, through red, brown and violet to black. The darker the soil, the harder, heavier and more resistant it is to moisture. Some laterites harden on exposure to air.

TABLE 5.5
Classification of soil particles

Material	Size of particles	Means of field identification
Gravel	60–2 mm	Coarse pieces of rock, which are round, flat or angular.
Sand	2–0.06 mm	Sand breaks down completely when dry; the particles are visible to the naked eye and gritty to the touch.
Silt	0.06–0.002 mm	Particles are not visible to the naked eye, but slightly gritty to the touch. Moist lumps can be moulded but not rolled into threads. Dry lumps are fairly easy to powder.
Clay	Smaller than 0.002 mm	Smooth and greasy to the touch. Holds together when dry and is sticky when moist.
Organic	Up to several centimetres	Spongy or stringy appearance. The organic matter is fibrous, rotten or partially rotten, several centimetres deep, with an odour of wet, decaying wood.

Gravel, sand and silt are sometimes subdivided into coarse, medium and fine fractions.

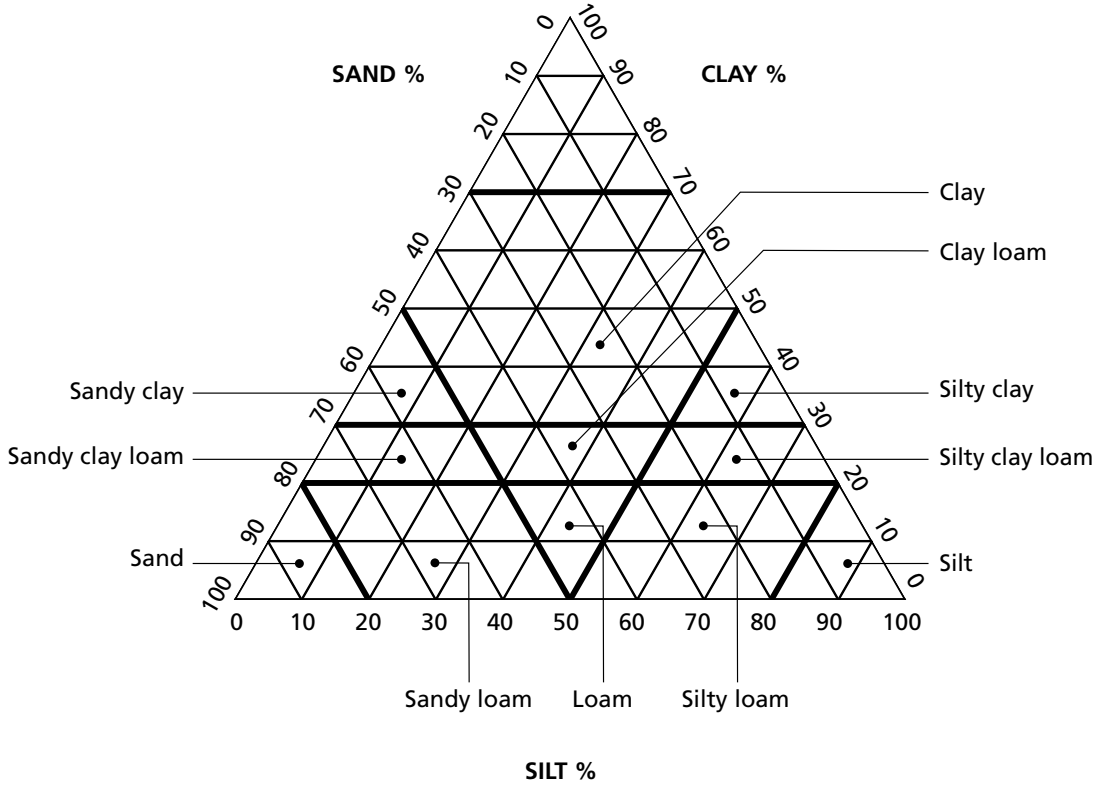


Figure 5.10 **Soil-classification triangle**

TABLE 5.6
Soil gradings suitable for construction

Use	Clay (%)	Silt (%)	Clay& Silt (%)	Sand (%)	Gravel (%)	Sand & Gravel (%)	Cobble (%)	Organic Matter (%)	Soluble salts (%)
Rammed-earth walls	5–20	10–30	15–35	35–80	0–30	50–80	0–10	0–03	0–1.0
Pressed- soil blocks	5–25	15–35	20–40	40–80	0–20	60–80	-	0–03	0–1.0
Mud bricks (adobe)	10–30	10–40	20–50	50–80	-	50–80	-	0–0.3	0–1.0
Ideal, general-purpose mix	15	20	35	60	5	65	-	0	0

If the soil at hand is not suitable, it may be improved by adding clay or sand. The best soils for construction are sandy loam and sandy clay loam. Sandy clay gives fair results if stabilized.

Plasticity index

Clays vary greatly in their physical and chemical characteristics. Although the extremely fine particles make it very difficult to investigate their properties, some can be conveniently expressed in terms of plasticity using standard tests.

Depending on the amount of moisture it contains, a soil may be liquid, plastic, semisolid or solid. As a soil dries, the moisture content decreases, as does the volume of the sample. With very high moisture content, the soil will flow under its own weight and is said to be liquid. At the liquid limit, the moisture content has fallen to the extent that the soil ceases to flow and becomes plastic; it is continuously deformed when a force is applied, but retains its new shape when the force is removed.

A further reduction of the moisture content will eventually cause the soil to crumble under load and not deform plastically. The moisture content at this point is known as the 'plastic limit'. The numerical difference between the moisture content at the liquid limit and at the plastic limit is called the 'plasticity index'. Both the liquid limit and the plasticity index are affected by the amount of clay and the type of clay minerals present.

A high liquid limit and plasticity index indicates a soil that has great affinity for water and will therefore be more susceptible to moisture movements, which can lead to cracks.

Example 5.1

The following index properties were determined for two soils X and Y.

Property	X	Y
Liquid limit	0.62	0.34
Plastic limit	0.26	0.19

Determine the plasticity index of X and Y.

Solution

The plasticity index is the range of moisture content over which the soil remains plastic. The bigger this range, the greater the proportion of clay particles.

For soil X, plasticity index = liquid limit - plastic limit = 0.62 - 0.26 = 0.36.
For soil Y, plasticity index = 0.34 - 0.19 = 0.15
Soil X contains more clay particles.

Soil-testing methods

As indicated above, some soils are more suitable for building material than others. It is therefore essential to have a means of identifying different types of soil. There are a number of methods, ranging from laboratory tests to simple field tests. Laboratory soil tests are recommended for the production of buildings on a large scale (i.e. several houses).

As soils can vary widely within small areas, samples of the soil to be tested must be taken from exactly the area where soil is going to be dug for the construction. Soil samples should be collected from several places distributed over the whole of the selected area. First remove the topsoil (any dark soil with roots and plants in it), which is usually less than 60 cm. Then dig a pit to a depth of 1.5 metres, and collect soil for the sample at various depths between 0.8 metres and 1.5 metres. The total volume required for a simple field test is about a bucketful, whereas a complete laboratory test requires about 50 kg. Mix the sample thoroughly, dry it in the sun, break up any lumps and pass it through a 5–10 mm screen.

In the laboratory, the classification by particle size involves sieving the coarse-grained material (sand and gravel) and sedimentation for fine-grained material (silt and clay). The plasticity index is determined using the Atterberg limit test.

Soil tests will only give an indication of the suitability of the soil for construction purposes and the type and amount of stabilizer to be used. However, other properties, such as workability and behaviour during compaction, may eliminate an otherwise suitable soil. Soil tests should therefore be combined with tests on the finished products, at least where high strength and durability are required for the design and use.

For small projects, a simple sedimentation test combined with a bar shrinkage test normally gives enough information about the proportions of various particle sizes and the plastic properties of the soil.

Simple sedimentation test

This test gives an impression of the grading of the soil and allows the combined silt and clay content to be calculated. Take a large, clear glass bottle or jar with a flat bottom and fill it one-third full with soil from the sample. Add water until the bottle is two-thirds full. Two teaspoons of salt may be added to dissolve the soil more rapidly. Close the bottle, shake it vigorously, and allow the contents to settle for 1 hour. Shake it again and let it settle for at least 8 hours.

The soil sample should now show a fairly distinct line, below which the individual particles can be seen with the naked eye. Measure the thickness of the combined silt and clay layer above the line, and calculate it as a percentage of the total height of the soil sample.

The test tends to give a lower figure than laboratory tests, as a result of some silt and clay being trapped in the sand, and because some material remains suspended in the water above the sample.

The main disadvantage with this test is that the silt and clay fractions cannot be determined separately. As silt behaves differently from clay, this could result in mistaken conclusions about the soil's suitability for stabilization and as a building material.

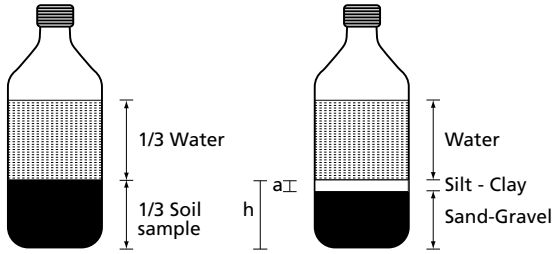


Figure 5.11 **Simple sedimentation**

Bar shrinkage test

This test gives an indication of the plasticity index of the soil, because the shrinkage ratio of the soil when dried in its plastic state is related to its plasticity index.

A wooden or metal box without a top and with a square cross-section of 30–40 mm per side and a length of 500–600 mm, is filled with soil from the sample (see Figure 5.12). Before filling, the soil should be mixed with water to slightly more than the liquid limit. The consistency is right when a V-shaped groove cut in the soil will close after about five taps on the box. Grease or oil the box, fill with the soil and compact it well, paying special attention to filling the corners. Smooth the surface by scraping off the excess soil. Place the box in the shade for 7 days. The drying can be hastened by placing the box at room temperature for 1 day, and then in an oven at 110 °C until the soil is dry.

If, after drying, the soil bar has more than three large cracks in addition to the end gaps the soil is not suitable. Measure the shrinkage ratio by pushing the dried sample to one end of the box and calculate the length of the gap as a percentage of the length of the box. The soil is not suitable for stabilization if the shrinkage ratio is more than 10 percent, i.e. a gap of 60 mm in a 600 mm long box. The higher the shrinkage ratio, the more stabilizer has to be used. The shrinkage ratio is calculated as follows:

$$\textit{Shrinkage ratio} = \frac{(\textit{Length of wet bar}) - (\textit{Length of dried bar})}{\textit{Length of wet bar}} \times 100 \quad (5.4)$$

Soil stabilization

The main weakness of earth as a building material is its low resistance to water. While overhanging eaves and verandas help considerably, tropical rains of any intensity can damage unprotected walls. Due to the clay fraction, which is necessary for cohesion, walls built of unstabilized soil will swell on taking up water, and shrink on drying. This may lead to severe cracking and difficulty in making protective renderings adhere to the wall.

However, the quality as a building material of nearly any inorganic soil can be improved considerably by the addition of a suitable amount of the correct stabilizer. The aim of soil stabilization is to increase the soil's resistance to destructive weather conditions, in one or more of the following ways:

1. By cementing the soil particles together, leading to increased strength and cohesion.
2. By reducing the movements (shrinkage and swelling) of the soil when its moisture content varies according to weather conditions.
3. By making the soil waterproof, or at least less permeable to moisture.

A great number of substances may be used for soil stabilization. Owing to the many different kinds of soil and types of stabilizer, there is no single solution for all cases. It is up to the builder to make trial blocks with various amounts and types of stabilizer.

Stabilizers in common use are:

- sand or clay;
- portland cement;
- lime;
- bitumen;

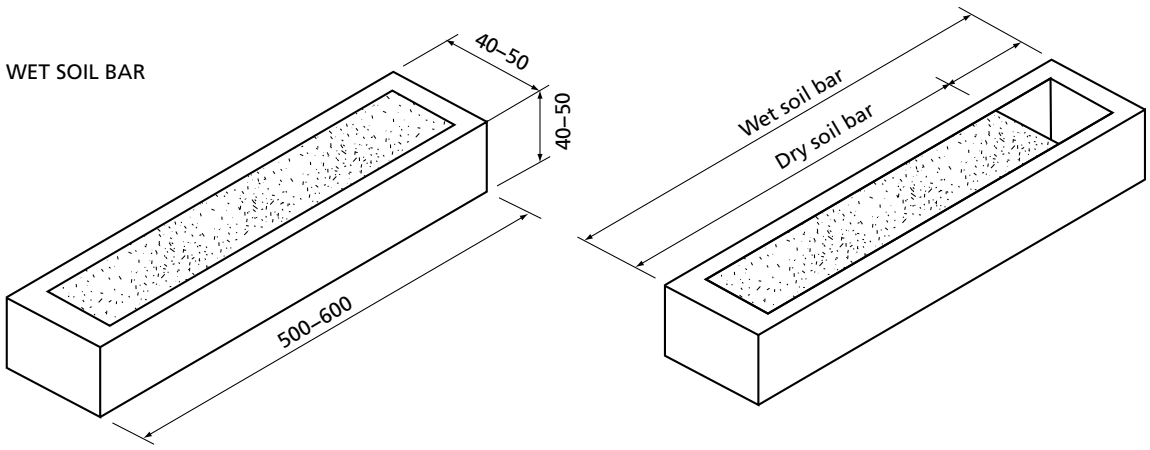


Figure 5.12 **Box for bar shrinkage test**

- pozzolana (e.g. fly ash, rice husk ash, volcanic ash);
- natural fibres (e.g. grass, straw, sisal, sawdust);
- sodium silicate (water-glass);
- commercial soil stabilizers (for roads);
- resins;
- whey;
- molasses;
- gypsum;
- cow dung.

Many other substances may also be used for soil stabilization, although their use is not well documented and test results are scarce.

Sand or clay is added to improve the grading of a soil. Sand is added to soils that are too clayey, and clay is added to soils that are too sandy. The strength and cohesion of the sandy soil is increased, while moisture movement of a clay soil is reduced. Improved grading of the soil material does not stabilize the soil to a high degree, but will increase the effect, and reduce the required amount, of other stabilizers. The clay or clayey soil must be pulverized before mixing with the sandy soil or sand. This may prove difficult in many cases.

Portland cement greatly improves the soil's compressive strength and imperviousness, and may also reduce moisture movement, especially when used with sandy soils. As a rough guide, sandy soils need 5–10 percent cement for stabilization, silty soils, 10–12.5 percent and clayey soils, 12.5–15 percent. Compaction when ramming or pressing blocks will greatly improve the result.

The cement must be thoroughly mixed with dry soil. This can be rather difficult, especially if the soil is clayey. As soon as water is added, the cement starts reacting and the mix must therefore be used immediately (1–2 hours). If the soil-cement hardens before moulding, it must be discarded. Soil-cement blocks should be cured for at least 7 days under moist or damp conditions.

Non-hydraulic lime, or slaked lime, gives best results when used with fine soils, i.e. silty and clayey soils. Lime decreases moisture movement and permeability, by reaction with the clay, to form strong bonds between the soil particles. The amount of lime used varies between 4 percent and 14 percent. Lime breaks down lumps and makes it easier to mix clayey soils. Curing at high temperatures strengthens the cementing molecules, which should be an advantage in the tropics. The curing time is longer than for soil-cement.

A *combination of lime and cement* is used when a soil has too much clay for cement stabilization, or too little clay for an extensive reaction with the lime. Lime will make the soil easier to work and the cement will increase the strength. Equal parts of lime and cement are used. Mixing the dry soil with lime first makes the soil more workable. Blocks are cured for at least 7 days under moist conditions.

Bitumen (or asphalt) emulsion and cutback are used mainly to improve the impermeability of the soil and keep it from losing its strength when wet, but may cause some decrease in dry strength. They are only used with very sandy soils because it would be very difficult to mix them with clayey soils. In its natural form, bitumen is too thick to be added to soil without heating, so it has to be thinned with other liquids to make it workable. The easiest way is to mix it with water to make an emulsion. After the emulsion has been added to the soil, the water will separate, leaving a bitumen film on the soil grains.

If the bitumen emulsion is fast-settling (i.e. the water separates too quickly before it is mixed into the soil), the bitumen must instead be dissolved in kerosene or naphtha. This mix is called 'cutback' and should be handled with care because it represents a fire hazard and explosion risk. After a soil has been treated with cutback, it must be spread out to allow the kerosene to evaporate.

The bitumen content used is 2–4 percent, as any more may seriously reduce the compressive strength of the soil.

A *combination of lime and pozzolana* makes a binder that can be almost as good as portland cement. It is used in the same way as a combination of lime and cement, but 2-4 parts of pozzolana are mixed to 1 part of lime, and the curing time is longer than for ordinary cement.

Natural fibres, used in a mixing ratio of about 4 percent, greatly reduce moisture movement, but will make dry-soil blocks weaker and more permeable to water.

Sodium silicate, or water-glass, is best used to coat the outside of soil blocks as a waterproofing agent.

Cob

Cob is used extensively in tropical Africa, where suitable soils are obtainable over wide areas. The best soil mix consists of gravel, sand, silt and clay in roughly equal proportions. Sometimes chopped grass or straw is added to reduce cracking. If the clay content is high, sand may be added. Laterite makes an excellent material for cob walling.

When a suitable soil has been found, the topsoil is removed and the subsoil dug up. Water is slowly added to the loose soil, which is then kneaded by treading until the soil has a wet, plastic consistency. Natural fibres are added for stabilization if required.

The wet cob is rolled into balls or lumps measuring about 20 cm in diameter, which are then bedded on the wall to form courses about 60 cm high. The outside of the wall may be scraped smooth. In arid and semi-arid climates, this type of wall may last for years if built on a proper foundation and protected from rain by a roof overhang or veranda.

Wattle and daub (mud and wattle)

This method of building small houses is very common in areas where bamboo or stalks (e.g. sisal) are available.

It consists of a framework of split bamboo, stalks or wooden sticks, supported by wood or bamboo poles. The soil, prepared as cob, is daubed on either side of the laths, which act as reinforcement. Although most soil is suitable for this construction, if it is too clayey there may be excessive cracking. To minimize cracking, stones are mixed with the soil, or laid in the wooden skeleton. When mudding the inside of a building, the soil is often taken from the floor. Although this increases the ceiling height, it greatly increases the likelihood of flooding during the rainy season.

During drying, the weight of the soil is transferred to the wooden structure, with the total weight of the construction eventually resting on the poles.

Wattle and daub construction generally has a short lifespan because of soil erosion, and the uneven settling of poles and damage by fungi and termites. However, the durability can be improved considerably (20–40 years) by using a proper foundation, raising the building off the ground, applying a surface treatment and using termite-resistant or treated poles.

Clay/straw

The technique of building walls of clay/straw has been highly developed in China, where grain storage bins of up to 8 m in diameter, 8.5 m in height and a 250-tonne holding capacity have been constructed with these materials.

Any type of straw can be used, but it must be of good quality. The clay should be of strong plasticity, containing less than 5 percent sand. Some lime may be added for stabilization if the sand content is a bit too high.

First, the straw bundles are produced. The straw is pruned level at the root ends and then divided into two halves, which are turned in opposite directions and placed together so that they overlap by about two-thirds of the length of the straw. The straw bundle is then spread out flat and soaked with clay mud. Thorough covering of each straw is essential for the final strength. The straw is then twisted together, and any excess mud removed. The final clay/straw bundle should be thick in the middle and tapered at both ends, be of 80–100 cm in length and roughly 5 cm in diameter at the middle. The ideal proportion of straw and clay is 1:7 on a dry weight basis.

The clay/straw bundles are placed on the wall either straight and flat, or slightly twisted together. Walls for grain bins should have a thickness in centimetres equal to the internal diameter in metres + 12, i.e. a 6-metre diameter bin should have a wall thickness of at least 18 cm. It is important to compact the wall thoroughly during construction to ensure high density, strength and durability. The wall must be built in separate layers, usually about 20 cm, and be left to dry out to about 50 percent moisture content before the next layer is added.

Rammed earth

This consists of ramming slightly damp soil between stout formwork using heavy rammers. It makes fairly strong and durable walls and floors when it is made thick enough with properly prepared, stabilized soil.

When used for walls, the soil may contain some cobble, but the maximum size should be less than one-quarter of the thickness of the wall. When cement is used for stabilization, it must be mixed with the dry soil by hand, or in a concrete mixer, until the dry mixture has a uniform greyish colour. The amount of cement required is approximately 5–7 percent for interior walls, 7–10 percent for foundations and exterior walls, and 10–15 percent for floors. However, the amount of stabilizer required will vary with the composition of the soil, the type of stabilizer and the use. For this reason, trial blocks should be made and tested to determine the correct amount of stabilizer.

Water is sprinkled on the soil while it is being mixed. If the soil is sticky because of high clay content, hand mixing will be necessary. When the correct amount of water has been added, the soil will form a firm lump when squeezed in the hand, and just enough moisture should appear on the surface to give a shiny appearance.

After the mixing has been completed, the soil should be placed in the formwork immediately. The formwork can be either fixed or sliding, but must be stout. The soil is placed in layers of about 10 cm, and each layer is thoroughly compressed with a ram weighing 8–10 kg before the next layer is placed. If water shows on the surface during ramming, the soil mix is too wet.

If cement or pozzolana has been used for stabilization, the product should be cured for 1–2 weeks in a moist condition before it is allowed to dry out. This can be done either by keeping the product enclosed in the formwork, or by covering it with damp bags or grass that are watered daily.

Adobe or sun-dried soil (mud) blocks

The best soil for adobe can be moulded easily, when plastic, into an egg-size ball, and when it is allowed to dry in the sun it becomes hard, shows little deformity and no more than very fine cracks. If wide cracks develop, the soil does not contain enough silt or sand, and sand may be added as a stabilizer.

Preparing the soil

When a suitable soil has been found, all topsoil must be removed. The soil is then loosened to a depth of 15 cm. If needed, water and sand are added and worked into the loose soil by treading it barefoot while turning the mass with a spade.

Water is added slowly and the soil mixed thoroughly until all lumps are broken up and it becomes homogeneous and plastic. When it is the right consistency for moulding, it is cast in a wooden mould made with one to three compartments and with dimensions as shown in Figure 5.13.

Before the mould is used for the first time it should be thoroughly soaked in oil. Because of the shrinkage, the finished blocks will be smaller than the moulds and, depending on bonding, will give a wall thickness of about 230 mm, 270 mm or 410 mm.

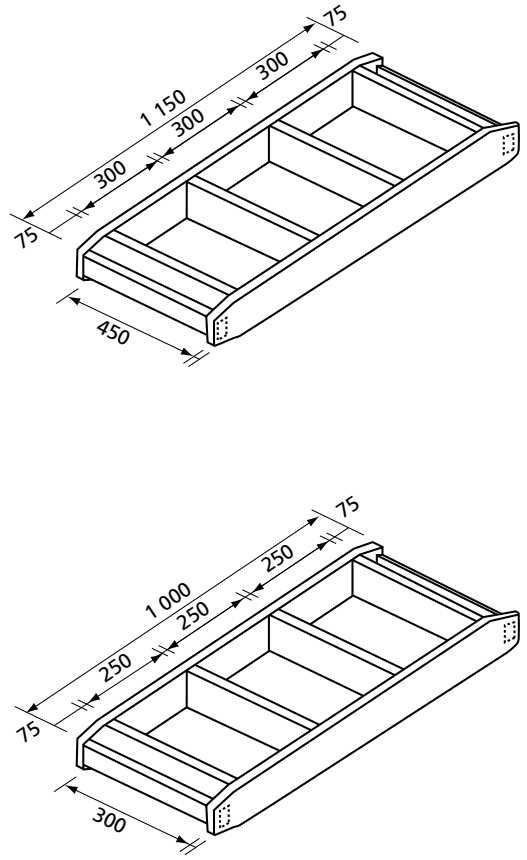


Figure 5.13 **Wooden moulds for making adobe blocks made of 100 × 25 mm sawn timber**

Moulding the blocks

To prevent sticking, the mould must be soaked in water before being placed on level ground, and filled with mud. The mud is kneaded until all corners of the mould are filled, and the excess is scraped off. The mould is lifted and the blocks are left on the ground to dry. The mould is dipped in water each time before repeating the process.

After drying for 3–4 days, the blocks will have hardened sufficiently to be handled, and are turned on edge to hasten drying. After a further 10 days, the blocks can be stacked loosely in a pile. Adobe blocks should dry out as slowly as possible to avoid cracks, with a total curing time of at least 1 month.

The quality of the blocks depends largely on the workmanship, especially the thoroughness with which they are moulded. If the quality is good, only 1 in 10 blocks should be lost from cracking, breakage or deformities.

Stabilized-soil blocks

When a suitable soil has been found, the topsoil should be removed and the subsoil dug out and spread out to dry in the sun for a few days.

Large particles and lumps must be removed before the soil is used, by breaking the larger lumps and passing all the soil through a 10 mm screen. If the proportion of gravel in the soil is high, a finer screen, of 4.5–6 mm, should be used. The wire screen, usually measuring about 1 metre square, is rocked in a horizontal position by one person holding handles at one end, with the other end suspended in ropes from above. The amount of loose, dry soil needed will normally be 1.4–1.7 times its volume in the compacted blocks.

Mixing

The amount of stabilizer to be used will depend on the type of soil, the type of stabilizer and the building component being made. Tables 5.7 and 5.8 give a guide to the necessary minimum mixing ratio of soil-cement for blocks compacted in a mechanical press. For blocks compacted in a hydraulic press, the cement requirement can be reduced considerably, whereas slightly more will be needed for hand-rammed blocks. The correct proportion of stabilizer is determined by making test blocks with varying proportions of stabilizer, as described later.

TABLE 5.7
Cement/soil ratio related to shrinkage ratio in the bar shrinkage test

Shrinkage	Cement to soil ratio
0–2.5%	1:18
2.5–5%	1:16
5–75%	1:14
7.5–10%	1:12

TABLE 5.8
Cement/soil ratio related to the combined silt and clay content in the simple sedimentation test

Clay & silt content	Interior walls	Exterior walls	Foundations	Floor slab
0–10%	1:16	1:16	1:16	1:8
10–25%	1:22	1:16	1:16	1:11
25–40%	1:22	1:11	1:11	1:11

The importance of thoroughly mixing the dry soil first with the stabilizer and then with the moisture, in two distinct steps, cannot be emphasized too strongly.

The quantity of cement and dry soil is measured with a measuring box, bucket or tin (never with a shovel), and put either on a clean, even and hard surface for hand mixing, or into a drum-type mixer (concrete mixer). They are mixed until the dry mixture has a uniform

TABLE 5.9
Batching for stabilized-soil blocks

Proportions cement/soil by volume	Approximate cement content by weight	Requirement of loose soil per 50 kg cement	Number of blocks per 50 kg cement Size of blocks				
			290×140×50	290×140×90	290×140×120	290×140×140	290×215×140
1:22	5%	1 080 litres	366	203	152	130	85
1:18	6%	880 litres	301	167	125	107	70
1:16	7%	780 litres	268	149	111	95	62
1:14	8%	690 litres	235	131	98	84	54
1:12	9%	590 litres	203	113	84	72	47
1:11	10%	540 litres	187	104	78	66	43
1:10	11%	490 litres	170	94	71	61	39
1:9	12%	440 litres	154	85	64	55	36
1:8.5	13%	420 litres	146	81	61	52	34
1:8	15%	390 litres	138	76	57	49	32

greyish colour. Water is added, preferably through a sprinkler, while continuing the mixing. When the correct amount of water has been added, the soil, when squeezed into a ball, should retain its shape without soiling the hand. The ball should be capable of being pulled apart without disintegrating, but it should disintegrate when dropped from shoulder height on to a hard surface.

Compaction by hand-ramming

Moulds with one or more compartments can be made from either hardwood or steel. The mould should have hinges at one or two corners to enable it to be opened easily without spoiling the block. As mould has no bottom, it is preferable to place it on a pallet, rather than directly on the ground, when moulding the block.

The mould is treated as often as required with oil to make the block surface smooth and to prevent the block from sticking to the mould. The soil mixture should be placed in layers in the mould, and each layer thoroughly compacted with a flat-bottomed ram weighing 4–5 kg. Each block may need as many as 80 good blows with the ram. The top of the block is levelled off, the block and mould are carried to the curing store where the mould is removed, then the whole process is repeated.

Compaction with a mechanical press

There are many mechanical block-making machines on the market, both motor-driven (enabling several blocks to be made at a time), and hand-operated.

They all consist of a metal mould in which a moist soil mix is compressed.

The moulding for a hand-operated press is carried out as follows:

1. The inside of the compaction chamber is cleaned and oiled, and a pallet is placed in the bottom, if required.
2. A measured amount of soil mix is poured into the compaction chamber and the soil is compacted into the corners by hand.

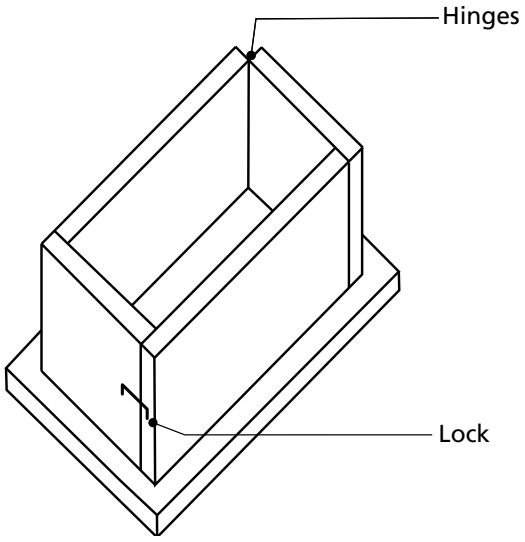


Figure 5.14 **Mould for hand-rammed stabilized-soil blocks made of 20 mm planed timber**

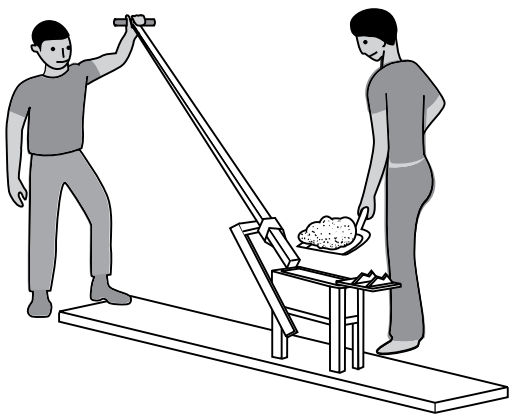


Figure 5.15 **Mechanical press for block making**

3. The lid is closed and the handle pulled down. The amount of soil mix is correct if the handle can be moved down to stop slightly above a horizontal level.
4. The block is ejected and carried on the pallet to the curing site, before returning the pallet to the press for reuse.

Curing of blocks

Soil-cement blocks should be placed on the ground, in the shade, as close together as possible, and be kept damp (e.g. with wet grass). After 1–2 days, the blocks can be carefully stacked and again kept damp for 1–2 weeks. After this period, the blocks are allowed to air dry for 2–3 weeks in a stacked pile before use.

Testing of blocks

In the laboratory, dry strength and wet strength are determined by crushing two well-cured blocks in a hydraulic press: the first in a dry state, and the second after having been soaked in water for 24 hours. Durability is tested by spraying the blocks with water according to a standard procedure, and making observations for any erosion or pitting.

In order to find out how much stabilizer is required, the following simple weather-resistance test carried out in the field may give a satisfactory answer.

At least three different soil mixes with different stabilizer-soil ratios are prepared, and at least three blocks are made from each of the different mixes.

Mixing, compaction and curing must be done in the same way as for the block production process. At the end of the curing period, three blocks are selected from each set, immersed in a tank, pond or stream all night, and dried in the sun all day. This wetting and drying process is repeated for 7 days.

The correct amount of stabilizer to use is the smallest amount with which all three blocks in a set pass the test. While a few small holes are acceptable on the compaction surface, if many holes appear on all surfaces the blocks are too weak. If the blocks have passed the test and the dry block produces a metallic ring when tapped with a hammer, they will have satisfactory durability and hardness.

If the blocks fail the test, the reason may be any of the following:

- unsuitable soil;
- insufficient amount of stabilizer;
- incorrect type of stabilizer;
- inadequately dried or lumpy soil;
- lumpy cement;
- insufficient mixing of the stabilizer;
- too much or too little water added;
- not enough compaction;
- incorrect curing.

Comparison of masonry units made of various materials

There are many methods for making bricks and blocks, several of which are suitable for local production because they are labour-intensive but do not require especially skilled labour.

The decision concerning which method of blockmaking or brickmaking to use depends on several factors, such as:

- the raw materials available;
- the characteristics of the soil;
- raw material and production costs;
- the requisite standards of stability, compression strength, water resistance, etc. (3 N/mm² is often regarded as the minimum compressive strength for use in one-storey buildings);
- the existing facilities for the maintenance of production tools and machines;
- the required productivity.

BURNT-CLAY BRICKS

Burnt-clay bricks have good resistance to moisture, insects and erosion, and create a good room environment. They are moderate in cost and have medium to high compressive strength.

Bricks can be made using sophisticated factory methods, simple labour-intensive methods, or a range of intermediate mechanized technologies. Labour-intensive production methods are the most suitable for rural areas where the demand for bricks is limited. Handmade bricks will be of comparatively lower quality, especially in terms of compressive strength, and will tend to have irregular dimensions. However, they are economical and require little capital investment or transportation costs. Bricks made in this manner have been used in buildings that have lasted for centuries. Their longevity depends on the quality of the ingredients, the skill of the artisans and the climate in which they are used.

Brickmaking

Five main ingredients are required for brickmaking: suitable clay and sand, water, fuel and manpower. The clay must be easily available, plastic when mixed with small amounts of water, develop strength upon drying and develop hard and durable strength when burned.

Suitable soils contain 25–50 percent clay and silt and 50–75 percent coarser material, as determined by the simple sedimentation test. The soil must be well graded. Another test consists of hand-rolling moistened soil into a long cylinder 10 mm in diameter on a flat surface, and then picking it up by one end and letting it hang unsupported.

A soil is adequate for brickmaking if the piece of cylinder that breaks off is between 50 mm and 150 mm long. In the bar shrinkage test, using a mould 300 mm long and 50 mm wide and deep, a suitable soil should show no cracking, or only a little on the surface, and should shrink less than 7 percent, i.e. less than 20 mm.

TABLE 5.10
Characteristics of masonry units

	Cost	Compressive strength	Resistance to moisture	Resistance to erosion	Uniformity of shape	Room comfort	Speed of production	Skill required to make	Labour requirements	Ease of transport	Energy requirements	Remarks
Sun-dried bricks (adobe bricks)	1	1	1	1	1-3	4	3	1	3	3	1	Most easily produced locally; much improved with stabilizers; least stable and durable.
Manually rammed stabilized-soil blocks	2	1-2	1-2	1-2	2-3	5	1	2	5	2	2	A little more effort; better quality and stability.
Mechanically pressed stabilized-soil blocks	2	2	2	2	4	5	2	2	4	3	2	Stronger; more durable.
Hydraulically pressed stabilized-soil blocks	3	3	3	3	4	5	3	3	3	3	2	Even stronger and more durable.
Locally made burnt-clay bricks	3-4	2-3	3	3-4	1-3	4	2	4	4	3-4	4	Labour-intensive production. Bricks are generally of low quality.
Factory-produced burnt-clay bricks	5	5	5	5	5	4	5	5	1-3	5	3	Commercial production is common. The plant requires large investment.
Concrete blocks (sand and cement)	5	5	4	5	5	3	3-4	4	2-3	4	5	Long life; strong but heavy. Local production is generally more labour-intensive than commercial.
Building stones	4	5	5	5	1-4	3	1	5	5	4	2	When locally available, a strong, durable and attractive material

Scale 1-5 1 = lowest 5 = highest

The clay is obtained by chipping it out of a clay bank and, where necessary, mixing it with sand to form a mixture that will not crack during drying. Water is gradually added to make the clay plastic.

When making bricks, the mould must be cleaned periodically with water. Before each brick is formed, the mould is sprinkled with sand. A lump, or 'clot,' of clay that is only slightly larger than required for a brick is rolled into a wedge shape and then dipped in sand, before being thrown, point down, into the mould. When thrown correctly, the mould will be completely filled, and the excess clay is then shaved off the top with a bowcutter. The sand in the mould and on the clot helps to release the newly formed brick.

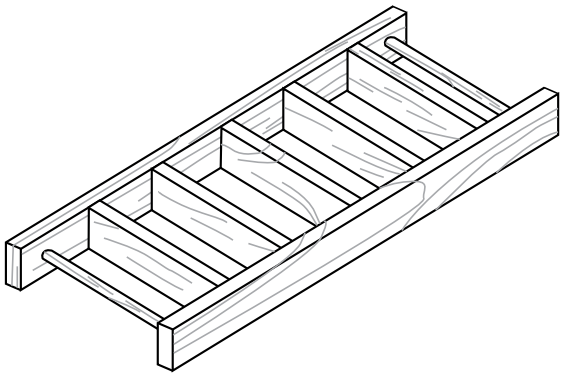


Figure 5.16 **Mould for brick-forming**

The bricks should be left to dry for about 3 days in the place where they were made. They will then be strong enough to be stacked, as shown in Figure 5.17, for

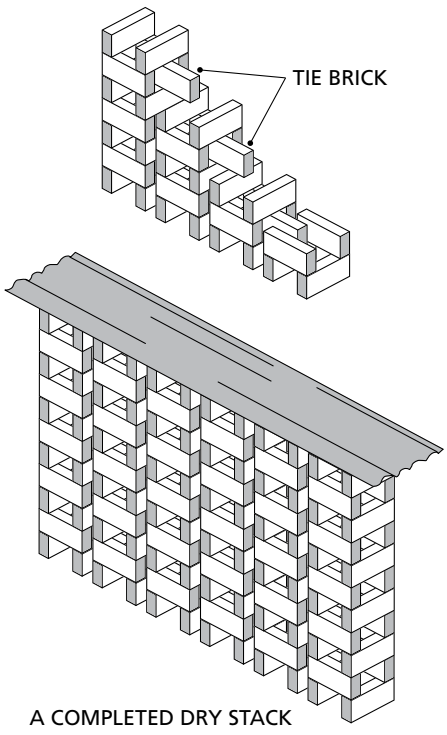


Figure 5.17 **Stacking pattern for brick-drying**

at least 1 week of further drying. Clay tends to become lighter in colour when dry and, when sufficiently dried, the brick should show no colour variation throughout the section area when it is broken in half. During drying, the bricks should be protected from rain.

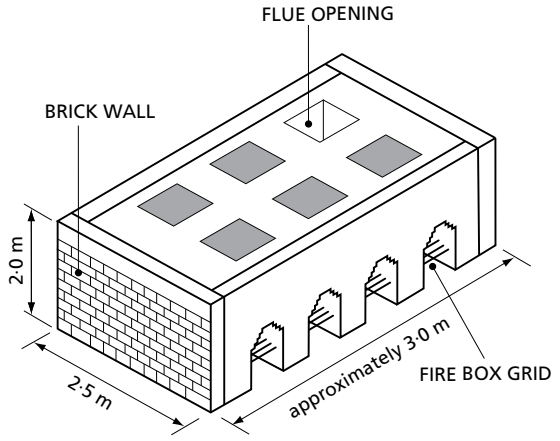


Figure 5.18 **Kiln for brick-firing**

Kiln construction and brick-firing

It is during firing that the bricks gain their strength. In high temperatures, the alkalis in the clay, together with small amounts of oxides of iron and other metals, chemically bond with the alumina and silica in the clay to form a dense and durable mass.

A kiln is a furnace or oven in which bricks are fired or heat-treated to develop hardness. Where brickmaking is carried out on a large scale, the firing operation is performed in a continuous-process kiln, referred to as a 'tunnel' kiln. For brickmaking on a small scale, firing is a periodic operation where the bricks are placed in the kiln, the fire started and heat developed, and then, after several days of firing, the fuel is cut off from the fire and the entire kiln and its load are allowed to cool naturally.

The kiln is filled with well-dried bricks, stacked in the same manner as during the drying process. The top of the stack in the kiln is then sealed with mud. Some openings are left for combustion gases to escape. Pieces of sheet metal are used to slide over the openings to control the rate at which the fire burns.

Although a range of fuels can be used in a kiln, wood or charcoal are the most common. When the kiln is at the prime heat for firing, a cherry-red hue develops (corresponding to a temperature range of 875–900 °C). This condition is maintained for about 6 hours. Sufficient fuel must be available when the burning starts because the entire load of bricks could be lost if the fires are allowed to die down during the operation. Firing with wood requires 4–5 days.

During firing, the bricks will shrink by as much as 10 percent. As they are taken out of the kiln, they should be sorted into different grades, the main criteria being strength, irregular dimensions, cracks and, sometimes, discoloration and stain.

BINDERS

When binders are mixed with sand, gravel and water, they make a strong and long-lasting mortar or concrete.

Binders can be broadly classified as non-hydraulic or hydraulic. The hydraulic binders harden through a chemical reaction with water, making them impervious to water and therefore able to harden under water. Portland cement, blast furnace cement (super sulphated), pozzolanas and high-alumina cement belong to the category of hydraulic binders. High-calcium limes (fat or pure limes) are non-hydraulic because they harden by reaction with the carbon dioxide in the air. However, if lime is produced from limestone containing clay, compounds similar to those in portland cement will be formed, i.e. hydraulic lime.

Lime

Non-hydraulic lime refers to high-calcium limes that are produced by burning fairly pure limestone (essentially calcium carbonate), in order to drive off the carbon dioxide, leaving calcium oxide or quicklime. The burning process requires a temperature of 900–1 100 °C. Quicklime must be handled with great care because it reacts with moisture on the skin and the heat produced may cause burns. When water is added to quicklime, considerable heat is generated, expansion takes place, breaking down the quicklime pieces into a fine powder, and the resulting product is calcium hydroxide, also called hydrated lime, or slaked lime.

After drying, the powder is passed through a 3-mm sieve, before being poured into bags for storage (in dry conditions) and distribution.

Process	Substance	Chemical formula
Burning	Limestone – quicklime	$CaC0_3$ - $CaO + C0_2$
Slaking	Quicklime – slaked lime	$CaO + H_20$ - $Ca(OH)_2$
Hardening	Slaked lime – limestone	$Ca(OH)_2 + CO_2$ - $CaC0_3 + H_20$

Slaked lime is used mainly in building because it is fat, i.e. it makes workable mortar and rendering and plaster mixes. Initially, a lime mortar becomes stiff by evaporation loss of water to absorptive materials such as bricks, but subsequent hardening depends on the chemical reaction with carbon dioxide from the air (carbonation) reforming the original calcium carbonate (limestone).

Non-hydraulic lime is also produced from limestone with a high content of magnesium carbonate. It is less easily slaked, but some of the remaining unslaked magnesium oxide may carbonate and produce greater strength than high-calcium lime.

Hydraulic lime is produced by mixing and grinding together limestone and clay material, and then burning it in a kiln.

It is stronger but less fat, or plastic, than non-hydraulic lime. During burning, the calcium oxide from the limestone reacts with siliceous matter from the clay to form dicalcium silicate. This compound may react with water, forming 'mineral glue' – tricalcium disilicate hydrate. The reaction is slow and may take weeks or months, but after some time a very good degree of strength is achieved.

The reaction that forms dicalcium silicate requires a very high temperature to be complete. In practical production, a lower temperature of 1 200 °C is used, leaving some of the ingredients in their original state. At this temperature, the limestone will lose the carbon dioxide and thus form quicklime. If the correct amount of water is added, the quicklime will slake, forming a fine powder. Note, however, that excess water will lead to premature hardening caused by hydraulic reaction.

Cement

Portland cement hardens faster and develops considerably higher strength than hydraulic lime. This is because cement contains tricalcium silicate. However, the manufacturing process is much more complicated than for lime. The ingredients are mixed in definite and controlled proportions, before being ground to a very fine powder. The fine grinding is necessary because the formation of tricalcium silicate can only take place in a solid state, and therefore only the surface of the particles in the mix is accessible for the chemical reaction, which requires a temperature of 1 250–1 900 °C to be completed.

During burning, the small particles of limestone and clay are sintered together to form clinker. After cooling, the clinker is ground to cement powder, with a small amount of gypsum being added during the grinding. The finer the cement particles, the larger the surface area available for hydration by water, and the more rapidly setting and hardening occurs. Cement is normally sold in 50 kg bags, but occasionally is available in bulk at a lower price.

Ordinary portland cement is the least expensive, and by far the most widely used, type of cement. It is suitable for all normal purposes.

Rapid-hardening portland cement is more finely ground, which accelerates the chemical reaction with water and develops strength more rapidly. It has the same strength after 7 days as ordinary portland cement does after 28 days. Early hardening may be useful where early stripping of formwork and early loading of the structure is required.

Low-heat portland cement develops strength very slowly. It is used in very thick concrete work where the heat generated by the chemical reactions in ordinary portland cement would be excessive and lead to serious cracking.

Chemistry of cement

The main components of standard portland cement are:

- lime (calcium oxide: 66%) in the form of limestone;
- silica (silicum dioxide: 22%), a component in most quartz, which forms the particles of clays;
- aluminium oxide (4%), found in large quantities in many clays. The proportion of aluminium oxide in the clay can be adjusted by the addition of bauxite, which is mainly water-soluble aluminium oxide;
- iron oxide (3%), found in iron ore and in clay;
- magnesium oxide (2%);
- sulphur dioxide (2%);
- miscellaneous components (1%).

The manufacturing process aims to produce a material with a high content of tricalcium silicate, usually 55–62 percent of the crystals in the clinker. Other crystals formed are: about 15 percent dicalcium silicate (the same component as the hydraulic binder in hydraulic lime), 8–10 percent tricalcium aluminate and 9 percent tetracalcium aluminate ferrite. As cement sinters during burning, it is very important for no calcium oxide (quicklime) to remain in the finished product.

The quicklime will remain embedded in the clinker, even after very fine grinding, and will not be available for slaking until the hardening process of the cement is quite far advanced. When the quicklime particles are finally slaked, they expand and break the structure already developed. The proportion of limestone in the initial mix must therefore be no more than 0.1 percent.

When cement is mixed with water, it initiates the chemical reactions that are so important for hardening. The most important of these is the formation of tricalcium disilicate hydrate, 'mineral glue', from hydrated calcium oxide and silica.

$$2(3CaO\ SiO_2) + 6H_2O = 3CaO\ 2SiO_2\ 3H_2O + 3Ca(OH)_2$$

and

$$2(2CaO\ SiO_2) + 3H_2O = 3CaO\ 2SiO_2\ 3H_2O + Ca(OH)_2$$

The reaction between dicalcium silicate and water is slow and does not contribute to the strength of the concrete until a considerable time has elapsed. Aluminate would interfere with these processes, hence the addition of gypsum at the end of the manufacturing process. The gypsum forms an insoluble compound with the aluminate.

During the hydration process, the cement chemically binds water corresponding to about one-quarter of its weight. Additional water evaporates, leaving voids, which reduce the density, and therefore the strength and durability, of the end products.

Pozzolana

A pozzolana is a siliceous material which, in finely divided form, can react with lime in the presence of

moisture at normal temperatures and pressures to form compounds possessing cementing properties. Unfortunately, the cementing properties of pozzolana mixtures are highly variable and unpredictable.

A wide variety of materials, both natural and artificial, may be pozzolanic. Silica constitutes more than half the weight of the pozzolana. Volcanic ash was the first pozzolana that the Romans used to make concrete for a host of large and durable buildings. Deposits of volcanic ash are likely to be found wherever there are active, or recently active, volcanoes.

Other natural sources of pozzolana are rock or earth in which the silica constituent contains the mineral opal, and the lateritic soils commonly found in Africa. Artificial pozzolana includes fly ash from the combustion of coal in thermoelectric power plants, burnt clays and shales, blast furnace slag formed in the process of iron manufacture, rice husk ash and the ash from other agricultural wastes.

The energy requirement for the manufacture of portland cement is very high. By comparison, lime and hydraulic lime can be produced with less than half the energy requirement, and natural pozzolana may be used directly without any processing. Artificial pozzolana requires some heating, but less than half that required for lime production.

Pozzolana and lime can be produced with much less sophisticated technology than portland cement. This means that pozzolana can be produced at relatively low cost and requires much less foreign exchange than cement. However, it takes 2–3 times the volume of pozzolana to make a concrete with the same strength as with portland cement, and this adds to the cost of transport and handling.

The main use of pozzolanas is for lime-pozzolana mortars, for blended pozzolanic cements and as an admixture in concrete. Replacing up to 30 percent of the portland cement with pozzolana will produce 65–95 percent of the strength of portland cement concrete at 28 days. The strength nominally improves with age because pozzolana reacts more slowly than cement, and at 1 year about the same strength is obtained.

CONCRETE

Concrete is a building material made by mixing cement paste (portland cement and water) with aggregate (sand and stone). The cement paste is the 'glue' that binds the particles in the aggregate together. The strength of the cement paste depends on the relative proportions of water and cement, with a more diluted paste being weaker. In addition, the relative proportions of cement paste and aggregate affect the strength, with a higher proportion of paste making stronger concrete.

The concrete hardens through the chemical reaction between water and cement, without the need for air. Once the initial set has taken place, concrete cures well under water. Strength is gained gradually, depending on the speed of the chemical reaction. Admixtures are sometimes included in the concrete mix to achieve certain properties. Reinforcement steel is used for added strength, particularly for tensile stresses.

Concrete is normally mixed at the building site and poured into formwork of the desired shape, in the position that the unit will occupy in the finished structure. Units can also be precast, either at the building site or at a factory.

Properties of concrete

Concrete is associated with high strength, hardness, durability, imperviousness and mouldability. It is a poor thermal insulator, but has high thermal capacity. Concrete is not flammable and has good fire resistance, but there is a serious loss of strength at high temperatures. Concrete made with ordinary portland cement has low resistance to acids and sulphates but good resistance to alkalis.

Concrete is a relatively expensive building material for farm structures. The cost can be lowered if some of the portland cement is replaced with pozzolana. However, when pozzolanas are used, the chemical reaction is slower and strength development is delayed.

The compressive strength depends on the proportions of the ingredients, i.e. the cement/water ratio and the cement aggregate ratio. As the aggregate forms the bulk of hardened concrete, its strength will also have some influence. Direct tensile strength is generally low, only $^1/_8$ to $^1/_{14}$ of the compressive strength, and is normally neglected in design calculations, especially in the design of reinforced concrete.

Compressive strength is measured by crushing cubes measuring 15 cm on all sides. The cubes are cured for 28 days under standard temperature and humidity conditions, before being crushed in a hydraulic press. Characteristic strength values at 28 days are those below which not more than 5 percent of the test results fall. The grades used are C7, C10, Cl5, C20, C25, C30, C40, C50 and C60, each corresponding to a characteristic crushing strength of 7.0 N/mm^2, 10.0 N/mm^2, 15.0 N/mm^2, etc.

TABLE 5.11
Typical strength development of concrete

	Average crushing strength	
	Ordinary Portland cement	
Age at test	Storage in air 18 °C RH 65% (N/mm^2)	Storage in water (N/mm^2)
1 day	5.5	-
3 days	15.0	15.2
7 days	22.0	22.7
28 days	31.0	34.5
3 months	37.2	44.1

(1 cement/6 aggregate, by weight, 0.6 water/cement ratio).

In some literature, the required grade of concrete is defined by the proportions of cement, sand and stone (so called nominal mixes), rather than the compressive strength. Therefore some common nominal mixes have been included in Table 5.12. Note, however, that the amount of water added to such a mix will have a great influence on the compressive strength of the cured concrete.

The leaner of the nominal mixes listed opposite the C7 and C10 grades are workable only with very well graded aggregates ranging up to quite large sizes.

TABLE 5.12
Suggested use for various concrete grades and nominal mixes

Grade	Nominal mix	Use
C7 C10	1:3:8 1:4:6 1:3:6 1:4:5 1:3:5	Strip footings; trench fill foundations; stanchion bases; non-reinforced foundations; oversite concrete and bindings under slabs; floors with very light traffic; mass concrete, etc.
C15 C20	1:3:5 1:3:4 1:2:4 1:3:3	Foundation walls; basement walls; structural concrete; walls; reinforced floor slabs; floors for dairy and beef cattle, pigs and poultry; floors in grain and potato stores, hay barns, and machinery stores; septic tanks and water storage tanks; slabs for farmyard manure; roads, driveways, paving and walks; stairways.
C25 C30 C35	1:2:4 1:2:3 1:1.5:3 1:1:2	All concrete in milking parlours, dairies, silage silos, and feed and drinking troughs; floors subject to severe wear and weather conditions, or weak acid and alkali solutions; roads and paving in frequent use by heavy machinery and lorries; small bridges; retaining walls and dams; suspended floors, beams and lintels; floors used by heavy, small-wheeled equipment, such as lift trucks; fencing posts and precast concrete components.
C40 C50 C60		Concrete in very severe exposure; prefabricated structural elements; prestressed concrete.

Ingredients

Cement

Ordinary Portland cement is used for most farm structures. It is sold in paper bags containing 50 kg, or approximately 37 litres. Cement must be stored in a dry place, protected from ground moisture, and the storage period should not exceed a month or two. Even damp air can spoil cement. It should be the consistency of powder when used. If lumps have developed, the quality has decreased, although it can still be used if the lumps can be crushed between the fingers.

Aggregate

Aggregate or ballast is either gravel or crushed stone. Aggregates that pass through a 5 mm sieve are called fine aggregate or sand. and those retained are called coarse aggregate or stone. The aggregate should be hard, clean and free from salt and vegetable matter. Too much silt and organic matter makes the aggregate unsuitable for concrete.

To test for silt, place 80 mm of sand in a 200 mm-high transparent bottle. Add water up to a height of 160 mm. Shake the bottle vigorously and allow the contents to settle until the following day. If the silt layer, which will settle on top of the sand, is less than 6 mm, the sand can be used without further treatment. If the silt content is higher, the sand must be washed.

To test for organic matter, place 80 mm of sand in a 200 mm-high transparent bottle. Add a 3 percent solution of sodium hydroxide up to 120 mm. Note that sodium hydroxide, which can be bought from a chemist, is dangerous to the skin. Cork the bottle and shake it vigorously for 30 seconds, then leave it standing until the following day. If the liquid on top of the sand turns dark brown or coffee-coloured, the sand should not be used. A 'straw' colour is satisfactory for most jobs, but not for those requiring the greatest strength or water resistance. Note, however, that some ferrous compounds may react with the sodium hydroxide to cause the brown colour.

Grading of the aggregate refers to proportioning of the different sizes of the aggregate material and greatly influences the quality, permeability and workability of the concrete. With a well-graded aggregate, the various particle sizes intermesh, leaving a minimum volume of voids to be filled with the more costly cement paste. The particles also flow together readily, i.e. the aggregate is workable, enabling less water to be used. The grading is expressed as a percentage by weight of aggregate passing through various sieves. A well-graded aggregate will have a fairly even distribution of sizes.

The *moisture content* in sand is important because the sand mixing ratio often refers to kilograms of dry sand, and the maximum amount of water includes the moisture in the aggregate. The moisture content is determined by taking a representative sample of 1 kg. The sample is accurately weighed and spread thinly on a plate, soaked with spirit (alcohol) and burned while stirring. When the sample has cooled, it is weighed again. The weight loss amounts to the weight of the water that has evaporated, and is expressed as a percentage by dividing the weight lost by the weight of the dried sample. The normal moisture content of naturally moist sand is 2.5–5.5 percent. The amount of water added to the concrete mixture should be reduced by the same percentage.

Density is the weight per volume of the solid mass, excluding voids, and is determined by placing 1 kilo of dry aggregate in 1 litre of water. The density is the weight of the dry aggregate (1 kg) divided by the volume of water forced out of place. Normal values for density of aggregate (sand and stone) are 2 600–2 700 kg/m^3 and, for cement, 3 100 kg/m^3.

Bulk density is the weight per volume of the aggregate, including voids, and is determined by weighing 1 litre of the aggregate. Normal values for coarse aggregate are 1 500–1 650 kg/m^3. Although completely dry and very wet sand have the same volume, the bulking characteristic of damp sand gives it greater volume. The bulk density of typical naturally moist sand is 15–25 percent lower than coarse aggregate of the same material, i.e. 1 300–1 500 kg/m^3.

The *size and texture of aggregate* affects the concrete. The larger particles of coarse aggregate should not exceed one-quarter of the minimum thickness of the concrete member being cast. In reinforced concrete, the coarse aggregate must be able to pass between the reinforcement bars, 20 mm being generally regarded as the maximum size.

While aggregate with a larger surface area and rough texture, i.e. crushed stone, allows greater adhesive forces to develop, it will give less workable concrete.

Stockpiles of aggregate should be situated close to the mixing place. Sand and stone should be kept separate. If a hard surface is not available, the bottom of the pile should not be used in order to avoid defilement with soil. In hot, sunny climates, a shade should be provided, or the aggregate should be sprinkled with water to cool it. Hot aggregate materials make poor concrete.

Water

Water should be reasonably free of impurities such as suspended solids, organic matter and salts. This requirement is usually satisfied by using water which is fit for drinking. Sea water can be used if fresh water is not available, but not for reinforced concrete, as the strength of the concrete will be reduced by up to 15 percent.

Batching

The concrete mix should contain enough sand to fill all the voids between the coarse aggregate, enough cement paste to cover all particles with a complete film, and enough water to complete the chemical reaction. Requirements for batching ordinary concrete mixes of various grades and workability are given in Appendix V: 1-2.

The *water–cement ratio* is an expression for the relative proportions of water, including the moisture in the damp aggregate, and cement in the cement paste. The strongest concrete is obtained with the lowest water-cement ratio which gives a workable mix that can be thoroughly compacted. Note that every 1 percent of water in excess of what is needed will reduce the strength by up to 5 percent. Water–cement ratio should however, not be below 0.4:1 since this is the minimum required to hydrate the cement.

The *aggregate–cement ratio* will influence on the concrete price since the amount of cement used per cubic meter will be changed. It is not possible to give a specific relationship between water-cement ratio, aggregate-cement ratio and workability, since it is influenced by the grading, shape and texture of the aggregate.

Workability describes the ease with which the concrete mix can be compacted. Workability can be increased by adding water to a given mixing ratio since this will increase the water–cement ratio and thereby reduce the strength. Instead it should be obtained by use of a well-graded aggregate (adjustment of the relative proportions of sand and stone), use of smooth and rounded rather than irregular shaped aggregate or by decreasing the aggregate–cement ratio.

Batching measuring is done by weight or by volume. Batching by weight is more exact but is only used at large construction sites. Batching by volume is used when constructing farm buildings. Accurate batching is more important for higher grades of concrete. Batching by weight is recommended for concrete of grade C30 and higher. Checking the bulk density of the aggregate will result in greater accuracy when grade C20 or higher is batched by volume. A 50 kg bag of cement can be split into halves by cutting across the middle of the top side of a bag lying flat on the floor. The bag is then grabbed at the middle and lifted so that the bag splits into two halves.

A bucket or box can be used as a measuring unit. The materials should be placed loosely in the measuring unit and not compacted. It is convenient to construct a cubic box with 335 mm sides, as it will contain 37 litres, which is the volume of 1 bag of cement. If the box is made without a bottom and placed on the mixing platform while being filled, it is easy to empty by simply lifting it. The ingredients should never be measured with a shovel or spade.

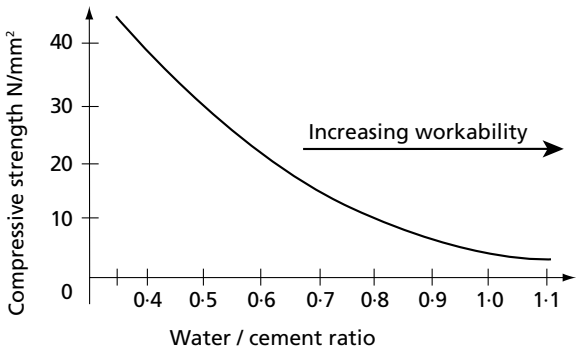


Figure 5.19 **Relation between compressive strength and water/cement ratio**

Calculating of the amount of ingredients is done from the number of cubic metres of concrete required.

The sum of the ingredient volumes will be greater than the volume of concrete, because the sand will fill the voids between the coarse aggregate. The volume of the materials will normally be 30–50 percent greater than in the concrete mix – 5 percent to 10 percent is

TABLE 5.13
Requirements per cubic metre for batching nominal concrete mixes

Proportions by volume	Cement (number of 50 kg bags)	Naturally moist aggregate[1]				Aggregate: cement	Sand to total aggregate
		Sand		Stones			
		(m^3)	(tonnes)	(m^3)	(tonnes)	(ratio)	(%)
1:4:8	3.1	0.46	0.67	0.92	1.48	13.4	31
1:4:6	3.7	0.54	0.79	0.81	1.30	11.0	37
1 5:5	3.7	0.69	1.00	0.69	1.10	10.9	47
1:3:6	4.0	0.44	0.64	0.89	1.42	10.0	31
1:4:5	4.0	0.60	0.87	0.75	1.20	9.9	41
1:3:5	4.4	0.49	0.71	0.82	1.31	8.9	35
1:4:4	4.5	0.66	0.96	0.66	1.06	8.7	47
1:3:4	5.0	0.56	0.81	0.74	1.19	7.7	40
1:4:3	5.1	0.75	1.09	0.57	0.91	7.6	54
1:2:4	5.7	0.42	0.62	0.85	1.36	6.7	31
1:3:3	5.8	0.65	0.94	0.65	1.03	6.5	47
1:2:3	6.7	0.50	0.72	0.74	1.19	5.5	37
1:1:5:3	7.3	0.41	0.59	0.82	1.30	5.0	31
1:2:2	8.1	0.60	0.87	0.60	0.96	4.4	47
1:1:5:2	9.0	0.50	0.72	0.67	1.06	3.9	40
1:1:2	10.1	0.37	0.54	0.75	1.19	3.3	31

[1] These quantities are calculated on the assumption that sand has a bulk density of 1 450 kg/m^3 and stone has a density of 1 600 kg/m^3. The density of the aggregate material is 2 650 kg/m^3.

allowed for waste and spillage. Adding cement does not noticeably increase the volume. The above assumptions are used in Example 5.2 to estimate roughly the amount of ingredients needed. Example 5.3 gives a more accurate method of calculating the amount of concrete obtained from the ingredients.

Example 5.2
Calculate the amount of materials needed to construct a rectangular concrete floor measuring 7.5 m by 4.0 m and 7 cm thick. Use a nominal mix of 1:3:6. Fifty kilograms of cement is equal to 37 litres.

Total volume of concrete required =
7.5 m × 4.0 m × 0.07 m = 2.1 m^3

Total volume of ingredients, assuming 30 percent decrease in volume when mixed and 5 percent waste = 2.1 m^3 + 2.1 (30% + 5%) m^3 = 2.84 m^3

The volume of the ingredients is proportional to the number of parts in the nominal mix. In this case, there is a total of 10 parts (1+3+6) in the mix, but the cement does not affect the volume, so only the 9 parts of sand and stone are used.

Cement = (2.84 × 1) / 9 = 0.32 m^3 or 320

Sand = (2.84 × 3) / 9 = 0.95 m^3

Stone = (2.84 × 6) / 9 = 1.89 m^3

Number of bags of cement required =
320 / 37 = 8.6 bags, i.e. 9 bags have to be bought.

Weight of sand required =
0.95 m^3 × 1.45 tonnes / m^3 = 1.4 tonnes

Weight of stone required =
1.89 m^3 × 1.60 tonnes / m^3 = 3.024 tonnes

Maximum size of stones = 70 mm × 1 / 4 = 17.5 mm

Example 5.3
Assume a 1:3:5 cement-sand-stone concrete mix by volume, using naturally moist aggregates and adding 62 litres of water. What will be the basic strength and volume of the mix if 2 bags of cement are used?

Additional assumptions:
Moisture content of sand: 4%
Moisture content of stones: 1.5%
Bulk density of the sand: 1 400 kg/m^3
Bulk density of the stones: 1 600 kg/m^3
Solid density of aggregate materials: 2 650 kg/m^3
Solid density of cement: 3 100 kg/m^3
Density of water: 1 000 kg/m^3

1. *Calculate the volume of the aggregate in the mix.*

Two bags of cement have a volume of
2 × 37 litres = 74 litres

The volume of sand is 3 × 74 litres = 222 litres

The volume of stones is 5 × 74 litres = 370 litres

2. *Calculate the weight of the aggregates.*

Sand 222 / 1 000 m³ × 1 400 kg/m³ = 311 kg

Stones 370 / 1 000 m³ × 1 600 kg/m³ = 592 kg

3. *Calculate the amount of water contained in the aggregate.*

Water in the sand is 311 kg × 4 / 100= 12 kg

Water in the stones is 592 kg × 1.5 / 100= 9 kg

4. *Adjust amounts in the batch for water content in aggregate.*

Cement 100 kg (unaltered)

Sand 311 kg – 12 kg = 299 kg

Stones 592 kg – 9 kg = 583 kg

Total amount of dry aggregate =
299 kg + 583 kg = 882 kg

Water = 62 kg + 12 kg + 9 kg = 83 kg

5. *Calculate the water–cement ratio and the cement–aggregate ratio*

Water–cement ratio =
(83 kg water) / 100 kg cement = 0.83

Aggregate–cement ratio =
(882 kg aggregate) / 100 kg cement = 8.8

The water–cement ratio indicates that the mix has a basic strength corresponding to a C10 mix. See Appendix V: 12.

6. *Calculate the 'solid volume' of the ingredients in the mix, excluding the air voids in the aggregate and cement.*

Cement 100 kg / 3 100 kg/m³ = 0.032 m³

Aggregate 882 kg / 2 650 kg/m³ = 0.333 m³

Water 83 kg / 1 000 kg / m³ = 0.083 m³

Total = 0.448 m³

The total volume of 1:3:5 mix obtained from 2 bags of cement is 0.45 m³.

Note that the 0.45 m³ of concrete is only two-thirds of the sum of the volumes of the components - 0.074 + 0.222 + 0.370.

Mixing

Mechanical mixing is the best way of mixing concrete. Batch mixers with a tilting drum for use on building sites are available in sizes of 85–400 litres. Power for drum rotation is supplied by a petrol engine or an electric motor, whereas the drum is tilted manually. The pear-shaped drum has internal blades for efficient mixing. Mixing should be continued for at least 2.5 minutes after all the ingredients have been added. For small-scale work in rural areas it may be difficult and rather expensive to use a mechanical mixer.

TABLE 5.14
Mixing-water requirements[1] for dense concrete for different consistencies and maximum sizes of aggregate

Maximum size of aggregate[2]	Water requirement (litres / m³) for concrete		
	1/2–1/3	1/3–1/6	1/6–1/2
	High workability	Medium workability	Plastic consistency
10 mm	245	230	210
14 mm	230	215	200
20 mm	215	200	185
25 mm	200	190	175
40 mm	185	175	160

[1] Includes moisture in aggregate. The quantities of mixing water are the maximum for use with reasonably well-graded, well-shaped, angular, coarse aggregate.
[2] For slump see Table 5.15.

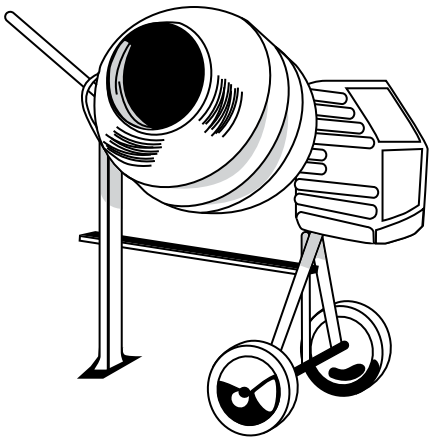


Figure 5.20 **Batch mixer**

A simple hand-powered concrete mixer can be manufactured from an empty oil drum set in a frame of galvanized pipe. Figure 5.21 shows a hand crank, but the drive can be converted easily to machine power.

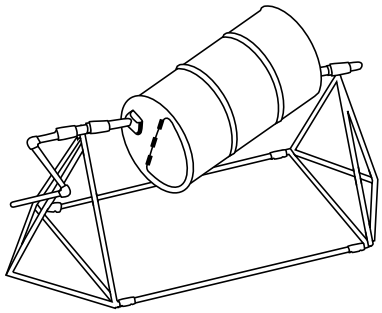


Figure 5.21 **Home-built concrete mixer**

Hand mixing is normally used for small jobs. Mixing should be done on a close-boarded platform or a concrete floor near to where the concrete is to be placed, and never on bare ground because of the danger of earth contamination.

The following method is recommended for hand mixing:

1. The measured quantities of sand and cement are mixed by turning them over with a shovel at least 3 times.
2. About three-quarters of the water is added to the mixture a little at a time.
3. Mixing continues until the mixture becomes homogeneous and workable.
4. The measured quantity of stones, after being wetted with part of the remaining water, is spread over the mixture and mixing continues, with all ingredients being turned over at least 3 times during the process, using as little water as possible to obtain a workable mix.

All tools and the platform should be cleaned with water when there is a break in the mixing, and at the end of the day.

Slump test

The slump test gives an approximate indication of the workability of the wet concrete mix. Fill a conically shaped bucket with the wet concrete mix and compact it thoroughly. Turn the bucket upside down on the mixing platform. Lift the bucket, place it next to the concrete heap and measure the slump, as shown in Figure 5.22.

Placing and compaction

Concrete should be placed with a minimum of delay after the mixing is completed, and certainly within 30 minutes. Special care should be taken when transporting wet mixes, because the vibrations of a moving wheelbarrow may cause the mix to segregate. The mix should not be allowed to flow, nor should it be dropped into position from a height of more than 1 metre. The concrete should be placed with a shovel in layers no deeper than 15 cm, and compacted before the next layer is placed.

When slabs are cast, the surface is levelled with a screed board, which is also used to compact the concrete mix as soon as it has been placed, to remove any trapped air. The less workable the mix, the more porous it is, and the more compaction is necessary. The concrete loses up to 5 percent of its strength for every 1 percent of entrapped air. However, excessive compaction of wet mixes brings fine particles to the top, resulting in a weak, dusty surface.

Manual compaction is commonly used for the construction of farm buildings. It can be used for mixes with high and medium workability, and for plastic mixes. Wet mixes used for walls are compacted by punting with a batten, stick or piece of reinforcement bar. Knocking on the formwork also helps. Less workable mixes, such as those used for floors and paving, are best compacted with a tamper.

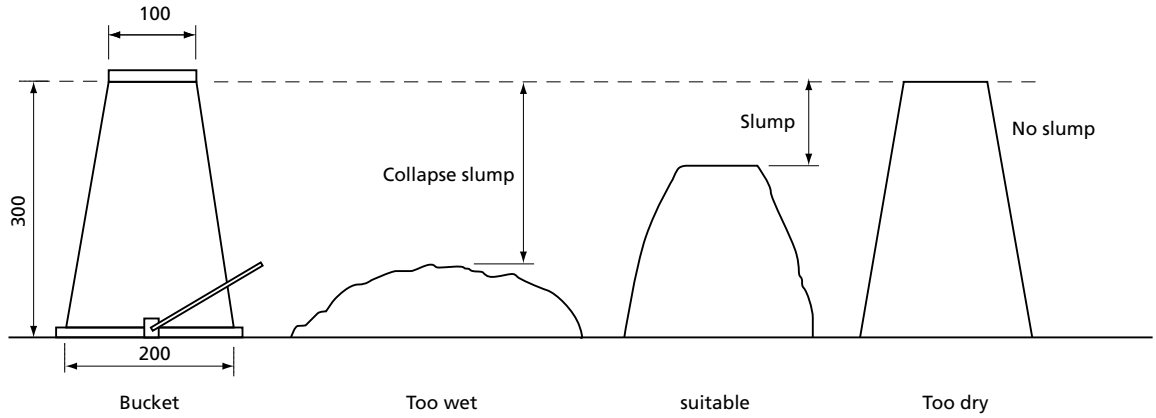


Figure 5.22 **Concrete slump test**

TABLE 5.15
Concrete slump for various uses

Consistency	Slump	Use	Method of compaction
High workability	$^1/_2$–$^1/_3$	Constructions with narrow passages and/or complex shapes. Heavily reinforced concrete.	Manual
Medium workability	$^1/_3$–$^1/_6$	All normal uses. Non-reinforced and normally reinforced concrete.	Manual
Plastic	$^1/_6$–$^1/_{12}$	Open structures with fairly open reinforcement, which are heavily worked manually for compaction, such as floors and paving. Mass concrete.	Manual or mechanical
Stiff	0–$^1/_2$	Non-reinforced or sparsely reinforced open structures, such as floors and paving, which are mechanically vibrated. Factory prefabrication of concrete goods. Concrete blocks.	Mechanical
Damp	0	Factory prefabrication of concrete goods.	Mechanical or pressure

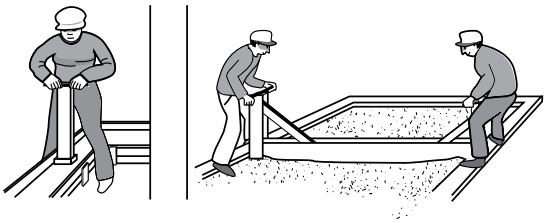


Figure 5.23 **Manual compaction of foundation and floor slab**

Only mechanical vibrators are capable of compacting stiffer mixes thoroughly. For walls and foundations, a poker vibrator (a vibrating pole) is immersed in the poured concrete mix at points up to 50 cm apart. Floors and paving are vibrated with a beam vibrator.

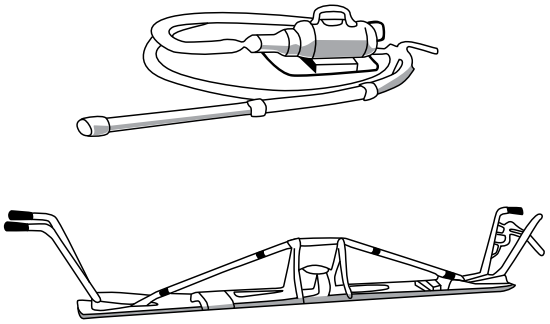


Figure 5.24 **Mechanical vibrators**

Construction joints

The casting should be planned in such a way that the work on a member can be completed before the end of the day. If cast concrete is left for more than 2 hours, it will set so much that there is no direct continuation between the old and new concrete. Joints are potentially weak and should be positioned where they will affect the strength of the member as little as possible. Joints should be straight, either vertical or horizontal. When resuming work, the old surface should be roughened and cleaned before being treated with a thick mixture of water and cement.

Formwork

Formwork provides the shape and surface texture of concrete members and supports the concrete during setting and hardening.

The simplest type of form is sufficient for pavement edges, floor slabs, pathways, etc.

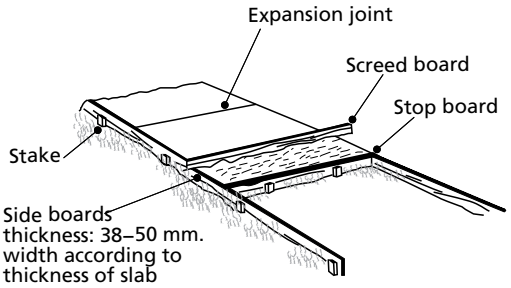


Figure 5.25 **Simple type of formwork for a concrete slab**

In large concrete slabs, such as floors, cracks tend to occur early in the setting period. In a normal slab where watertightness is not essential, this can be controlled by laying the concrete in squares, with joints between them, allowing the concrete to move slightly without causing cracks in the slab. The distance between the joints should not exceed 3 metres. The simplest type is a called a *dry joint*. The concrete is poured directly against the already hardened concrete of another square.

A more sophisticated method is a *filled joint*. A minimum gap of 3 mm is left between the squares, and filled with bitumen or any comparable material.

Forms for walls must be strongly supported because when concrete is wet it exerts great pressure on the side boards. The greater the height, the greater the pressure. A concrete wall will not normally be thinner

than 10 cm, or 15 cm in the case of reinforced concrete. If it is higher than 1 metre, it should not be less than 20 cm thick, to make it possible to compact the concrete properly with a tamper. The joints of the formwork must be tight enough to prevent loss of water and cement.

If the surface of the finished wall is to be visible, and no further treatment is anticipated, tongued and grooved boards, planed on the inside, can be used to provide a smooth and attractive surface. Alternatively, 12-mm plywood sheets can be used. The dimensions and spacing of studs and ties are shown in Figure 5.26. The proper spacing and installation of the ties is important to prevent distortion or complete failure of the forms.

Not only must forms be well braced, they must also be anchored securely to prevent them from floating up, allowing the concrete to run out from underneath.

The forms should be brushed with oil and watered thoroughly before filling with concrete. This is done to prevent water in the concrete from being absorbed by the wooden boards, and to stop the concrete from sticking to the forms. Although soluble oil is best, used engine oil mixed with equal parts of diesel fuel is the easiest and cheapest material in practice.

If handled carefully, wooden forms can be used several times before they are abandoned. If there is a recurrent need for the same shape, it is advantageous to make the forms of steel sheets.

Although the formwork can be taken away after 3 days, leaving it for 7 days makes it easier to keep the concrete wet.

In order to save on material for the formwork and its supporting structure, tall silos and columns are cast using a slip form. The form is not built to the full height of the silo, and may in fact be only a few metres high. As casting of the concrete proceeds, the form is lifted. The work needs to proceed at a speed that allows the concrete to set before it leaves the bottom of the form. This technique requires complicated design calculations, skilled labour and supervision.

Curing concrete

Concrete will set in 3 days, but the chemical reaction between water and cement continues for much longer. If the water disappears through evaporation, the chemical reaction will stop. It is therefore very important to keep the concrete wet (damp) for at least 7 days.

Premature drying out may also result in cracking caused by shrinkage. During curing, the strength and impermeability increases and the surface hardens against abrasion. Watering of the concrete should start as soon as the surface is hard enough to avoid damage, but not later than 10–12 hours after casting. Covering the concrete with sacks, grass, hessian, a layer of sand or polythene helps to retain the moisture and protects the surface from dry winds. This is particularly important in tropical climates.

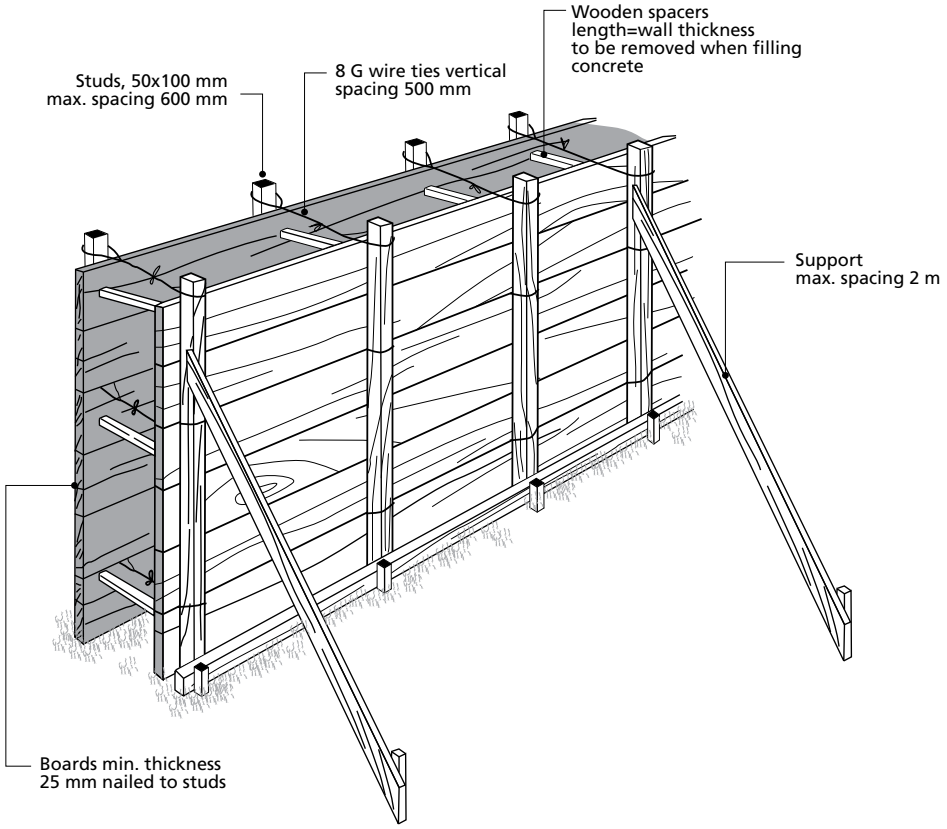


Figure 5.26 **Dimensions and spacing of studs and ties in formwork for walls**

Temperature is also an important factor in curing. For temperatures above 0 °C and below 40 °C, strength development is a function of temperature and time. At temperatures above 40 °C, the stiffening and hardening may be faster than desired and result in lower strength.

Figure 5.27 shows the approximate curing time needed to achieve characteristic compressive strength at various curing temperatures for concrete mixes using ordinary portland cement.

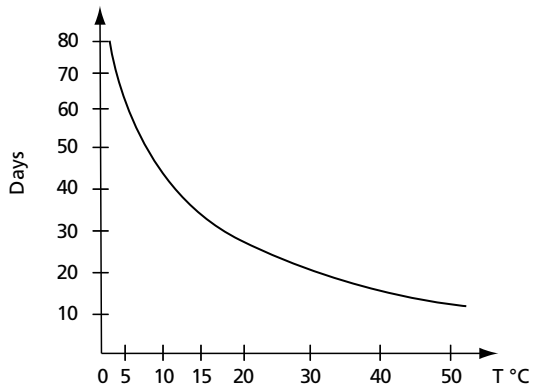


Figure 5.27 **Curing times for concrete**

Finishes on concrete

The surface of newly laid concrete should not be worked until some setting has taken place. The type of finish should be compatible with the intended use. In the case of a floor, a non-skid surface for humans and animals is desirable.

Tamped finish: The tamper leaves a coarse, rippled surface when it has been used to compact the concrete.

Tamper-drawn finish: A less pronounced ripple can be produced by moving a slightly tilted tamper on its tail end over the surface.

Broomed finish: A broom of medium stiffness is drawn over the freshly tamped surface to give a fairly rough texture.

Wood-float finish: For a smooth, sandy texture the concrete can be wood-floated after tamping. The float is used with a semicircular sweeping motion, the leading edge being slightly raised; this levels out the ripples and produces a surface with a fine, gritty texture, a finish often used for floors in animal houses.

Steel trowel finish: Steel trowelling after wood floating gives a smoother surface with very good wearing qualities. However, it can be slippery in wet conditions.

Surfaces with the aggregate exposed can be used for decorative purposes, but can also give a rough, durable surface on horizontal slabs. This surface can be obtained by removing cement and sand by spraying water on the new concrete, or by positioning aggregate by hand in the unset concrete.

Reinforced concrete

Concrete is strong in compression but relatively weak in tension. The underside of a loaded beam, such as a lintel over a door, is in tension.



Figure 5.28 **Stresses in a concrete lintel**

Concrete subject to tension loading must be reinforced with steel bars or mesh. The amount and type of reinforcement should be carefully calculated or, alternatively, a standard design obtained from a reliable source should be followed without deviating from the design.

Important factors affecting reinforced concrete:

1. The steel bars should be cleaned of rust and dirt before they are placed.
2. In order to obtain good adhesion between the concrete and the steel bars, the bars should be overlapped where they join by at least 40 times the diameter. When plain bars are used, the ends of the bars must be hooked.
3. The reinforcement bars should be tied together well and supported so that they will not move when concrete is placed and compacted.
4. The steel bars must be in the tensile zone and be covered with concrete to a thickness of 3 times the diameter, or by at least 25 mm, to protect them from water and air, which causes rusting.
5. The concrete must be well compacted around the bars.
6. Concrete should be at least C20 or 1:2:4 nominal mix, and have a maximum aggregate size of 20 mm.

Concrete floors are sometimes reinforced with welded steel mesh or chicken wire, placed 25 mm beneath the upper surface of the concrete, to limit the size of any cracking. However, such load-distributing reinforcement is necessary only when loadings are heavy, the underlying soil is not dependable, or when cracking must be minimized, as in water tanks.

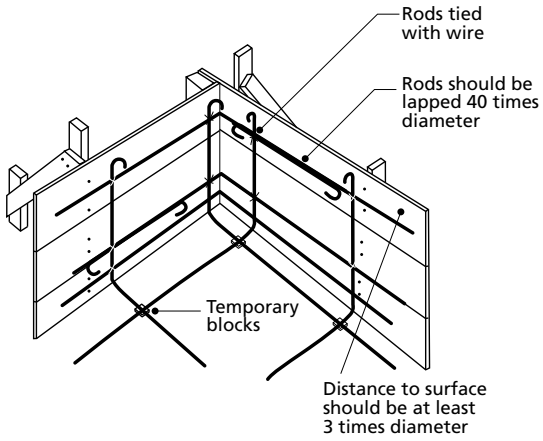


Figure 5.29 **Placing reinforcement bars**

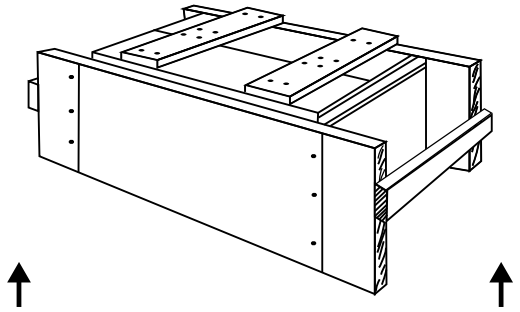


Figure 5.30 **Wooden mould for solid concrete blocks**

CONCRETE BLOCKS, SAND AND CEMENT BLOCKS

It is faster to build with concrete blocks than with bricks, and using concrete blocks reduces the mortar requirement by half or more. If face-shell bedding is used, in which the mortar is placed only along the edges of the blocks, the consumption of mortar is reduced by a further 50 percent. However, the total amount of cement required for the blocks and mortar is far greater than that required for the mortar in a brick wall.

Concrete blocks are often made of 1:3:6 concrete with a maximum aggregate size of 10 mm, or a cement-sand mixture with a ratio of 1:7, 1:8 or 1:9. If properly cured, these mixtures produce concrete blocks with compression strength well above what is required in a one-storey building. The blocks may be solid, cellular or hollow. Cellular blocks have cavities with one end closed, while in hollow blocks the cavities pass through. Lightweight aggregate, such as cracked pumice stone, is sometimes used.

Blocks are made to a number of coordinating sizes, the actual sizes being about 10 mm less in order to allow for the thickness of the mortar.

Block manufacturing

Blocks can be made using a simple block-making machine driven by an engine, or operated by hand. They can also be made using simple wooden moulds on a platform or floor. The mould can be lined with steel plates, to prevent damage during tamping and to reduce wear on the mould. Steel moulds are often used in large-scale production. The wooden mould is initially oiled overnight and need not be oiled each time it is filled. It is sufficient to wipe it clean with a cloth. The concrete, with a stiff or plastic consistency, is placed in the mould in layers, and each layer is compacted with a 3-kg rammer.

The mould in Figure 5.30 has a lid made so that it can pass through the rest of the mould. The slightly tapered sides can be removed by lifting the handles, while holding down the lid with one foot.

The mould illustrated in Figure 5.31 has a steel plate cut to the shape of the block, which is used as a lid and held down as the hollow-making pieces are withdrawn. Bolts are then loosened and the sides of the mould are removed with a swift motion. All parts of the mould should be slightly tapered so that they can be removed easily from the block.

As from the day after the blocks have been made, water is sprinkled on the blocks for 2 weeks during curing. After 48 hours, the blocks can be removed for stacking, but wetting must continue. After curing, the blocks are dried. If damp blocks are placed in a wall, they will shrink and cause cracks. To ensure maximum drying, the blocks are stacked interspaced, exposed to the prevailing wind and, in the case of hollow blocks, with the cavities laid horizontal to form a continuous passage for the circulating air.

Decorative and ventilating blocks

Decorative concrete or sand-cement blocks serve several purposes:

- to provide light and security without installing windows or shutters;
- to provide permanent ventilation;
- to give an attractive appearance.

In addition, some are designed to keep out rain, while others include mosquito proofing.

While blocks with a simple shape can be made in a wooden mould by inserting pieces of wood to obtain the desired shape, more complicated designs usually require a professionally made steel mould.

MORTAR

Mortar is a plastic mixture of water and binding materials, used to join concrete blocks, bricks or other masonry units.

It is desirable for mortar to hold moisture, be plastic enough to stick to the trowel and the blocks or bricks, and to develop adequate strength without cracking.

Mortar need not be stronger than the units it joins. In fact, cracks are more likely to appear in the blocks or bricks if the mortar is excessively strong.

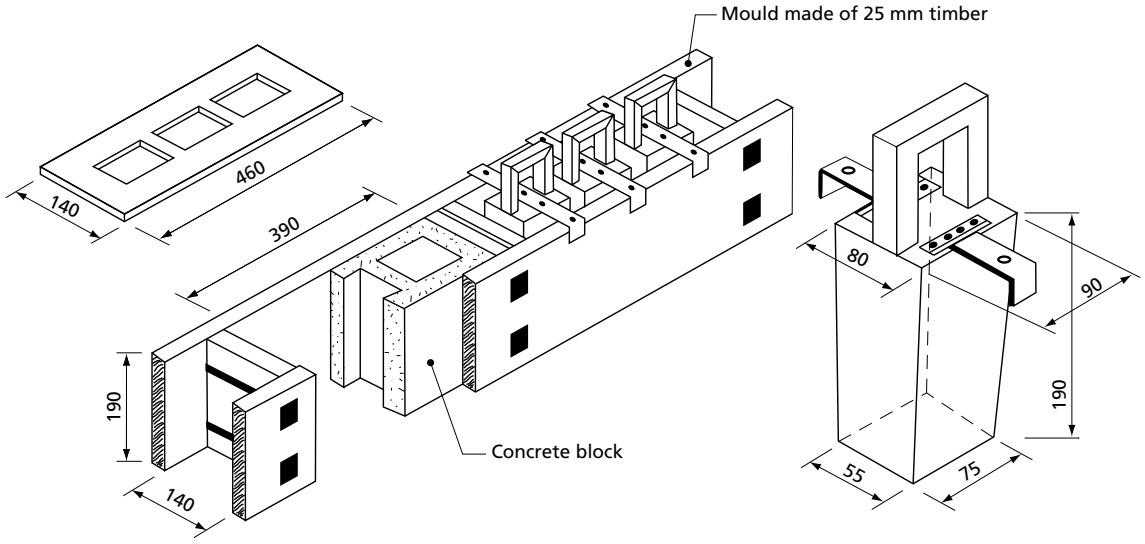


Figure 5.31 **Mould for hollow or cellular concrete blocks**

There are several types of mortar, each suitable for particular applications and varying in cost. Most of these mortars include sand as an ingredient. In all cases, the sand should be clean, free of organic material, well graded (a variety of sizes) and not exceed 3 mm of silt in the sedimentation test. In most cases, particle size should not exceed 3 mm, as this would make the mortar 'harsh' and difficult to work with.

Lime mortar is typically mixed using 1 part lime to 3 parts sand. Two types of lime are available. Hydraulic lime hardens quickly and should be used within an hour. It is suitable for both above- and below-ground applications. Non-hydraulic lime requires air to harden, and can only be used above ground. If it is smoothed off while standing, a pile of this type of lime mortar can be stored for several days.

Cement mortar is stronger and more waterproof than lime mortar, but it is difficult to work with because it is not 'fat' or plastic and falls away from the blocks or bricks during placement. In addition, cement mortar is more costly than other types. Consequently, it is used in only a few applications, such as a damp-proof course or in some limited areas where heavy loads are expected. A 1:3 mix using fine sand is usually required to obtain adequate plasticity.

Compo mortar is made with cement, lime and sand. In some localities, a 50:50 cement-lime mix is sold as mortar cement. The addition of the lime reduces the cost and improves workability. A 1:2:9, cement-lime-sand mix is suitable for general purposes, while a 1:1:6 is better for exposed surfaces, and a 1:3:12 can be used for interior walls, or stone walls, where the extra plasticity is helpful.

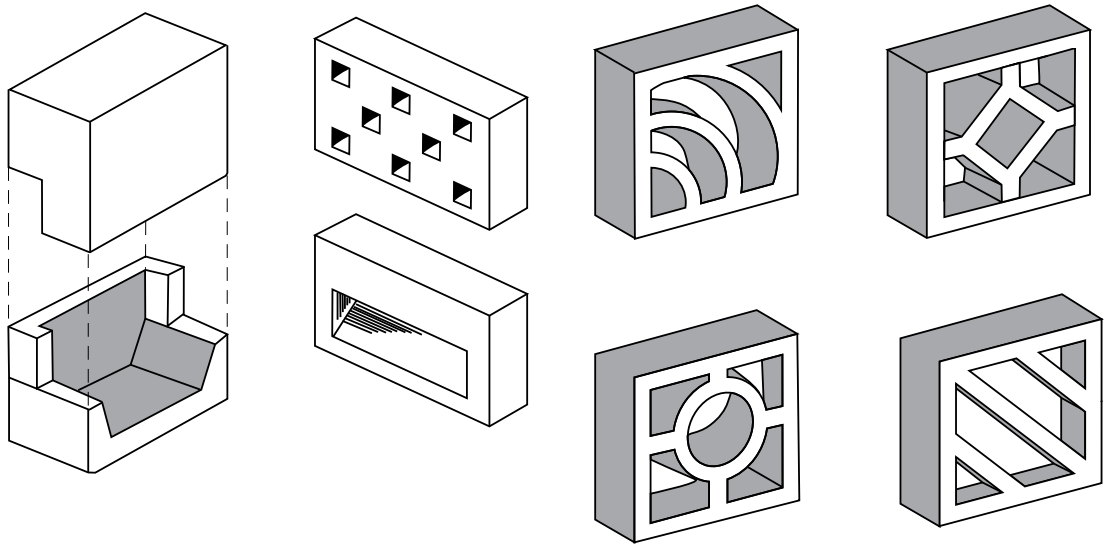


Figure 5.32 **Ventilating and decorative concrete blocks**

Mortar can also be made using pozzolana, bitumen, cutback or soil. A 1:2:9 lime-pozzolana-sand mortar is roughly equivalent to a 1:6 cement-sand mortar. Adobe and stabilized soil blocks are often laid in a mortar of the same composition as the blocks.

Tables 5.16 and 5.17 provide information on the materials required for a cubic metre of various mortars, and the amount of mortar per square metre, for several building units.

Starting with cement mortar, strength decreases with each type, although the ability to accommodate movement increases.

TABLE 5.16
Materials required per cubic metre of mortar

Type	Cement bags	Lime (kg)	Sand (m^3)
Cement mortar 1:5	6.0	-	1.1
Compo mortar 1:1:6	5.0	100.0	1.1
Compo mortar 1:2:9	3.3	13.5	1.1
Compo mortar 1:8	3.7	-	1.1
Compo mortar 1:3:12	2.5	150.0	1.1
Lime mortar 1:3	-	200.0	1.1

TABLE 5.17
Mortar required for various types of wall

Type of wall	Amount required per m^2 wall
11.5 cm brick wall	0.25 m^3
22.2 cm brick wall	0.51 m^3
10 cm sand-cement block wall	0.008 m^3
15 cm sand-cement block wall	0.011 m^3
20 cm sand-cement block wall	0.015 m^3

Finishing mortar

This is sometimes used on floors and other surfaces to give a smooth finish, or as an extremely hard coating to increase resistance to wear. While such a top coating is prone to cracking, it seldom increases strength, and is difficult to apply without causing loose or weak parts. Concrete floors can normally be cast to the finished level directly, and be given a sufficiently smooth and hard surface without a top coating.

For coating, a mix of 1 part cement and 2–4 parts sand is used. The coating is placed in a 1–2 cm thick layer with a steel trowel. Before application, the surface of the underlying concrete slab should be cleaned and moistened.

Plastering and rendering

The term 'plastering' is usually applied to interior walls and ceilings to give jointless, hygienic and usually smooth surfaces, often over uneven backgrounds. Exterior plastering is usually called 'exterior rendering'.

Cement plaster can be used on most types of wall, but it does not adhere well to soil-block walls, as shrinking and swelling tend to crack the plaster. The mixing ratio is 1 part cement and 5 parts sand and, if the plaster is too harsh, 0.5–1 part of lime can be added. The wall is first moistened and then the plaster is applied in two coats of about 5 mm each, allowing at least 24 hours between layers. Cement plaster should not be applied on a wall while it is exposed to the sun.

Dagga plaster is a mixture of clay soil (such as red or brown laterite), stabilizer and water. The plaster is improved by adding lime or cement as a stabilizer and bitumen for waterproofing. A good mixture is 1 part lime or cement, 3 parts clay, 6 parts sand, 0.2 parts bitumen and water. Dagga plaster is applied on previously moistened earth or adobe brick walls in a layer 10–25 mm thick.

FERROCEMENT

Ferrocement is a highly versatile form of reinforced concrete made with closely spaced light reinforcing rods or wire mesh, and a cement and sand mortar. It can be worked with relatively unskilled labour.

The function of the wire mesh and reinforcing rods is first to act as a lath, providing the form to support the mortar in its plastic state, while, in the hardened state, it absorbs the tensile stresses in the structure, which the mortar alone is not able to withstand.

The reinforcing can be assembled in any desired shape, and the mortar applied in layers to both sides. Simple shapes, such as water tanks, can be assembled using wooden sticks as support for the reinforcing while the first coat of mortar is applied.

The mortar should have a mixing ratio of 1:2 to 1:4 cement/sand by volume, using the richer mix for the thinnest structures. The water/cement ratio should be below 0.5/1.0. Lime can be added in the proportion 1 part lime to 5 parts cement in order to improve workability.

The mechanical behaviour of ferrocement depends on the type, quantity, orientation and strength of the mesh and reinforcing rods. The most common types of mesh used are illustrated in Figure 5.33.

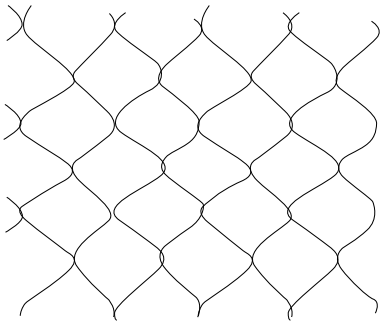
Standard galvanized mesh (galvanized after weaving) is adequate. Although non-galvanized wire has adequate strength, the problem of rusting limits its use.

A construction similar to ferrocement has recently been developed for small water tanks, sheds, huts, etc. It consists of welded 150 mm-square reinforcement mesh (6 mm rods), covered with hessian and plastered in the same way as ferrocement.

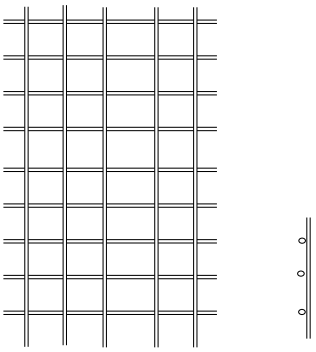
FIBRE-REINFORCED CONCRETE

Fibre-reinforced concrete members can be made thinner than those with conventional reinforcement because there is no need for a corrosion-protection covering over the steel bars. The fibres improve flexible strength and resistance to cracking.

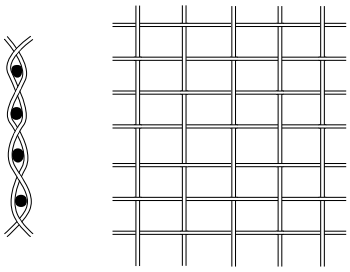
Commonly used fibres include asbestos, steel (0.25 mm diameter), sisal and elephant grass.



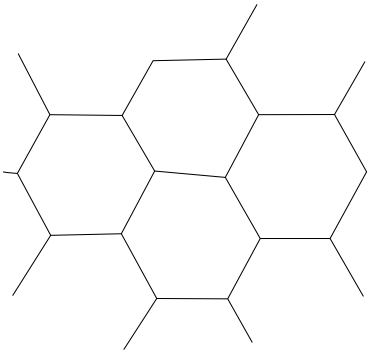
a. Hexagonal wire mesh (chicken wire mesh)



b. Welded wire mesh - strongest



c. Woven mesh - strong



d. Expanded wire mesh

Figure 5.33 **Reinforcement meshes for ferrocement**

Asbestos cement (AC)

Asbestos, which is a silicate of magnesium, is found as a rock that can be split into extremely thin fibres ranging from 2 mm to 900 mm long. These have good resistance to alkalis, neutral salts and organic solvents, and the varieties used for building products have good resistance to acids. Asbestos is non-combustible and able to withstand high temperatures without alteration.

Inhalation of asbestos dust causes asbestosis (a disease of the lungs) and asbestos is now used only where no alternative fibre is available. Workers must wear masks and take great care not to inhale any asbestos dust!

As the fibres are strong in tension and flexible, they are used as reinforcement with Portland cement, lime and bitumen binders, in asbestos-cement and asbestos-silica-lime products, vinyl floor tiles and in bitumen felts. Asbestos-cement is used in farm structures for corrugated roofing sheets, ridges and sanitary pipes.

Sisal-fibre-reinforced cement (SFRC)

Sisal and other vegetable fibres have only recently come into use for cement reinforcement.

Sisal fibre can be used as short, discontinuous fibres (15–75 mm in length), or as continuous long fibres exceeding 75 mm in length. Sometimes both short and long fibres are used together. The manner in which the fibres are incorporated into the matrix affects the properties of the composite, both in the fresh state and in the hardened state.

Sisal fibres may deteriorate if not treated. Although the alkalinity of the concrete helps to protect the fibres from outside attack, it may itself attack the fibres chemically by decomposing the lignin.

Sisal fibre reinforcing is used with various cement-sand mixing ratios, depending on the use:

Wall plastering	1:3
Guttering	1:2
Roofing tiles	1:1
Corrugated roofing sheets	1:0.5

The sand should be passed through a sieve with 1.5 mm to 2 mm holes (e.g. mosquito netting). The mixing water must be pure and the mix kept as dry as possible, while still being workable.

Between 16 grams and 17 grams of short (25 mm), dry sisal fibres are added to the mix for each kilogram of cement. The short fibres are mixed into the dry cement and sand before adding water. As sisal fibres have a high water-absorption capacity, some extra water may have to be added to the mix to compensate for this.

When mixing, there is a tendency for the fibres to ball and separate out from the rest of the mix. This tendency will increase with longer fibres but, if fibres shorter than 25 mm are used, the reinforcing effect will be reduced. In most cases, the mix is then trowelled onto a mesh of full-length sisal fibres.

Making corrugated reinforced roofing sheets

Home-made reinforced corrugated roofing is usually cast to standard width, but to only 1 metre in length because of its additional weight. Commercial asbestos-cement roofing is heavier than corrugated steel, and the home-made sheets are still heavier. Special attention must therefore be given to rafter or truss sizes to ensure a safe structure.

Although the casting procedure for sisal-fibre-reinforced cement is tricky, once the proper equipment has been assembled and several sheets have been made, the process becomes much easier.

A concrete block cast over a 1-metre length of asbestos-cement roofing is needed as a face for casting the roof sheets. The block is cast within a 100 mm-high form, which will give a block of sufficient strength after a few days curing. Two or more 1-metre lengths of asbestos-cement roofing will be needed, as well as a piece of 18 mm plywood, measuring 1.2 metres by 1.2 metres, and a sheet of heavy-duty polythene, measuring 2.25 metres long and 1 metre wide. The polythene is folded in the middle and a thin batten, measuring 9 mm by 15 mm, is stapled at the fold. Strips of 9 mm plywood or wood are nailed along two edges of the plywood sheet, leaving exactly 1 metre between them, as shown in Figure 5.34.

Below are the steps to follow in the casting procedure:

1. Fit an asbestos cement sheet onto the moulding block and cover with the piece of plywood, with the edge strips at the ends of the sheet. The polythene is placed over the plywood and the top sheet is folded back off the plywood.
2. Prepare a mix of 9 kg cement, 4.5 kg sand, 150 grams of short sisal fibres (25 mm) and 4.5 litres of water. Also prepare four 60-gram bundles of sisal fibres that are as long as possible.
3. Use one-third of the mortar mix to trowel a thin, even layer over the polythene. Take two of the four sisal bundles and distribute the fibres evenly, with the second bundle at right angles to the first, forming a mat of fibres. This is covered with mortar and another mat made from the remaining two bundles. Finally, all the sisal is covered with the remaining mortar, and the surface is screeded even with the edge strips on the plywood.
4. Cover with the top sheet of polythene, ensuring that the mortar is of even thickness all over and that no air bubbles remain under the polythene.
5. While holding the batten strip at the fold in the polythene, carefully remove the plywood sheet to allow the new sisal-cement sheet to fall onto the asbestos-cement sheet. At the same time, press the new sheet into the corrugations using a PVC drain pipe 90 mm in diameter. Compact the new sheet by placing another asbestos sheet on top, and treading on it. Holes for mounting are punched with a 5 mm dowel 25 mm from the end in the gulleys (crests when mounted on the roof) of the fresh sheet.
6. Remove from the moulding block the asbestos sheet bearing the sisal-cement sheet, and leave it until the cement in the new sheet has set (preferably 2 days). Then carefully remove the new sheet, peel off the polythene and cure the new sheet for at least 1 week, preferably immersed in a water tank.
7. If more polythene and asbestos-cement sheets are available, casting can proceed immediately.

Walls using the sisal-cement plastering technique

Soil blocks can be used for inexpensive walls with good thermal insulation. However, they are easily damaged by impact and eroded by rain. One way of solving these problems is to plaster the face of the wall. Ordinarily, mortar plaster tends to crack and peel off, as it does not expand at the same rate as the soil. This can be overcome by letting long sisal fibres pass through the wall, to be incorporated into the mortar on each face. The double skin so formed provides sufficient strength

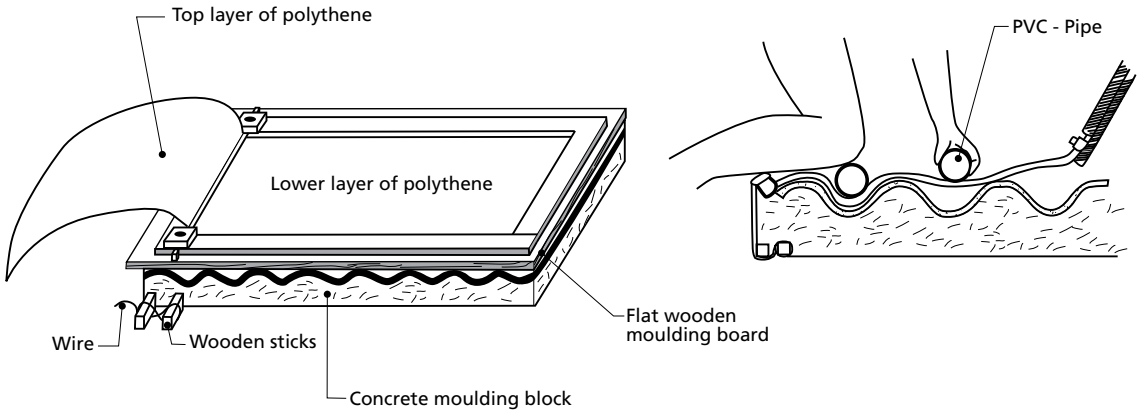


Figure 5.34 **Plywood casting board and polythene 'envelope'**

and waterproofing to the wall to enable soil blocks to be laid without mortar between the blocks to join them.

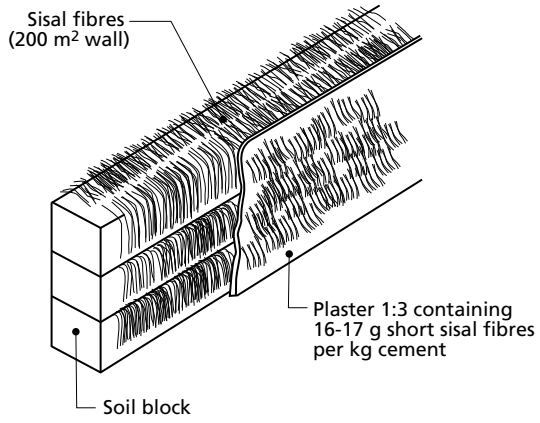


Figure 5.35 **Sisal-cement plastering technique**

METALS

Several ferrous metals (those containing iron) are useful in the construction of farm buildings and other rural structures. Cast iron is used for making sanitary waste pipes and fittings.

Steel consists of iron, plus a small percentage of carbon in chemical combination. High-carbon or 'hard' steel is used for tools with cutting edges. Medium-carbon steel is used for structural members such as I-beams, reinforcing bars and implement frames. Low-carbon or 'mild' steel is used for pipes, nails, screws, wire, screening, fencing and corrugated roof sheets.

Non-ferrous metals, such as aluminium and copper, are corrosion-resistant and are often chosen for this quality. Copper is used for electric wire, tubing for water supply and for flashing. Aluminium is most commonly used for corrugated roofing sheets, gutters and the accompanying nails. Using nails of the same material avoids the problem of corrosion caused by electrolytic action. Brass is a corrosion-resistant alloy of copper and zinc used extensively for building hardware.

Corrosion

Air and moisture accelerate corrosion in ferrous materials unless they are protected. Acids tend to corrode copper, while alkalis, such as that found in animal waste, portland cement and lime, as well as in some soils, cause rapid corrosion of aluminium and zinc. Electrolytic action, caused by slight voltages set up when dissimilar metals are in contact with each other in the presence of water, also encourages corrosion in some metals. Aluminium is particularly prone to electrolytic corrosion.

Corrosion can be reduced by the careful selection of metal products for the application, by reducing the time that the metal will be wet by preventing condensation and promoting good drainage, by avoiding contact between dissimilar metals, and by using corrosion-inhibiting coatings.

Corrosion-inhibiting coatings

Copper, aluminium, stainless steel and cast iron tend to form oxide coatings that provide a considerable amount of self-protection from corrosion. However, most other steels require protective coatings if they are exposed to moisture and air. Methods used include zinc coating (galvanizing), vitreous enamel glazing and painting. Painting is the only practical method for field application, although grease and oil will provide temporary protection.

Before painting, the metal surface must be clean, dry and free from oil. Both bituminous and oil-based paints with metallic oxide pigments offer good protection, if they are carefully applied in continuous layers. Two to three coats provides the best protection.

BUILDING HARDWARE

Nails

A nail relies on the grip around its shank and the shear strength of its cross-section to give strength to a joint. It is important to select the right type and size of nail for any particular situation. Nails are specified by their type, length and gauge (the higher the gauge number, the smaller the shank diameter). See Table 5.18. Most nails are made from mild steel wire. In a corrosive environment, galvanized, copper-plated, copper or aluminium nails are used. A large number of nail types and sizes are available on the market. Below is a description of the nails most commonly used in farm buildings.

Round plain-headed nails or round wire nails are used for general carpentry work. As they have a tendency to split thin members, the following rule is often used: the diameter of the nail should not exceed $^1/_7$ of the thickness of the timber.

TABLE 5.18
Dimensions and approximate number per kilogram of commonly used sizes of round wire nails

Length		Diameter	Approximate
(inches)	(mm)	(mm)	number/kg
6	150	6.0	29
5	125	5.6	42
4	100	4.5	77
3	75	3.75	154
2.5	65	3.35	230
2	50	2.65	440
1.5	40	2.0	970
1	25	1.8	1 720

Lost-head nails have a smaller head, which can be set below the surface of the wood. Their holding power is lower because the head can be pulled through the wood more easily.

Panel pins are fine wire nails with small heads, used for fixing plywood and hardboard panels.

Clout or slate nails have large heads and are used for fixing tiles, slates and soft boards. Felt nails have even larger heads.

Concrete nails are made from harder steel, which allows them to be driven into concrete or masonry work.

Staples are U-shaped nails with two points, and are used mainly to fasten wires.

Roofing nails have a square, twisted shank and a washer attached to the head. Roofing felt or rubber may be used under the washer to prevent leakage. The nail and the washer should be galvanized to prevent corrosion. They are used for fixing corrugated-sheet materials and must be long enough to penetrate at least 20 mm into the wood. Alternatively, wire nails with used bottle caps for washers can be used.

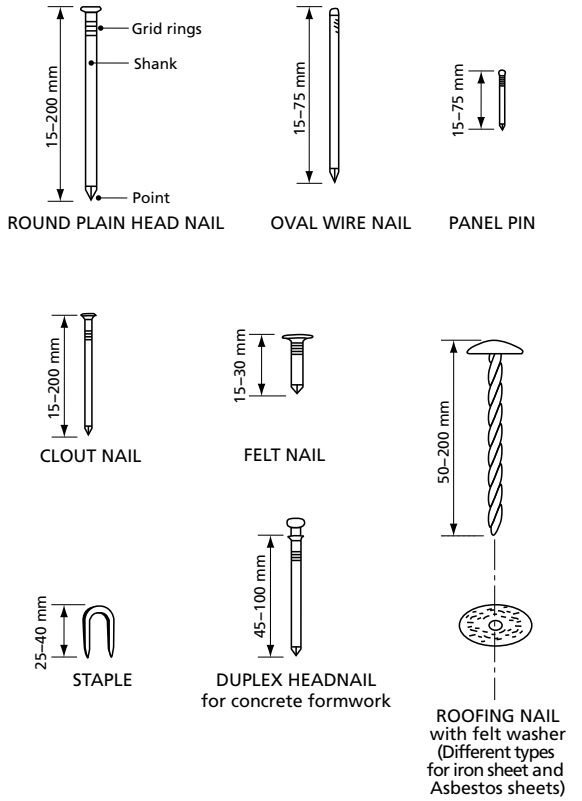


Figure 5.36 **Types of nails**

Screws and bolts

Wood screws have a thread, which gives them greater holding power and resistance to withdrawal than nails, and they can be removed easily without damaging the wood. For a screw to function properly, it must be inserted by rotation, and not by being driven with a hammer. It is usually necessary to drill a pilot hole for the shank of the screw. Screws made of mild steel are normally preferred because they are stronger. A wide range of finishes, such as galvanized, painted and plated, are available.

Screws are classified according to the shape of their head, as countersunk, raised, round or recessed (not slotted across the full width). Coach screws have a square head and are turned with a spanner. They are used for heavy construction work and should have a metal washer under the head to prevent damage to the wood surface. Screws are sold in boxes containing a gross (144 screws), and are specified by their material, finish, type, length and gauge. Unlike the wire gauge used for nails, the larger the screw-gauge number, the greater the diameter of the shank.

Bolts provide even stronger joints than either nails or screws. As the joint is secured by tightening the nut onto the bolt, in most cases the load becomes entirely a shear force. Bolts are used for heavy loads, such as at the joints in a gantry hoist frame, at the corners of a ring beam installed for earthquake protection, or to secure the hinges of heavy doors. Most bolts used with wood have a rounded head, with a square shank just under the head. Only one spanner is required for these 'coach' bolts. Square-head bolts, requiring two spanners, are also available. Washers help to prevent the nuts from sinking into the wood.

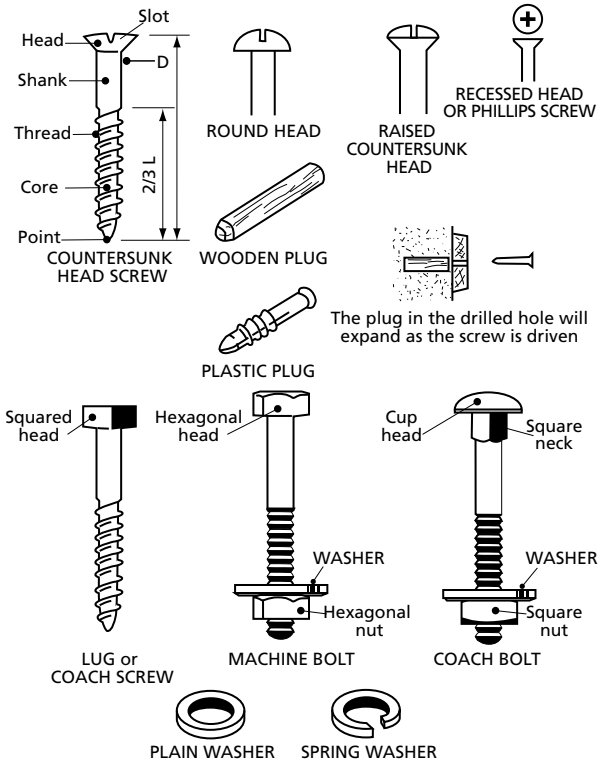


Figure 5.37 **Types of wood screws and bolts**

TABLE 5.19
Conversion of screw gauge to millimetres

Screw gauge	0	1	2	3	4	5	6	7	8	9	10	12	14	16	18	20	24	28	32
Nominal diameter of unthreaded shank (mm)	1.52	1.78	2.08	2.39	2.74	3.10	3.45	3.81	4.17	4.52	4.88	5.59	6.30	7.01	7.72	8.43	9.86	11.28	12.70

Hinges

Hinges are classified by their function, length of nap and the material from which they are made, and come in many different types and sizes. Hinges for farm buildings are manufactured mainly from mild steel and are provided with a corrosion-inhibiting coating. The most common types are described below.

The *steel butt hinge* is commonly used for windows, shutters and small doors, as it is cheap and durable. If the pin can be removed from the outside, it is not burglarproof. The flaps are usually set in recesses in the door or window and the frame.

The *H-hinge* is similar to the butt hinge but is usually surface mounted.

The *T-hinge* is used mostly for hanging match-boarded doors. For security reasons, the strap of the T-hinge should be fixed to the door with at least one coach bolt, which cannot be unscrewed easily from the outside.

The *band-and-hook hinge* is a stronger type of T-hinge and is used for heavy doors and gates. This type is suitable for fabrication at the site or by the local blacksmith.

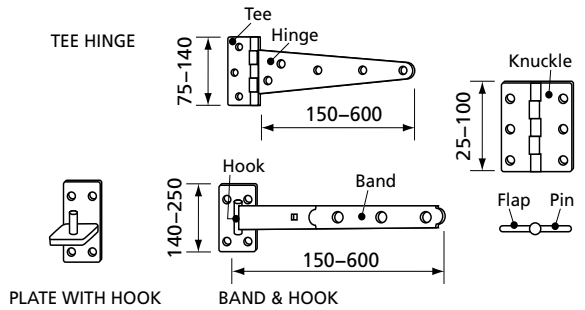


Figure 5.38 **Types of hinges**

Locks and latches

Any device used to keep a door in the closed position can be classified as a lock or latch. A lock is activated by means of a key, whereas a latch is operated by a lever or bar. Locks can be obtained with a latch bolt so that the door can be kept in a closed position without using the key. Locks in doors are usually fixed at a height of 1 050 mm. Some examples of common locks and latches used in farm buildings are illustrated in Figure 5.39.

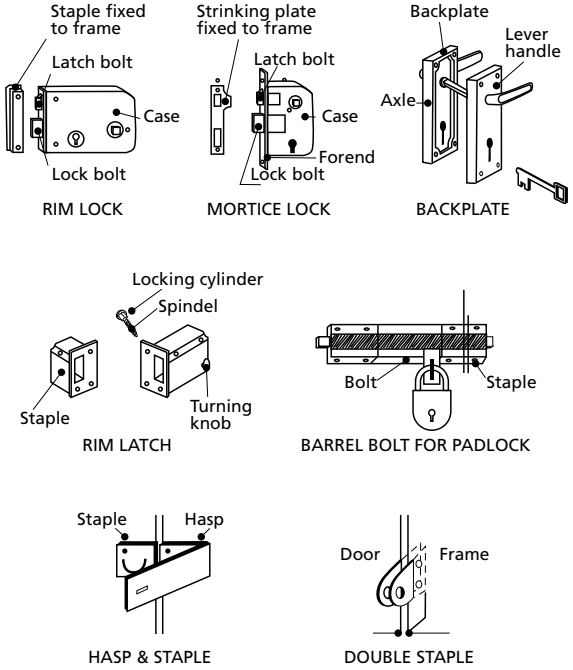


Figure 5.39 **Types of locks and latches**

GLASS

Glass suitable for general window glazing is made mainly from soda, lime and silica. The ingredients are heated in a furnace to about 1 500 °C, and fuse together in the molten state. Sheets are then formed by a process of drawing, floating or rolling. The ordinary glazing quality is manufactured by drawing in thicknesses ranging from 2 mm to 6 mm. It is transparent, with 90 percent light transmission. As the two surfaces are never perfectly flat or parallel, there is always some visual distortion. Plate glass is manufactured with ground and polished surfaces, and should be free of imperfections.

Glass in buildings is required to resist loads, including wind loads, impacts from people and animals, and sometimes thermal and other stresses. Generally the thickness increases with the area of the glass pane. Glass is elastic right up to its breaking point but, as it is also completely brittle, there is no permanent set or warning of impending failure. The support provided for glass will affect its strength performance. Glass should be cut to give a minimum clearance of 2 mm all around the frame to allow for thermal movements.

PLASTICS

Plastics are among the newest building materials, ranging from materials strong enough to replace metal, to foam-like products. Plastics are considered to be mainly organic materials derived from petroleum and, to a small extent, coal, which at some stage in their processing are plastic when heated.

The range of properties is so great that generalizations are difficult to make. However, plastics are usually light in weight and have a good strength-to-weight ratio, but rigidity is lower than that of virtually all other building materials, and creep is high.

Plastics have low thermal conductivity and thermal capacity, but thermal movement is high. They resist a wide range of chemicals and do not corrode, but they tend to become brittle with age.

Most plastics are combustible and may release poisonous gases in a fire. Some are highly flammable, while others are difficult to burn.

Plastics lend themselves to a wide range of manufacturing techniques, and products are available in many forms, both solid and cellular, from soft and flexible to rigid, and from transparent to opaque. Various textures and colours are available (many of which fade if used outdoors). Plastics are classified as:

- *Thermoplastics,* which always soften when heated and harden again on cooling, provided they are not overheated.
- *Thermosetting plastics,* which undergo an irreversible chemical change in which the molecular chains crosslink so that subsequently they cannot be appreciably softened by heat. Excessive heating causes charring.

Thermoplastics

Polythene is tough, waterproof and oilproof, and can be manufactured in many colours. In buildings, it is used for cold water pipes, plumbing and sanitary ware, and polythene film (translucent or black). Film should not be subjected unnecessarily to prolonged heat over 50 °C, or to direct sunlight. The translucent film will last for only 1–2 years if exposed to sunlight, but the carbon pigmentation of black film increases resistance to sunlight.

Polyvinyl chloride (PVC) will not burn and can be made in rigid or flexible form. It is used for rainwater goods, drains, pipes, ducts, electric cable insulation, etc.

Acrylics, a group of plastics containing polymethyl methacrylate, which transmit more light than glass and are easy to mould or curve into almost any shape.

Thermosetting plastics

The main uses for thermosetting plastics in buildings are as impregnants for paper fabrics, binders for particle boards, adhesives, paints and clear finishes. Phenol formaldehyde (bakelite) is used for electrical insulating accessories, and urea formaldehyde is used for particle board manufacture.

In most cases, epoxy resins are provided in two parts: a resin and a curing agent. They are extremely tough and stable, and adhere well to most materials. Silicone resins are water-repellent and used for waterproofing in masonry. Note that fluid plastics can be very toxic.

Plastics used for seepage protection in dams

Seepage from dams is a common problem. Occasionally, site conditions and the lack of local clay may require the use of synthetic liners, also called geomembranes, to line the dam and overcome the problem of seepage. If the correct product is selected and good installation procedures are used, only normal maintenance will be needed during the service life of the dam.

Three types of lining material are available: low-density plastic sheeting; woven polyethylene fabric; and high density polyethylene (HDPE) sheeting. All of these products are susceptible to degradation by introduced chemicals. The most suitable product for a specific job depends on a number of factors. These include: site conditions, cost, resistance to sunlight, strength, resistance to puncturing and the method of joining.

Low-density plastic sheeting

Commonly referred to as 'builder's plastic', these sheets are normally black or orange in colour. Low-density plastic sheeting is manufactured in various thicknesses, with the recommended thickness being 0.2–0.3 mm. This sheeting punctures easily, as it is relatively thin. It is suitable for use on low slopes (less than 2:1, i.e. 2 metres horizontal to 1 metre vertical) and on sites free of sticks, small stones and abrasive materials. Extreme care needs to be taken during installation. Low-density plastic breaks down quickly in sunlight if it is not covered with soil.

Woven polyethylene fabric

This has a polyethylene coating on both sides, and is blue or green in colour. Woven polyethylene fabrics are generally the most suitable as dam liners in temperate countries, and are sold according to weight, not thickness. Fabric weight of about 250 grams per square metre is normally selected for farm dams. Heavier grades are required where puncturing is a concern. Although polyethylene fabrics are not UV resistant, their life expectancy can be increased to 15–20 years with soil cover.

It is normal practice to cover these fabrics with at least a 300 mm layer of soil. Owing to the need to provide this cover, sites with steep batters (greater than 2:1) are not suitable. For woven polyethylene fabrics used as dam liners, the batter slopes of the embankment and excavations should not exceed 2:1, although a gentler slope is preferable to ensure that any soil cover stays on the liner.

High-density polyethylene (HDPE) sheeting

High-density polyethylene sheeting, which is black in colour, does not require soil cover, but it is the most expensive of lining materials. Installation is generally undertaken using fusion-weld joining equipment. Thicknesses range from 0.4 mm to 2.5 mm. It is suitable for sites where puncturing of cheaper products cannot be avoided, or where steep slopes (steeper than 2:1) preclude the use of other products.

HDPE is the most widely used geomembrane, and offers the most cost-effective liner for large, exposed, lining projects. This product has been used in landfills, wastewater treatment lagoons, animal waste lagoons, mining applications and water storage. It has the following advantages:

- soil covering is not required;
- it has high overall chemical resistance and is resistant to ozone and UV;
- it is cost effective for large projects;
- it is suitable for potable water.

Plastic components used with dam liners

In the process of lining dams, there may be needed one or more additional components that will ensure the longevity of the earth dam. These components include:

(a) Geosynthetics:

These are synthetic materials made from polymers (geomembranes are also classified under geosynthetics). When these materials are used together with dam liners (geomembranes), the service life of the earth dam is extended. The geosynthetics commonly used together with dam liners include:

1. *Geonets:* These are open grid-like materials formed by a continuous extrusion of parallel sets of polymeric ribs intersecting at a constant acute angle. They are used in the design of drainage systems, particularly on slopes and are a viable alternative to the common sand and gravel systems.
2. *Geocells:* These are constructed from polymeric strips, which are joined together to form a 3-dimensional network. They are used to stabilize the side slopes of dams and other earth structures. This usually involves filling the cells with soil.
3. *Geogrids:* These are stiff or flexible polymer grid-like sheets with large uniformly distributed apertures. These apertures allow direct contact between soil particles on either side of the sheet. Their main use is to reinforce unstable soils.

Combination of two or more of the geosynthetics, e.g. geogrid and geomembrane, are referred to as geocomposites. Several combinations are possible and this area has attracted interest of many research establishments. The main uses of geocomposites embrace the entire range of uses of the geosynthetics discussed above, e.g. reinforcement, drainage, liquid barrier, etc.

(b) Degradable erosion mats:

These are made of flexible erosion control blankets that are used to keep soil and seeds stable until vegetation completely covers the dam catchment. As they are made of organic materials, they eventually breakdown and become part of the soil.

RUBBER

Rubbers are similar to thermosetting plastics. In the manufacturing process, a number of substances are mixed with latex, a natural polymer. Carbon black is added to increase strength in tension and to improve wearing properties.

After forming, the product is vulcanized by heating under pressure, usually with sulphur present. This process increases the rubber's strength and elasticity. Ebonite is a fully vulcanized, hard rubber.

Modified and synthetic rubbers (elastomers) are increasingly being used for building products. Unlike natural rubbers, they often have good resistance to oil and solvents. One such rubber, butyl, is extremely tough, has good weather resistance, excellent resistance to acids and very low permeability to air. Synthetic rubber fillers and nail washers are used with metal roofing.

BITUMINOUS PRODUCTS

These include bitumen (asphalt in the United States), coal tar and pitch. They are usually dark brown or black and, in general, they are durable materials that are resistant to many chemicals. They resist the passage of water and water vapour, especially if they have been applied hot.

Bitumen occurs naturally as rock asphalt or lake asphalt, or can be distilled from petroleum. It is used for road paving, paint, damp-proof membranes, joint filler, stabilizer in soil blocks, etc.

PAINTS

Paint preserves, protects and decorates surfaces, and enables them to be cleaned easily. All paints contain a binder that hardens. Other ingredients found in various paints include: pigments, strainers, extenders, driers, hardeners, thinners, solvents and gelling agents. Some water-thinned paints contain emulsifiers.

Owing to the cost involved, few buildings in rural areas are painted. When paint can be afforded, priority should be given to painting surfaces likely to rust, rot or decay because of exposure to rain or dampness, and to rooms such as a kitchen or a dairy, where hygiene demands easily cleaned surfaces. White and other light

colours reflect more light than dark colours, and can be used in a sitting room or a workshop to make the room lighter.

Painting

Adequate preparation of the surface to be painted is essential. The surface should be smooth (not shiny, because this would not give good adhesion), clean, dry and stable. Old, loose paint should be brushed off before a new coat is applied. Most commercial paints are supplied with directions for use, which should be read carefully before the work is started. The paint film is usually built up in two or more coats;

Priming paints are used for the first coat, to seal and protect the surface and to give a smooth surface for subsequent coats. They are produced for application to wood, metal and plaster.

Undercoating paints are sometimes used to obscure the primer, as a further protective coating and to provide the correct surface for the finishing paint.

Finishing paints are produced in a wide range of colours and finishes (e.g. matt, semi-matt or gloss). Some commonly used types of paint for farm structures are detailed below, but many others are manufactured with special properties, making them water- and chemical-resistant, heat-resistant, fire-retardant, anti-condensation, fungicidal or insecticidal, for example.

Estimation of quantities of paint required

The volume of paint required for a particular paint job can be determined from knowledge of the following:

1. Surface area of the surface(s) to be painted.
2. Spreading rate of the paint being used.
3. The number of coats needed.

Spreading rates

The spreading rate of paint is the area that a specific volume of paint will cover at a specified film thickness. Two standard measurements are used to describe the film thickness of a coating: mils and microns. A micron is a metric system measurement equal to 0.001 millimetres.

The spreading rate in microns may be calculated as follows:

Any liquid will cover 1 000 square metres per litre at 1 micron wet. Therefore, a 100 percent volume/solids material will cover 1 000 m^2 per litre dry when applied at 1 micron wet and, because it is 100 percent solids, it will yield a 1 micron-thick dry film. However, if a coating is less than 100 percent solids, then the dry film thickness will be thinner because the volatile portion of the volume will evaporate and leave the film, thereby reducing the dried film volume or thickness.

Assuming a material has 42 percent volume of solids, the area that it will cover when a dry film thickness of 38.1 microns is required may be calculated as follows:

1 000 m^2 / litre × 0.42 = 420 m^2 / litre at 1 micron thickness.

Assuming 38.1 microns dry is desired, then:

420 m^2 / litre / 38.1 = 11.0 m^2 / litre

A coating with 42 percent volume solids, applied at 11.0 m^2 / litre, will produce a dry film that is 38.1 microns thick.

Example 5.4

The living room walls require painting, excluding the ceiling. The walls are 3 metres high, with a total of 18 metres of wall length. The total door and window area is 3 m^2. If a spreading rate of 11 square metres per litre is used, and only two coats of paint are required, work out how much paint is needed.

To work out how much paint is needed:

- Take the surface area = (3×18) -3 = 51 m^2
- The spreading rate is 11 m^2 / litre
- The number of coats needed = 2
- The required litres of paint = (51m^2 / 11m^2 / litres) × 2 coats = 9 litres in total (i.e. a 10-litre pail)

Oil- and resin-based paints

Oil paints are based on naturally drying oils (e.g. linseed oil). They are being gradually replaced by alkyd and emulsion paints.

Alkyd paints are oil-based paints, modified by the addition of synthetic resins to improve durability, flexibility, drying and gloss. They are quite expensive.

Synthetic resin paints contain substantial proportions of thermosetting resins, such as acrylics, polyurethane or epoxides, and are often packed in two parts. They have excellent strength, adhesion and durability, but are very expensive.

Bituminous paints are used to protect steelwork and iron sheeting from rust, and to protect wood from decay. They are black or dark in colour, and tend to crack in hot sunlight. They can be overpainted with ordinary paint only after a suitable sealer has been applied.

Varnishes are either oil/resin or spirit-based and used mainly to protect wood with a transparent finish, but protection is inferior to opaque finishes. Spirit-based varnish is used only for interior surfaces.

Water-based paints

Non-washable distemper consists of chalk powder, mixed with animal glue dissolved in hot water. It is cheap, but easily rubbed or washed off, and therefore suitable only for whitening ceilings.

Washable distemper (water paint) consists of drying oil or casein, emulsified in water with the addition of pigments and extenders. Hardening is slow but, after a month, it can withstand moderate scrubbing. It weathers fairly well outdoors and is reasonably cheap.

Whitewash (limewash) consists of lime mixed with water. It can be used on all types of wall, including earth walls, and is cheap, but its lack of water resistance and poor weathering properties make it inferior to emulsion

paint for outdoor surfaces. However, the addition of tallow or cement gives some degree of durability for external use. Whitewash can be made in the following way:

- Mix 8 litres (9 kg) of quicklime with about 18 litres of boiling water, adding the water slowly and stirring constantly until a thin paste results.
- Add 2 litres of salt and stir thoroughly.
- Add water to bring the whitewash to a suitable consistency.
- If external quality is required, add a handful of cement per 10 litres of whitewash just before use.

In *emulsion paints*, the pigments and binder (vinyl, acrylic, urethane or styrene polymers) are dispersed as small globules in water. They harden quickly, are quite tough and weather-resistant, and the cost is moderate. Although they adhere well to most supports, because they are permeable an oil-based primer may be required to seal porous exterior surfaces.

Cement-based paints are often used for exteriors, and are quite inexpensive. They contain white portland cement, pigments (if other colours are desired) and water-repellents, and are sold in powder form. Water is added just before use to obtain a suitable consistency. Paint that has thickened must not be thinned further. It adheres well to brickwork, concrete and renderings, but not to timber, metal or other types of paint. Surfaces should be dampened before painting.

Cement slurries make economical surface coatings on masonry and concrete, but earth walls that shrink and swell will cause the coating to peel off. Slurries are mixtures of cement and/or lime, clean fine sand and enough water to make a thick liquid. A good slurry can be made using 1 part cement, 1 part lime and up to 4 parts sand. It is applied on the dampened surface with a large brush or a used bag, hence the name 'bag washing'.

REVIEW QUESTIONS

1. (a) Explain how the following factors affect construction material choice:
   (i) resource utilization in the choice of construction materials;
   (ii) social costs and shadow prices.
   (b) Define the following for cement:
   (i) hydration;
   (ii) setting.
   (c) Briefly describe the Pozzolana as a building material.

2. (a) Outline three disadvantages of soil as a construction material.
   (b) During the bar shrinkage test the following results were obtained:
   - Length of wet bar = 600 mm
   - Length of dry bar = 420 mm

   Find the shrinkage ratio and state the conclusion that may be drawn from this result.
   (c) Briefly describe how burnt (soil) bricks are made.

3. (a) Name five methods for seasoning wood.
   (b) Briefly outline the Bethel full-cell process of timber preservation.

4. Briefly describe: geonets, geocells and degradable erosion mats.

5. The tensile strength of blue gum timber is 50 MPa at a moisture content of 12 percent. If the strength determined in its green state was 42 MPa, and its fibre saturation point occurs at a moisture content of 25 °C, find the strength of this timber at a moisture content of 8 percent.
   If the density of the wood was 1.4 g/cm^3 at moisture content of 12 percent, find the density at a moisture content of 8 percent.

6. (a) Briefly describe glass as a building material.
   (b) Briefly describe three main types of paint.
   (i) Assuming paint has 42 percent volume of solids, find the area that 1 litre will cover when a dry film thickness of 38.1 microns is required.
   (ii) The walls of a room are 3 metres high, with a total of 30 metres of wall length. The total door and window area is 3 square metres. If the spreading rate is 11 square metres per litre, and only two coats of paint are required, work out how much paint is needed.

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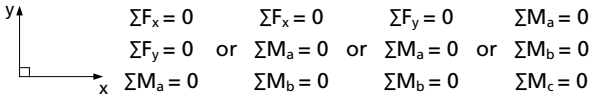
Chapter 6
Basic mechanics

BASIC PRINCIPLES OF STATICS

Statics is the branch of mechanics that deals with the equilibrium of stationary bodies under the action of forces. The other main branch – dynamics – deals with moving bodies, such as parts of machines.

Static equilibrium

A planar structural system is in a state of static equilibrium when the resultant of all forces and all moments is equal to zero, i.e.



where F refers to forces and M refers to moments of forces.

Static determinacy

If a body is in equilibrium under the action of coplanar forces, the statics equations above must apply. In general, three independent unknowns can be determined from the three equations. Note that if applied and reaction forces are parallel (i.e. in one direction only), then only two separate equations can be obtained and thus only two unknowns can be determined. Such systems of forces are said to be statically determinate.

Force

A force is defined as any cause that tends to alter the state of rest of a body or its state of uniform motion in a straight line. A force can be defined quantitatively as the product of the mass of the body that the force is acting on and the acceleration of the force.

$P = ma$

where
P = applied force
m = mass of the body (kg)
a = acceleration caused by the force (m/s^2)

The *Système Internationale* (SI) units for force are therefore kg m/s^2, which is designated a Newton (N). The following multiples are often used:

1 kN = 1 000 N, 1 MN = 1 000 000 N

All objects on earth tend to accelerate toward the centre of the earth due to gravitational attraction; hence the force of gravitation acting on a body with the mass (m) is the product of the mass and the acceleration due to gravity (g), which has a magnitude of 9.81 m/s^2:

$F = mg = v\rho g$

where:
F = force (N)
m = mass (kg)
g = acceleration due to gravity (9.81m/s^2)
v = volume (m^3)
ρ = density (kg/m^3)

Vector

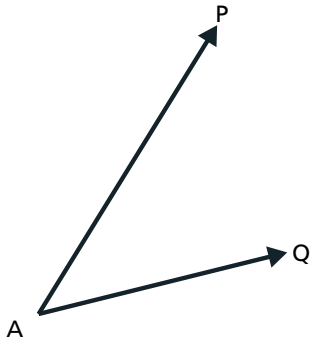
Most forces have magnitude and direction and can be shown as a vector. The point of application must also be specified. A vector is illustrated by a line, the length of which is proportional to the magnitude on a given scale, and an arrow that shows the direction of the force.

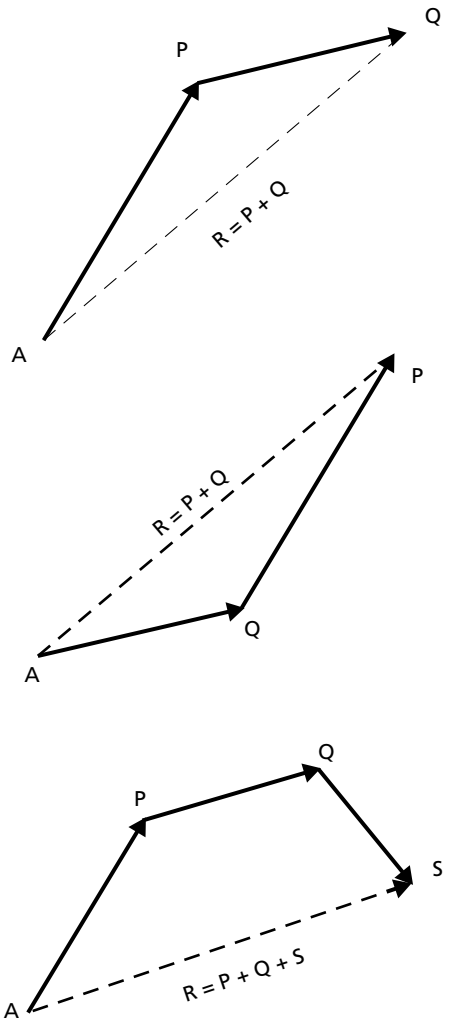
Vector addition

The sum of two or more vectors is called the resultant. The resultant of two concurrent vectors is obtained by constructing a vector diagram of the two vectors.

The vectors to be added are arranged in tip-to-tail fashion. Where three or more vectors are to be added, they can be arranged in the same manner, and this is called a polygon. A line drawn to close the triangle or polygon (from start to finishing point) forms the resultant vector.

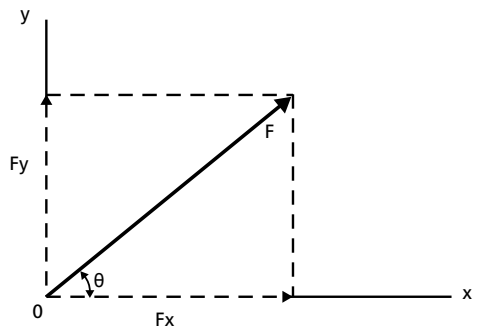
The subtraction of a vector is defined as the addition of the corresponding negative vector.





Resolution of a force

In analysis and calculation, it is often convenient to consider the effects of a force in directions other than that of the force itself, especially along the Cartesian (xx-yy) axes. The force effects along these axes are called vector components and are obtained by reversing the vector addition method.



F_y is the component of F in the y direction $F_y = F \sin\theta$
F_x is the component of F in the x direction $F_x = F \cos\theta$

Concurrent coplanar forces

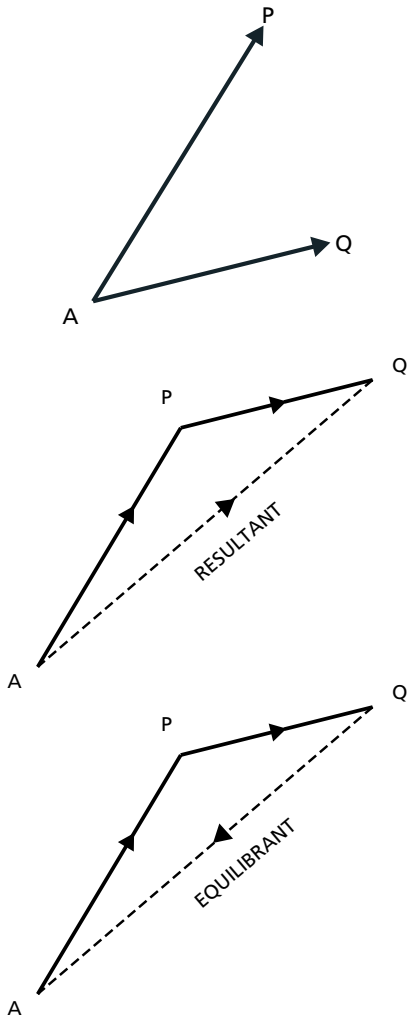
Forces whose lines of action meet at one point are said to be *concurrent. Coplanar* forces lie in the same plane, whereas *non-coplanar* forces have to be related to a three-dimensional space and require two items of directional data together with the magnitude. Two coplanar non-parallel forces will always be concurrent.

Equilibrium of a particle

When the resultant of all forces acting on a particle is zero, the particle is in *equilibrium,* i.e. it is not disturbed from its existing state of rest (or uniform movement).

The closed triangle or polygon is a graphical expression of the equilibrium of a particle.

The equilibrium of a particle to which a single force is applied may be maintained by the application of a second force that is equal in magnitude and direction, but opposite in sense, to the first force. This second force, which restores equilibrium, is called the *equilibrant*. When a particle is acted upon by two or more forces, the *equilibrant* has to be equal and opposite to the resultant of the system. Thus the *equilibrant* is the vector drawn closing the vector diagram and connecting the finishing point to the starting point.



Free-body diagram of a particle

A sketch showing the physical conditions of a problem is known as a *space diagram*. When solving a problem it is essential to consider all forces acting on the body and to exclude any force that is not directly applied to the body. The first step in the solution of a problem should therefore be to draw a *free-body diagram*.

A free-body diagram of a body is a diagrammatic representation or a sketch of a body in which the body is shown completely separated from all surrounding bodies, including supports, by an imaginary cut, and the action of each body removed on the body being considered is shown as a force on the body when drawing the diagram.

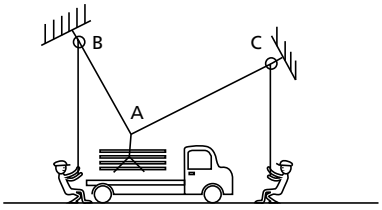
To draw a free-body diagram:

1. Choose the free body to be used, isolate it from any other body and sketch its outline.
2. Locate all external forces on the free body and clearly mark their magnitude and direction. This should include the weight of the free body, which is applied at the centre of gravity.
3. Locate and mark unknown external forces and reactions in the free-body diagram.
4. Include all dimensions that indicate the location and direction of forces.

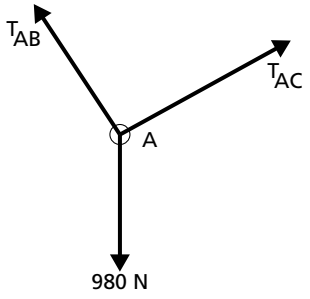
The free-body diagram of a rigid body can be reduced to that of a particle. The free-body of a particle is used to represent a point and all forces working on it.

Example 6.1

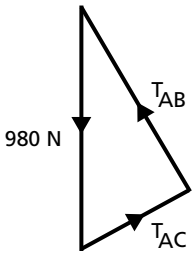
Determine the tension in each of the ropes AB and AC



Space diagram

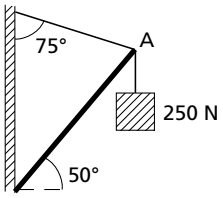


Free body diagram for point A

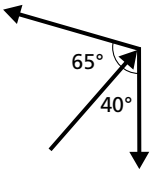


Example 6.2

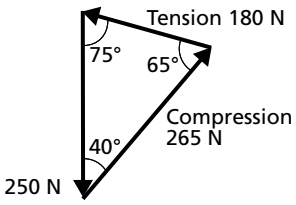
A rigid rod is hinged to a vertical support and held at 50° to the horizontal by means of a cable when a weight of 250 N is suspended as shown in the figure. Determine the tension in the cable and the compression in the rod, ignoring the weight of the rod.



Space diagram



Free-body diagram for point A



Force triangle

The forces may also be calculated using the law of sines:

$$\frac{\textit{Compression in rod}}{\sin 75^\circ} = \frac{\textit{Tension in cable}}{\sin 40^\circ} = \frac{250\ \text{N}}{\sin 65^\circ}$$

Point of concurrency

Three coplanar forces that are in equilibrium must all pass through the same point. This does not necessarily apply for more than three forces.

If two forces (which are not parallel) do not meet at their points of contact with a body, such as a structural member, their lines of action can be extended until they meet.

Collinear forces

Collinear forces are parallel and concurrent. The sum of the forces must be zero for the system to be in equilibrium.

Coplanar, non-concurrent, parallel forces

Three or more parallel forces are required. They will be in equilibrium if the sum of the forces equals zero and the sum of the moments around a point in the plane equals zero. Equilibrium is also indicated by two sums of moments equal to zero.

Reactions

Structural components are usually held in equilibrium by being secured to rigid fixing points; these are often other parts of the same structure. The fixing points or supports will react against the tendency of the applied forces (loads) to cause the member to move. The forces generated in the supports are called reactions.

In general, a structural member has to be held or supported at a minimum of two points (an exception to this is the cantilever). Anyone who has tried 'balancing' a long pole or a similar object will realize that, although only one support is theoretically necessary, two are needed to give satisfactory stability.

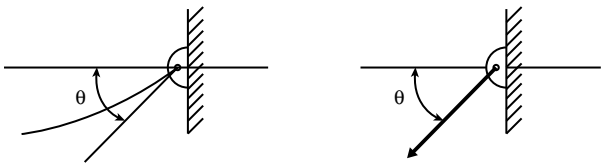
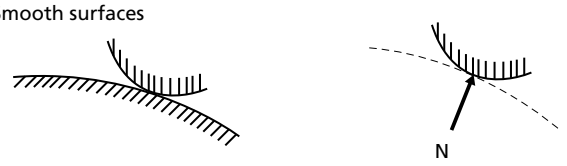
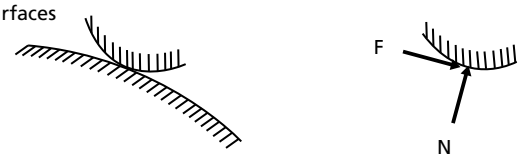
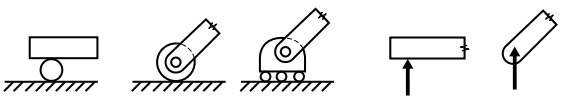
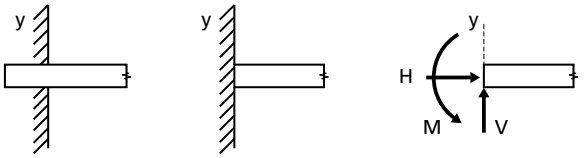
Resultant of gravitational forces

The whole weight of a body can be assumed to act at the centre of gravity of the body for the purpose of determining supporting reactions of a system of forces that are in equilibrium. Note that, for other purposes, the gravitational forces cannot always be treated in this way.

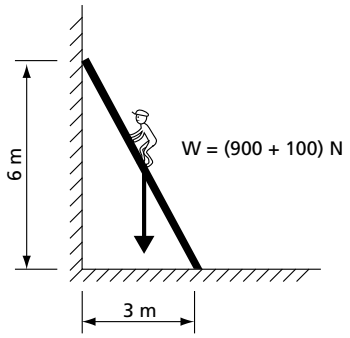
Example 6.3

A ladder rests against a smooth wall and a person weighing 900 N stands on it at the middle. The weight

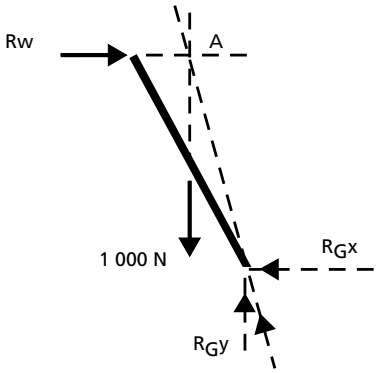
TABLE 6.1
Actions and reactions

Flexible cable or rope		Force exerted by the cable or rope is always tension away from the fixing, in the direction of the tangent to the cable curve.
Smooth surfaces		Reaction is normal to the surface, i.e., at right angles to the tangent.
Rough surfaces		Rough surface is capable of supporting a tangental force as well as a normal reaction. Resultant reaction is vectorial sum of these two.
Roller support		Reaction is normal to the supporting surface only.
Pin support		A freely hinged support is fixed in position, hence the two reaction forces, but is not restrained in direction - it is free to rotate.
Built-in support		The support is capable of providing a longitudinal reaction (H), a lateral or transverse reaction (V), and a moment (M). The body is fixed in position and fixed in direction.

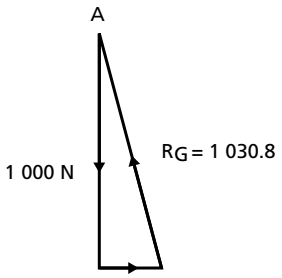
of the ladder is 100 N. Determine the support reactions at the wall (R_W) and at the ground (R_G).



Space diagram



Free-body diagram of ladder



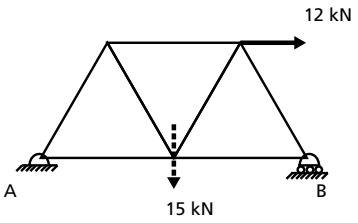
Force diagram

As the wall is smooth, the reaction R_W must be at right angles to the surface of the wall and is therefore horizontal. A vertical component would have indicated a friction force between the ladder and the wall. At the bottom, the ladder is resting on the ground, which is not smooth, and therefore the reaction R_G must have both a vertical and a horizontal component.

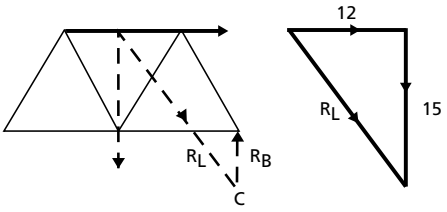
As the two weight forces in this example have the same line of action, they can be combined into a single force, reducing the problem from one with four forces to one with only three forces. The point of concurrency (A) can then be found, giving the direction of the ground reaction force. This in turn enables the force vector diagram to be drawn, and hence the wall and ground reactions determined.

Example 6.4

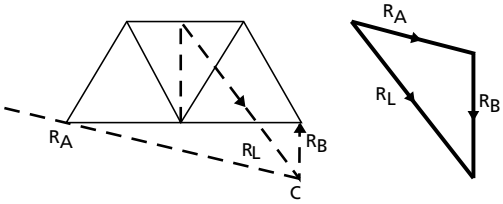
A pin-jointed framework (truss) carries two loads, as shown. The end A is pinned to a rigid support, while the end B has a roller support. Determine the supporting reactions graphically:



1. Combine the two applied forces into one and find the line of action.
2. Owing to the roller support reaction R_B will be vertical. Therefore the resultant line (R_L) must be extended to intersect the vertical reaction of support B. This point is the point of concurrency for the resultant load, the reaction at B and the reaction at A.



3. From this point of concurrency, draw a line through the support pin at A. This gives the line of action of the reaction at A.



4. Use these three force directions and the magnitude of R_L to draw the force diagram, from which R_A and R_B can be found.

Answer: R_A = 12.2 kN at 21° to horizontal.
R_B = 12.7 kN vertical.

The link polygon (see an engineering handbook) may also be used to determine the reactions to a beam or a truss, though it is usually quicker and easier to obtain the reactions by calculation, the method shown in Example 6.4, or a combination of calculation and drawing.

However, the following conditions must be satisfied.

1. All forces (apart from the two reactions) must be known completely, i.e. magnitude, line of action and direction.
2. The line of action of one of the reactions must be known.
3. At least one point on the line of action for the other reaction must be known (2 and 3 reduce the number of unknowns related to the equations of equilibrium to an acceptable level).

Moments of forces

The effect of a force on a rigid body depends on its point of application, as well as its magnitude and direction. It is common knowledge that a small force can have a large turning effect or leverage. In mechanics, the term 'moment' is used instead of 'turning effect'.

The moment of force with a magnitude (F) about a turning point (O) is defined as: $M = F \times d$, where d is the perpendicular distance from O to the line of action of force F. The distance d is often called lever arm. A moment has dimensions of force times length (Nm). The direction of a moment about a point or axis is defined by the direction of the rotation that the force tends to give to the body. A clockwise moment is usually considered as having a positive sign and an anticlockwise moment a negative sign.

The determination of the moment of a force in a coplanar system will be simplified if the force and its point of application are resolved into its horizontal and vertical components.

Example 6.5

As the ladder in Example 6.3 is at rest, the conditions of equilibrium for a rigid body can be used to calculate the reactions. By taking moments around the point where the ladder rests on the ground, the moment of the reaction R_G can be ignored as it has no lever arm (moment is zero). According to the third condition for equilibrium, the sum of moments must equal zero, therefore:

$(6 \times R_W) - (900 \text{ N} \times 1.5 \text{ m}) - (100 \text{ N} \times 1.5 \text{ m}) = 0$
$R_W = 250$ N

The vertical component of R_G must, according to the second condition, be equal but opposite to the sum of the weight of the ladder and the weight of the person on the ladder, because these two forces are the only vertical forces and the sum of the vertical forces must equal zero, i.e.

$R_{Gy} = 1\,000$ N

Using the first condition of equilibrium it can be seen that the horizontal component of R_G must be equal but opposite in direction to R_W, i.e.

$R_{GX} = 250$ N

Because R_G is the third side of a force triangle, where the other two sides are the horizontal and vertical components, the magnitude of R_G can be calculated as:

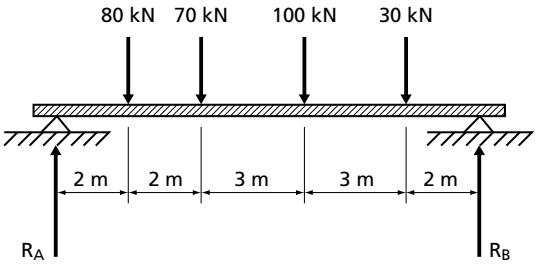
$(1\,000^2 + 250^2)^{½} = 1\,030.8$ N

Resultant of parallel forces

If two or more parallel forces are applied to a horizontal beam, then theoretically the beam can be held in equilibrium by the application of a single force (reaction) that is equal and opposite to the resultant R. The equilibrant of the downward forces must be equal and opposite to their resultant. This provides a method for calculating the resultant of a system of parallel forces. However, two reactions are required to ensure the necessary stability, and a more likely arrangement will have two or more supports.

The reactions R_A and R_B must both be vertical because there is no horizontal force component. Furthermore, the sum of the reaction forces R_A and R_B must be equal to the sum of the downward-acting forces.

Beam reactions



The magnitude of the reactions may be found by the application of the third condition for equilibrium, i.e. the algebraic sum of the moments of the forces about any point must be zero.

Take the moments around point A, then:

$(80 \times 2) + (70 \times 4) + (100 \times 7) + (30 \times 10) - (R_B \times 12) = 0$;

Giving $R_B = 120$ kN

R_A is now easily found with the application of the second condition for equilibrium.

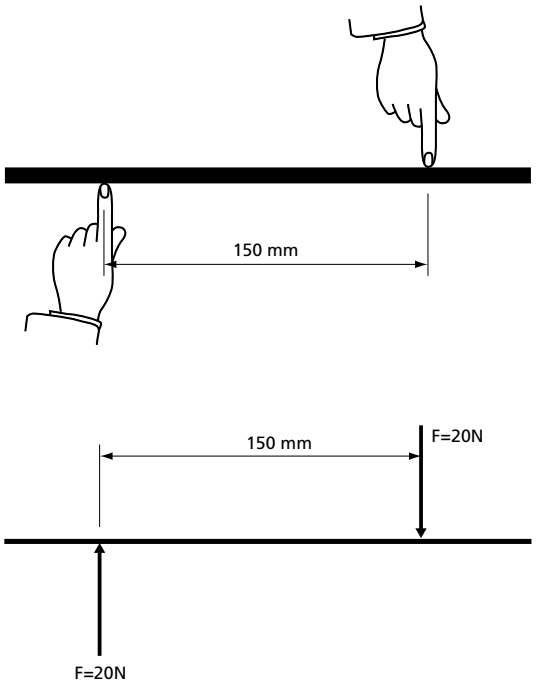
$R_A - 80 - 70 - 100 - 30 + R_B = 0$; with $R_B = 120$ kN gives:

$R_A = 160$ kN.

Couples

Two equal, parallel and opposite but non-collinear forces are said to be a couple.

A couple acting on a body produces rotation. Note that the couple cannot be balanced by a single force. To produce equilibrium, another couple of equal and opposite moment is required.



Loading systems

Before any of the various load effects (tension, compression, bending, etc.) can be considered, the applied loads must be rationalized into a number of ordered systems. Irregular loading is difficult to deal with exactly, but even the most irregular loads may be reduced and approximated to a number of regular systems. These can then be dealt with in mathematical terms using the principle of superposition to estimate the overall combined effect.

Concentrated loads are those that can be assumed to act at a single point, e.g. a weight hanging from a ceiling, or a person pushing against a box.

Concentrated loads are represented by a single arrow drawn in the direction, and through the point of action, of the force. The magnitude of the force is always indicated.

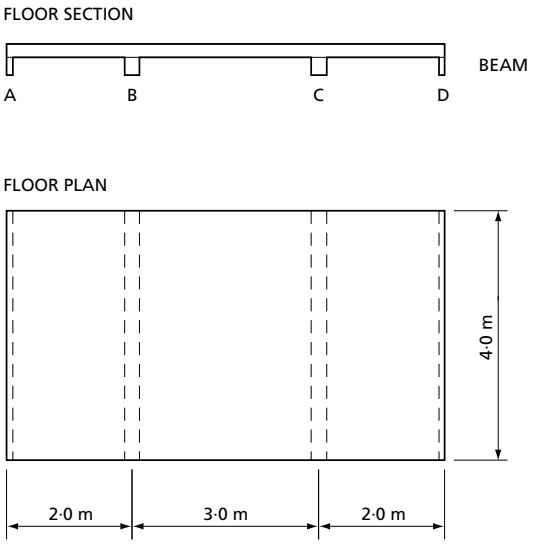
Uniformly distributed loads, written as UDL, are those that can be assumed to act uniformly over an area or along the length of a structural member, e.g. roof loads, wind loads, or the effect of the weight of water on a horizontal surface. For the purpose of calculation, a UDL is normally considered in a plane.

In calculating reactions, uniformly distributed loads can in most, but not all, cases be represented by a concentrated load equal to the total distributed load passing through the centre of gravity of the distributed load.

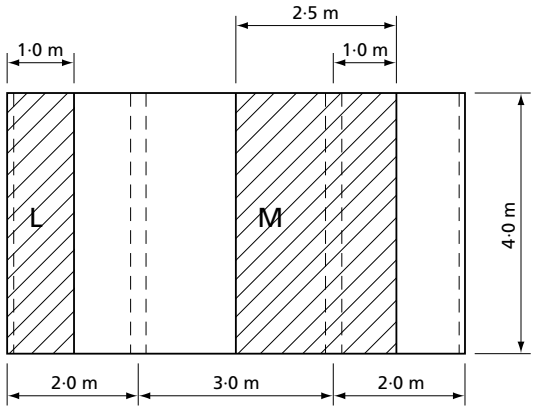
This technique must not be used for calculation of shear force, bending moment or deflection.

Example 6.6

Consider a suspended floor where the loads are supported by a set of irregularly placed beams. Let the load arising from the weight of the floor itself and the weight of any material placed on top of it (e.g. stored grain) be 10 kPa. Determine the UDL acting on beam A and beam C.



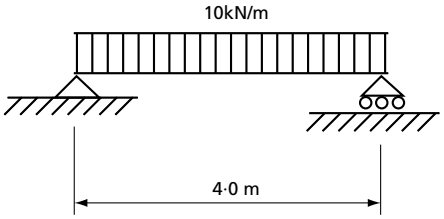
It can be seen from the figure below that beam A carries the floor loads contributed by half the area between the beams A and B, i.e. the shaded area L. Beam C carries the loads contributed by the shaded area M.



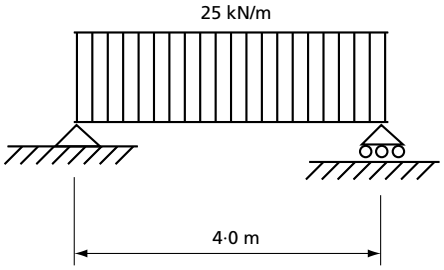
Therefore beam A carries a total load of:

1 m × 4 m × 10 kPa = 40 kN, or 40 kN / 4 = 10 kN / m.

In the same way, the loading of beam C can be calculated to 25 kN / m. The loading per metre run can then be used to calculate the required size of the beams.

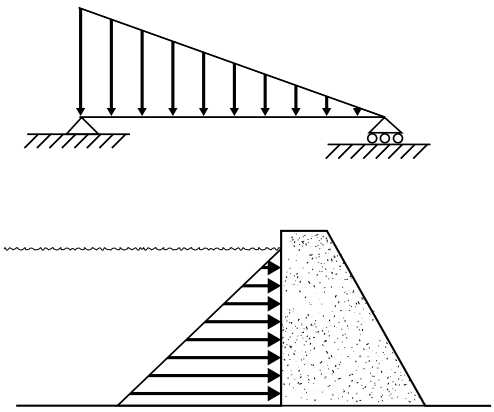


Loading of beam A



Loading of beam C

Distributed load with linear variation is another common load situation. The loading shape is triangular and is the result of such actions as the pressure of water on retaining walls and dams.



Distributed loads with linear variation

Shear force and bending moment of beams

A beam is a structural member subject to lateral loading in which the developed resistance to deformation is of a flexural character. The primary load effect that a beam is designed to resist is that of bending moments but, in addition, the effects of transverse or vertical shearing forces must be considered.

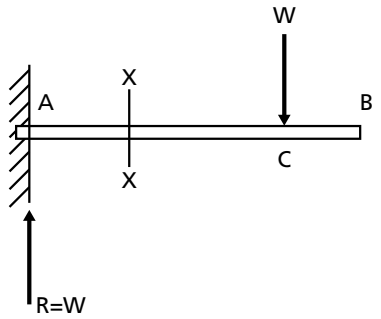
Shear force (V) is the algebraic sum of all the transverse forces acting to the left or to the right of the chosen section.

Bending moment (M) at any transverse cross-section of a straight beam is the algebraic sum of the moments, taken about an axis passing through the centroid of the cross-section, of all the forces applied to the beam on either side of the chosen cross-section.

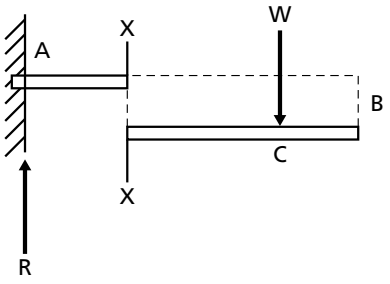
Consider the cantilever AB shown in (A). For equilibrium, the reaction force at A must be vertical and equal to the load W.

The cantilever must therefore transmit the effect of load W to the support at A by developing resistance (on vertical cross-section planes between the load and the support) to the load effect called shearing force. Failure to transmit the shearing force at any given section, e.g. section x-x, will cause the beam to fracture as in (B).

(A)



(B)

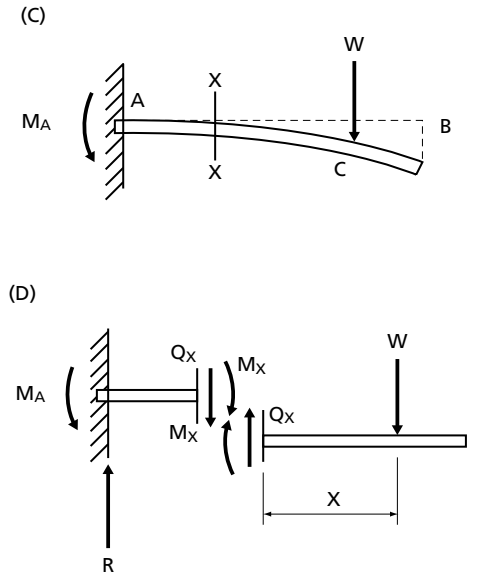


The bending effect of the load will cause the beam to deform as in (C). To prevent rotation of the beam at the support A, there must be a reaction moment at A, shown as M_A, which is equal to the product of load W and the distance from W to point A.

The shearing force and the bending moment transmitted across the section x-x may be considered as the force and moment respectively that are necessary to maintain equilibrium if a cut is made severing the beam at x-x. The free-body diagrams of the two portions of the beam are shown in (D).

Then the shearing force between A and C = Q_x = W and the bending moment between A and C = M_x = $W \times AC$.

Note: Both the shearing force and the bending moment will be zero between C and B.



Definitions

Shear force (*Q*) is the algebraic sum of all the transverse forces acting to the left or to the right of the chosen section.

Bending moment (*M*) at any transverse cross section of a straight beam is the algebraic sum of the moments, taken about an axis passing through the centroid of the cross section, of all the forces applied to the beam on either side of the chosen cross section.

Table 6.2 shows the sign convention for shear force (*Q*) and bending moment (*M*) used in this book. Shearing forces, which tend to make the part of the beam to the left move up and the right part move down, are considered positive. The bending moment is considered positive if the resultant moment is clockwise on the left and anticlockwise on the right. These tend to make the beam concave upwards and are called *sagging* bending moments. If the moment is anticlockwise on the left and clockwise on the right, the beam will tend to become convex upwards – an effect called hogging.

TABLE 6.2
Shearing and bending forces

Load effect	Symbol	Sign convention		Units
		Positive (+)	Negative (–)	
Shearing force	Q	Up on the left	Down on the left	N kN
Bending moment	M	Sagging (top fibre in compression)	Hogging (top fibre in tension)	Nm kNm Nmm

Shear-force variation

Concentrated loads will change the value of the shear force only at points where they occur, i.e. the shear force remains constant in between. When the load is uniformly distributed, however, the shear force will vary at a uniform rate. Thus it will be seen that uniform loads cause gradual and uniform change of shear, while concentrated loads bring a sudden change in the value of the shear force.

Bending moment variation

Concentrated loads will cause a uniform change of the bending moment between the points of action of the loads. In the case of uniformly distributed loads, the rate of change of the bending moment will be parabolic. Maximum bending moment values will occur where the shear force is zero or where it changes sign.

Shear-force (SF) and bending-moment (BM) diagrams

Representative diagrams of the distribution of shearing forces and bending moments are often required at several stages in the design process. These diagrams are obtained by plotting graphs with the beams as the base and the values of the particular effect as ordinates. It is usual to construct these diagrams in sets of three, representing the distribution of loads, shearing forces and bending moments respectively. These graphical representations provide useful information regarding:

1. The most likely section where a beam may fail in shear or in bending.
2. Where reinforcement may be required in certain types of beam, e.g. concrete beams.
3. The shear-force diagram will provide useful information about the bending moment at any point.
4. The bending-moment diagram gives useful information on the deflected shape of the beam.

Some rules for drawing shear-force and bending-moment diagrams are:

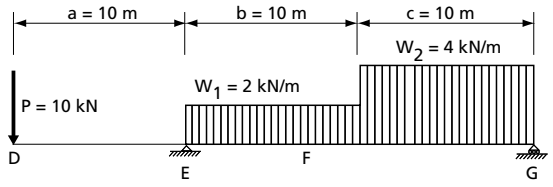
1. In the absence of distributed loads, the shear-force diagram consists of horizontal steps and the bending-moment diagram is a series of straight lines.
2. For a beam (or part of a beam) carrying a UDL only, the shear-force diagram is a sloping straight line and the bending diagram is a parabola.
3. At the point where the shear-force diagram passes through zero (i.e. where the SF changes sign), the BM has a maximum or minimum value.
4. Over a part of the span for which SF is zero, the bending moment has a constant value.
5. At a point where the bending-moment diagram passes through zero, the curvature changes from concave upwards to concave downwards or vice versa. This point is referred to as point of inflexion.
6. If a beam is subjected to two or more different systems of loading, the resulting shear and bending moment at a given section is the algebraic sum of the values at the section. This is referred to

as the principle of superposition and applies also to bending stresses, reactions and deflections.

The following example demonstrates the construction of diagrams representing shearing forces and bending moments.

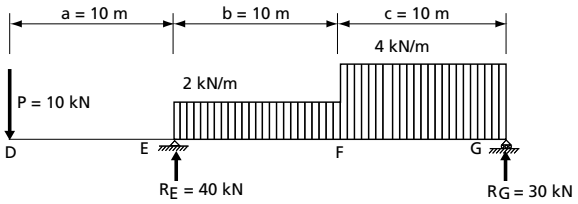
Example 6.7

The distribution of loads in a simply supported beam is as given in the diagram below. Determine the reactions at the supports and draw the shear-force and bending-moment diagram.



Solution:

(a) Draw the free-body diagram of the beam.



(b) Determine the reactions at the supports. First use the condition for equilibrium of moments about a point:

$\Sigma M_E = 0$

$M_E = (P \times a) + (w_1 \times b \times b / 2) + w_2 \times c(b+c / 2)$
$- R_G(b + c) = 0$

$M_E = -(10 \times 10) + (2 \times 10 \times 5) + 4 \times 10 \times (15)$
$- R_G (20) = 0$

$R_G = 30$ kN

$\Sigma F_y = 0$ hence

$\Sigma F_y = R_E + R_G - P-(w_1 \times b) - (w_2 \times c) = 0$

$\Sigma F_y = R_E + 30 - 10 - (2 \times 10) - (4 \times 10) = 0$

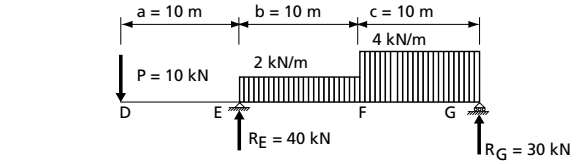
$R_E = 40$ kN

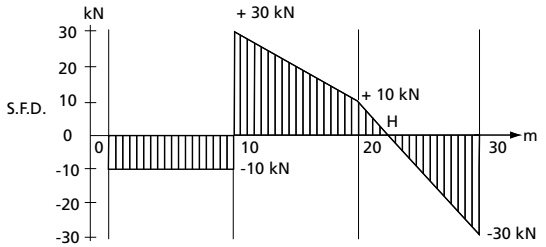
(c) Draw the shear-force diagram (SFD) directly below the loading diagram and choose a convenient scale to represent the shear force.

Calculate the values of the shear force to the left and to the right of all critical points. Critical points are:

- at concentrated loads;
- at reactions;
- at points where the magnitude of a distributed load changes.

1. Consider a section through the beam just to the left of D, and find the algebraic sum of all vertical forces to the left of this section. $\Sigma F_y = 0$, therefore, shear force to the left of D is zero.
2. Consider a section just to the right of D, algebraic sum of forces to the left of this section is 10 kN down to the left. Hence, shear force to the right of D is 10 kN (negative).
3. The same result as in point 2 above will be found for any such section between D and E. The shear-force diagram between D and E is thus a horizontal line at -10 kN.
4. Consider a section just to the right of E; the algebraic sum of forces to the left of this section is made up of P and R_E given that the shear force equals (-10 + 40) kN = + 30 kN, i.e. up to the left of section. Thus at E the shear-force diagram changes from -10 kN to + 30 kN.
5. As we approach the right-hand end of the beam we find the mathematics easier to consider on the right-hand side of any section. Section just to the left of F. Shear force = (4 kN / m × 10 m) - (30 kN) using the sign convention to determine positive or negative. Shear force here equals + 40 - 30 = + 10 kN.
6. Section just to the right of F. Shear force = + 40 - 30 = + 10 kN (i.e. no sudden change at F).
7. Section just to the left of G. Shear force = -30 kN
8. Variation of shear under a distributed load must be linear.





Note the following from the shear-force diagram:

- Maximum shear force occurs at E and G where the values are + 30 kN and - 30 kN respectively. These two transverse sections are the two most likely points for failure in shear.
- The maximum bending moment will occur where the shear force is zero or where the shear force changes sign. However, note that cantilevered beams will always have maximum bending at the fixed end.

The shear-force diagram in the example has two points where the shear force is zero. One is at E and the other is between H and G. The position of H can be calculated from the fact that at F the shear force is 10 kN and, under the action of UDL to the right of F, it reduces at the rate of 4 kN / m. It will read a value of zero after 2.5 m, i.e. the point H is 2.5 m to the right of F.

(d) Draw the bending-moment diagram directly under the shear-force diagram and choose a convenient scale to represent the bending moment. Calculate values of the bending moment at all critical points. Critical points for bending moment are:

- ends of the beam;
- where the shear force is zero or changes sign;
- other points that experience has shown to be critical.

Values of bending moment are calculated using the definition and sign convention, and considering each load (to one side of the point) separately. It is the effect that one load would have on the bent shape at the chosen point that determines the sign.

1. For the bending moment at D consider the left side of this point $M_D = 0$

2. For the bending moment at E consider the left side of this point $M_E = P \times a$ and the beam would assume a hogging shape:

   $M_E = -(10 \times 10) = -100$ kNm

3. For the bending moment at F consider the loads to the right of this point, a sagging beam results and:

   $M_F = -(4 \times 10 \times 10 / 2) + (30 \times 10) = 100$ kNm

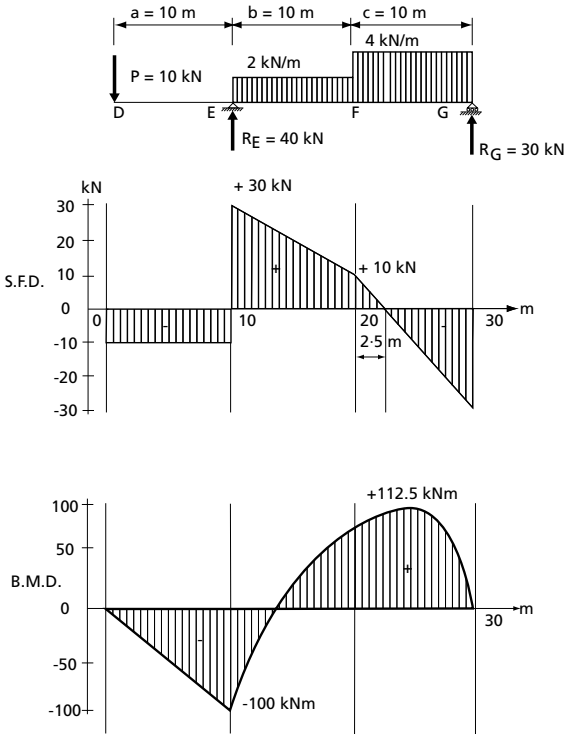
4. The bending moment at G is obviously zero

5. At point H we have the maximum bending moment: considering the forces to the right of this point gives

   $M_H = -(4 \times 7\,512 \times 7\,5) + (30 \times 7\,5)$
   $= 112.5$ (sagging)

6. The variation of the bending moment under a UDL is parabolic

7. If the inclusion of other points would be helpful in drawing the curve, they should also be plotted.



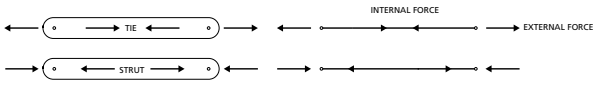
Note the following from the bending-moment diagram:

- The maximum negative bending-moment hogging (100 kNm) occurs at E and the maximum positive bending moment sagging (112.5 kNm) occurs at a point between F and G. When designing beams in materials such as concrete, the steel reinforcement would have to be placed according to these moments.
- The bending-moment diagram will also give an indication as to how the loaded beam will deflect. Positive bending moments (sagging) cause compression in the top fibres of the beam, hence they tend to bend the beam with the concave side downwards.
- At the supported ends of a simple beam and at the free end of a cantilevered beam, where there can be no resistance to bending, the bending moment is always zero.

Forces in pin-jointed frames

Designing a framework necessitates finding the forces in the members. For the calculation of primary stresses, each member is considered to be pin-jointed at each end so that it can transmit an axial force only in the direction of the line connecting the pin joints at each end. The force can be a pure tension (conventionally designated positive), in which case the member is called a tie, or a pure compression (conventionally designated negative), when the member is called a strut.

These are internal forces that must be in equilibrium with the external applied forces.

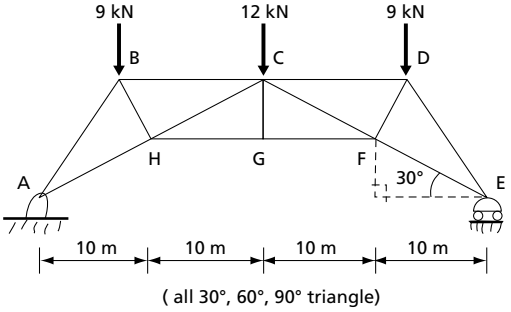


A number of different techniques can be used to determine the forces in the members.

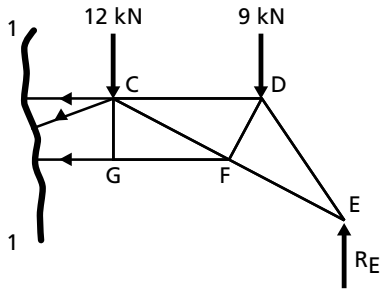
Joint analysis: This is based on considering the equilibrium of each joint in turn and using the free-body diagram for each joint.

Method of sections: The free-body diagram considered is for a portion of the framework to one side or the other of a cut section. The forces in the members cut by the section are included in the free-body diagram. Application of the equations of equilibrium will solve the unknown forces in the cut section. This provides an analytical solution and is most useful when requiring the answers for one or two members only.

Example 6.8



Find the forces and their direction in the members BH and HG by using the method of sections.



F_{HG} is found by taking a moment about point C, considering the right hand section (RHS) of the cut 1-1 is in equilibrium. The forces F_{HC} and F_{BC} have no moment about point CBL because they intersect at and pass through the point.

$\Sigma M_c = 0\ (F_{HG} \times CG) + (9 \times CD) - (R_E \times 20) = 0$

$CG = FX = 10 \tan 30° = 5.774$

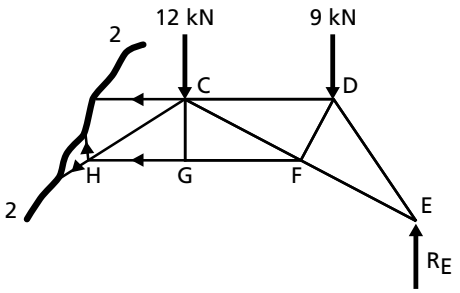
$CD = DE = FE / \cos 30°$

$FE = EX / \cos 30° = 11.547$ m

$CD = 11\ 547 / \cos 30° = 13.333$ m

$RE = (9 + 12 + 12\ ) / 2 = 15$ kN

Hence $(F_{HG} \times 5.774) + (9 \times 13.333) - (15 \times 20) = 0$
$F_{HG} = 31.17$



Take section 2-2.

$HC = FE = 11.547\ (F_{BH} \times 11.547) + (9 \times 13.333)$
$- (15 \times 20) = 0\ F_{BH} = 15.59$ kN

It can therefore be seen that F_{GH} and F_{BH} must be clockwise to have equilibrium about point C. The members GH and HB are therefore in tension.

MECHANICS OF MATERIALS

Direct stress

When a force is transmitted through a body, the body tends to change its shape. Although these deformations are seldom visible to the naked eye, the many fibres or particles that make up the body transmit the force throughout the length and section of the body, and the fibres doing this work are said to be in a state of stress. Thus, a stress may be described as a mobilized internal reaction that resists any tendency towards deformation. As the effect of the force is distributed over the cross-section area of the body, stress is defined as force transmitted or resisted per unit area.

$$\text{Thus Stress} = \frac{\text{Force}}{\text{Area}}$$

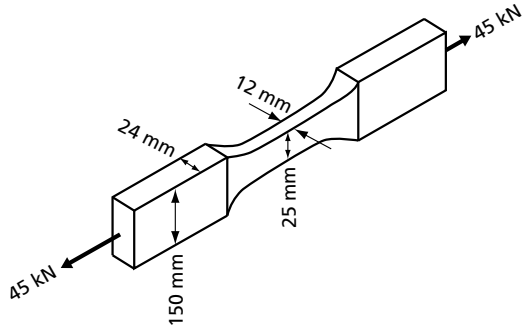
The SI unit for stress is Newtons per square metre (N / m²). This is also called a Pascal (Pa). However, it is often more convenient to use the multiple N / mm².

Note that 1 N / mm² = 1 MN / m² = 1 MPa

Tensile and compressive stress, which result from forces acting perpendicular to the plane of cross-section in question, are known as normal stress and are usually symbolized with σ (the Greek letter sigma), sometimes given a suffix t for tension (σ_t) or c for compression (σ_c). Shear stress is produced by forces acting parallel or tangential to the plane of cross-section and is symbolized with τ (Greek letter tau).

Tensile stress

Example 6.9



Consider a steel bar that is thinner at the middle of its length than elsewhere, and that is subject to an axial pull of 45 kN.

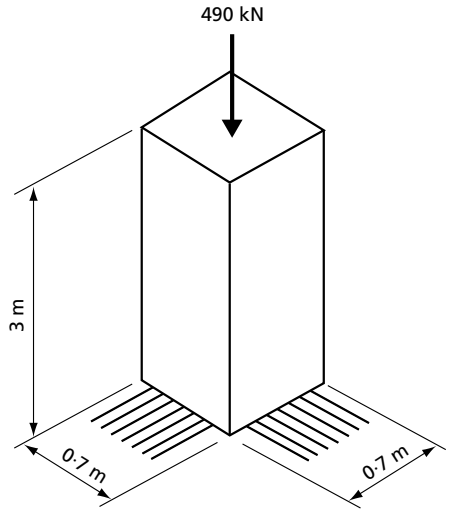
If the bar were to fail in tension, it would be as a result of breaking where the amount of material is at a minimum. The total force tending to cause the bar to fracture is 45 kN at all cross-sections but, whereas the effect of the force is distributed over a cross-sectional area of 1 200 mm² for part of the length of the bar, it is distributed over only 300 mm² at the middle position. Thus, the tensile stress is greatest in the middle and is:

$$\sigma_t = \frac{45\,\text{kN}}{300\,\text{mm}^2} = 150\,\text{MPa}$$

Compressive stress

Example 6.10

A brick pier is 0.7 metres square and 3 metres high and weighs 19 kN / m³. It is supporting an axial load from a column of 490 kN. The load is spread uniformly over the top of the pier, so the arrow shown in the diagram merely represents the resultant of the load. Calculate (a) the stress in the brickwork immediately under the column, and (b) the stress at the bottom of the pier.



Solution a

Cross-section area = 0.49 m²

$$\text{Stress} = \sigma_c = \frac{490\,\text{kN}}{0.49\,\text{m}^2} = 1\,000\ \text{kPa or 1 MPa}$$

Solution b

Weight of pier = 0.7 m × 0.7 m × 3.0 m × 19 kN / m³
= 28 kN

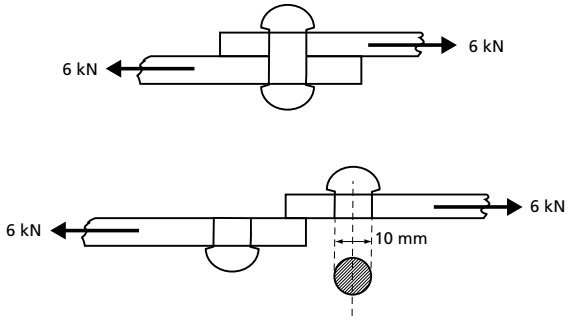
Total load = 490 + 28 = 518 kN and

$$\text{Stress} = \sigma_c = \frac{518\,\text{kN}}{0.49\,\text{m}^2} = 1\,057\ \text{kPa}$$

Shear stress

Example 6.11

A rivet is used to connect two pieces of flat steel. If the loads are large enough, the rivet could fail in shear, i.e. not breaking but sliding of its fibres. Calculate the shear stress of the rivet when the steel bars are subject to an axial pull of 6 kN.



Note that although the rivets do, in fact, strengthen the connection by pressing the two steel bars together, this strength cannot be calculated easily owing to friction and is therefore neglected, i.e. the rivet is assumed to give all the strength to the connection.

Cross-section area of rivet = $1/4 \times \pi \times 10^2 = 78.5$ mm²

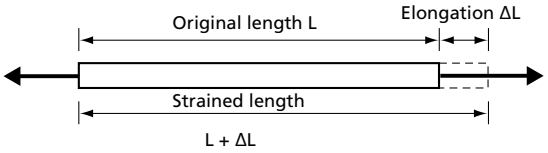
$$\text{Shear stress} = \tau = \frac{6\,\text{kN}}{78.5\,\text{mm}^2} = 76\ \text{MPa}$$

Strain

When loads of any type are applied to a body, the body will always undergo dimension changes; this is called *deformation*. Tensile and compressive stresses cause changes in length, torsional-shearing stresses cause twisting, and bearing stresses cause indentation in the bearing surface.

In farm structures, where a uniaxial state of stress is the usual stress considered, the major deformation is in the axial direction. Although there are always small deformations present in the other two dimensions, they are seldom significant.

$$\text{Direct strain} = \frac{\text{Change in length}}{\text{original length}} = \varepsilon = \frac{\Delta L}{L}$$



By definition *strain* is a ratio of change and thus it is a dimensionless quantity.

Elasticity

All solid materials deform when they are stressed and, as the stress increases, the deformation also increases. In many cases, when the load causing the deformation is removed, the material returns to its original size and shape and is said to be elastic. If the stress is steadily increased, a point is reached when, after the removal of the load, not all of the induced strain is recovered. This limiting value of stress is called the *elastic limit*.

Within the elastic range, strain is proportional to the stress causing it. This is called *the modulus of elasticity*. The greatest stress for which strain is still proportional is called the *limit of proportionality* (Hooke's law).

Thus, if a graph is drawn of stress against strain as the load is gradually applied, the first portion of the graph will be a straight line. The slope of this straight line is the constant of proportionality, modulus of elasticity (E), or Young's modulus and should be considered as a measure of the stiffness of a material.

$$\text{Modulus of elasticity} = E = \frac{\text{Stress}}{\text{Strain}} = \frac{FL}{A\Delta L}$$

The modulus of elasticity will have the same units as stress (Pa). This is because strain has no units.

A convenient way of demonstrating elastic behaviour is to plot a graph of the results of a simple tensile test carried out on a thin mild steel rod. The rod is hung vertically and a series of forces are applied at the lower end. Two gauge points are marked on the rod and the distance between them is measured after each force increment has been added. The test is continued until the rod breaks.

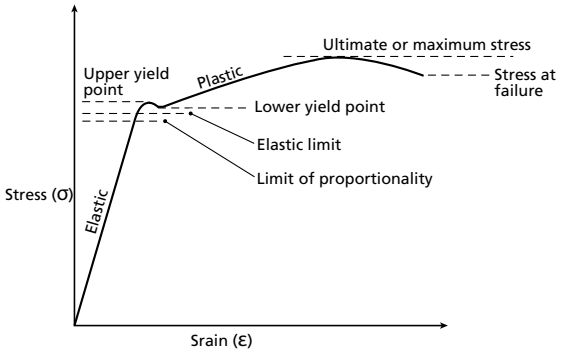


Figure 6.1 **Behaviour of a mild steel rod under tension**

Example 6.12

Two timber posts, measuring 150 millimetres square and 4 metres high, are subjected to an axial load of 108 kN each. One post is made of pine timber (E = 7 800 MPa) and the other is Australian blackwood (E = 15 300 MPa). How much will they shorten because of the load?

Cross-section area A = 22 500 mm²; length L = 4 000 mm

$$\text{Pine: } \Delta L = \frac{FL}{AE} = \frac{108\,000 \times 4\,000}{22\,500 \times 7\,800} = 2.5\ \text{mm}$$

$$\text{Australian blackwood: } \Delta L = \frac{FL}{AE} = \frac{108\,000 \times 4\,000}{22\,500 \times 15\,300} = 1.3\ \text{mm}$$

Factor of safety

The permissible stresses must, of course, be less than the stresses that would cause failure of the members of the structure – in other words there must be an ample safety margin. (In 2 000 BC, a building code declared the life of the builder to be forfeit should the house collapse and kill the owner).

Also, deformations must be limited because excessive deflection may give rise to problems such as cracking of ceilings, partitions and finishes, as well as adversely affecting the functional needs.

Structural design is not an exact science and, while calculated values of reactions, stresses, etc. may be mathematically correct for the theoretical structure (i.e. the model), they may be only approximate as far as the actual behaviour of the structure is concerned.

For these and other reasons, it is necessary to ensure that the design stress, working stress, allowable stress and permissible stress are less than the ultimate stress or the yield stress. This margin is called the *factor of safety.*

$$\text{Design stress} = \frac{\text{Ultimate (or yield) stress}}{\text{factor of safety}}$$

In the case of a material such as concrete, which does not have a well defined yield point, or brittle materials that behave in a linear manner up to failure, the factor of safety is related to the ultimate stress (maximum stress before breakage). Other materials, such as steel, have a yield point where a sudden increase in strain occurs, and at which point the stress is lower than the ultimate stress. In this case, the factor of safety is related to the yield stress in order to avoid unacceptable deformations.

The value of the factor of safety has to be chosen with a variety of conditions in mind, such as the:

- accuracy in the loading assumptions;
- permanency of the loads;
- probability of casualties or big economic losses in case of failure;
- purpose of the building;
- uniformity of the building material;
- workmanship expected from the builder;
- strength properties of the materials;
- level of quality control ensuring that the materials are in accordance with their specifications;
- type of stresses developed;
- cost of building materials.

Values of 3 to 5 are normally chosen when the factor of safety is related to ultimate stress, and values of 1.4 to 2.4 are chosen when related to yield-point stress.

In the case of building materials such as steel and timber, different factors of safety are sometimes considered for common loading systems and for exceptional loading systems, in order to save materials. Common loadings are those that occur frequently, whereas a smaller safety margin may be considered for exceptional loadings, which occur less frequently and seldom at full intensity, e.g. wind pressure, earthquakes, etc.

STRUCTURAL ELEMENTS AND LOADING

Applied loads

Applied loads fall into three main categories: dead loads, wind loads and other imposed loads.

Dead loads are loads resulting from the self-weight of all permanent construction, including roof, walls, floor, etc. The self-weight of some parts of a structure, e.g. roof cladding, can be calculated from the manufacturer's data sheets, but the self-weight of the structural elements cannot be accurately determined until the design is completed. Hence estimates of self-weight of some members must be made before commencing a design analysis and the values checked upon completion of the design.

Wind loads are imposed loads, but are usually treated as a separate category owing to their transitory nature and their complexity. Very often wind loading proves to be the most critical load imposed on agricultural buildings. Wind loads are naturally dependent on wind speed, but also on location, size, shape, height and construction of a building.

Specific information concerning various load types is presented in Chapter 8.

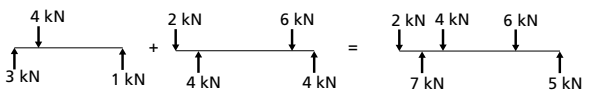
When designing a structure, it is necessary to consider which combination of dead and imposed loads could give rise to the most critical loading condition. Not all the imposed loads will necessarily reach their maximum values at the same time. In some cases (for example, light open sheds), wind loads may tend to cause the roof structure to lift, producing an effect opposite in direction to that of the dead load.

Imposed loads are loads related to the use of the structure and to the environmental conditions, e.g. weight of stored products, equipment, livestock, vehicles, furniture and people who use the building. Imposed loads include earthquake loads, wind loads and snow loads where applicable, and are sometimes referred to as superimposed loads because they are in addition to the dead loads.

Dynamic loading results from a change of loading, resulting directly from the movement of loads. For example, a grain bin may be affected by dynamic loading if filled suddenly from a suspended hopper; it is not sufficient to consider the load solely when the bin is either empty or full.

Principle of superposition

This principle states that the effect of a number of loads applied at the same time is the algebraic sum of the effects of the loads applied singly.

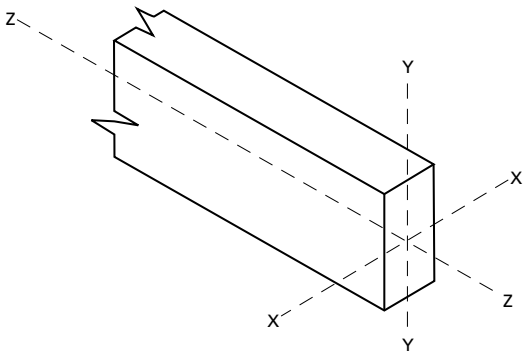


Using standard load cases and applying the principle of superposition, complex loading patterns can be solved. Standard case values of shear force, bending moment or deflection at particular positions along a member can be evaluated, after which the total value of such parameters for the actual loading system can be found by algebraic summation.

Effects of loading

After the loads have been transformed into definable load systems, the designer must consider how the loads will be transmitted through the structure. Loads are not transmitted as such, but as load effects.

It is usual practice to orientate the Cartesian z-z axis along the length of the member and the x-x and y-y axes along the horizontal and vertical cross-sectional axes respectively, when considering a structural member that occupies a certain space (see the figure below).



Primary load effects

A primary load effect is defined as being the direct result of a force or a moment, which has a specific orientation with respect to the three axes. Any single load or combination of loads can give rise to one or more of these primary load effects. In most cases, a member will be designed basically to sustain one load effect, usually the one producing the greatest effect.

In more complex situations, the forces and moments are resolved into their components along the axes, after which the load effects are first studied separately for one axis at a time, and subsequently their combined effects are considered when giving the member its size and shape.

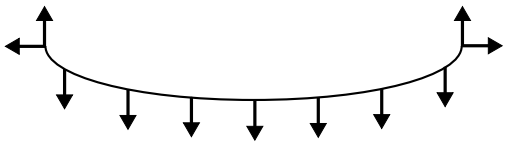
The choice of material for a member may be influenced to some extent by the type of loading. For instance, concrete has little or no strength in tension and is therefore unsuitable for use alone as a tie.

Tension, compression, shear, bending and torsion are all primary load effects. Secondary load effects, such as deflection, are derived from the primary load effects.

Structural elements

Cable

Cables, cords, strings, ropes and wires are flexible because of their small lateral dimensions in relation to their length, and therefore have very limited resistance to bending. Cables are the most efficient structural elements because they allow every fibre of the cross-section to resist the applied loads up to any allowable stress. However, their application is limited by the fact that they can be used only in tension.

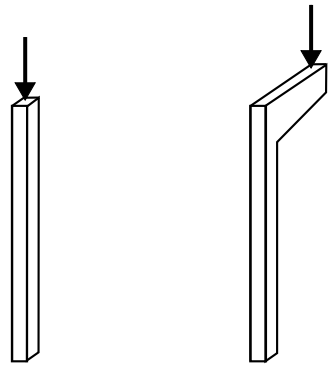


Rod

Rods, bars and poles are used to resist tensile or compressive loads. In a rod or a bar under axial tension, the full cross section can be considered and the full allowable stress for the material can be used in design calculations.

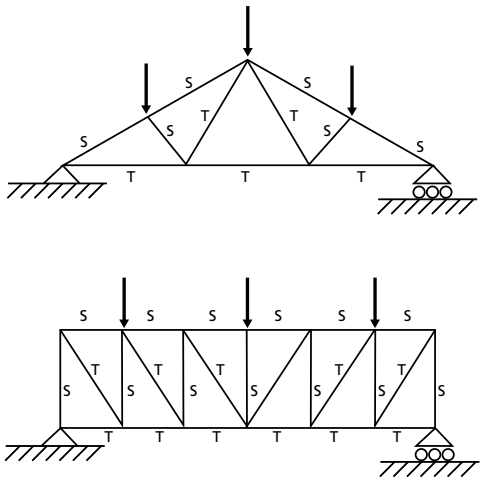
Column

Rods or bars under compression are the basis for vertical structural elements such as columns, stanchions, piers and pillars. They are often used to transfer load effects from beams, slabs and roof trusses to the foundations. They may be loaded axially or they may have to be designed to resist bending when the load is eccentric.



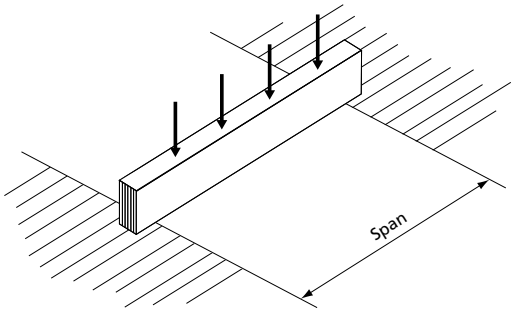
Ties and struts

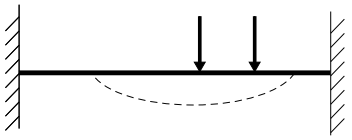
When bars are connected with pin joints and the resulting structure loaded at the joints, a structural framework called a pin-jointed truss or lattice frame is obtained. The members are subjected only to axial loads and members in tension are called *ties*, while members in compression are called *struts*.



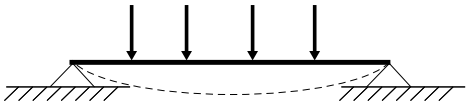
Beam

A beam is a member used to resist a load acting across its longitudinal axis by transferring the effect over a distance between supports – referred to as the *span.*

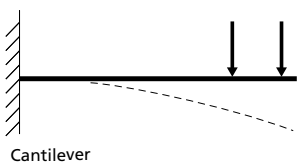




Built - in ends



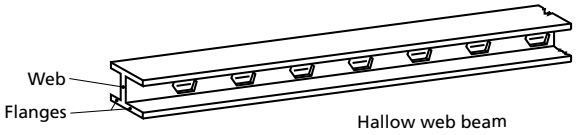
Deflection shape
Simply supported



Cantilever

The load on a beam causes longitudinal tension and compression stresses, and shear stresses. Their magnitudes will vary along, and within, the beam.

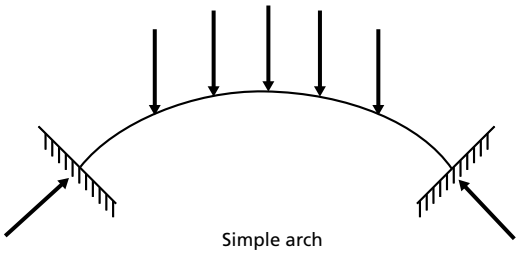
The span that a beam can usefully cover is limited by the self-weight of the beam, i.e. it will eventually reach a length when it is capable of supporting only itself. To a degree, this problem is overcome with the hollow web beam and the lattice girder or frame. The safe span for long, lightly loaded beams can be increased somewhat by removing material from the web, even though the shear capacity will be reduced.



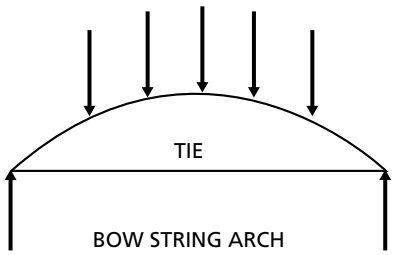
Hallow web beam

Arch

The arch can be shaped such that, for a particular loading, all sections of the arch are under simple compression with no bending. Arches exert vertical and horizontal thrusts on their supports, which can prove troublesome in the design of supporting walls. This problem of horizontal thrust can be eliminated by connecting a tension member between the support points.



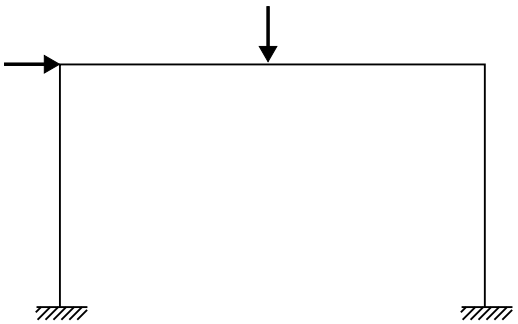
Simple arch



BOW STRING ARCH

Frames

Plane frames are also made up of beams and columns, the only difference being that they are rigidly connected at the joints. Internal forces at any cross-section of the plane frame member are: bending moment, shear force and axial force.



PROPERTIES OF STRUCTURAL SECTIONS

When designing beams in bending, columns in buckling, etc., it is necessary to refer to a number of basic geometrical properties of the cross-sections of structural members.

Area

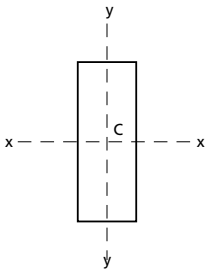
Cross-section areas (*A*) are generally calculated in square millimetres, because the dimensions of most structural members are given in millimetres, and values for design stresses found in tables are usually given in Newtons per millimetre square (N / mm²).

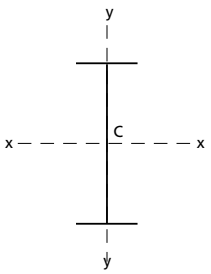
Centre of gravity or centroid

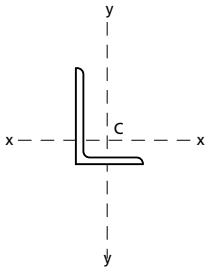
This is a point about which the area of the section is evenly distributed. Note that the centroid is sometimes outside the actual cross-section of the structural element.

Reference axes

It is usual to consider the reference axes of structural sections as those passing through the centroid. In general, the x-x axis is drawn perpendicular to the greatest lateral dimension of the section, and the y-y axis is drawn perpendicular to the x-x axis, intersecting it at the centroid.







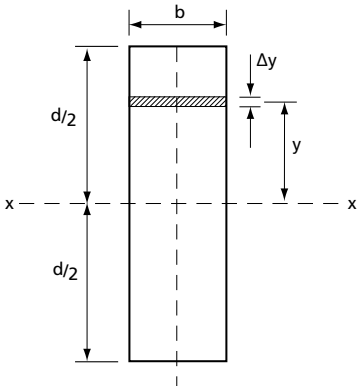
Moment of inertia

The area moment of inertia (I), or to use the more correct term, *second moment of area*, is a property that measures the distribution of area around a particular axis of a cross-section, and is an important factor in its resistance to bending. Other factors, such as the strength of the material from which a beam is made, are also important for resistance to bending, and are allowed for in other ways. The moment of inertia measures only how the geometric properties or shape of a section affect its value as a beam or slender column. The best shape for a section is one that has the greater part of its area as distant as possible from its centroidal, neutral axis.

For design purposes, it is necessary to use the moment of inertia of a section about the relevant axis or axes.

Calculation of moment of inertia

Consider a rectangle that consists of an infinite number of strips. The moment of inertia about the x-x axis of such a strip is the area of the strip multiplied by the square of the perpendicular distance from its centroid to the x-x axis, i.e. $b \times \Delta y \times y^2$



The sum of all such products is the moment of inertia about the x-x axis for the whole cross-section.

By applying calculus and integrating as follows, the exact value for the moment of inertia can be obtained.

$$I_{xx} = \int_{-d/2}^{+d/2} by^2\,dy = \frac{bd^3}{12}$$

For a circular cross-section:

$$I_{xx} = \frac{\pi D^4}{64}$$

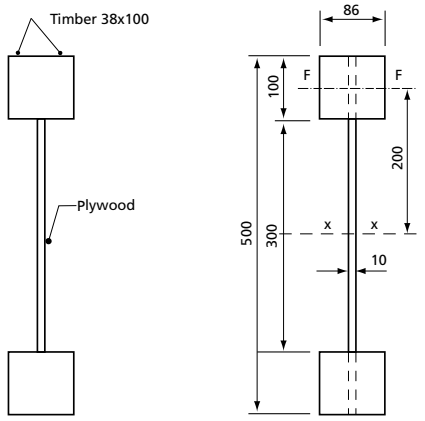
Moments of inertia for other cross-sections are given later and in Table 4.3. For structural rolled-steel sections, the moment of inertia can be found tabulated in handbooks. Some examples are given in Appendix V.3.

Principle of parallel axes

According to the principle of parallel axes, if the moment of inertia of any area (e.g. top flange of the beam shown below) about any axis is parallel to its centroidal axis, then the product of the area of the shape and the square of the perpendicular distance between the axes must be added to the moment of inertia about the centroidal axis of that shape.

Example 6.13

Determine the moment of inertia about the x-x axis and the y-y axis for the I-beam shown in the figure. The beam has a web of 10 mm plywood and the flanges are made of 38 mm by 100 mm timber, which are nailed and glued to the plywood web.



Solution:

The entire cross-section of both the beam and the cross-section of the web have their centroids on the x-x axis, which is therefore their centroidal axis. Similarly, the F-F axis is the centroidal axis for the top flange.

I_{xx} of the web using $\frac{bd^3}{12} = \frac{10 \times 300^3}{12} = 22.5 \times 10^6 \text{ mm}^4$

The moment of inertia of one flange about its own centroidal axis (F-F):

I_{FF} of one flange $= \frac{86 \times 100^3}{12} = 7.2 \times 10^6 \text{ mm}^4$

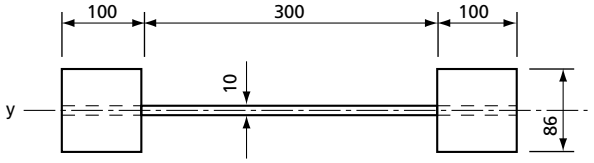
and from the principle of parallel axes, the I_{xx} of one flange equals:

$(7.2 \times 10^6) + (86 \times 100 \times 200^2) = 351.2 \times 10^6 \text{ mm}^4$

Thus the total I_{xx} of the web plus two flanges equals:

$I_{xx} = (22.5 \times 10^6) + (351.2 \times 10^6) + (351.2 \times 10^6)$
$= 725 \times 10^6 \text{ mm}^4$

The I_{yy} of the above beam section is most easily found by adding the I_{yy} of the three rectangles of which it consists, because the y-y axis is their common neutral axis, and moments of inertia may be added or subtracted if they are related to the same axis.



$$I_{yy} = 2 \times \frac{100 \times 86^3}{12} + \frac{300 \times 10^3}{12}$$
$$= 2 \times 5.3 \times 10^6 + 0.025 \times 10^6$$
$$= 10.6 \times 10^6 \text{ mm}^4$$

Section modulus

In problems involving bending stresses in beams, a property called *section modulus* (Z) is useful. It is the ratio of the moment of inertia (I) about the neutral axis of the section to the distance (C) from the neutral axis to the edge of the section.

Unsymmetrical cross-sections

Sections for which a centroidal reference axis is not an axis of symmetry will have two section moduli for that axis.

$$Z_{xx1} = \frac{I_{xx}}{y_1} \quad ; \quad Z_{xx2} = \frac{I_{xx}}{y_2}$$

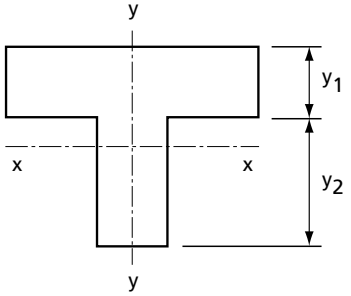
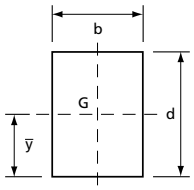
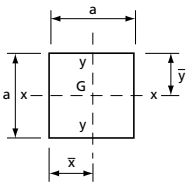
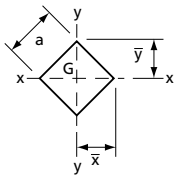
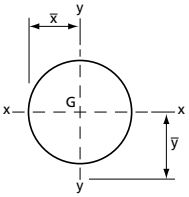
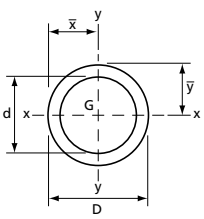


TABLE 6.3
Properties of structural sections

	Section	Area (mm^2) or (m^2)	Moment of inertia (mm^4) or (m^4)		Section modulus (mm^3) or (m^3)		Radius of gyration (mm) or (m)		Distance from extreme fibre to centroid (mm) or (m)	
		A	I_{xx}	I_{yy}	Z_{xx}	Z_{yy}	r_{xx}	r_{yy}	$\bar{y}$	$\bar{x}$
	Rectangle	bd	$\frac{bd^3}{12}$	$\frac{db^3}{12}$	$\frac{bd^2}{6}$	$\frac{db}{6}$	$\frac{d}{12}$ $\frac{d}{\sqrt{12}}$	$\frac{b}{12}$ $\frac{b}{\sqrt{12}}$	$\bar{y}=\frac{d}{2}$ $\bar{y}=\frac{d}{2}$	
	Square	a^2	$\frac{a^4}{12}$	$\frac{a^4}{12}$	$\frac{a^3}{6}$	$\frac{a^3}{6}$	$\frac{a}{\sqrt{12}}$	$\frac{a}{\sqrt{12}}$	$\bar{y}=\bar{x}=\frac{a}{2}$	
	Square with diagonal axes	a^2	$\frac{a^4}{12}$	$\frac{a^4}{12}$	$\frac{a^3}{6\sqrt{2}}$	$\frac{a^3}{6\sqrt{2}}$	$\frac{a}{\sqrt{12}}$	$\frac{a}{\sqrt{12}}$	$\bar{y}=\bar{x}=\frac{a}{2}$	
	Circle	$\frac{\pi D^2}{4}$	$\frac{\pi D^4}{64}$	$\frac{\pi D^4}{64}$	$\frac{\pi D^3}{32}$	$\frac{\pi D^3}{32}$	$\frac{D}{4}$	$\frac{D}{4}$	$\bar{y}=\frac{D}{2}$ $\bar{x}=\frac{D}{2}$	
	Annulus	$\frac{\pi(D^2-d^2)}{4}$	$\frac{\pi(D^4-d^4)}{64}$	$\frac{\pi(D^4-d^4)}{32}$	$\frac{\pi(D^3-d^3)}{32}$	$\frac{\pi(D^3-d^3)}{32}$	$4\sqrt{(D^2+d^2)}$	$4\sqrt{(D^2+d^2)}$	$\bar{y}=\frac{D}{2}$ $\bar{x}=\frac{D}{2}$	

Radius of gyration

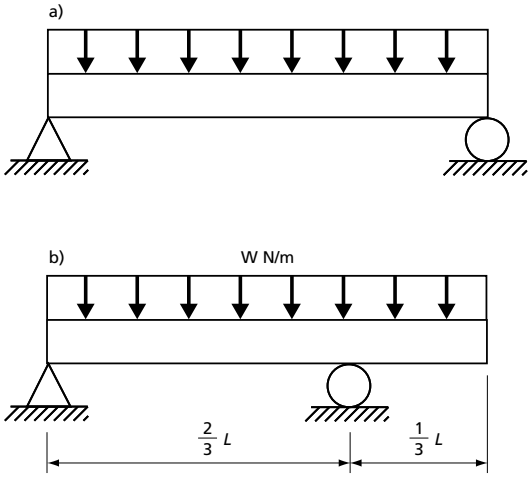
Radius of gyration (r) is the property of a cross-section that measures the distribution of the area of the cross-section in relation to the axis. In structural design, it is used in relation to the length of compression members, such as columns and struts, to estimate their slenderness ratio and hence their tendency to buckle. Slender compression members tend to buckle about the axis for which the radius of gyration is a minimum value. From the equations, it will be seen that the least radius of gyration is related to the axis about which the least moment of inertia occurs.

Therefore, $r_{xx}=\sqrt{\frac{I_{xx}}{A}}$ and $r_{yy}=\sqrt{\frac{I_{yy}}{A}}$

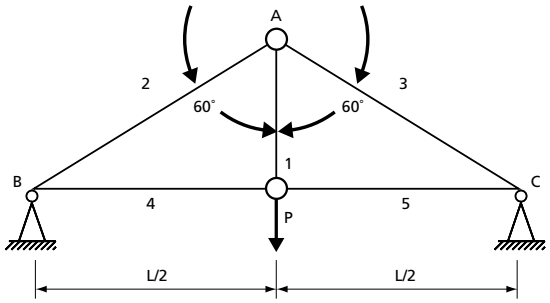
(general relationship $I = Ar^2$)

REVIEW QUESTIONS

1. Sketch the shear and bending moment diagrams for the beams below, indicating values of shear force and bending moment at the key points.



2. Find the reactions on beam BC.



3. Two concentrated loads of 100 kN and 200 kN advance along a girder with a 20-metre span, the distance between the loads being 8 metres. Find the position of the section that has to support the greatest bending moment, and calculate the value of the bending moment.

4. A load of 100 kN, followed by another load of 50 kN, at a distance of 10 metres, advances across a girder with a 100-metre span. Obtain an expression for the maximum bending moment at a section of the girder at a distance of z metres from an abutment.

FURTHER READING

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Salvadori, M. & Heller, R. 1986. *Structure in architecture: the building of buildings.* 3rd edition. Englewood Cliffs, New Jersey, Prentice-Hall.

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Chapter 7
Structural design

INTRODUCTION

Structural design is the methodical investigation of the stability, strength and rigidity of structures. The basic objective in structural analysis and design is to produce a structure capable of resisting all applied loads without failure during its intended life. The primary purpose of a structure is to transmit or support loads. If the structure is improperly designed or fabricated, or if the actual applied loads exceed the design specifications, the device will probably fail to perform its intended function, with possible serious consequences. A well-engineered structure greatly minimizes the possibility of costly failures.

Structural design process

A structural design project may be divided into three phases, i.e. planning, design and construction.

Planning: This phase involves consideration of the various requirements and factors affecting the general layout and dimensions of the structure and results in the choice of one or perhaps several alternative types of structure, which offer the best general solution. The primary consideration is the function of the structure. Secondary considerations such as aesthetics, sociology, law, economics and the environment may also be taken into account. In addition there are structural and constructional requirements and limitations, which may affect the type of structure to be designed.

Design: This phase involves a detailed consideration of the alternative solutions defined in the planning phase and results in the determination of the most suitable proportions, dimensions and details of the structural elements and connections for constructing each alternative structural arrangement being considered.

Construction: This phase involves mobilization of personnel; procurement of materials and equipment, including their transportation to the site, and actual on-site erection. During this phase, some redesign may be required if unforeseen difficulties occur, such as unavailability of specified materials or foundation problems.

Philosophy of designing

The structural design of any structure first involves establishing the loading and other design conditions, which must be supported by the structure and therefore must be considered in its design. This is followed by the analysis and computation of internal gross forces, (i.e. thrust, shear, bending moments and twisting moments), as well as stress intensities, strain, deflection and reactions produced by loads, changes in temperature, shrinkage, creep and other design conditions. Finally comes the proportioning and selection of materials for the members and connections to respond adequately to the effects produced by the design conditions.

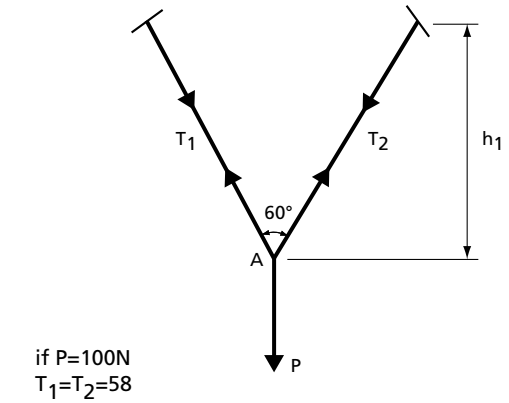
The criteria used to judge whether particular proportions will result in the desired behavior reflect accumulated knowledge based on field and model tests, and practical experience. Intuition and judgment are also important to this process.

The traditional basis of design called elastic design is based on allowable stress intensities which are chosen in accordance with the concept that stress or strain corresponds to the yield point of the material and should not be exceeded at the most highly stressed points of the structure, the selection of failure due to fatigue, buckling or brittle fracture or by consideration of the permissible deflection of the structure. The allowable – stress method has the important disadvantage in that it does not provide a uniform overload capacity for all parts and all types of structures.

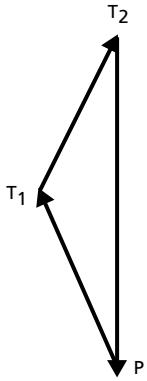
The newer approach of design is called the strength design in reinforced concrete literature and plastic design in steel-design literature. The anticipated service loading is first multiplied by a suitable load factor, the magnitude of which depends upon uncertainty of the loading, the possibility of it changing during the life of the structure and for a combination of loadings, the likelihood, frequency, and duration of the particular combination. In this approach for reinforced-concrete design, theoretical capacity of a structural element is reduced by a capacity-reduction factor to provide for small adverse variations in material strengths, workmanship and dimensions. The structure is then proportioned so that depending on the governing conditions, the increased load cause fatigue or buckling or a brittle-facture or just produce yielding at one internal section or sections or cause elastic-plastic displacement of the structure or cause the entire structure to be on the point of collapse.

Design aids

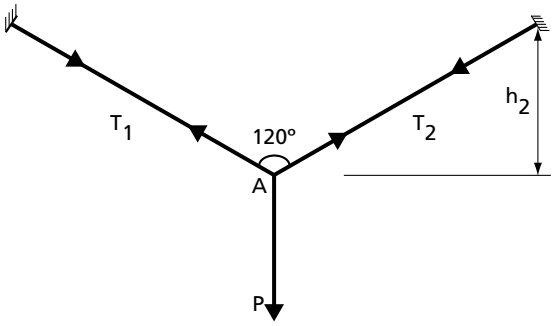
The design of any structure requires many detailed computations. Some of these are of a routine nature. An example is the computation of allowable bending moments for standard sized, species and grades of dimension timber. The rapid development of the

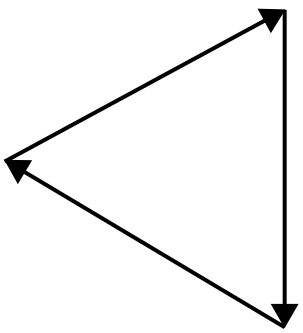


if P=100N
$T_1=T_2=58$



FORCE DIAGRAM FOR POINT A





if P=100N
then
$T_1=T_2=100N$

FORCE DIAGRAM FOR POINT A

computer in the last decade has resulted in rapid adoption of Computer Structural Design Software that has now replaced the manual computation. This has greatly reduced the complexity of the analysis and design process as well as reducing the amount of time required to finish a project.

Standard construction and assembly methods have evolved through experience and need for uniformity in the construction industry. These have resulted in standard details and standard components for building construction published in handbooks or guides.

Design codes

Many countries have their own structural design codes, codes of practice or technical documents which perform a similar function. It is necessary for a designer to become familiar with local requirements or recommendations in regard to correct practice. In this chapter some examples are given, occasionally in a simplified form, in order to demonstrate procedures. They should not be assumed to apply to all areas or situations.

DESIGN OF MEMBERS IN DIRECT TENSION AND COMPRESSION

Tensile systems

Tensile systems allow maximum use of the material because every fibre of the cross-section can be extended to resist the applied loads up to any allowable stress.

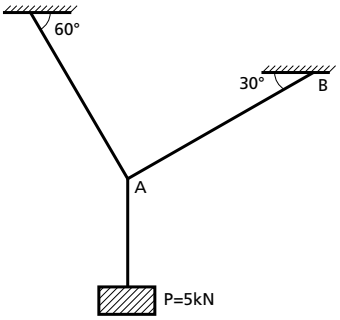
As with other structural systems, tensile systems require depth to transfer loads economically across a span. As the sag *(h)* decreases, the tensions in the cable (T_1 and T_2) increase. Further decreases in the sag would again increase the magnitudes of T_1 and T_2 until the ultimate condition, an infinite force, would be required to transfer a vertical load across a cable that is horizontal (obviously an impossibility).

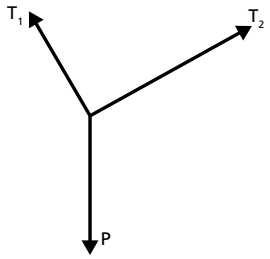
A distinguishing feature of tensile systems is that vertical loads produce both vertical and horizontal reactions. As cables cannot resist bending or shear, they transfer all loads in tension along their lengths. The connection of a cable to its supports acts as a pin joint (hinge), with the result that the reaction *(R)* must be exactly equal and opposite to the tension in the cable *(T)*. The *R* can be resolved into the vertical and horizontal directions producing the forces *V* and *H*. The horizontal reaction *(H)* is known as the thrust.

The values of the components of the reactions can be obtained by using the conditions of static equilibrium and resolving the cable tensions into vertical and horizontal components at the support points.

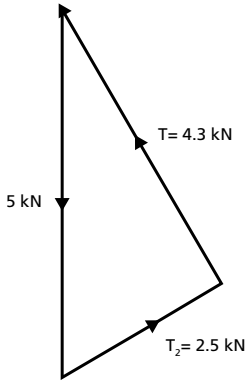
Example 7.1

Two identical ropes support a load *P* of 5 kN, as shown in the figure. Calculate the required diameter of the rope, if its ultimate strength is 30 MPa and a safety factor of 4.0 is applied. Also determine the horizontal support reaction at *B*.





Free body diagram



The allowable stress in the rope is

$$\frac{30}{4} = 7.5\ N/\text{mm}^2 = 7.5\ \text{MPa}$$

$$Stress = \frac{Force}{Area}$$

Therefore:

$$Area\ required = \frac{4.3 \times 10^3}{7.5} = 573\ \text{mm}^2$$

$$A = \pi r^2 = \frac{\pi d^2}{4}$$

Thus:

$$d = \sqrt{\frac{4 \times 573}{\pi}} = 27\ \text{mm (min)}$$

At support B, the reaction is composed of two components:

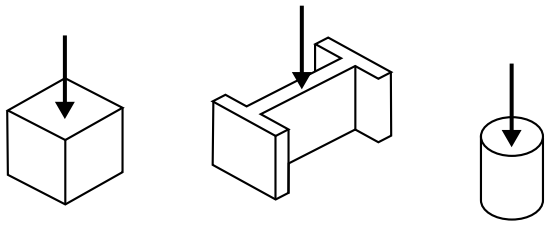
$B_v = T_2 \sin 30° = 2.5 \sin 30° = 1.25$ kN

$B_H = T_2 \cos 30° = 2.5 \cos 30° = 2.17$ kN

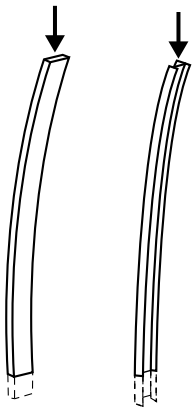
Short columns

A column which is short (i.e. the height is small compared with the cross-section area) is likely to fail because of crushing of the material.

Note, however, that slender columns, which are tall compared with the cross-section area, are more likely to fail from buckling under a load much smaller than that needed to cause failure from crushing. Buckling is dealt with later.



Short columns



Slender columns

Example 7.2

A square concrete column, which is 0.5 m high, is made of a nominal concrete mix of 1:2:4, with a permissible direct compression stress of 5.3 MPa (N / mm²). What is the required cross-section area if the column is required to carry an axial load of 300 kN?

$$A = \frac{F}{\sigma} = \frac{300\ 000\ \text{N}}{5.3\ \text{N/mm}^2} = 56\ 604\ \text{mm}^2$$

i.e. the column should be minimum 238 mm square.

DESIGN OF SIMPLE BEAMS

Bending stresses

When a sponge is put across two supports and gently pressed downwards between the supports, the pores at the top will close, indicating compression, and the pores at the bottom will open wider, indicating tension. Similarly, a beam of any elastic material, such as wood or steel, will produce a change in shape when external loads are acting on it.

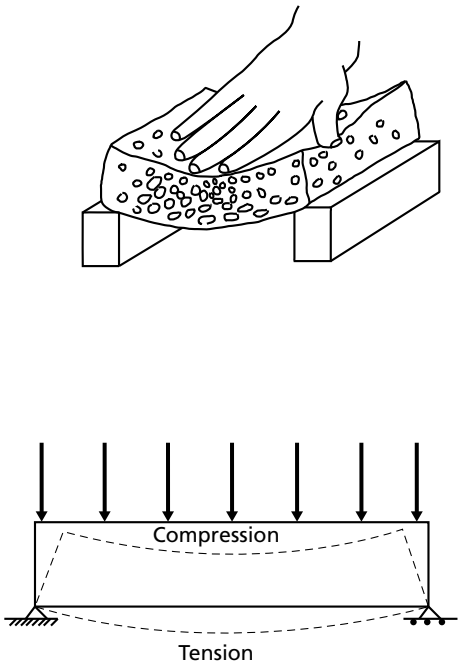


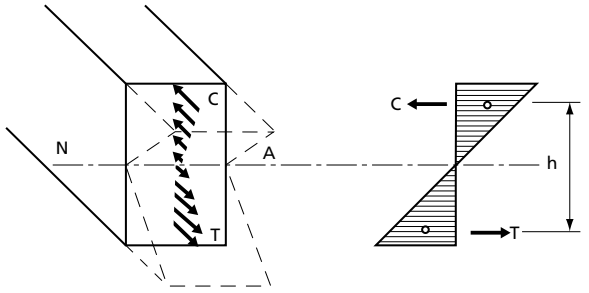
Figure 7.1 **Bending effects on beams**

The stresses will vary from maximum compression at the top to maximum tension at the bottom. Where the stress changes from compressive to tensile, there will be one layer that remains unstressed and this is called the neutral layer or the neutral axis (NA).

This is why beams with an I-section are so effective. The main part of the material is concentrated in the flanges, away from the neutral axis. Hence, the maximum stresses occur where there is maximum material to resist them.

If the material is assumed to be elastic, then the stress distribution can be represented by two triangular shapes with the line of action of the resultant force of each triangle of stress at its centroid.

The couple produced by the compression and tension triangles of stress is the internal-reaction couple of the beam section.

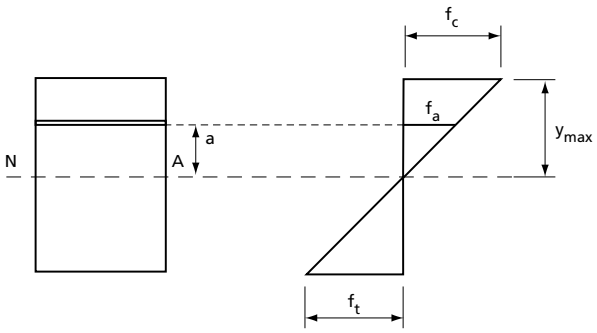


The moment caused by the external loads acting on the beam will be resisted by the moment of this internal couple. Therefore:

$M = M_R = C$ (or T) $\times h$

where:
M = the external moment
M_R = the internal resisting moment
C = resultant of all compressive forces on the cross-section of the beam
T = resultant of all tensile forces on the cross-section of the beam
h = lever arm of the reaction couple

Now consider a small element with the area *(R)* at a distance *(a)* from the neutral axis (NA).



Note that it is common practice to use the symbol f for bending stress, rather than the more general symbol. Maximum compressive stress (f_c) is assumed to occur in this case at the top of the beam. Therefore, by similar triangles, the stress in the chosen element is:

$$\frac{f_a}{a} = \frac{f_c}{y_{max}}, \quad f_a = a \times \frac{f_c}{y_{max}}$$

As force = stress × area, then the force on the element = $f_a \times R = a \times (f_c / y_{max}) \times R$

The resisting moment of the small element is:
force × distance *(a)* = $a \times (f_c / y_{max}) \times R \times a = Ra^2 \times (f_c / y_{max})$

The total resisting moment of all such small elements in the cross-section is:

$M_R = \Sigma\, Ra^2 \times (f_c / y_{max})$

But $\Sigma\, Ra^2$ = I, the moment of inertia about the neutral axis, and therefore

$M_R = I \times (f_c / y_{max})$

As the section modulus $Z_c = I / y_{max}$, therefore

$M_R = f_c \times Z_c = M$;

Similarly

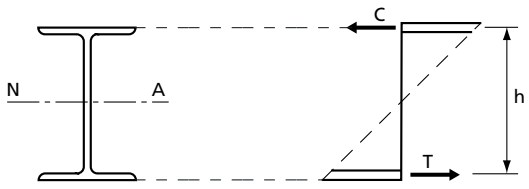
$M_R = f_t \times Z_t = M$

The maximum compressive stress *(f_c)* will occur in the cross-section area of the beam where the bending moment *(M)* is greatest. A size and shape of cross-section, i.e. its section modulus *(Z)*, must be selected so that the f_c does not exceed an allowable value. Allowable working stress values can be found in building codes or engineering handbooks.

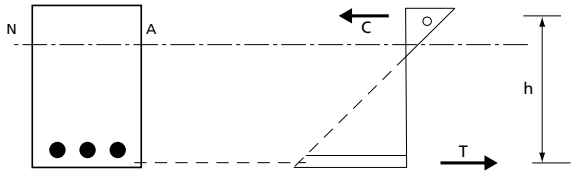
As the following diagrams show, the concept of a 'resisting' couple can be seen in many structural members and systems.



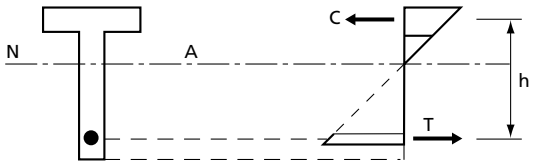
Rectangular beams



Girders and I –beams ($^1/_6$ web area can be added to each flange area for moment resistance)



Rectangular reinforced-concrete beams (note that the steel bars are assumed to carry all the tensile forces).



Reinforced-concrete T-beams

In summary the following equation is used to test for safe bending:

$f_w \geq f = M_{max} / Z$

where:
f_w = allowable bending stress
f = actual bending stress
M_{max} = maximum bending moment
Z = section modulus

Horizontal shear

The horizontal shear force *(Q)* at a given cross-section in a beam induces a shearing stress that acts tangentially to the horizontal cross-sectional plane. The average value of this shear stress is:

$$\tau = \frac{Q}{A}$$

where A is the transverse cross-sectional area.

This average value is used when designing rivets, bolts and welded joints.

The existence of such a horizontal stress can be illustrated by bending a paper pad. The papers will slide relative to each other, but in a beam this is prevented by the developed shear stress.

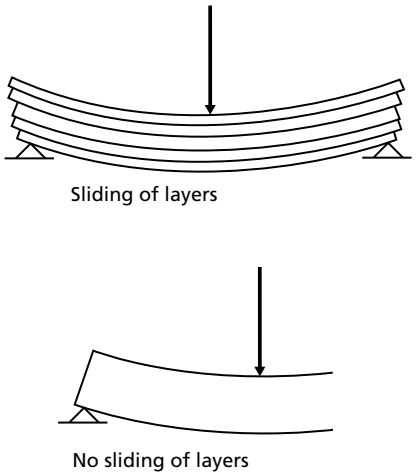


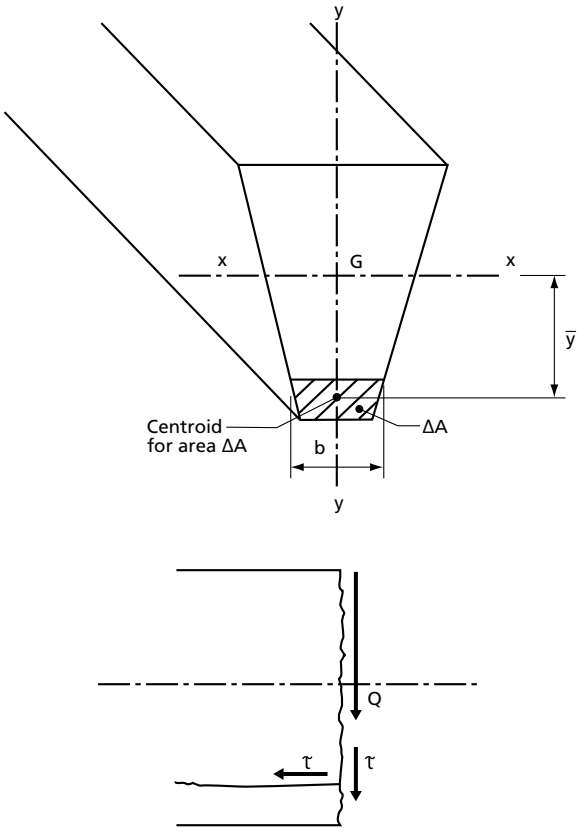
Figure 7.2 **Shearing effects on beams**

However, the shear stresses are not equal across the cross-section. At the top and bottom edge of the beam they must be zero, because no horizontal shear stresses can develop.

If the shear stresses at a certain distance from the neutral axis are considered, their value can be determined according to the following formula:

$$\tau = \frac{Q \times \Delta A \times \bar{y}}{I \times b}$$

where:
τ = shear stress
Q = shear force
ΔA = area for the part of the section being sheared off
$\bar{y}$ = perpendicular distance from the centroid of PA to the neutral axis
I = moment of inertia for the entire cross-section
b = width of the section at the place where shear stress is being calculated.



Maximum horizontal shear force in beams

It can be shown that the maximum shear stress τ_{max} in a beam will occur at the neutral axis. Thus, the following relations for the maximum shear stress in beams of different shapes can be deduced, assuming the maximum shear force *(Q)* to be the end reaction at a beam support (column).

For rectangular sections $\tau_{max} = \frac{3Q}{2bd} = \frac{3Q}{2A} = 1.5\frac{Q}{A}$

For square sections $\tau_{max} = \frac{3Q}{2a^2} = 1.5\frac{Q}{A}$

For circular sections $\tau_{max} = \frac{16Q}{3\pi D^2} = \frac{4Q}{3A}$

For I-shaped sections of steel beams, a convenient approximation is to assume that all shearing resistance is afforded by the web plus the part of the flanges that forms a continuation of the web.

Thus:

For I-sections $\tau_{max} \approx \frac{Q}{d \times t}$

where:
d = depth of beam
t = thickness of web

If timber and steel beams with spans normally used in buildings are made large enough to resist the tensile and compressive stresses caused by bending, they are usually strong enough to resist the horizontal shear stresses also. However, the size or strength of short, heavily loaded timber beams may be limited by these stresses.

Deflection of beams

Excessive deflections are unacceptable in building construction, as they can cause cracking of plaster in ceilings and can result in jamming of doors and windows. Most building codes limit the amount of allowable deflection as a proportion of the member's length, i.e. $^1/_{180}$, $^1/_{240}$ or $^1/_{360}$ of the length.

For standard cases of loading, the deflection formulae can be expressed as:

$$\delta_{max} = K_c \times \frac{WL^3}{EI}$$

where:
δ_{max} = maximum deflection (mm)
K_c = constant depending on the type of loading and the end support conditions
W = total load (N)
L = effective span (mm)
E = modulus of elasticity (N/mm²)
I = moment of inertia (mm⁴)

It can be seen that deflection is greatly influenced by the span L, and that the best resistance is provided by beams which have the most depth *(d)*, resulting in a large moment of inertia.

Note that the effective span is greater than the clear span. It is convenient to use the centre to centre distance of the supports as an approximation of the effective span.

Some standard cases of loading and resulting deflection for beams can be found later in this section.

Design criteria

The design of beams is dependent upon the following factors:

1. Magnitude and type of loading
2. Duration of loading
3. Clear span
4. Material of the beam
5. Shape of the beam cross-section

Beams are designed using the following formulae:

1. Bending stress

$$f_w \geq f = \frac{M_{max}}{Z}$$

where:
f_w = allowable bending stress
f = actual bending stress
M_{max} = maximum bending moment
Z = section modulus

This relationship derives from simple beam theory and

$$\frac{M_{max}}{I_{NA}} = \frac{f_{max}}{y_{max}}$$

and

$$\frac{I_{NA}}{y_{max}} = Z$$

The maximum bending stress will be found in the section of the beam where the maximum bending moment occurs. The maximum moment can be obtained from the bending-moment diagram.

2. Shear stress

For rectangular cross-sections:

$$\tau_w \geq \tau = \frac{3 \times Q_{max}}{2 \times A} = \frac{3Q_{max}}{2bd}$$

For circular cross-sections:

$$\tau_w \geq \tau = \frac{4 \times Q_{max}}{3 \times A} = \frac{16Q_{max}}{3\pi d^2}$$

For I-shaped cross-sections of steel beams

$$\tau_w \geq \tau = \frac{Q_{max}}{A}$$

where:
τ_w = allowable shear stress
τ = actual shear stress
Q_{max} = maximum shear force
A = cross-section area

Like allowable bending stress, allowable shear stress varies for different materials and can be obtained from a building code. Maximum shear force is obtained from the shear-force diagram.

3. Deflection

In addition, limitations are sometimes placed on maximum deflection of the beam (δ_{max}):

$$\delta_{max} = K_c \times \frac{WL^3}{EI}$$

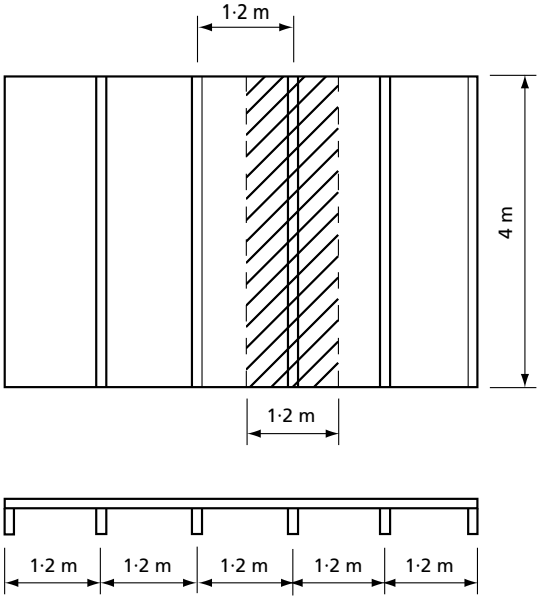
Example 7.3

Consider a floor where beams are spaced at 1 200 mm and have a span of 4 000 mm. The beams are seasoned cypress with the following properties:

f_w = 8.0 N/mm², τ_w = 0.7 MPa (N/mm²), E = 8.400 MPa (N/mm²), density 500 kg/m³

Loading on floor and including floor is 2.5 kPa.

Allowable deflection is $L/240$



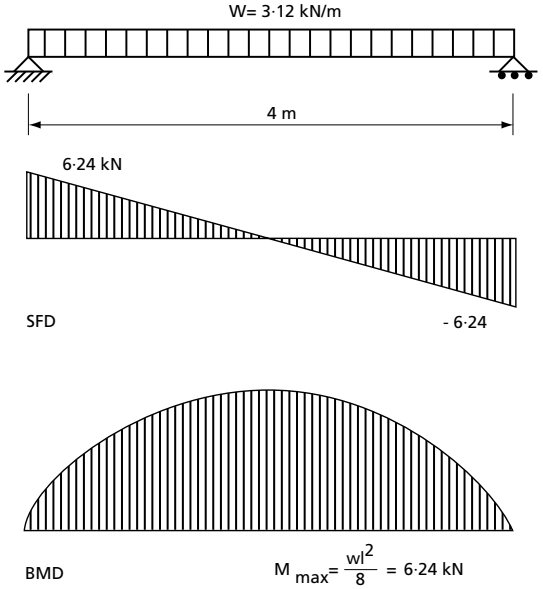
(i) Beam loading: w = 1.2 m × 2.5 kN/m² = 3 kN/m

Assume a 100 mm by 250 mm cross-section for the beams.

(ii) Beam mass = 0.1 × 0.25 × 500 × 9.81 = 122.6 N/m = 0.12 kN/m

Total w = 3 + 0.12 = 3.12 kN/m

(iii) Calculate reactions and draw shear-force and bending-moment diagrams



iii) Calculate maximum bending moment (M_{max}) using the equation for a simple beam, uniformly loaded (see Table 7.1)

$$M_{max} = \frac{wL^2}{8} = \frac{3.12 \times 4^2}{8} = 6.24 \text{ kNm} = 6.24 \times 10^6 / \text{Nmm}$$

iv) Find the required section modulus *(Z)*

$$Z_{req} = \frac{M_{max}}{f_w} = \frac{6.24 \times 10^6}{8} = 0.78 \times 10^6 \text{ mm}^3$$

v) Find a suitable beam depth, assuming 100 mm breadths:

From Table 6.3, the section modulus for a rectangular shape is $Z = {}^1/_6 \times bd^2$

$$\therefore d = \sqrt{\frac{6Z}{b}} = \sqrt{\frac{6 \times 0.78 \times 10^6}{100}} = 216 \text{ mm}$$

Choose a 100 mm by 225 mm timber. The timber required is a little less than that assumed. No recalculations are required unless it is estimated that a smaller size timber would be adequate if a smaller size had been assumed initially.

vi) Check for shear loading:

$$\tau = \frac{3Q_{max}}{2A} = \frac{3 \times 6.24 \times 10^3}{2 \times 100 \times 225} = 0.42 \text{ MPa}$$

As the safe load for the timber is 0.7 N/mm² (MPa) the section is adequate in resistance to horizontal shear.

vii) Check deflection to ensure that it is less than ${}^1/_{240}$ of the span (from Table 7.1)

$$\delta_{max} = \frac{-5}{384} \times \frac{WL^3}{EI}$$

where:
E = 8 400 MPa (N/mm²)

$$I = \frac{bd^3}{12} = \frac{100 \times 225^3}{12} = 95 \times 10^6 \text{ mm}^4$$

W = 3.12 kN/m × 4 m = 12.48 kN = 12.48 × 10³ N
L = 4 × 10³mm

$$\delta_{max} = \frac{-5}{384} \times \frac{12.48 \times 10^3 \times 4^3 \times 10^9}{8400 \times 95 \times 10^6} = -13 \text{ mm}$$

The allowable deflection, 400/240 = 16.7 >13. The beam is therefore satisfactory.

Bending moments caused by askew loads

If the beam is loaded so that the resulting bending moment is not about one of the main axes, the moment has to be resolved into components acting about the main axes. The stresses are then calculated separately relative to each axis and the total stress is found by adding the stresses caused by the components of the moment.

Example 7.4

Design a timber purlin that will span rafters 2.4 m on centre. The angle of the roof slope is 30° and the purlin will support a vertical dead load of 250 N/m and a wind load of 200 N/m acting normal to the roof. The allowable bending stress *(f_w)* for the timber used is 8 MPa. The timber density is 600 kg/m³.

1. Assume a purlin cross-section size of 50 mm × 125 mm. Find an estimated self-load.

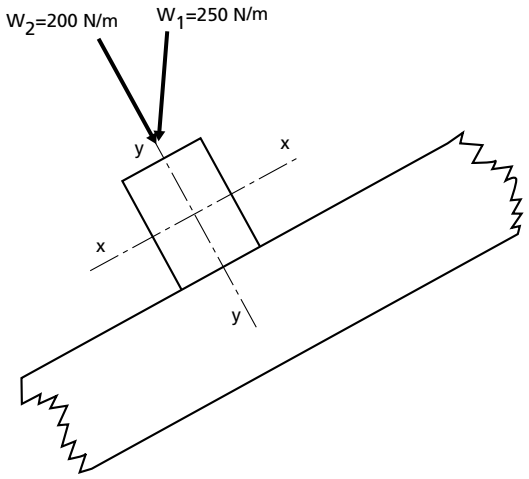
W = 0.05 × 0.125 × 600 × 9.81 = 37 N/m

The total dead load becomes 250 + 37 = 287 N/m

2. Find the components of the loads relative to the main axes.

W_x = 200 N/m + 287 N/m × *cos* 30° = *448.5* N/m

W_y = 287 N/m × *sin* 30° = 143.5 N/m



3. Calculate the bending moments about each axis for a uniformly distributed load. The purlin is assumed to be a simple beam.

$$M_{max} = \frac{WL}{8} = \frac{wL^2}{8}$$

$$M_{max\,x} = \frac{w_x \times L^2}{8} = \frac{448.5 \times 2.4^2}{8} = 323 \times 10^3 \text{ Nmm}$$

$$M_{max\,y} = \frac{w_y \times L^2}{8} = \frac{143.5 \times 2.4^2}{8} = 103 \times 10^3 \text{ Nmm}$$

4. The actual stress in the timber must be no greater than the allowable stress.

$$f = \frac{M_{max\,x}}{Z_x} + \frac{M_{max\,z}}{Z_y} \leq f_w$$

5. Try the assumed purlin size of 50 × 125 mm.

$$Z_x = \frac{bd^2}{6} = \frac{50 \times 125^2}{6} = 130 \times 10^3 \text{ mm}^3$$

$$Z_y = \frac{bd^2}{6} = \frac{125 \times 50^2}{6} = 52 \times 10^3 \text{ mm}^3$$

$$f = \frac{323 \times 10^3}{130 \times 10^3} + \frac{103 \times 10^3}{52 \times 10^3} = 2.5 + 2 = 4.5 \text{ N/mm}^2 = 4.5 \text{ MPa}$$

This size is safe, but a smaller size may be satisfactory. Try 50 mm × 100 mm.

$$Z_x = \frac{bd^2}{6} = \frac{50 \times 100^2}{6} = 83 \times 10^3 \text{ mm}^3$$

$$Z_y = \frac{bd^2}{6} = \frac{100 \times 50^2}{6} = 42 \times 10^3 \text{ mm}^3$$

$$f = \frac{323 \times 10^3}{83 \times 10^3} + \frac{103 \times 10^3}{42 \times 10^3} = 3.9 + 2.5 = 6.4 \text{ N/mm}^2 = 6.4 \text{ MPa}$$

This is much closer to the allowable stress. To save money, 50 mm × 75 mm should also be tried. In this case $f > f_w$ and therefore 50 mm × 100 mm is chosen.

Universal steel beams

Steel beams of various cross-sectional shapes are commercially available. Even though the properties of their cross-sections can be calculated with the formulae given in the section 'Design of members in direct tension and compression', it is easier to obtain them from handbook tables. These tables will also take into consideration the effect of rounded edges, welds, etc.

Sections of steel beams are indicated with a combination of letters and a number, where the letters represent the shape of the section and the number represents the dimension, usually the height, of the section in millimetres, e.g. IPE 100. In the case of HE sections, the number is followed by a letter indicating the thickness of the web and flanges, e.g. HE 180B.

An example of an alternative method of notation is 305 × 102 UB 25, i.e. a 305 mm by 102 mm universal beam weighing 25 kg/m.

The following example demonstrates another method of taking into account the self-weight of the structural member being designed.

Example 7.5

Design a steel beam, to be used as a lintel over a door opening, which is required to span 4.0 m between centres of simple supports. The beam will be carrying a 220 mm thick and 2.2 m high brick wall, weighing 20 kN/m³. Allowable bending stress is 165 MPa.

Uniformly distributed load caused by brickwork is 0.22 × 2.2 × 4.0 × 20 = 38.7 kN.

Assumed self-weight for the beam is 1.5 kN.

(Note: the triangular load distribution for bricks above the lintel would result in a slightly lower load value).

Total uniformly distributed load W = 38.7 + 1.5 = 40.2 kN

$$M_{max} = \frac{WL}{8} = \frac{40.2 \times 4.0}{8} = 20.1 \text{ kNm} = 20.1 \times 10^6 \text{ Nmm}$$

$$Z_{req} = \frac{20.1 \times 10^6}{165} = 0.122 \times 10^6 \text{ mm}^3 = 122 \text{ cm}^2$$

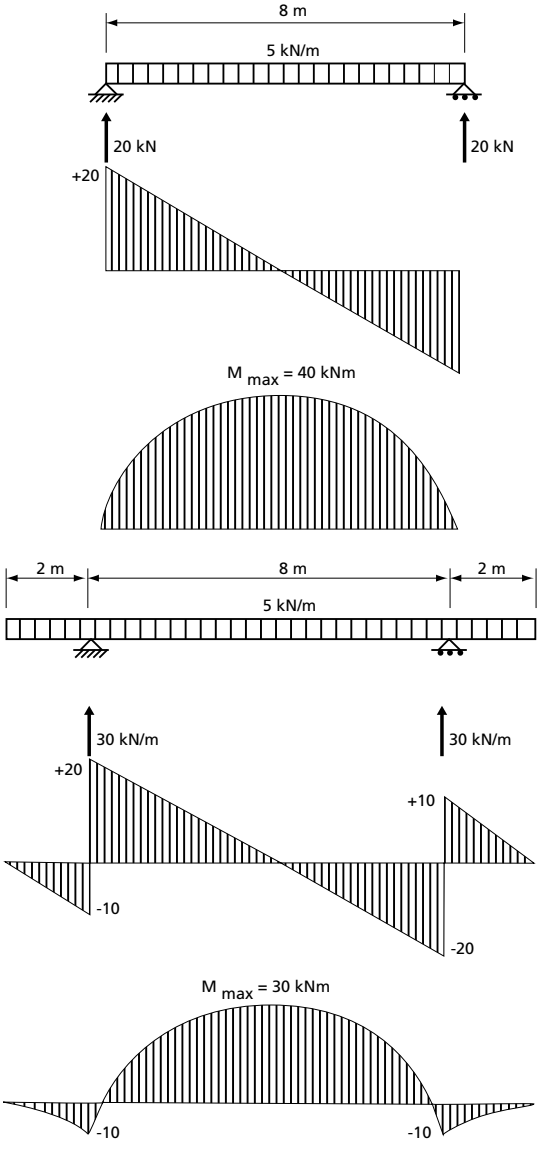
Suitable sections as found in a handbook would be:

Section	Z_{x-x}	Mass
INP 160	117 cm³	17.9 kg/m
IPE 180	146 cm³	18.8 kg/m
HE 140A	155 cm³	24.7 kg/m
HE 120A	144 cm³	26.7 kg/m

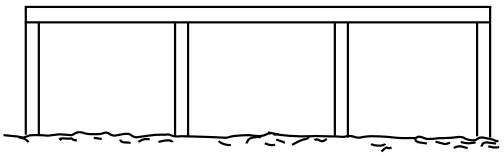
Choose INP 160 because it is closest to the required section modulus and has the lowest weight. Then recalculate the required Z using the INP 160 weight: 4.0 × 17.9 × 9.81 = 702 N, which is less than the assumed self-weight of 1.5 kN. A recheck on the required Z reveals a value of 119 cm³, which is close enough.

Continuous beams

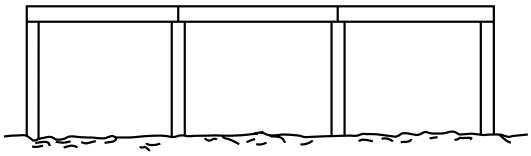
A single continuous beam extending over a number of supports will safely carry a greater load than a series of simple beams extending from support to support. Consider the shear force and bending moment diagrams for the following two beam loadings:



Although the total value of the load has increased, the maximum shear force remains the same but the maximum bending is reduced when the beam is cantilevered over the supports.



Continuous beam



Simple beam

Although continuous beams are statically indeterminate and the calculations are complex, approximate values can be found with simplified equations. Conservative equations for two situations are as follows:

Load concentrated between supports: $BM = \frac{WL}{6}$

Load uniformly distributed: $BM = \frac{WL}{12}$

It is best to treat the two end sections as simple beams.

STANDARD CASES OF BEAM LOADING

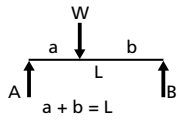
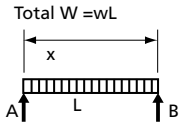
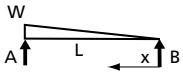
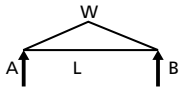
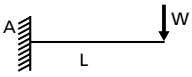
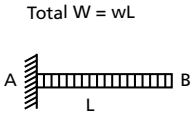
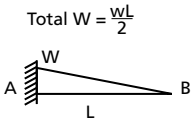
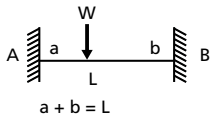
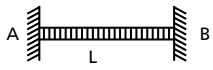
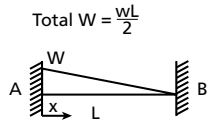
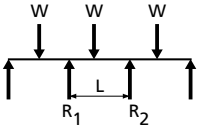
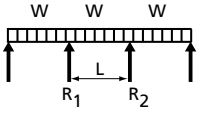
A number of beam loading cases occur frequently and it is useful to have standard expressions available for them. Several of these cases will be found in Table 7.1.

COMPOSITE BEAMS

In small-scale buildings the spans are relatively small and, with normal loading, solid rectangular or square sections are generally the most economical beams. However, where members larger than the available sizes and/or length of solid timber are required, one of the following combinations may be chosen:

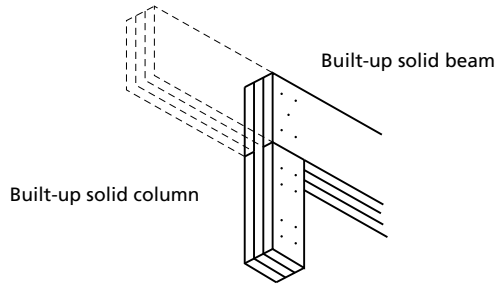
1. Arranging several pieces of timber or steel into a structural frame or truss.
2. Universal steel beams.
3. Built-up timber sections with the beam members nailed, glued or bolted together into a solid section, or with the beam members spaced apart and only connected at intervals.
4. Strengthening the solid timber section by the addition of steel plates to form a 'flitch-beam'.
5. Plywood web beams with one or several webs.
6. Reinforced-concrete beams.

TABLE 7.1
Beam equations

Loading diagram	Shear force at *x*: *Qx*	Bending moment at *x*: *Mx*	Deflection at *x*: δ*x*
	$Q_A = \frac{Wb}{L}$ $Q_B = -\frac{Wa}{L}$	$M_c = \frac{Wab}{L}$ When $a = b$ $M_c = \frac{WL}{4}$	$\delta_c = \frac{Wa^2b^2}{3EIL}$
	$Q_A = \frac{W}{2}$ $Q_B = -\frac{W}{2}$	$M_{max} = \frac{WL}{8}$ at $x = \frac{L}{2}$	$\delta_{max} = \frac{5WL^3}{384EI}$ at $x = \frac{L}{2}$
	$Q_A = \frac{2W}{3} = \frac{wL}{3}$ $Q_B = -\frac{W}{3} = -\frac{wL}{6}$	$M_{max} = 0.064mL^2$ at $x = 0.577L$	$\delta_{max} = 0.00652\frac{wL^4}{EI}$ at $x = 0.519$
	$Q_A = \frac{W}{2} = \frac{wL}{4}$ $Q_B = -\frac{W}{2} = -\frac{wL}{4}$	$M_{max} = \frac{wL^2}{12}$ at $x = \frac{L}{2}$	$\delta_{max} = \frac{wL^4}{120EI}$ at $x = \frac{L}{2}$
	$Q_A = Q_B = W$	$M_A = -WL$	$\delta_B = \frac{WL^3}{3EI}$
	$Q_A = W$ $Q_A = 0$	$M_A = -\frac{WL}{2} = -\frac{wL^2}{2}$	$\delta_B = \frac{WL^3}{3EI} = \frac{wL^4}{3EI}$
	$Q_A = W$ $Q_A = 0$	$M_A = -\frac{WL}{3} = -\frac{wL^2}{6}$	$\delta_B = \frac{wL^4}{30EI}$
	$Q_A = \frac{Wb}{L}$ $Q_B = -\frac{Wa}{L}$	$M_A = -\frac{Wab^2}{L^2}$ $M_B = -\frac{Wa^2b}{L^2}$	$\delta_C = \frac{Wa^3b^3}{3EIL}$
	$Q_A = \frac{W}{2}$ $Q_B = -\frac{W}{2}$	$M_A = M_B = -\frac{WL}{12}$	$\delta_C = \frac{WL^3}{384EI}$
	$Q_A = \frac{2W}{3}$ $Q_B = -\frac{W}{3}$	$M_A = -\frac{WL}{10} = -\frac{wL^2}{20}$ $M_B = -\frac{WL}{15} = -\frac{wL^2}{30}$	$\delta_{max} = \frac{wL^4}{764EI}$ at $x = 0.475L$
	$Q_A = \frac{W}{2}$	$M_{max} = \frac{WL}{6}$ *	$\delta_{max} = \frac{wL^3}{192EI}$
	$Q_A = \frac{W}{2}$	$M_{max} = \frac{WL}{12}$ *	$\delta_{max} = \frac{wL^3}{384EI}$

Built-up timber beams

When designing large members, there are advantages in building up solid sections from smaller pieces because these are less expensive and easier to obtain. Smaller pieces also season properly without checking. The composite beams may be built up in ways that minimize warping and permit rigid connections between columns and beams. At the same time the importance of timber defects is decreased, because the load is distributed to several pieces, not all with defects in the same area.



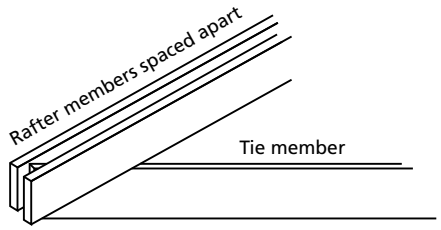


Figure 7.3 **Built-up beams and trusses**

Built-up solid beams are normally formed by using vertical pieces nailed or bolted together: Nailing is satisfactory for beams up to about 250 mm in depth, although these may require the use of bolts at the ends if the shear stresses are high. Simply multiplying the strength of one beam by the number of beams is satisfactory, provided that the staggered joints occur over supports.

Built-up sections with the members spaced apart are used mainly where the forces are tensile, such as in the bottom chords of a truss. Where used in beams designed to resist bending, buckling of the individual members may have to be considered if those members have a large depth-to-width ratio. However, this can be avoided by appropriate spacing of stiffeners that connect the spaced members at intervals.

Where the loading is heavy, the beam will require considerable depth, resulting in a large section modulus to keep the stresses within the allowable limit. If sufficient depth cannot be obtained in one member, it may be achieved by combining several members, such as gluing the members together to form a laminate.

COLUMNS

Although the column is essentially a compression member, the manner in which it tends to fail and the amount of load that causes failure depend on:

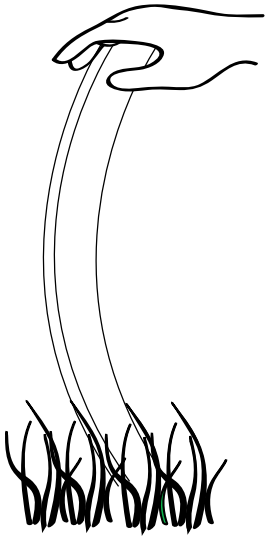
1. The material of which the column is made.
2. The shape of cross-section of the column.
3. The end conditions of the column.

The first point is obvious: a steel column can carry a greater load than a timber column of similar size.

Columns with a large cross-section area compared with the height are likely to fail by crushing. These 'short columns' have been discussed earlier.

Buckling of slender columns

If a long, thin, flexible rod is loaded axially in compression, it will deflect a noticeable amount. This phenomenon is called buckling and occurs when the stresses in the rod are still well below those required to cause a compression/shearing-type failure. Buckling is dangerous because it is sudden and, once started, is progressive.



Although the buckling of a column can be compared with the bending of a beam, there is an important difference in that the designer can choose the axis about which a beam bends, but normally the column will take the line of least resistance and buckle in the direction where the column has the *least lateral unsupported dimension.*

As the loads on columns are never perfectly axial and the columns are not perfectly straight, there will always be small bending moments induced in the column when it is compressed.

There may be parts of the cross-section area where the sum of the compressive stresses caused by the load on the column could reach values larger than the allowable or even the ultimate strength of the material.

Therefore the *allowable compressive strength* δ_{cw} is reduced by a factor k_λ, which depends on the slenderness ratio and the material used.

$$P_{bw} = k_\lambda \times \delta_{cw} \times A$$

where:
P_{bw} = allowable load with respect to buckling
k_λ = reduction factor, which depends on the slenderness ratio
δ_{cw} = allowable compressive stress
A = cross-section area of the column

When the load on a column is not axial but eccentric, a bending stress is induced in the column as well as a direct compressive stress. This bending stress will need to be considered when designing the column with respect to buckling.

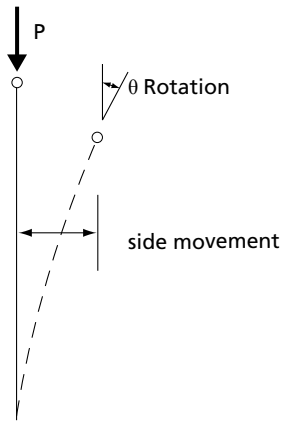
Slenderness ratio

As stated earlier, the relationship between the length of the column, its lateral dimensions and the end fixity conditions will strongly affect the column's resistance to buckling. An expression called the slenderness ratio has been developed to describe this relationship:

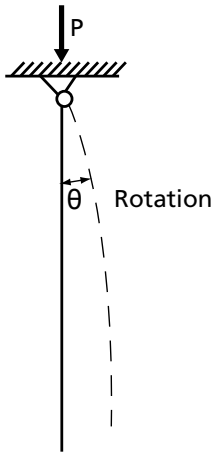
$$\lambda = \frac{KL}{r} = \frac{l}{r}$$

where:
λ = slenderness ratio
K = effective length factor whose value depends on how the ends of the column are fixed
L = length of the column
r = radius of gyration ($r = I / A$)
l = effective length of the column ($K \times L$)

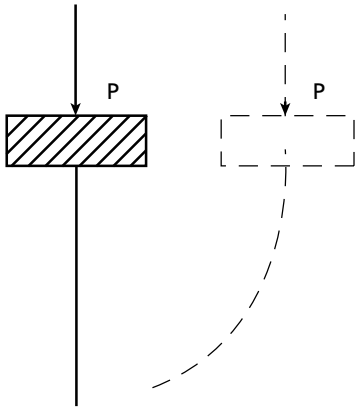
There are four types of end condition for a column or strut:



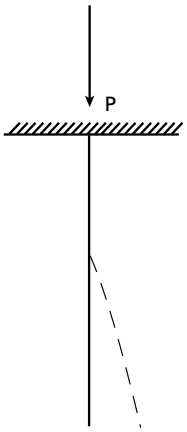
1. Total freedom of rotation and side movement – like the top of a flagpole. This is the weakest end condition.



2. Fixed in position but not in direction (pinned).

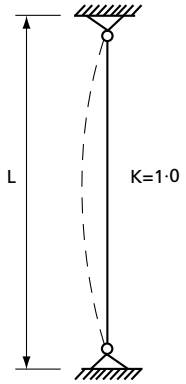


3. Fixed in direction but not in position.

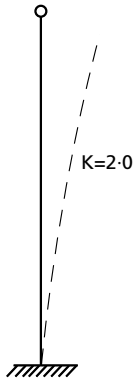


4. Fixed in position and in direction.

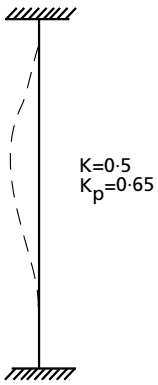
The consideration of the two end conditions together results in the following theoretical values for the effective length factor (K_p is the factor usually used in practice).



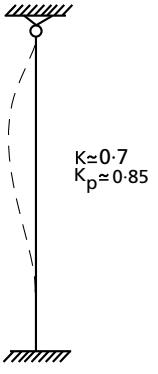
Both ends pinned



One end fixed in direction and position, the other free



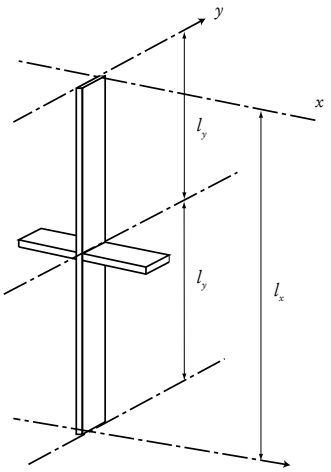
Both ends fixed in direction and position



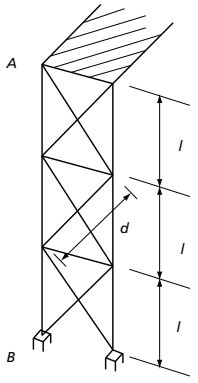
One end pinned, the other fixed in direction and position

Columns and struts with both ends fixed in position and effectively restrained in direction would theoretically have an effective length of half the actual length. However, in practice this type of end condition is almost never perfect and therefore somewhat higher values for K are used and can be found in building codes. In fact, in order to avoid unpleasant surprises, the ends are often considered to be pinned (K_p = 1.0) even when, in reality, the ends are restrained or partially restrained in direction.

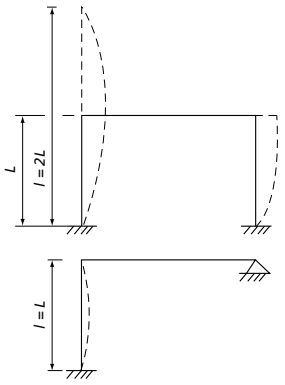
The effective length can differ with respect to the different cross-sectional axes:



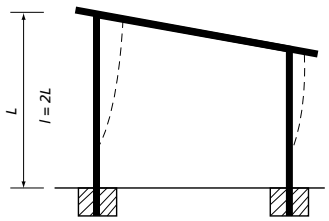
1. A timber strut that is restrained at the centre has only half the effective length when buckling about the *y-y* axis as when buckling about the *x-x* axis. Such a strut can therefore have a thickness of less than its width.



2. In the structural framework, the braces will reduce the effective length to l when the column *A-B* is buckling sideways but, as there is no bracing restricting buckling forwards and backwards, the effective length for buckling in these directions is 3l. Similarly, the bracing struts have effective lengths of 1/2 d and d respectively.



3. The leg of a frame, which is pinned to the foundation, has the effective length $l = 2\ L$ but, if the top is effectively secured for sideways movement, the effective length is reduced to $l = L$.



4. In a system of post and lintel where the bottom of the post is effectively held in position and secured in direction by being cast in concrete, the effective length $l = 2\ L$.

Axially loaded timber columns

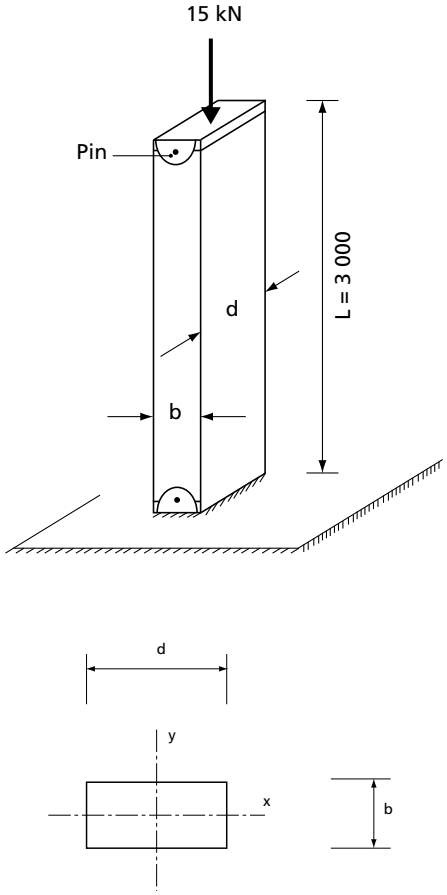
Timber columns are designed with the following formulae:

$$\lambda = \frac{KL}{r} \text{ and } P_{bw} = k_{\lambda} \times \delta_{cw} \times A$$

Note that in some building codes a value of slenderness ratio in the case of sawn timber is taken as the ratio between the effective length and the least lateral width of the column *l/b*.

Example 7.6

Design a timber column that is 3 metres long, supported as shown in the figure and loaded with a compressive load of 15 kN. Allowable compressive stress (σ_{cw}) for the timber is 5.2 MPa.



1. In this case, the end conditions for buckling about the *x-x* axis are not the same as about the *y-y* axis. Therefore both directions must be designed for buckling (Where the end conditions are the same, it is sufficient to check for buckling in the direction that has the least radius of gyration).

Find the effective length for buckling about both axes. Buckling about the *x-x* axis, both ends pinned:

$l_x = 1.0 \times 3\ 000 = 3\ 000$ mm

Buckling about the *y-y* axis, both ends fixed:

$l_y = 0.65 \times 3\ 000 = 1\ 950$ mm

TABLE 7.2
Reduction factor (k_λ) for stresses with respect to the slenderness ratio for wood columns

Slenderness ratio	*l/b*	2.9	5.8	8.7	11.5	14.4	17.3	20.2	23.0	26.0	28.8	34.6	40.6	46.2	52.0
	l/r	10	20	30	40	50	60	70	80	90	100	120	140	160	180
	k_λ	1.0	1.00	0.91	0.81	0.72	0.63	0.53	0.44	0.35	0.28	0.20	0.14	0.11	0.40

b = least dimension of cross-section; r = radius of gyration

2. Choose a trial cross-section, which should have its largest lateral dimension resisting the buckling about the axis with the largest effective length. Try 50 mm × 125 mm. The section properties are:

$A = b \times d = 50 \times 125 = 6\,250$ mm²

$$r_x = \frac{d}{2\sqrt{3}} = \frac{125}{2\sqrt{3}} = 36.1 \text{ mm}$$

$$r_y = \frac{b}{2\sqrt{3}} = \frac{50}{2\sqrt{3}} = 14.4 \text{ mm}$$

3. Find the allowable load with regard to buckling on the column for buckling in both directions.

$$\lambda_x = \frac{l_x}{r_x} = \frac{3\,000}{36.1} = 83 \text{ gives } k_{\lambda x} = 0.41 \text{ (from Table 7.2)}$$

$$\lambda_y = \frac{l_y}{r_y} = \frac{1\,950}{14.4} = 135 \text{ gives } k_{\lambda y} = 0.16 \text{ (from Table 7.2)}$$

$P_w = k_\lambda \times \sigma_c \times A$
$P_{wx} = 0.41 \times 5.2 \times 6\,250$ mm² = 13 325 N
$P_{wy} = 0.16 \times 5.2 \times 6\,250$ mm² = 5 200 N

4. As the allowable load with respect to buckling is smaller than the actual load, a bigger cross-section needs to be chosen. Try 75 mm × 125 mm and repeat steps 2 and 3.

Section properties:

$A = 75 \times 125 = 9\,375$ mm²

$$r_x = \frac{125}{2\sqrt{3}} = 36.1 \text{ mm}$$

$$r_y = \frac{75}{2\sqrt{3}} = 21.7 \text{ mm}$$

Find the allowable buckling load for the new cross-section:

$$\lambda_x = \frac{l_x}{r_x} = \frac{3\,000}{36.1} = 83 \quad \text{gives } k_{\lambda x} = 0.41$$

$$\lambda_y = \frac{l_y}{r_y} = \frac{1\,950}{21.7} = 90 \quad \text{gives } k_{\lambda y} = 0.16$$

$P_{wx} = 0.41 \times 5.2 \times 9\,375 = 19\,988$ N, say 20 kN
$P_{wy} = 0.35 \times 5.2 \times 9\,375 = 17\,063$ N, say 17 kN

The allowable load with respect to buckling on the column with cross-section 75 mm × 125 mm is therefore 17 kN. Although this is bigger than the actual load, further iterations to find the precise section to carry the 15 kN are not necessary.

The compressive stress in the chosen cross-section will be:

$$\sigma_c = \frac{F}{A} = \frac{15\,000}{9\,375} = 1.6 \text{ MPa}$$

This is much less than the allowable compressive stress, which makes no allowance for slenderness.

Axially loaded steel columns

The allowable loads for steel columns with respect to buckling can be calculated in the same manner as for timber. However, the relation between the slenderness ratio and the reduction factor (k_λ) is slightly different, as seen in Table 7.3.

Example 7.7

Calculate the safe load on a hollow square steel stanchion whose external dimensions are 120 mm × 120 mm. The walls of the column are 6 mm thick and the allowable compressive stress σ_{cw} = 150 MPa. The column is 4 metres high and both ends are held effectively in position, but one end is also restrained in direction.

The effective length of the column $l = 0.85L = 0.85 \times 4\,000 = 3\,400$ mm.

$$r_x = r_y = \sqrt{\frac{I}{A}} = \sqrt{\frac{BD^3 - bd^3}{12(BD - bd)}} = \sqrt{\frac{120^4 - 108^4}{12(120^2 - 108^2)}} = 46.6$$

$$\lambda = \frac{l}{r} = \frac{3\,400}{46.6} = 73 \text{ gives } k_\lambda = 0.72 \text{ by interpolation}$$

$P_w = k_\lambda \times \sigma_{cw} \times A = 0.72 \times 150\ (120^2 - 108^2) = 295$ kN.

TABLE 7.3
Reduction factor (k_λ) for stresses with respect to the slenderness ratio for steel columns

λ	10	20	30	40	50	60	70	80	90	100	110	120	130	140
k_λ	0.97	0.95	0.92	0.90	0.86	0.81	0.74	0.67	0.59	0.51	0.45	0.39	0.34	0.30
λ	150	160	170	180	190	200	210	220	230	240	250	300	350	
k_λ	0.26	0.23	0.21	0.19	0.17	0.15	0.14	0.13	0.12	0.11	0.10	0.07	0.05	

Axially loaded concrete columns

Most building codes permit the use of plain concrete only in short columns, that is to say, columns where the ratio of the effective length to least lateral dimension does not exceed 15, i.e. $l/r \leq 15$. If the slenderness ratio is between 10 and 15, the allowable compressive strength must be reduced. The tables of figures relating to l/b in place of a true slenderness ratio are only approximate, as radii of gyration depend on both b and d values in the cross-section and must be used with caution. In the case of a circular column:

$b = \frac{D}{4} \times \sqrt{12} \approx 0.87D$, where

D = the diameter of the column.

TABLE 7.4
Permissible compressive stress (P_{cc}) in concrete for columns (MPa or N/mm²)

Concrete mix	Slenderness ratio, *l/b*					
	≤ 10	11	12	13	14	15
Prescribed						
C10	3.2	3.1	3.0	2.9	2.8	2.7
C15	3.9	3.8	3.7	3.6	3.5	3.4
C20	4.8	4.6	4.5	4.3	4.2	4.1
Nominal						
1:3:5	3.1	3.0	2.9	2.8	2.7	2.6
1:2:4	3.8	3.7	3.6	3.5	3.4	3.3
1:1.5:3	4.7	4.5	4.4	4.2	4.1	4.0

Higher stress values may be permitted, depending on the level of work supervision.

Example 7.8

A concrete column with an effective length of 4 metres has a cross-section of 300 mm by 400 mm. Calculate the allowable axial load if a nominal 1:2:4 concrete mix is to be used.

Slenderness ratio

$$\frac{l}{b} = \frac{4000}{300} = 13.3$$

Hence Table 7.4 gives $P_{cc} = 3.47$ N/mm² by interpolation.

$P_w = P_{cc} \times A = 3.47 \times 300 \times 400 = 416.4$ kN.

Eccentrically loaded timber and steel columns

Where a column is eccentrically loaded, two load effects need to be considered:

The axial compressive stress caused by the load and the bending stresses caused by the eccentricity of the load.

Obviously, by the law of superposition, the added stresses of the two load effects must be below the allowable stress.

Therefore $\frac{\sigma}{P_{cw}} + \frac{f}{f_w} \leq 1$ i.e.

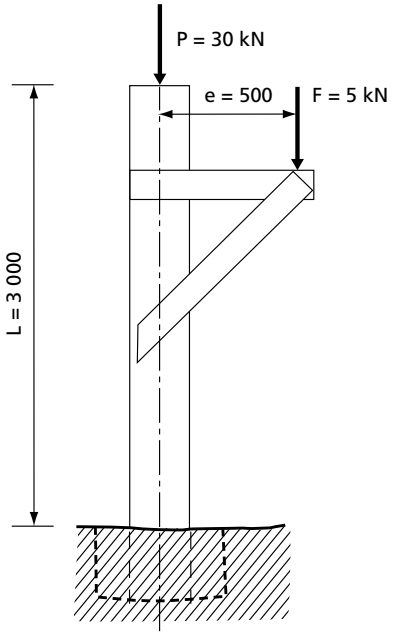
$$\frac{\textit{axial compressive stress}}{\textit{allowable compressive stress}} + \frac{\textit{bending stress}}{\textit{allowable bending stress}} \leq 1$$

$\frac{\sigma_c}{k_\lambda \times \sigma_{cw}} + \frac{f}{f_w} \leq 1$ which can be transferred to:

$$\frac{P_1}{K_\lambda \times A} + \frac{\sigma_{cw}}{f_w} \times \frac{M}{Z} \leq \sigma_{cw}$$

Example 7.9

Determine within 25 mm the required diameter of a timber post loaded as shown in the figure. The bottom of the post is fixed in both position and direction by being cast in a concrete foundation. Allowable stresses for the timber used are $\sigma_{cw} = 9$ MPa and $f_w = 10$ MPa.



The load of 5 kN on the cantilever causes a bending moment of $M = F \times e = 5$ kN × 0.5 m = 2.5 kNm in the post below the cantilever.

The effective length of the post = $L \times K = 3\,000 \times 2.1 = 6\,300$ mm. Try a post with a diameter of 200 mm.

The cross-sectional properties are:

$$A = \frac{\pi D^2}{4} = \frac{\pi \times 200^2}{4} = 31\,400 \text{ mm}^2$$

$$Z = \frac{\pi D^3}{32} = \frac{\pi \times 200^3}{32} = 785\,400 \text{ mm}^2$$

$$r = \frac{D}{4} = \frac{200}{4} = 50 \text{ mm}$$

The slenderness ratio $= \frac{l}{r} = \frac{6\,300}{50} = 126$

Interpolation in Table 7.3 gives $k_\lambda = 0.18$

$$\frac{P_1}{K_\lambda \times A} + \frac{\sigma_{cw}}{f_w} \times \frac{M}{Z} \leq \sigma_{cw}$$

$$\frac{30\,000}{0.18 \times 31\,400} + \frac{9}{10} \times \frac{2.5 \times 10^6}{785\,400} = 8.17 \text{ N/mm}^2 \leq 9 \text{ N/mm}^2$$

If the post has a diameter of 200 mm, it will be able to carry the loads, but the task was to determine the diameter within 25 mm. Therefore a diameter of 175 mm should also be tried.

$$\lambda = \frac{6\,300}{43.75} = 144 \qquad k_\lambda = 0.13$$

$$\frac{30\,000}{0.13 \times 24050} + \frac{9}{10} \times \frac{2.5 \times 10^6}{167\,480} = 23 \text{ N/mm}^2 > 9 \text{ N/mm}^2$$

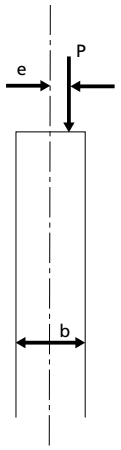
This diameter is too small, so a diameter of 200 mm should be chosen. It will be appreciated that the choice of effective length based on end fixity has a great effect on the solution.

Plain and centrally reinforced concrete walls

Basically walls are designed in the same manner as columns, but there are a few differences. A wall is distinguished from a column by having a length that is more than five times the thickness.

Plain concrete walls should have a minimum thickness of 100 mm.

Where the load on the wall is eccentric, the wall must have centrally placed reinforcement of at least 0.2 percent of the cross-section area if the eccentricity ratio e/b exceeds 0.20. This reinforcement may not be included in the load-carrying capacity of the wall.



Many agricultural buildings have walls built of blocks or bricks. The same design approach as that shown for plain concrete with axial loading can be used. The maximum allowable compressive stresses must be ascertained, but the reduction ratios can be used as before.

Example 7.10

Determine the maximum allowable load per metre of a 120 mm thick wall, with an effective height of 2.8 metres and made from concrete grade C 15: (a) when the load is central; (b) when the load is eccentric by 20 mm.

Slenderness ratio, $\frac{l}{b} = \frac{2\,800}{120} = 23.3$

Interpolation gives:

$$P_{cw} = 2.8 - \frac{3.3}{5}(2.8 - 2.0) = 2.27 \text{ N/mm}^2 = 2.27 \text{ MPa}$$

Allowable load $P_w = A \times P_{cw} = 1.0 \times 0.12 \times 2.27 \times 10^6$
$= 272.4$ kN/m wall

Ratio of eccentricity $\frac{e}{b} = \frac{20}{120} = 0.167$

A double interpolation gives:

$P_{cw} = 1.06 \text{ N/mm}^2 = 1.06 \text{ MPa}$

Allowable load

$$P_w = A \times P_{cw} = 1.0 \times 0.12 \times \frac{1.06 \times 10^6}{1\,000} = 127.2 \text{ kN/m wall}$$

Central reinforcement is not required because $\frac{e}{b} < 20$

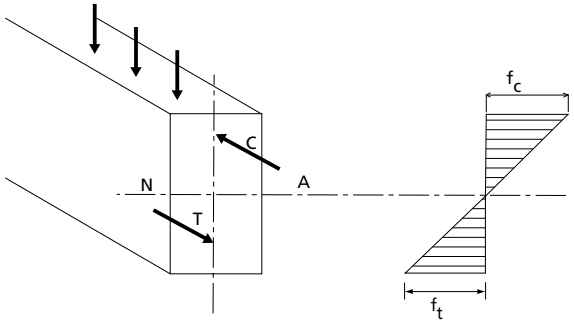
TABLE 7.5
Allowable compressive stress, P_{cw} for concrete used in walls (N/mm²)

Concrete grade or mix	Slenderness ratio *l/b*	Ratio of eccentricity of the load e/b					
		Plain concrete walls			Centrally reinforced concrete walls		
		0.00	0.10	0.20	0.30	0.40	0.50
C20	25	2.4	1.7	0.9	-	-	-
	20	3.3	2.3	1.4	0.8	0.4	0.3
	15	4.1	3.0	2.0	0.8	0.4	0.3
	≤ 10	4.8	3.7	2.7	0.8	0.4	0.3
C15	25	2.0	1.3	0.7	-	-	-
	20	2.8	1.9	1.1	0.7	0.35	0.25
	15	3.4	2.4	1.7	0.7	0.35	0.25
	≤ 10	3.9	3.0	2.2	0.7	0.35	0.25
C10	20	2.3	1.6	1.0	0.5	0.3	0.2
	15	2.7	2.0	1.4	0.5	0.3	0.2
	≤10	3.2	2.5	1.8	0.5	0.3	0.2
1:1:3	25	2.3	1.6	0.8	-	-	-
1:1:2	20	3.2	2.2	1.3	0.8	0.4	0.3
	15	4.1	2.9	1.9	0.8	0.4	0.3
	≤ 10	4.7	3.6	2.6	0.8	0.4	0.3
1:2:3	20	3.0	2.1	1.3	0.7	0.35	0.25
	15	3.7	2.7	1.9	0.7	0.35	0.25
	≤10	4.3	3.4	2.5	0.7	0.35	0.25
1:2:4	20	2.7	1.8	1.0	0.6	0.3	0.2
	15	3.3	2.3	1.6	0.6	0.3	0.2
	≤ 10	3.8	2.9	2.1	0.6	0.3	0.2

Higher values of stress may be permitted, depending on the level of work supervision.

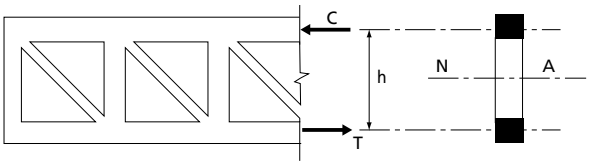
TRUSSES

It can be seen from the stress distribution of a loaded beam that the greatest stress occurs at the top and bottom extremities of the beam.



This led to the improvement on a rectangular section by introducing the I-section in which the large flanges were situated at a distance from the neutral axis. In effect, the flanges carried the bending in the form of tension stress in one flange and compression stress in the other, while the shear was carried by the web.

For these situations where bending is high but shear is low, for example in roof design, material can be saved by raising a framework design. A truss is a pinpointed framework.



A truss concentrates the maximum amount of materials as far away as possible from the neutral axis. With the resulting greater moment arm *(h)*, much larger moments can be resisted.

Resistance of a truss at a section is provided by:

$M = C \times h = T \times h$

where:
$C = T$ in parallel chords and:
C = compression in the top chord of the truss.
T = tension in bottom chord of a simply supported truss.
h = vertical height of truss section.

If either C or T or h can be increased, then the truss will be capable of resisting heavier loads. The value of h can be increased by making a deeper truss.

Allowable C- or T-stresses can be increased by choosing a larger cross-section for the chords of the truss, or by changing to a stronger material.

A framework or truss can be considered as a beam with the major part of the web removed. This is possible where bending stresses are more significant than shear stresses. The simple beam has a constant section along its length, yet the bending and shear stresses vary. The truss, comprising a number of simple members, can be fabricated to take into account this change in stress along its length.

The pitched-roof truss is the best example of this, although the original shape was probably designed to shed rainwater. Roof trusses consist of sloping rafters that meet at the ridge, a main tie connecting the feet of the rafters and internal bracing members. They are used to support a roof covering in conjunction with purlins, which are laid longitudinally across the rafters, with the roof cover attached to the purlin. The arrangement of the internal bracing depends on the span.

Rafters are normally divided into equal lengths and, ideally, the purlins are supported at the joints so that the rafters are only subjected to axial forces. This is not always practicable because purlin spacing is dependent on the type of roof covering. When the purlins are not supported at the panel joints, the rafter members must be designed for bending as well as axial force. See Figure 7.2.

The internal bracing members of a truss should be triangulated and, as far as possible, arranged so that long members are in tension and compression members are short to avoid buckling problems.

The outlines in Figure 7.3 give typical forms for various spans. The thick lines indicate struts.

The lattice girder, also called a truss, is a plane frame of open web construction, usually with parallel chords or booms at top and bottom. There are two main types, the N- (or Pratt) girder and the Warren girder. They are very useful in long-span construction, in which their small depth-to-span ratio, generally about $^1/_{10}$ to $^1/_{14}$, gives them a distinct advantage over roof trusses.

Steel and timber trusses are usually designed assuming pin-jointed members. In practice, timber trusses are assembled with bolts, nails or special connectors, and steel trusses are bolted, riveted or welded. Although these rigid joints impose secondary stresses, it is seldom necessary to consider them in the design procedure. The following steps should be considered when designing a truss:

1. Select general layout of truss members and truss spacing.
2. Estimate external loads to be applied including self-weight of truss, purlins and roof covering, together with wind loads.
3. Determine critical (worst combinations) loading. It is usual to consider dead loads alone, and then dead and imposed loads combined.
4. Analyse the framework to find forces in all members.
5. Select the material and section to produce in each member a stress value that does not exceed the permissible value. Particular care must be taken with compression members (struts), or members normally in tension but subject to stress reversal caused by wind uplift.

Unless there are particular constructional requirements, roof trusses should, as far as possible, be spaced to achieve minimum weight and economy of materials used in the total roof structure. As the distance between trusses is increased, the weight of the purlins tends to increase more rapidly than that of the trusses. For spans up to around 20 m, the spacing of steel trusses is likely to be about 4 metres and, in the case of timber, 2 metres.

The pitch, or slope, of a roof depends on locality, imposed loading and type of covering. Heavy rainfall may require steep slopes for rapid drainage; a slope of 22° is common for corrugated steel and asbestos roofing sheets. Manufacturers of roofing material usually make recommendations regarding suitable slopes and fixings.

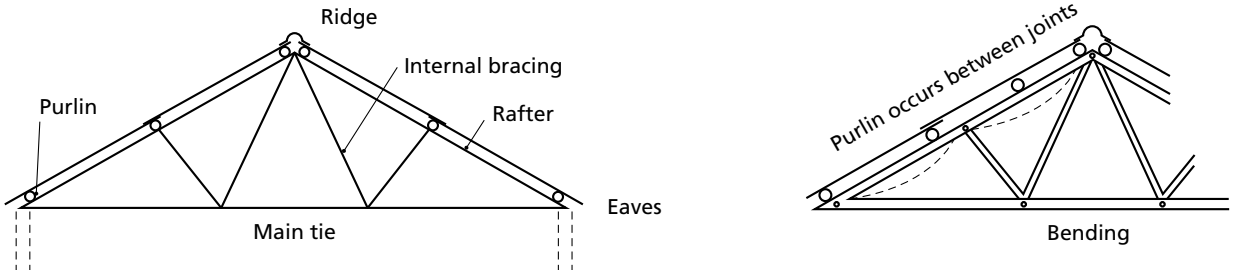


Figure 7.4 **Truss components**

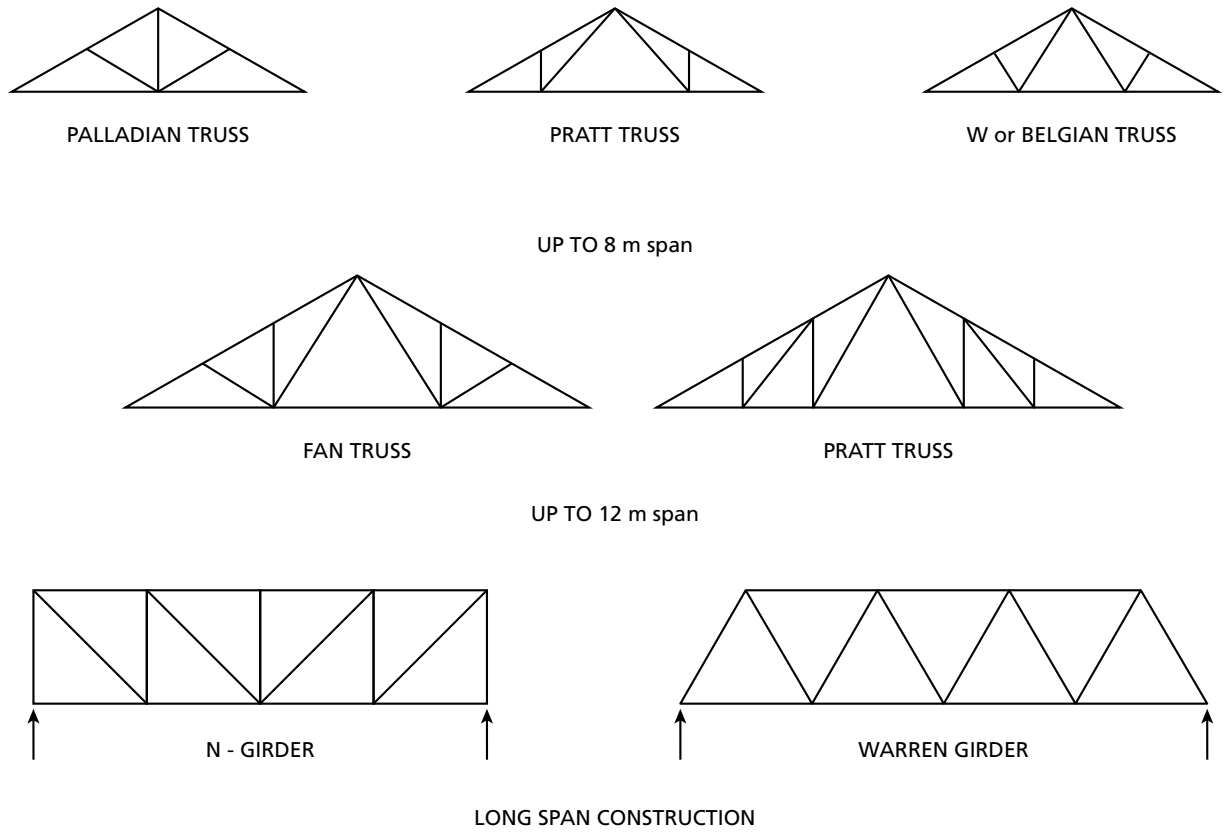


Figure 7.5 **Types of trusses**

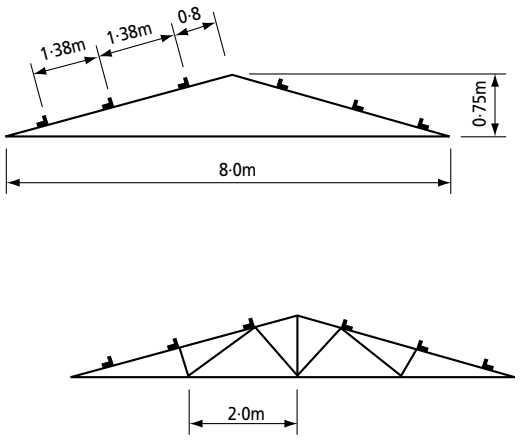
To enable the designer to determine the maximum design load for each member, the member forces can be evaluated either by calculation or graphical means, and the results tabulated as shown:

Member	Dead Load D	Imposed Load I	Dead + imposed Load D + I	Wind Load W	Design Load

A simplified approach can be taken if the intention is to use a common section throughout. Once the layout has been chosen, the member that will carry the maximum load can be established. An understanding of the problems of instability of compression members will lead the designer to concentrate on the top chord or rafter members. A force diagram or method of sections can then be used to determine the load on these members and the necessary size.

Example 7.11

A farm building comprising block walls carries steel roof trusses over a span of 8 metres. Roofing sheets determine the purlin spacings. Design the roof trusses.



LAYOUT CHOSEN
(nodes at purlin points)

Assume a force analysis shows maximum rafter forces of approximately 50 kN in compression ($D + I$) and 30 kN in tension ($D + W$), outer main tie member 50 kN tension ($D + I$) and 30 kN compression ($D + W$). A reversal of forces caused by the uplift action of wind will cause the outer main tie member to have 50 kN of tension and 30 kN of compression.

Consulting a structural engineering handbook reveals that a steel angle with a section of 65 mm × 50 mm × 6 mm and an effective length of 1.8 m can safely carry 29 kN in compression.

Rafter: Using two angles back-to-back will be satisfactory because the distance between restraints is only 1.38 m. (Note that angles must be battened together along the length of the rafter).

Main Tie: The 65 mm × 50 mm × 6 mm section can carry the required tensile force. Although its length is a little greater than 1.8 m, the compressive load brought about by wind uplift is safe as the design codes allow a greater slenderness ratio for intermittent loads such as wind.

Finished Design: Note the use of a sole plate to safely distribute the load to the blockwork wall to ensure that the bearing stress of the blocks is not exceeded. See Figure 7.4.

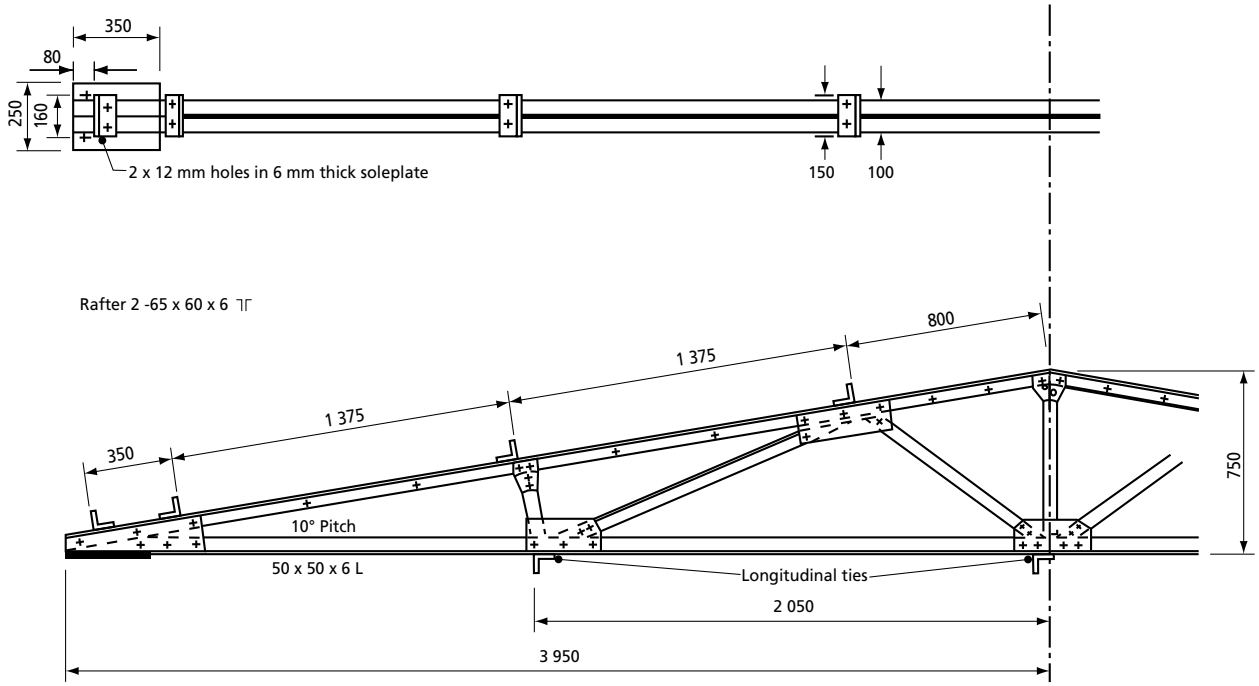
FRAMES

Apart from the roof truss, there are a number of other structural frames commonly used in farm building construction. They include portal frames, pole barns and post-and-beam frames.

A single-bay *portal frame* consists of a horizontal beam or pitched rafters joined rigidly to vertical stanchions on either side to form a continuous plane frame. For design purposes, portal frames can be classified into three types: fixed base, pinned base (two pins), pinned base and ridge (three pins).

The rigid joints and fixed bases have to withstand bending moments and all bases are subjected to horizontal, as well as vertical, reactions. Hence foundation design requires special attention. The externally applied loads cause bending moments, shear forces and axial forces in the frame.

Portal frames are statically indeterminate structures and the complexity of the analysis precludes coverage here. However, the results of such calculations for a number of standard cases of loading are tabulated in handbooks. Using these and the principle of superposition, the designer can determine the structural section required for the frame. Determining the maximum values of the bending moment, shear force and axial force acting anywhere in the frame allows the selection of an adequate section for use throughout the frame. Care must be exercised to ensure that all joints and connections are adequate.



Notes:
All welds to be 4mm fillet
All bolts to be M16
Gusset plates to be 8mm thick
Internal bracing shown 65 x 50 x 6 to use common section
(size can be reduced if others available)
All sections in grade 43 steel
Purlin supports: 70 x 70 x 6 with 2 x 6 ø holes

Figure 7.6 **Finished design of the roof truss**

Portal frames may be made of steel, reinforced concrete or timber. With wider spans the structural components become massive if timber or reinforced concrete is used. Hence, steel frames are most common for spans over 20 m. At the eaves, where maximum bending moments occur, the section used will need a greater depth than at other points in the frame.

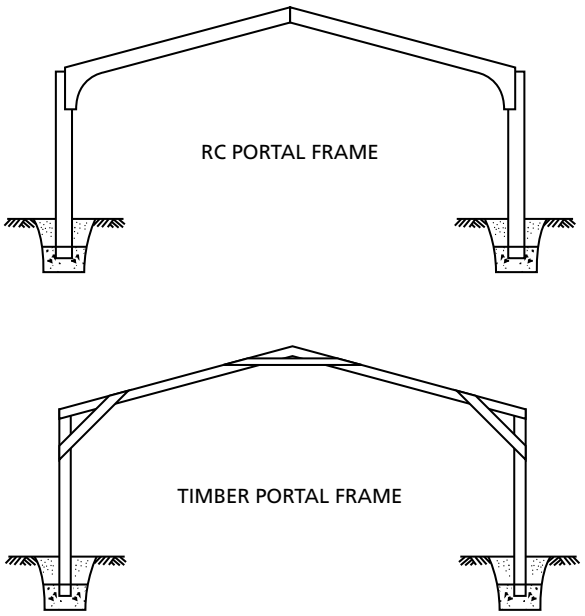


Figure 7.7 **Portal or rigid frame**

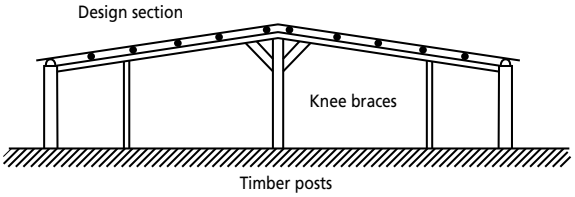
Pole barns are usually built with a relatively simple foundation, deeper than usual, and backfilled with rammed earth. Pole barns are braced between columns and rafters in each direction. The braces serve to reduce the effective length of compression members and the effective span of rafters and other beam members. This leads to a structure that is simple to analyse and design, and can be a low-cost form of construction.

A *shed-type* building is a simple construction consisting of beams (horizontal or sloping), supported at their ends on walls or posts. There may be one or more intermediate supports depending on the width of the building. Purlins running longitudinally support the roof cover.

As the principal members are simple or continuous beams (very often timber of rectangular section), the stress-analysis aspect of the design is straightforward. When the beam is supported by timber posts, the design of the posts is not difficult because the load is assumed to be axial. Like the poles in the pole barn, the foundation can consist of a simple pad of concrete beneath the post, or the base of the post can be set into concrete.

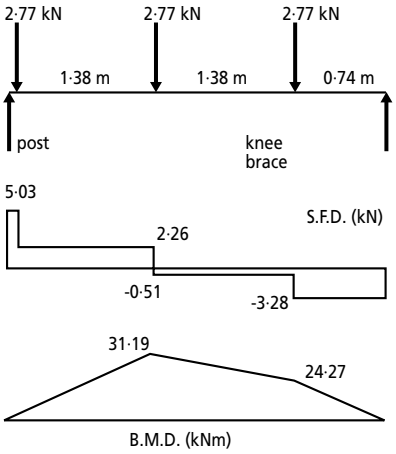
Example 7.12

Design the roof of a building using block walls, timber posts and rafters as shown in the figures below.



It is assumed that the knee braces reduce the effective span of the rafters between the central wall and the timber posts.

The moments and forces involved are as shown in the diagram below. Self-weights and service load have been estimated. Continuity over post and brace has been disregarded. This provides a simple but safe member.



Self-weights and service load have been estimated. Continuity over post and brace have been disregarded. This provides a simple safe member.

Maximum shear force = 5 kN

Maximum bending moment = 3 120 kN/ mm².

Try two rafters at 38 × 200 (back to back)

$$\text{Maximum shear stress} = \frac{3Q}{2bd} = \frac{3}{2} \times \frac{5\,000}{76 \times 200}$$

$$= 0.49 \text{ N/mm}^2 = 0.49 \text{ MPa}$$

$$\text{Maximum bending stress} = \frac{M_y}{I} = \frac{M}{Z}$$

$$= \frac{3\,120 \times 10^3 \times 6}{76 \times 200^2} = 6.2 \text{ N/mm}^2$$

Tables of allowable stresses indicate that most hardwoods, but not all softwoods, are adequate.

The load transferred to the outer wall by rafters is a little over 3 kN. Assuming that the strength of the blocks is at least 2.8 MPa (N/mm²), the area required is:

$$\frac{3\,000}{2.8} = 1\,072 \text{ mm}^2$$

As the rafter underside is 76 mm, the minimum interface across the wall is:

$$\frac{1\,072}{76} = 14 \text{ mm}$$

Hence there is no problem of load transfer to the wall.

Assume posts are 100 mm × 100 mm and 2.5 m long, then $l / b = 25$ and Table 7.2 gives $K = 0.38$

With $\sigma_c = 5.2$ MPa (N/mm²) allowable for design, 0.38 × 5.2 N/mm² × $100^2 \approx 20$ kN.

Therefore the load is within the safety margin.

CONNECTIONS

Timber structure

The methods used to join members include lapped and butt connectors. Bolt and connector joints, nailed joints and glued joints, and sometimes a combination of two types, are examples of lapped connections. Butt connections require the use of plates or gussets. In all cases the joints should be designed by calculating the shear forces that will occur in the members.

If two members overlap, the joint is called a *single-lap joint*. If one is lapped by two other members, i.e. sandwiched between them, it is called a *double-lap joint*.

With a single lap, the joint is under eccentric loading. While for small-span trusses carrying light loads this is not significant, when the joints carry large loads eccentricity should be avoided by the use of double-lap joints. Double members are also used to obtain a satisfactory arrangement of members in the truss as a whole.

Sandwich construction enables the necessary sectional area of a member to be obtained by the use of relatively thin timbers, with any double members in compression being blocked apart and fixed in position to provide the necessary stiffness.

Butt joints

The use of gussets permits members to butt against each other in the same plane, avoids eccentric loading on the joints and, where necessary, provides a greater joining area than is possible with lapped members. This is often an important factor in nailed and glued joints. Arrangement of members on a single centre line is usually possible with gussets.

When full-length timber is not available for a member, a butt joint with cover plates can be used to join two pieces together. This should be avoided, if possible, for the top members (rafters) of a truss and positioned near mid-span for the bottom member (main tie).

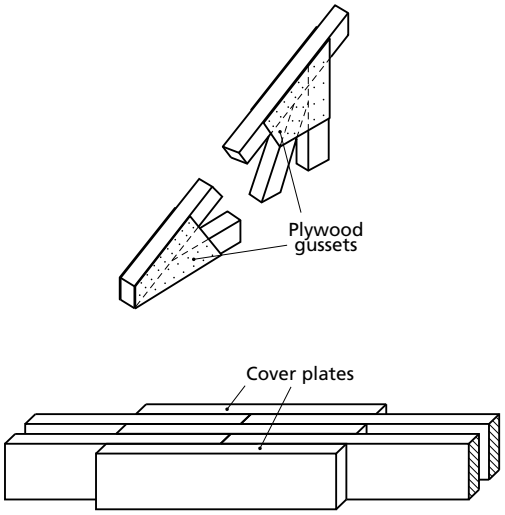


Figure 7.8 **Butt joints**

Bolt and connector joints

Simple bolted joints should only be used for lightly loaded joints because the bearing area at the hole (hole diameter × member thickness) and the relatively low bearing stress allowed for the timber compared with that of the steel bolt, may cause the timber hole to elongate and fail.

Timber connectors are metal rings or toothed plates used to increase the efficiency of bolted joints. They are embedded half into each of the adjacent members and transmit loads from one to the other. The type most commonly used for light structures is the toothed-plate connector, a mild-steel plate cut and stamped to form triangular teeth projecting on each side that embed in the surfaces of the members on tightening the bolt that passes through the joint. The double-sided toothed connector transmits the load and the bolt is assumed to take no load.

Glued joints

Glues made from synthetic resins produce the most efficient form of joint, as strong as or even stronger than the timber joint, and many are immune to attack by dampness and decay. With this type of joint,

all contact surfaces must be planed smooth and the necessary pressure applied during setting of the glue. Bolts or nails that act as clamps are often used and left in place.

The members may be glued directly to each other using lapped joints, or single-thickness construction may be used by the adoption of gussets. As with nailed joints, lapped members may not provide sufficient gluing area and gussets must then be used to provide the extra area.

Glued joints are more often used when trusses are prefabricated because control over temperature, joint fit and clamping pressure is essential. For home use, glue is often used together with nail joints.

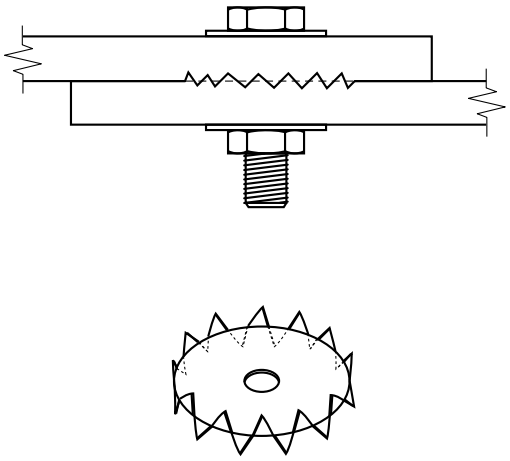


Figure 7.9 **Double-sided toothed plate connector**

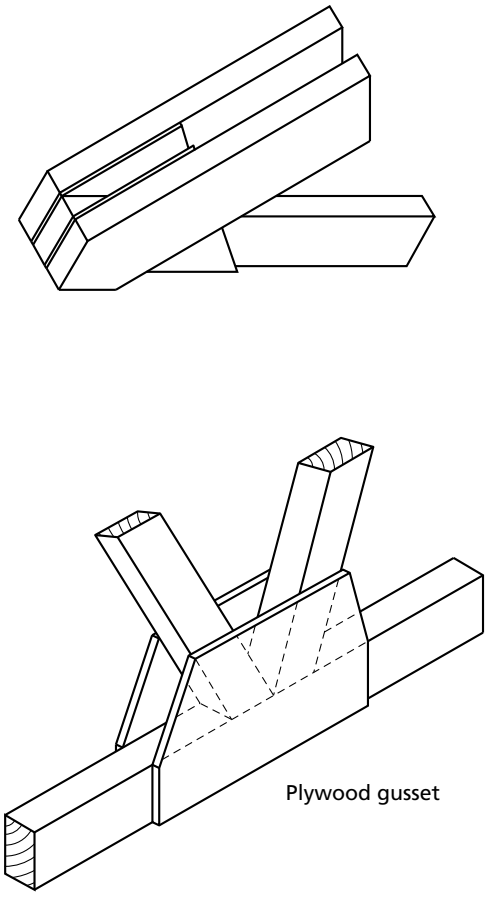


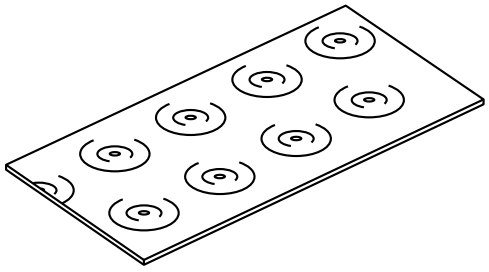
Figure 7.10 **Truss gussets**

Nailed joints

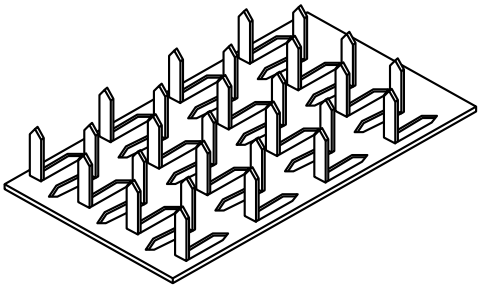
Although joining by nails is the least efficient of the three methods mentioned, it is an inexpensive and simple method, and can be improved upon by using glue in combination with the nails.

When trusses are prefabricated in factories, nailing plates are often used to connect the member. These fasteners come in two types:

1. A thin-gauge plate called a *pierced-plate fastener*, which has holes punched regularly over its surface to receive nails. The pierced plate can also be used for on-site fabrication.
2. A heavier plate with teeth punched from the plate and bent up 90 degrees, called a *toothed-plate fastener*, or connector. This type, in which the teeth are an integral part of the plate, must be driven in by a hydraulic press or roller.



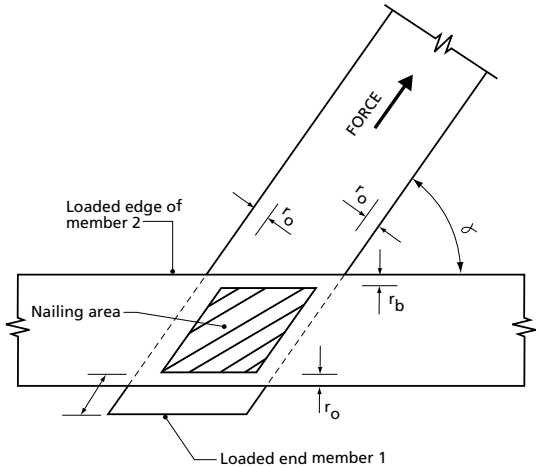
Pierced plate fastener

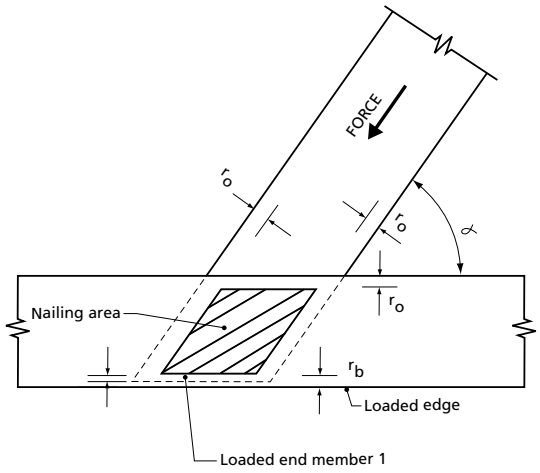


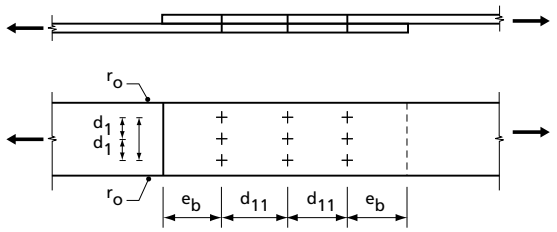
Toothed plate fastener

Figure 7.11 **Nailing plates for truss construction**

TABLE 7.6
Minimum nailing distances







	Nailing area					
x	r_o	d_1	d_{11}	r_b	e_0	e_b
0	5d	5d	10d	5d	-	15d
10	5d	5d	10d	5.5d	8d	15d
20	5d	5d	10d	6d	8d	15d
30	5d	5d	10d	6.5d	8d	15d
40	5d	5d	10d	7d	8d	15d
50	5d	5d	10d	7.5d	8d	15d
≤ 60	5d	5d	10d	8d	8d	15d

d : Diameter of the nail (mm).
r_0 : Distance from the extreme row of nails to the unloaded edge of member.
d_1 : Distance between two nails in the nailing area, measured perpendicular to the axis of the member.
d_{11} : Distance between two nails measured parallel to the axis of the member.
r_b : Distance from the extreme row of nails to the loaded edge of the member.
e_0 : Distance from the nearest row of nails to the unloaded end of member.
e_b : Distance from the nearest row of nails to the loaded end of the member.

In order to permit the development of the full load at each nail and to avoid splitting the wood, minimum spacing between nails and distances from the edges and ends of the member are necessary.

Nailing patterns for use on timber structures are usually available locally. They depend on the quality and type of nails and timber used, and are based on the safe lateral nail load.

The Housing Research and Development Unit of the University of Nairobi investigated timber nailed joints made with spacings in accordance with the continental standard for timber joints, which proved to be satisfactory. The main principles are given in tables 7.6 and 7.7.

Connections in steel structures

Connections may be bolted, riveted or welded. The principal design considerations are shear, tension and compression, and the calculations are relatively straightforward for the types of design covered.

STABILITY

Stability problems in a building are chiefly the result of horizontal loads, such as those resulting from wind pressure, storage of granular products against walls, soil pressure against foundations and sometimes earthquakes.

Overturning of foundation walls and foundation piers and pads is counteracted by the width of the footing and the weight of the structure. Only in special cases will it be necessary to give extra support in the form of buttresses.

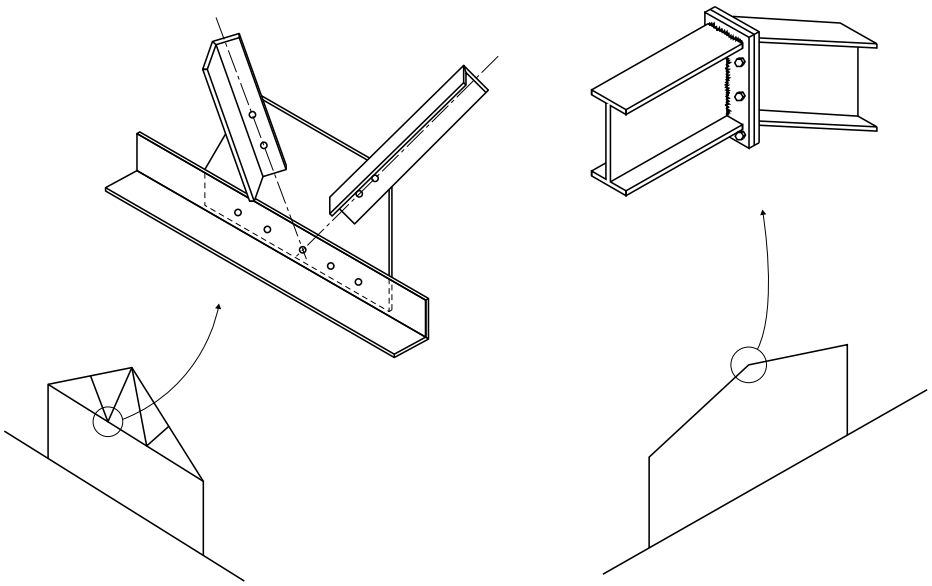
Overturning of external walls is counteracted by the support of perpendicular walls and partitions. Note, however, that not all types of wall, for example framed walls, are adequately rigid along their length without diagonal bracing. If supporting walls are widely spaced and/or the horizontal loads are large, extra support can be supplied by the construction of piers, columns or buttresses. See Chapter 8.

Diagonal bracing is used to make framed walls and structures stiff. Long braces should preferably transfer the load with a tensile stress to avoid buckling. Braces

TABLE 7.7
Basic lateral loads per nail

Continental nail diameter (mm)			2.1	2.4		2.8	3.1		3.4		3.8	4.2		4.6	5.1	5.6		6.1
Kenya nail diameter (mm)	1.8	2.0			2.65			3.35		3.75			4.5			5.6	6.0	
Basic lateral nail load (N)	90	120	140	190	220	250	310	350	370	430	450	540	600	630	750	880	960	1 000

(If the case of pre-bored nail holes 0.8 times nail diameter, the lateral nail load can be increased by 25%)



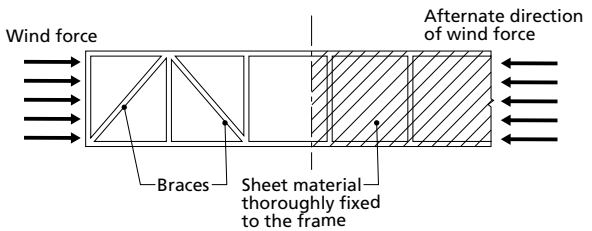
Connections in single shear at bottom boom of truss

Bolts in shear and tension at ridge of portal frame

Figure 7.12 **Connections for steel frames**

are usually supplied in pairs, i.e. on both diagonals, so that one will always be in tension independently of the wind direction.

If the framed wall is covered with a sheet material, such as plywood, chipboard or metal sheets, the lateral forces on the frame can be counteracted by shear in the sheets. This design requires the sheets to be securely fixed to the frame, both horizontally and vertically. The sheets must be strong enough to resist buckling or failure through shear.



Masonry and concrete walls that are stiff and capable of resisting lateral wind loading are called shear walls.

Portal or rigid frame buildings are normally stable laterally, when the wind pressure acts on the long sides. However, when the wind loads occur at the gable ends, the frames may need extra support from longitudinal bracing. Tension rods are frequently used.

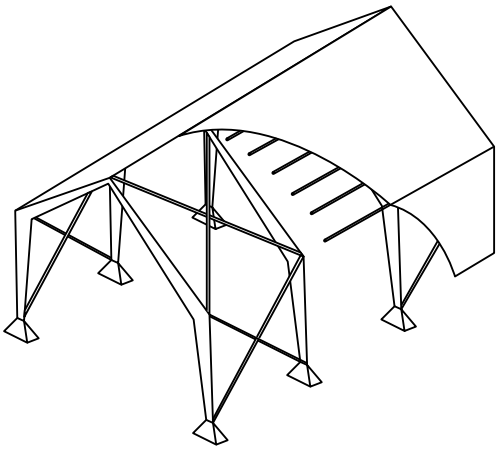


Figure 7.13 **Bracing for portal frame**

Post-and-beam or shed-frame buildings will, in most cases, require wind bracing, both along and across the building because there are no rigid connections at the top of the wall to transfer loads across and along the building. The same applies to buildings employing roof trusses. End bracing should be installed.

Walls with long spans between the supporting crosswalls, partitions or buttresses tend to bend inwards under the wind load, or outwards if bulk grain or other produce is stored against the wall. At the bottom of the wall this tendency is counteracted by the rigidity of the foundation (designed not to slide) and the support of a floor structure. The top of the wall is given stability by the support of the ceiling or roof structure, or a specially designed wall beam that is securely anchored to the wall.

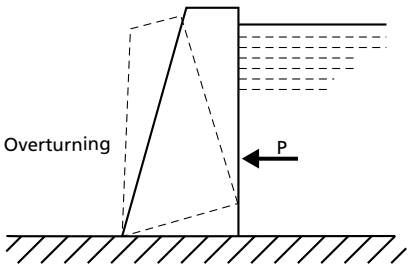
The designer must consider the ability of the building to withstand horizontal loading from any and all directions, without unacceptable deformation.

RETAINING WALLS

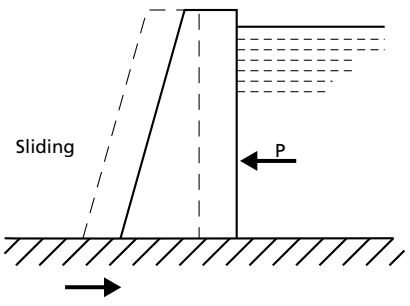
Wall failure

Walls are commonly used to retain soil on sloping sites, water in a pond or bulk products within a storage area. There are several limiting conditions which, if exceeded, can lead to the failure of a retaining wall. Each must be addressed in designing a wall.

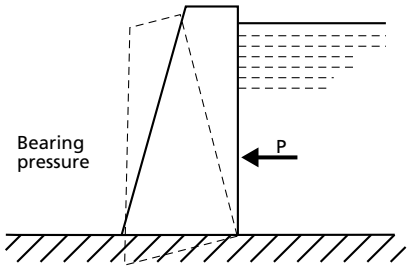
1. *Overturning:* This occurs when the turning moment resulting from lateral forces exceeds that exerted by the self-weight of the wall. The factor of safety against overturning should be at least two.



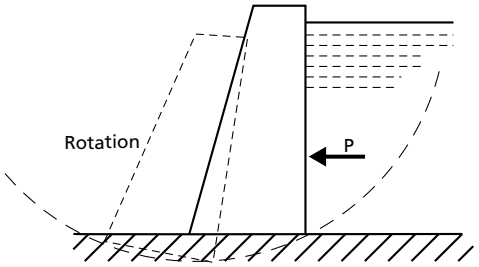
2. *Sliding:* The wall will slide if the lateral thrust exceeds the frictional resistance developed between the base of the wall and the soil. The factor of safety against sliding should be about two.



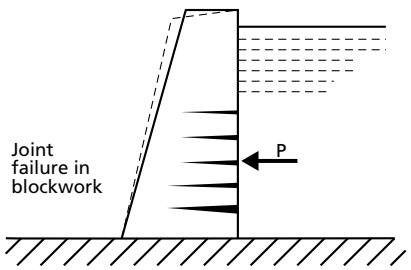
3. *Bearing on ground:* The normal pressure between the base of the wall and the soil beneath can cause a bearing failure of the soil, if the ultimate bearing capacity is exceeded. Usually the allowable bearing pressure will be one-third of the ultimate value. Note that the pressure distribution across the base is not constant.



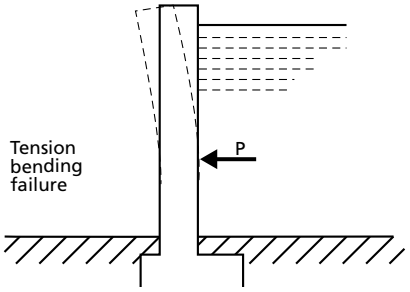
4. *Rotational Slip:* The wall and a large amount of the retained material rotate about point *O* if the shear resistance developed along a circular arc is exceeded. The analysis is too complex to include here.



5. *Wall material failure:* The structure itself must be capable of withstanding the internal stresses set up, that is to say, the stresses must not exceed allowable values. Factors of safety used here depend on the material and the level of the designer's knowledge of the loads actually applied. Naturally, both shear and bending must be considered, but the most critical condition is likely to be tension failure of the 'front' facet.



Gravity walls and dams are dependent on the effect of gravity, largely from the self-weight of the wall itself, for stability. Other types of wall rely on a rigid base, combined with a wall designed against bending, to provide an adequate structure.

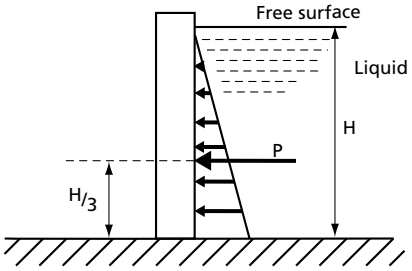


Pressure exerted by retained material

Liquid pressure

The pressure in a liquid is directly proportional to both the depth and the specific weight of the liquid *(w)* which is the weight per unit volume, $w = \rho g$ (N/m³),

where:
ρ = density of liquid (kg/m³)
g = gravitational acceleration (9.81 m/s²)

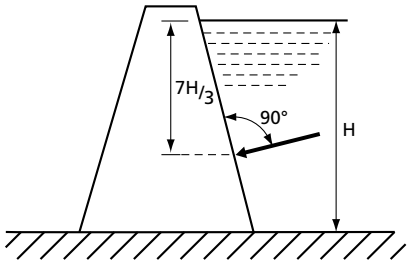


The pressure at a given depth acts equally in all directions, and the resultant force on a dam or wall face is normal to the face. The pressure from the liquid can be treated as a distributed load with linear variation in a triangular load form, with a centroid two-thirds of the way down the wet face.

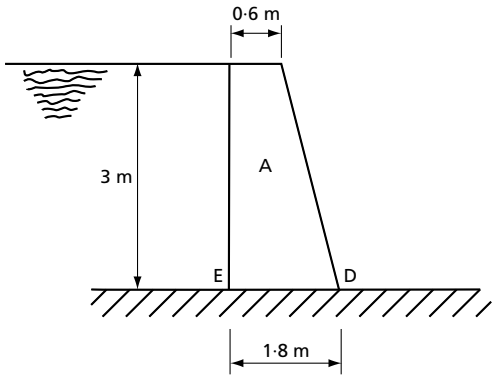
p = ρ*gH* = *wH* (N/m²) and:

$$P = \frac{wH^2}{2} \text{ acting at a depth of } \frac{2}{3}H$$

It should be noted that a wall retaining a material that is saturated (waterlogged) must resist this liquid pressure in addition to the lateral pressure from the retained material.



Example 7.13
Design of a gravity wall retaining water



Consider a mass concrete dam with the cross-section shown, which retains water to 3 m depth.

Assume:
Ground safe bearing capacity: 300 kPa.
Coefficient of sliding friction at base: 0.7.
Specific weight of concrete: 23 kN/m³.

1. *Find water force P:*
All calculations per metre length of wall:

$$P = \frac{wH^2}{2} = \frac{9.8 \times 10^3 \times 3^2}{2} = 44.1 \text{ kN}$$

(acting one metre up face)

2. *Find mass of one metre length of wall*:

$W = A \times$ specific weight

$$= 3 \times \frac{(0.6 + 1.8)}{2} \times 23 = 82.8 \text{ kN}$$

3. *Find line of action of* w: Taking moments of area about vertical face:

$$\overline{X} = \frac{A_1X_1 + A_2X_2}{A_1 + A_2}$$

$$= \frac{(3 \times 0.6 \times 0.3) + (0.6 \times 3 \times 1.0)}{1.8 + 1.8} = 0.65 \text{ m}$$

Hence the self-weight of the wall acts 0.25 m to left of the base centre line.

4. *Find the vertical compressive stress on the base*:

$$P_c = \frac{W}{A} = \frac{82.8}{1 \times 1.8} = 46 \text{ kPa}$$

5. *Find the moment about the centre line of the base*

$M = (1 \times 44.1) - (0.25 \times 82.8)$; (clockwise) - (anticlockwise)
M = 23.4 kNm

6. *Find the bending stresses/pressures*

$$\sigma_b = P_b = \frac{MI}{Y_{max}} \quad \text{where:}$$

$$I = \frac{bd^3}{12} = \frac{1 \times 1.8^3}{12} = 0.486 \text{ m}^4$$

$$Y_{max} = \pm \frac{1.8}{2} = \pm 0.9 \text{ m}$$

$$\sigma_b = P_b = \pm \frac{23.4 \times 0.486}{0.9} = 12.6 \text{ kPa}$$

7. *Find the actual stresses/pressures*

$$\sigma = P = \frac{W}{A} + \frac{M_y}{I}$$

$\sigma_E = P_E$ = 46 + 12.6 = 58.6 kPa (compression)
$\sigma_D = P_D$ = 46 - 12.6 = 33.4 kPa (compression)

(Note: Compression only indicates the resultant P, and W would intersect the base line within its middle third).

8. *Compare maximum pressure with allowable bearing capacity*:

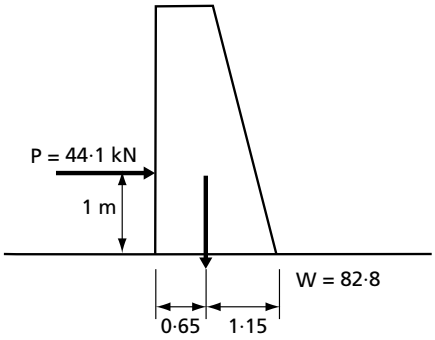
P_{max} = 58.6 kPa

This is less than the allowable safe bearing capacity of the soil. Hence the wall-soil interface is safe against bearing failure.

9. *Compare actual stresses in the wall with allowable values*:

Maximum stress = 58.6 kPa (compression) and no tensile stress at any point across wall. Hence the wall material is safe.

10. *Check overturning*

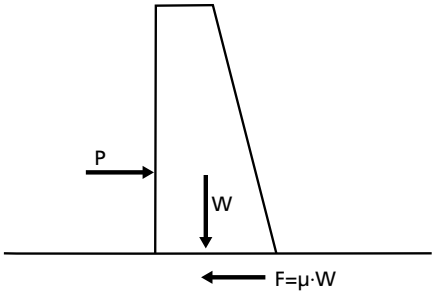


Overturning moment about D = 44.1 × 1 = 44.1 kNm
Stabilising moment about D = 82.8 × 1.15 = 95.22 kNm

Factor of safety against overturning = 94.22 / 44.1 = 2.16

The wall is safe against overturning.

11. *Check sliding*

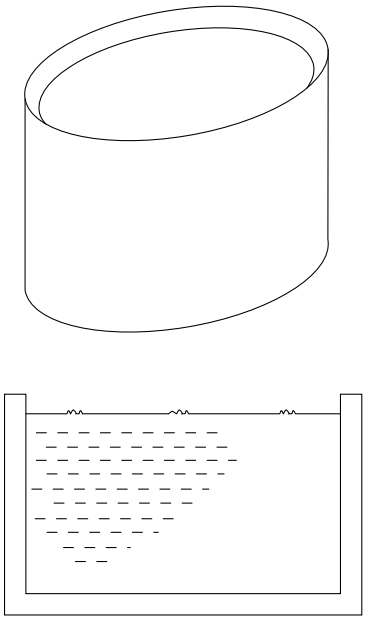


Frictional resistance = μW
μW= 0.7 × 82.8 = 58 kN
Horizontal thrust = P = 44.1 kN

As the required factor against sliding is 2, there is a deficiency of (2 × 44.1) - 58 = 30.2 kN.

Additional anchorage against sliding should be provided.

Example 7.14
Design a circular water tank with the following dimensions/properties:
Diameter 5 m, depth of water 3 m
Water weighs 9.8 × 10^3 N/m^3
Pressure *(P)* at a depth of 3 m



$P_3 = wH = 9.8 \times 10^3 \times 3 = 29.4$ kPa

This acts vertically over the entire base; therefore the base should be designed for a uniformly distributed load (UDL) of 29.4 kPa.

Pressure P_3 also acts laterally on the side wall at its bottom edge. This pressure decreases linearly to zero at the water surface.

$$\text{Total force on base} = P_3 A_B = 29.4 \times \frac{(\pi \times 5^2)}{4} = 577.3 \text{ kN}$$

(acting at the centre of the base)

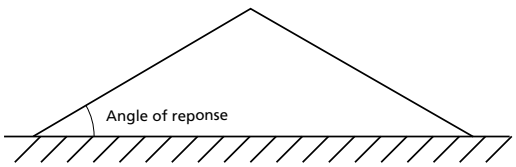
Total force on the side per metre of perimeter wall:

$$\frac{P_3 H}{2} = \frac{29.4 \times 3}{2} = 44.1 \text{ kN/m run}$$

(acting one metre above base)

Pressure exerted by granular materials

Granular materials such as sandy soils, gravelly soils and grain possess the property of internal friction (friction between adjacent grains), but are assumed not to possess the property of cohesion. If a quantity of such material in a dry condition is tipped on to a flat surface, it will form a conical heap: the shape maintained by this internal friction between grains. The angle of the sloping side is known as the *angle of repose*.



For a dry material, the angle of repose is usually equal to the angle of shearing resistance of the material. This angle of shearing resistance is called the *angle of internal friction* (θ). The angle of friction is the essential property of a granular material on which Rankine's theory is based. This theory enables the lateral pressure to be expressed as a proportion of the vertical pressure, which was shown (before) to depend on specific weight and depth only.

In this case, at a depth h the active lateral pressure is given by:

$$P = k \times w \times h$$

where:
k = a constant dependent on the materials involved.

Although there is some friction between the retained material and the wall face, usually this is disregarded, giving a relatively simple relationship for k:

$$k = \frac{1 - sin\theta}{1 + sin\theta}$$

where:
θ = the angle of friction

$$p_a = \frac{1 - sin\theta}{1 + sin\theta} \times wH (\text{N/m}^2)$$

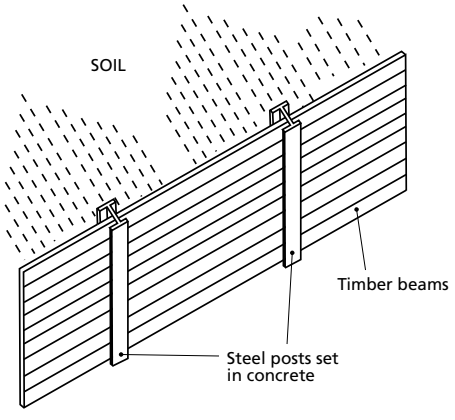
where:
p_a = total force per metre of wall-face (N)

$$P_a = \frac{1 - sin\theta}{1 + sin\theta} \times \frac{wH^2}{2} \quad \text{(N/m length of wall)}$$

P_a = total force per metre of wall face (N)

This gives the approximate horizontal resultant force on a vertical wall face when it is retaining material that is level with the top of the wall. If the surface of the retained material is sloping up from the wall at an angle equal to its angle of repose, a modification is required.

Example 7.15
Wall retaining soil



Consider the wall shown retaining loose sandy soil to a depth of 2 metres. Tables provide angle of friction equal to 35° and specific weight equal to 18.6 kN/m³. Assuming a smooth vertical surface and horizontal soil surface, Rankine's theory gives:

$$P = \frac{1 - sin\theta}{1 + sin\theta} \times \frac{wH^2}{2}$$

$$P = \frac{1 - sin35°}{1 + sin35°} \times \frac{18.6 \times 2^2}{2} \text{ kN/m length of wall}$$

$P = 10.1$ kN/m length of wall.

If steel posts are placed at 2.5 m centres, each post can be approximated to a vertical cantilever beam 2.5 m long, carrying a total distributed load of 10.1 × 2.5 = 25.25 kN of linear variation from zero at the top to a maximum at the base. The steel post and foundation concrete must be capable of resisting the applied load, principally in bending but also in shear.

The timber crossbeams can be analysed as beams simply supported over a span of 2.5 m, each carrying a uniformly distributed load. This load is equal to the product of the face area of the beam and the pressure in the soil at a depth indicated by the centroid of the area of the beam face.

$$p_a = \frac{1 - sin\theta}{1 + sin\theta} \times wh$$

if beam face is 0.3 m high,

h = 2.0 – 0.15= 1.85 m

P = 0.27 × 18.6 × 1.85 = 9.29 kN/m²

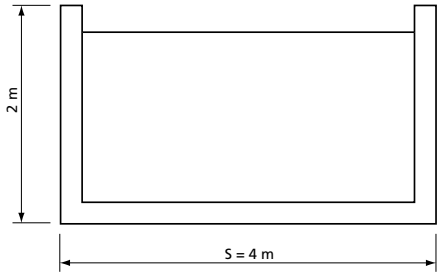
Total uniformly distributed load on the beam
= 9.29 × 0.3 × 2.5 = 6.97 kN

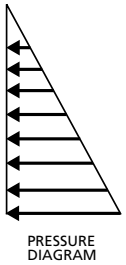
The maximum bending moment at the centre of the span can be determined and the beam section checked.

Example 7.16
Grain storage bin
(The theory given does not apply to deep bins). A shallow bin can be defined as one with a sidewall height of less than

$\frac{S}{2} tan\left(45° + \frac{\theta}{2}\right)$ for a square bin of side length S.

Consider a square bin of side length 4 metres retaining shelled maize/corn to a depth of 2 metres. Assume θ = 27°; specific weight is 7.7 kN/m³.





Critical height is:

$$\frac{S}{2} tan\left(45° + \frac{\theta}{2}\right) = \frac{4}{2} tan\left(45° + 13.5°\right) = 2 \times 1.63 = 3.26 \text{ m}$$

Design in the same way as the shallow bin because the depth of grain is only 2 metres.

Maximum pressure at the base of the wall:

$$P = \frac{1 - sin\theta}{1 + sin\theta} \times wH$$

$$= \frac{1 - sin27°}{1 + sin27°} \times 7.7 \times 2 = 5.78 \text{ kN/m}^2$$

or resultant force $P = \frac{5.78 \times 2^2}{2} = 11.56$ kN/m

(acting $^2/_3$ m above the base of the wall).

Note that the design of the wall is complex if it consists of a plate of uniform thickness, but if the wall is thought of as comprising a number of vertical members cantilevered from the floor, an approach similar to that for the soil-retaining wall can be used.

DESIGNING FOR EARTHQUAKES

In areas where earthquakes occur frequently, buildings must be designed to resist the stresses caused by tremors. While the intensity of tremors can be much greater in loosely compacted soil than in firm soil or solid bedrock, one- and two-storey buildings are at greater risk on firm ground or bedrock because of the shorter resonance periods.

Casualties are most likely to be caused by the collapse of walls causing the roof to fall, and the failure of projecting elements such as parapets, water tanks, non-monolithic chimneys and loose roof coverings. Outbreaks of fire caused by fractures in chimneys or breaks in mains supply lines present an additional hazard.

While small buildings with timber frame walls, or a wooden ring beam supported by the posts of a mud-and-pole wall, can resist quite violent earthquakes, the following measures will increase the resistance of a large building to collapse from earth tremors:

- Use a round or rectangular shape for the building. Other shapes such as 'L' 'T' or 'U' should be divided into separate units. To be effective, this separation must be carried down through to the foundation.
- Avoid large spans, greatly elongated walls, vault-and-dome construction and wall openings in excess of one-third of the total wall area.
- Construct a continuously reinforced footing that rests on uniform soil at a uniform depth – even on sloping ground.
- Fix the roof securely, either to a continuously reinforced ring beam on top of the walls, or to independent supports, which will not fail even if the walls collapse.
- Avoid projecting elements, brittle materials and heavy materials on weak supports.
- Avoid combustible materials near chimneys and power lines.

Ductile structures have many joints that can move slightly without failing, e.g. bolted trusses. Such structures have a greater capacity to absorb the energy of earthquake waves. A symmetrical, uniformly distributed ductile framework with the walls securely fixed to the frame is suitable for large buildings.

Masonry walls are sensitive to earthquake loads and tend to crack through the joints. It is therefore important to use a good mortar and occasionally reinforcing will be required.

REVIEW QUESTIONS

1. Define structural design.
2. Briefly describe the structural design process.
3. Why is it important to take into account deflection of structural elements during design phase?
4. Outline factors that influence design of beams.
5. Which measures improve the resistance of buildings to earthquake?
6. Calculate section moduli for a T –section, flange 150 mm by 25 mm, web thickness 25 mm and overall depth, 150 mm.
7. A 10 m long T section beam is simply supported, with the flange uppermost, from the right-hand end and at a point 2.5 m from the left-hand end. The beam is to carry a uniformly distributed load of 8 kN/m over the entire length. The allowable flange and web thickness is 25 mm. If the allowable maximum tensile strength and compressive stress are 125 MPa and 70 MPa respectively. Determine the size of the flange.
8. A short hollow cylindrical column with an internal diameter of 200 mm and external diameter of 250 mm carries a compressive load of 600 kN. Find the maximum permissible eccentricity of the load if (a) the tensile stress in the column must not exceed 15 MPa; (b) the compressive stress must not exceed 76 MPa.
9. Design a section of a trapezoidal masonry retaining wall 10 metres high, to retain earth weighing 16 000 N/m^3. The angle of repose for the earth is 25° when the earth surface is horizontal and level with the top of the wall. The weight of the masonry wall is 25 000 N/m^3.
10. A reinforced concrete beam is 200 mm wide, has an effective depth of 450 mm and four 20 mm diameter reinforcing bars. If the section has to resist a bending moment of 50×10^6 N mm, calculate the stresses in steel and concrete. The modular ratio of steel to concrete is equal to 18.

FURTHER READING

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Chapter 8
Elements of construction

INTRODUCTION

When designing a building, an architect plans for spatial, environmental and visual requirements. Once these requirements are satisfied, it is necessary to detail the fabric of the building. The choice of materials and the manner in which they are put together to form building elements, such as the foundation, walls, floor and roof, depend largely upon their properties relative to environmental requirements and their strength.

The process of building construction thus involves an understanding of: the nature and characteristics of a number of materials; the methods to process them and form them into building units and components; structural principles; stability and behaviour under load; building production operations; and building economics.

The limited number of materials available in the rural areas of Africa has resulted in a limited number of structural forms and methods of construction. Different socio-economic conditions and cultural beliefs are reflected in varying local building traditions. While knowledge of the indigenous building technology is widespread, farmers and their families normally can erect a building using traditional materials and methods without the assistance of skilled or specialized craftsmen. However, population growth and external influences are gradually changing people's lives and agricultural practices, while some traditional materials are becoming scarce.

Hence, a better understanding of traditional materials and methods is needed to allow them to be used more efficiently and effectively. While complete understanding of the indigenous technology will enable architects to design and detail good but cheap buildings, new materials with differing properties may need to be introduced to complement the older ones and allow for new structural forms to develop.

LOADS ON BUILDING COMPONENTS

Loads are usually divided into the following categories:

Dead loads, which result from the mass of all the elements of the building, including footings, foundation, walls, suspended floors, frame and roof. These loads are permanent, fixed and relatively easy to calculate.

Live loads, which result from the mass of animals, people, equipment and stored products. Although the mass of these loads can be calculated readily, the fact that the number or amount of components may vary considerably from time to time makes live loads more difficult to estimate than dead loads. Live loads also include the forces resulting from natural phenomena, such as wind, earthquakes and snow.

Where wind velocities have been recorded, the following equation can be used to determine the expected pressures on building walls:

$$q = 0.0127\ V^2 k$$

where:
q = basic velocity pressure (Pa)
V = wind velocity (m/s)
$k = (h/6.1)^{2/7}$
h = design height of building, in metres (eave height for low and medium roof pitches)
6.1 = height at which wind velocities were often recorded for Table 8.1.

While the use of local wind velocity data allows the most accurate calculation of wind pressures on buildings, in the absence of such data, estimates can be made using the Beaufort wind scale given in Table 8.1.

TABLE 8.1
Beaufort wind scale

		Velocity in m/s at a height of 6.1 m above ground
Strong breeze	Large branches in motion; whistling in telephone wires; umbrellas used with difficulty	11–14
Moderate gale	Whole trees in motion; difficult to walk against wind	up to 17
Fresh gale	Twigs break off trees; very difficult to walk against wind	21
Strong gale	Some structural damage to buildings	24
Whole gale	Trees uprooted: considerable structural damage to buildings	28
Storm	Widespread destruction	33

From the United States Weather Bureau

TABLE 8.2
Wind-pressure coefficients for gable-roof farm buildings

H:W Windward wall coefficient		Windward roof coefficient Roof slope		Leeward roof coefficient	Leeward wall coefficient
Completely closed		15°	30°		
1:6:7	0.70	-0.20	0.19	-0.5	-0.4
1:5	0.70	-0.27	0.19	-0.5	-0.4
1:33	0.70	-0.41	0.16	-0.5	-0.4
1.2	0.70	-0.60	0.00	-0.5	-0.4
Open on both sides		< 30°	30°		
Windward slope		+0.6	+0.8		
Leeward slope		-0.6	-0.8		

H = height to eaves, W = width of building

Some idea of the worst conditions to be expected can be formed by talking to long-time residents of the area.

The effect of wind pressure on a building is influenced by the shape of the roof and whether the building is open or completely closed. Table 8.2 gives coefficients used to determine expected pressures for low-pitch and high-pitch gable roofs and open and closed buildings. Note that there are several negative coefficients, indicating that strong anchors and joint fasteners are just as critical as strong structural members.

Data on earthquake forces is very limited. The best recommendation for areas prone to earthquakes is to use building materials that have better-than-average tensile characteristics, to design joint fasteners with an extra factor of safety, and to include a ring beam at the top of the building wall.

TABLE 8.3
Mass of building materials

Material		kg/m³	kg/m²
Concrete		2 400	
Steel		7 850	
Dense woods (19 mm)		900	17.0
Softwoods (19 mm)		580	11.0
Plywood (12 mm)			7.3
Galvanized roofing			3.9
Concrete hollow block wall	100 mm		145
	200 mm		275
	300 mm		390
Brick walls	100 mm		180
	200 mm		385

Snow loads are a factor only in very limited areas at high altitudes in east and southeast Africa. Local information on the mass of snow loads should be used.

Table 8.3 provides information useful in determining dead loads and Tables 8.4 and 8.5 give information relevant to live loads.

TABLE 8.4
Loads on suspended floors

		kPa
Cattle	Tie stalls	3.4
	Loose housing	3.9
	Young stock (180 kg)	2.5
Sheep		1.5
Horses		4.9
Pigs	(90 kg) Slatted floor	2.5
	(180 kg) Slatted floor	3.2
Poultry	Deep litter	1.9
	Cages	Variable
Repair shop (allowance)		3.5
Machinery storage (allowance)		8

TABLE 8.5
Mass of farm products

Product	Angle of repose		Mass kg/m³
	Emptying	Filling	
Maize (shelled)	27	16	720
Maize (ear)	-	-	450
Wheat	27	16	770
Rice (paddy)	36	20	577
Soybeans	29	16	770
Dry beans	-	-	770
Potatoes	-	37	770
Silage	-	-	480–640
Groundnuts (unshelled)			218
Hay (loose)			65–80
Hay (baled)			190–240

FOOTINGS AND FOUNDATIONS

A foundation is necessary to support the building and the loads within or on the building. The combination of footing and foundation distributes the load on the bearing surface, keeps the building level and plumb,

and reduces settling to a minimum. When properly designed, there should be little or no cracking in the foundation, and no water leaks.

The footing and foundation should be made of a material that will not fail in the presence of ground or surface water. Before the footing for the foundation can be designed, it is necessary to determine the total load to be supported. If, for some reason, the load is concentrated in one or more areas, this will need to be taken into consideration. Once the load is determined, the soil-bearing characteristics of the site must be studied.

Soil bearing

The top layer of soil is seldom suitable for a footing. The soil is likely to be loose, unstable and contain organic material. Consequently, the topsoil should be removed and the footing trench deepened to provide a level, undisturbed surface for the entire building foundation. If this is not feasible because of a sloping site, the footing will need to be stepped. This procedure is described later and illustrated in Figure 8.5.

The footing should never be placed on a filled area unless there has been sufficient time for consolidation. This usually takes at least one year with a normal amount of rainfall. The bearing capacity of soil is related to the soil type and the expected moisture level. Table 8.6 provides typical allowable soil-bearing values.

TABLE 8.6
Soil-bearing capacities

Soil type	kPa
Soft, wet, pasty or muddy soil	27–35
Alluvial soil, loam, sandy loam (clay +40–70 percent sand)	80–160
Sandy clay loam (clay +30 percent sand), moist clay	215–270
Compact clay, nearly dry	215–270
Solid clay with very fine sand	–430
Dry compact clay (thick layer)	320–540
Loose sand	160–270
Compact sand	215–320
Red earth	–320
Murram	–430
Compact gravel	750–970
Rock	–1700

An extensive investigation of the soil is not usually necessary for small-scale buildings. Foundation and pier footings can easily be designed to keep within the safe bearing capacity of the soil found on the building site.

Site drainage

It is desirable to site any building on well drained land. However, other considerations such as access roads, water supply, existing services or a shortage of land may dictate the use of a poorly drained area.

If a building site with poor natural drainage must be used, it can be improved by the use of contour interceptor drains or subsurface drains in order to cut off the flow of surface water or to lower the level of the water table. Apart from protecting the building against damage from moisture, drainage will also improve the stability of the ground and lower the humidity of the site. Figures 8.1 and 8.2 illustrate these methods.

Subsurface drains are usually laid 0.6 metres to 1.5 metres deep and the pipe layout arranged to follow the slope of the land. The spacing between drains will vary between 10 metres for clay soils to 50 metres for sand. Subsurface drains are usually formed from butt-joined clay pipes laid in narrow trenches. In cases where it is desirable to catch water running on the surface, the trench is backfilled almost to the top with rubble, either continuously along the trench or in pockets.

A trench filled with rubble or broken stone will provide passage for water and is effective in dealing with flows on the surface. Pipes and trenches belonging to the main site drainage system may cause uneven settling if allowed to pass close to, or under, buildings. Where needed, a separate drain surrounding the building, installed no deeper than the footing, is used to drain the foundation trench.

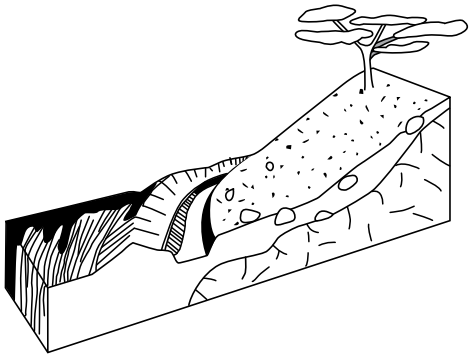


Figure 8.1 **Contour interceptor drain**

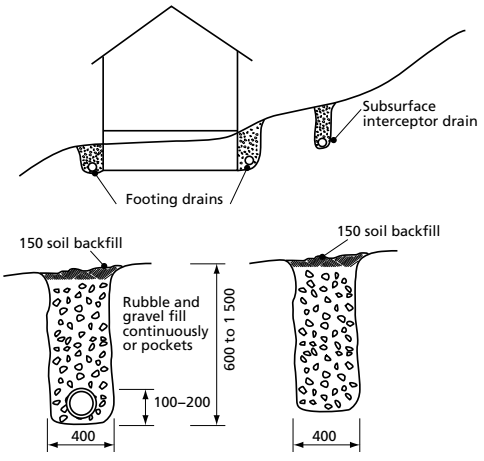


Figure 8.2 **Subsurface site drains**

Foundation footings

A footing is an enlarged base for a foundation designed to distribute the building load over a larger area of soil and to provide a firm, level surface for constructing the foundation wall.

A foundation wall, regardless of the material used for its construction, should be built on a continuous footing of poured concrete. Although the footing will be covered, and lean mixes of concrete are considered satisfactory, a footing that is strong enough to resist cracking also helps to keep the foundation from cracking. A 1:3:5 ratio of cement–sand–gravel is suggested, with 31 litres of water per 50 kg sack of cement. The amount of water assumes dry aggregates. If the sand is damp, the water should be reduced by 4 litres to 5 litres.

The total area of the footing is determined by dividing the total load (including an estimated mass for the footing itself) by the bearing, by dividing the area by the length. In many cases the width required for light farm buildings will be equal to, or less than, the foundation wall planned.

In that case, a footing that is somewhat wider than the foundation is still recommended for at least two reasons. The footings conform to small variations in the trench and bridge small areas of loose soil, making a good surface on which to begin a foundation wall of any kind. The footings are easily made level, and this makes it easier to install the forms for a poured-concrete wall or to start the first course of a block or brick wall.

Even when not required for loading, it is common practice to pour a concrete footing that is as deep as the wall is thick, and twice as wide. The foundation footings for large, heavy buildings require reinforcing. However, this is seldom necessary for lightweight rural buildings. Once a firm footing is in place, a number of different materials are suitable for building a foundation. Figure 8.3 shows footing proportions for walls, piers and columns.

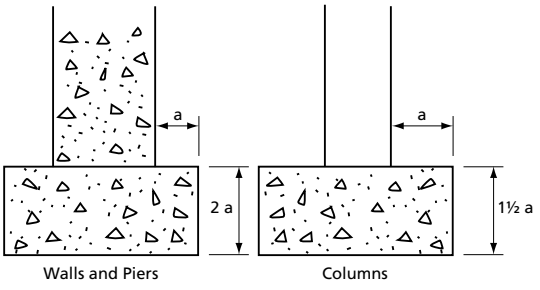


Figure 8.3 **Footing proportions for walls, piers and columns**

Although continuous wall footings are frequently loaded very lightly, this is not the case for column and pier footings. It is therefore important to estimate carefully the proportion of the building load to be carried by each pier or column. Figure 8.4 illustrates the load distribution on a building with a gable roof and a suspended floor.

If wall footings are very lightly loaded, it is advisable to design any pier or column footings required for the building with approximately the same load per unit of area. Then if any settling occurs, it should be uniform throughout. For the same reason, if part of the footing or foundation is built on rock, the balance of the footing should be twice as wide as usual for the soil and loading. Footings must be loaded evenly because eccentric loading may cause tipping and failure.

If a foundation is installed on a sloping site, it may be necessary to dig a stepped trench and install a stepped footing and foundation. It is important for all sections to be level and for each horizontal section of the footing to be at least twice as long as the vertical drop from the previous section. Reinforcing in the wall is desirable, as shown in Figure 8.5.

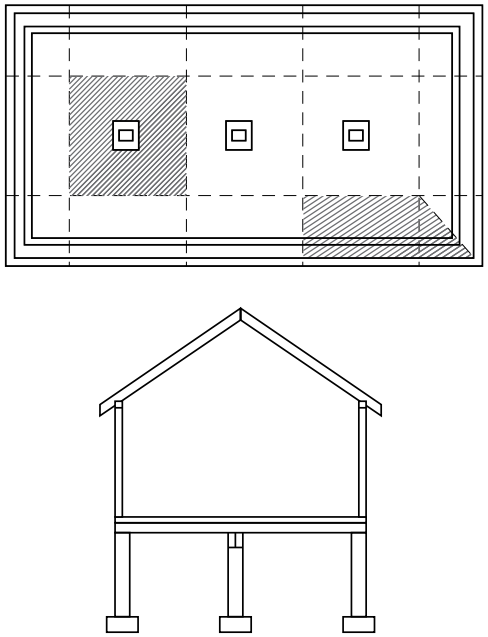


Figure 8.4 **The division of loads on footings. Each pier footing must carry one-eighth of the floor load. The wall must carry five-eighths of the floor load and the entire roof and wall load.**

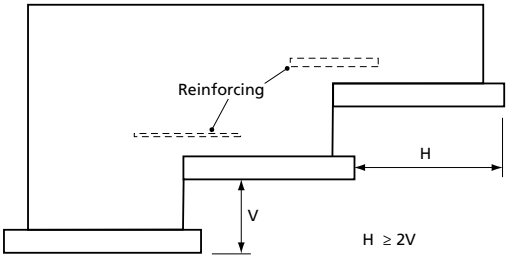


Figure 8.5 **Stepped footing and foundation**

The procedure for finding an appropriate footing is illustrated in Figure 8.4.

Example 8.1
Assume a building is 16 metres long and 8 metres wide. The roof framing plus the expected wind load totals 130 kN. The wall above the foundation is 0.9 kN/m. The floor will be used for grain storage and will support as much as 7.3 kPa. The floor structure is an additional 0.5 kPa.

The foundation wall and piers are each 1 metre high above the footing. The wall is 200 mm thick and the piers are 300 mm square. The soil on the site is judged to be compact clay in a well-drained area. Find the size of the foundation and pier footing that will safely support the loads. Assume that the weight of the mass 1 kg equals approximately 10 N. The mass of concrete is 2 400 kg/m³.

Solution:
1. The division of the load on each wall is as follows:

Roof load – 50 percent on each wall, 130 kN	65 kN
Wall load – for each side 16 × 0.9 kN	14.4 kN
Floor load – each side carries 7/32 × 998.4 kN	218.4 kN
Foundation load – each side, 16 × 0.2 × 24 kN	76.8 kN
Estimated footing 0.4 × 0.2 × 16 × 24 kN	30.7 kN
Total on one side	405.3 kN
Force per unit of length 405.3/16	25.3 kN/m
Using for practical reasons and assumed width of 0.4, 25.3/0.4	63.3 kPa

Compact clay at 215–217 kPa easily carries the load.

2. The division of the load on each pier is:

Floor load – $^1/_8$ × 998 kN	124.8
Pier 0.3 × 0.3 × 1 × 24 kN	2.2
Footing estimate 0.8 × 0.8 × 0.5 × 24 kN	7.7
Total	134.7 kN
Load/m²	210 kN/m²
OK but 1 × 1 × 0.7 gives more equal wall loading	144 kPa (kN/m²)

The most logical action to take would be to add one or more piers, which would allow both smaller footings and smaller floor support members.

Footing trenches

The trench must be dug deep enough to reach firm, undisturbed soil. For light buildings in warm climates, this may be as little as 30 cm. However, for large, heavy buildings, footing trenches may need to be up to 1 metre deep.

Pockets of soft material should be dug out and filled with concrete, stones or gravel. The trenches should be free of standing water when the concrete is poured for the footing.

A level trench of the correct depth can be ensured by stretching lines between the setting-out profiles (batter boards) and then using a boning rod to check the depth of the trench as it is dug out.

The footing forms should be carefully levelled so that the foundation forms may be easily installed, or a brick or block wall begun. If the foundation walls are to be made of bricks or concrete blocks, it is important for the footings to be a whole number of courses below the top of the finished foundation level.

Alternatively, the footing can be cast directly in the trench. While this saves the cost of footing forms, care must be taken to ensure that no soil from the sides is mixed in the concrete. The proper thickness for the footing can be ensured by installing guiding pegs with the tops set level at the correct depth at the centre of the foundation trench.

Types of foundation

Foundations may be divided into several categories suitable for specific situations.

Continuous wall foundations may be used either as basement walls or as curtain walls. A continuous wall for the basement of a building must not only support the building but also provide a waterproof barrier capable of resisting the lateral force of the soil on the outside. However, because of the structural problems and the difficulty of excluding water, it is recommended to avoid basement constructions in all but a few special circumstances.

Curtain walls are also continuous in nature but, because they are installed in a trench in the soil, they are not usually subjected to appreciable lateral forces and do not need to be waterproof. Curtain walls may be constructed, after which the earth can be backfilled on both sides, or they can be made of concrete poured directly into a narrow trench. Only the portion above ground level requires a form when the concrete is poured as shown in Figure 8.9. Curtain walls are strong, relatively watertight and give good protection against rodents and other vermin.

Pier foundations are often used to support the timber frames of light buildings with no suspended floors. They require much less excavation and building material. The stone or concrete piers are usually set on footings. However, for very light buildings, the pier may take the form of a precast concrete block set on firm soil a few centimetres below ground level. The size of the piers is often given by the weight required to resist wind uplift of the whole building.

Pad and pole foundations consist of small concrete pads poured in the bottom of holes, which support pressure-treated poles. The poles are long enough to extend and support the roof structure. This is probably the least expensive type of foundation and is very satisfactory for light buildings with no floor loads and where pressure-treated poles are available.

A floating slab or raft foundation consists of a poured-concrete floor in which the outer edges are thickened to between 20 cm and 30 cm and reinforced. This is a simple system for small buildings that must have a secure joint between the floor and the sidewalls.

A pier and ground-level beam foundation is commonly used where extensive filling has been necessary and the foundation would have to be very deep in order to reach undisturbed soil. It consists of a reinforced concrete beam supported on piers. The piers need to be deep enough to reach undisturbed soil and the beam must be embedded in the soil deeply enough to prevent rodents from burrowing under it. For very light buildings such as greenhouses, timber ground-level beams may be used.

Piles are long columns that are driven into soft ground where they support their load by friction with the soil rather than by a firm layer at their lower end. They are seldom used for farm buildings.

Foundation materials

The foundation material should be at least as durable as the rest of the structure. Foundations are subject to attack by moisture, rodents, termites and, to a limited extent, wind. The moisture may come from rain, surface water or groundwater and, although a footing drain can reduce the problem, it is important to use a foundation material that will not be damaged by water or the lateral force created by saturated soil on the outside of the wall.

In some cases the foundation must be watertight in order to prevent water from penetrating into a basement or up through the foundation and into the building walls above. Any foundation should be continued for at least 150 mm above ground level to give adequate protection to the base of the wall from moisture, surface water, etc.

Stones

Stones are strong, durable and economical to use if they are available near the building site. Stones are suitable for low piers and curtain walls, where they may be laid up without mortar if economy is a major factor, although it is difficult to make them watertight, even if laid with mortar. Also, it is difficult to exclude termites from buildings with stone foundations because of the numerous passages between the stones. However, laying the top course or two in good, rich mortar and installing termite shields can overcome the termite problem to a large degree.

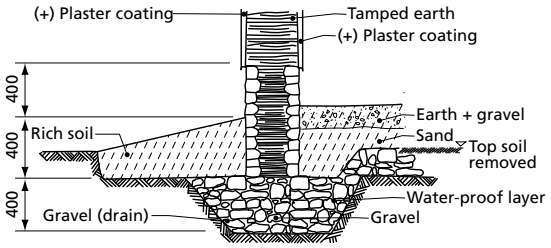
Earth

The primary advantage of using earth as a foundation material is its low cost and availability. It is suitable only in very dry climates. Where rainfall and soil moisture are too high for an unprotected earth foundation, they may be faced with stones, as shown in Figure 8.6, or shielded from moisture with polythene sheet, as in Figure 8.8.

Poured concrete

Concrete is one of the best foundation materials because it is hard, durable and strong in compression. It is not damaged by moisture and can be made nearly watertight for basement walls. It is easy to cast into the unique shapes required for each foundation.

For example, curtain walls can be cast in a narrow trench with very little formwork required. The principle disadvantage is the relatively high cost of the cement required to make the concrete.



Foundation wall from outside in:
-Bitumen coating
-Stone facing with cement-lime mortar
-Tamped earth
-Stone with cement-lime mortar
-Ant and water proofing
-Plaster coating

Figure 8.6 **Earth foundation faced with stones**

Concrete blocks

Concrete blocks may be used to construct attractive and durable foundation walls. The forms required for poured-concrete walls are unnecessary and, because of their large size, concrete blocks will lay up faster than bricks. A block wall is more difficult to make watertight than a concrete wall and does not resist lateral forces as well as a poured-concrete wall.

Bricks

Stabilized earth bricks or blocks have the same inherent restrictions as monolithic earth foundations. They are suitable only in very dry areas and even there they need protection from moisture. Adobe bricks are too easily damaged by water or ground moisture to be used for foundations. Locally made burnt bricks can often be obtained at low cost, but only the best quality bricks are satisfactory for use in moist conditions. Factory-made bricks are generally too expensive to be used for foundations.

Foundation construction

Stone foundations

If the stones available are relatively flat, they may be laid up dry (without mortar), starting on firm soil in the bottom of a trench. This makes a very low-cost foundation suitable for a light building. If monolithic earth walls are to be constructed on top of the stone foundation, no binder is necessary for the stones. If masonry units of any type are to be used, it would be prudent to use mortar in the last two courses of stone in order to have a firm level base on which to start the masonry wall. If a timber frame is planned, mortar for

the top courses, plus a metal termite shield, is necessary to provide a level surface and to exclude termites.

If the stones available are round or very irregular in shape, it is best to lay them up with mortar to provide adequate stability. Figure 8.7 shows earth forms being used to hold stones of irregular shape, around which a grout is poured to stabilize them. Stones to be laid in mortar or grout must be clean in order to bond well.

Figure 8.7a shows a mortar cap on which a concrete block wall is constructed. Figure 8.7b shows a stone shield to protect the base of an earth-block wall and Figure 8.7c shows the embedding of poles in a stone foundation, together with a splash shield. Proper shielding may reduce the risk of a termite infestation.

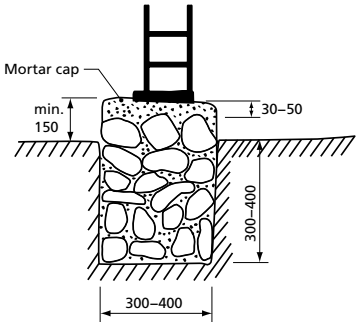


Figure 8.7a

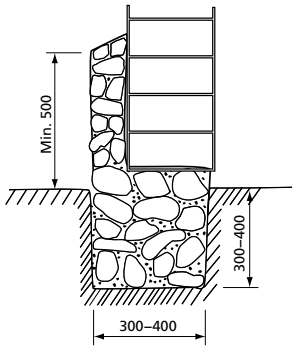


Figure 8.7b

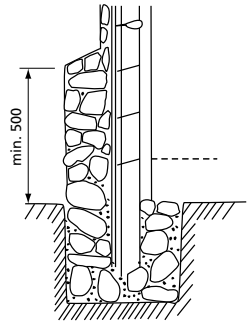


Figure 8.7c

Figure 8.7 **Stone foundations**

Earth foundations

Although more moisture-resistant materials are generally recommended for foundations, circumstances may dictate the use of earth. Figure 8.6 shows an earth foundation that has been faced with fieldstones. The joints have been filled with a cement–lime mortar, and the entire surface coated with bitumen.

Figure 8.8 illustrates the use of sheet polythene to exclude moisture from a foundation wall. While either of these methods helps to seal out moisture, the use of earth for foundation walls should be limited to dry-land regions.

Place the polythene sheet on a thin layer of sand or on a concrete footing. Overlap the single sheets by at least 20 cm. Construct a foundation wall from stabilized rammed earth or stabilized-soil blocks. Once the wall has hardened and dried out, the polythene is unrolled and soil backfilled in layers in the foundation trench. Fasten the ends of the sheet to the wall and protect with a drip deflection strip, a skirting or malting and plaster.

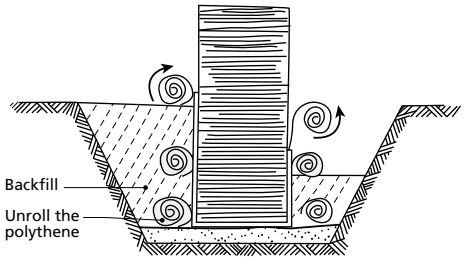


Figure 8.8 **An earth foundation protected from moisture with polythene sheet**

CONCRETE FOUNDATIONS

For light buildings, a curtain wall may be poured directly into a carefully dug trench 15 cm to 25 cm wide. To have the finished wall extend above the ground, forms built of 50 mm × 200 mm timber can be anchored along the top of the trench.

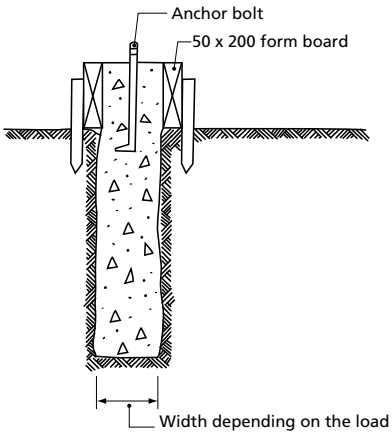


Figure 8.9 **Curtain wall poured in a trench**

A relatively lean 1:4:8 mix of concrete can be used. The concrete must be placed carefully to keep the walls of the trench from breaking off and mixing in, thereby causing weak spots. If the soil is not stable enough to allow digging of a trench form, a wide excavation and the use of simple forms will be required.

Additional information on ratios, materials, forms, placing and curing concrete is provided in Chapter 5.

Concrete-block foundations

It is desirable for all dimensions of a block wall to be divisible by 225 mm. This allows full- or half-blocks to be used at all corners and openings without the need to cut blocks to odd lengths. Blocks must be dry when used because otherwise the mortar joints will not develop full strength.

Concrete block foundations should be started in a full bed of mortar on a poured-concrete footing. A 1:1:5 ratio of cement–lime–sand makes a good mortar. The corner blocks should be carefully located and checked for levelness and plumb. After several blocks have been laid adjacent to the corners, a line stretched between the corners can be used to align the top outside edge of each course of blocks.

Following the first course, face-shell bedding is used, as shown in Figure 8.10. This means that mortar is placed along the vertical edges of one end and the side edges of the top of the block. This will save up to 50 percent of the mortar and is about three-quarters as strong as full bedding.

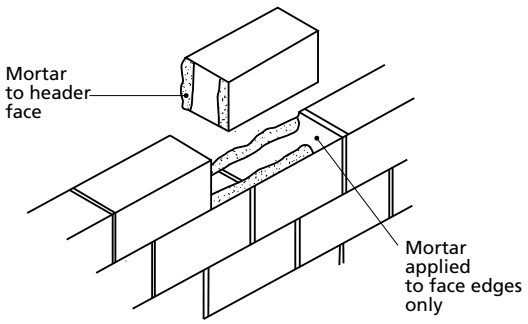


Figure 8.10 **Face-shell bonding in a block wall**

Masonry units must be overlapped to ensure that the vertical joints are staggered to provide adequate strength. Where small units such as bricks are used, the bonding must be both along and across the wall. However, blocks are only bonded longitudinally. Cross-bonding is required only at points of reinforcement such as pilasters. Although a half-lap bond is normal where necessary to permit bonding at returns and intersecting walls, this may be reduced to one-quarter of the block length, but not less than 65 mm.

The strength of blocks of either dense or lightweight aggregate is sufficient for normal small-scale work but, where loading is heavy, only dense concrete blocks are suitable. Hollow blocks may be used for load-bearing walls, but the courses directly supporting floor and roof structures should be built of solid construction in order to distribute the loading over the length of the wall and thus avoid the concentration of stresses.

The thickness, length and height of the wall determine its structural stability. Table 8.7 indicates suitable relationships for free-standing, single-thickness, unreinforced concrete block walls not externally supported and not tied or fixed at the top, and designed to resist wind pressure. Longer and higher walls and walls retaining (for example) bulk grain may need the extra strength of being tied to a pier or crosswall.

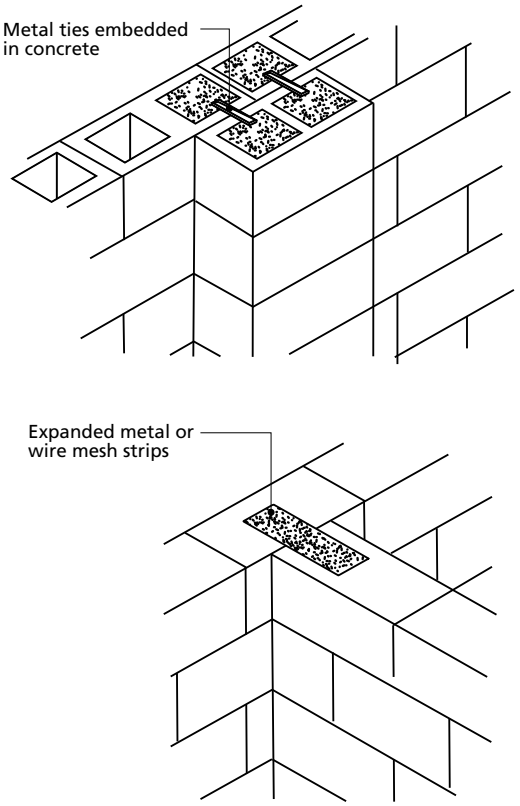


Figure 8.11 **Reinforcing block walls**

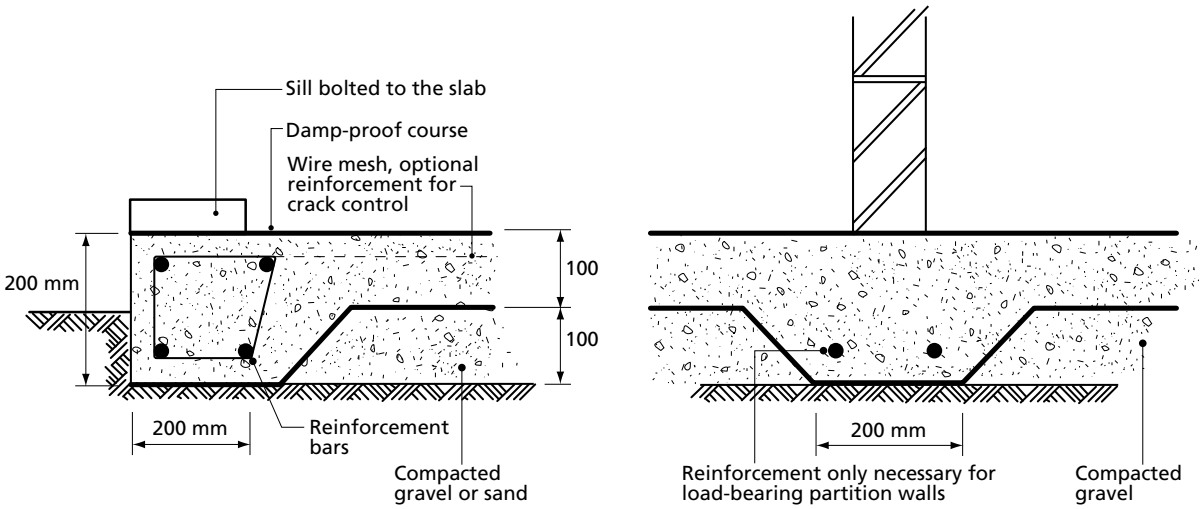


Figure 8.12 **Design of a floating-slab foundation**

TABLE 8.7
Stabilizing hollow-block walls

Thickness of wall	Height of wall	Maximum length of wall panel between piers, crosswalls, etc.
100 mm	1.8 metres	3.6 metres
150 mm	3.0 metres	3.0 metres
215 mm	3.6 metres	4.0 metres
215 mm	4.5 metres	3.0 metres
305 mm	4.5 metres	4.0 metres

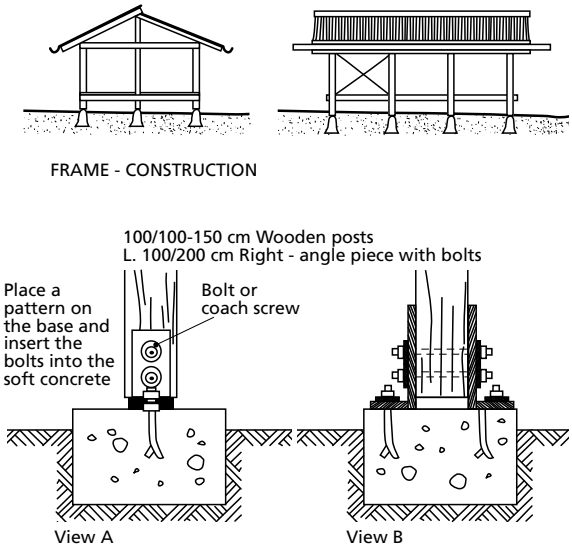


Figure 8.13 **Face-shell bonding in a block wall**

Floating-slab or raft foundation

A slab foundation is a large concrete floor covering the entire building area, through which all the loads from the building are transmitted to the soil. It serves as both building floor and foundation and is well suited to garages, shops, small stores and homes without basements. The concrete floor and the foundation are cast in one piece.

The slab is cast about 100 mm thick and lightly reinforced at the top to prevent shrinkage cracks. Steel bars are placed at the bottom, under walls or columns, to resist tensile stresses in these zones. Light surface slabs can also be used to carry lightly loaded structures on soils subject to general earth movement.

As with all foundations, the centre of gravity of the loads should coincide with the centre of the slab. This is facilitated when the building has a simple, regular plan with load-bearing elements such as walls, columns or chimneys located symmetrically about the axis of the building.

Pier foundation

Isolated piers or columns are normally carried on independent concrete footings, sometimes called pad foundations, with the pier or column bearing on the centre point of the footing. The area of footing is determined by dividing the column load by the safe bearing-capacity of the soil. The shape is usually square, and the thickness is governed by the same considerations as for foundation footings.

They are made not less than one-and-a-half times the projection of the slab beyond the face of the pier or column, or the edge of the base-plate of a steel column. They should never be less than 150 mm thick. As in the case of strip footings, when a column base is very wide, a reduction in thickness may be obtained by reinforcing the concrete.

When piers are used to support prefabricated building frames of steel or laminated wood, the bolts for anchoring the frame to the piers must be grouted into the concrete and very accurately positioned. This requires skilled labour and supervision.

Post or pole foundation

For lightweight buildings without suspended floors, posts or pressure-treated pole frames are suitable and inexpensive. The posts are placed in holes dug into the soil and a footing provided at each post. This is important because otherwise either gravity loads or wind uplift can lead to building failure.

The concrete pad under the pole provides the necessary support for gravity loads. The concrete collar around the base of the pole offers resistance to uplift. The pole is secured to the collar by several spikes driven into the base prior to placing the pole on the pad and pouring the concrete for the collar. While earth backfill should be well tamped to provide the greatest resistance to uplift, a concrete collar that extends to ground level offers better protection against ground moisture and termites.

Bracing of the poles to the roof and other building frame members provides adequate lateral stability. Figure 8.14 illustrates the pad and collar design.

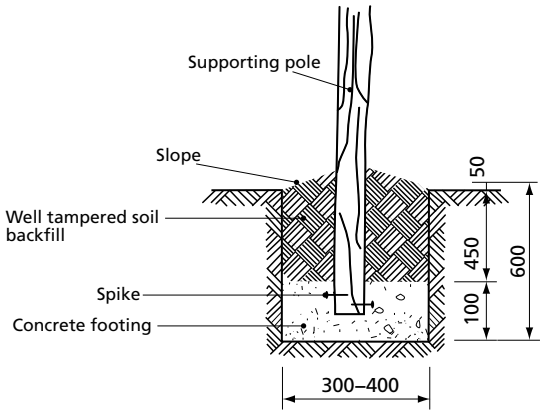


Figure 8.14 **Pole foundation**

Pier and ground-level beam foundation

As mentioned previously, this design may be chosen for applications where safe bearing layers are so deep that they make a curtain wall very expensive. The ground-level beam must be designed to carry safely the expected load. Ordinarily the beam is made 150 to 200 mm wide and 400 to 600 mm apart.

First the piers are formed and poured on footings of suitable size. The soil is then backfilled to 150 mm below the top of the piers. After placing 150 mm of gravel in the trench to bring the level even with the top of the piers, forms are constructed and the beam is poured. The reinforcing shown in Figure 8.15 is necessary. The size and spacing must be carefully calculated.

Protective elements for foundations

Waterproofing

Several steps can be taken to prevent ground or surface water from penetrating a foundation wall. If the building is located on sloping land where a footing drain can be terminated at ground level within a reasonable distance, the installation of a continuous drain around the outside of the foundation will reduce both the possibility of leaks and the lateral force of saturated soil bearing against the wall.

The recommended drain design consists of a 100 mm drain tile placed slightly above the level of the bottom of the footing. The tile should be installed with little or no gradient so that the groundwater level will remain equal at all points along the footing. Gravel is used to start the backfilling for the first 500 mm, and then the excavated soil is returned and tamped in layers sloping away from the wall.

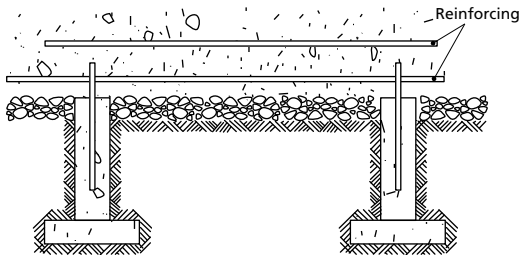


Figure 8.15 **Pier and ground-level beam foundation**

The water resistance of poured concrete basement foundation walls may be improved by applying a heavy coat of bituminous paint. Block walls should be given two coats of cement plaster from the footing to above ground level, and then covered with a finish coat of bituminous paint.

Moisture creeping up the foundation wall by capillary action can cause considerable damage to the lower parts of a wall made of soil or wood. While a mortar cap on top of the foundation wall usually provides a sufficient barrier, the extra protection of a strip of bituminous felt is sometimes required. To be effective, such a damp-proof course must be set at least 150 mm above the ground and be of the same width as the wall above.

Pitch-roof buildings that are not equipped with eave gutters can be further protected from excessive moisture around the foundation by the installation of a splash apron made of concrete. The apron should extend at least 150 mm beyond the drip-edge of the eaves and slope away from the wall with an incline of approximately 1:20. A thickness of 50 mm of 1:3:6 concrete should be adequate.

Foundations for arch or rigid frames

Additional resistance to lateral forces is needed for foundation walls supporting arch or rigid-frame buildings. This can be accomplished with buttresses or pilasters, or by tying the wall into the floor. Figure 8.16 shows each of these methods.

Termite protection

Subterranean termites occur throughout east Africa and cause considerable damage to buildings by eating the cellulose in wood. They must have access to the soil or some other constant source of water. They can severely damage timber in contact with the ground, and may extend their attack to the roof timbers of high buildings. They gain access to unprotected structures through cracks in concrete or masonry walls, through the wood portion of the house or by building shelter tubes over foundation posts and walls.

The main objective of termite control is to break contact between the termite colony in the ground and the wood in the building. This can be done by blocking the passage of the termites from soil to wood, by constructing a slab floor under the entire building, and/or installing termite shields, treating the soil near the foundation and under concrete slabs with suitable chemicals, or by a combination of these methods.

Creepers, climbers and other vegetation likely to provide a means of access for termites should not be permitted to grow on, or near, a building.

Chemical protection is useful if termite shields are not available, but it is recommended for use in combination with mechanical protection. Creosote oil, sodium arsenite, pentachlorophenol, pentachlorophenol, pentachlorphenate, copper napthenate, benzene hexachloride and dieldrin are the main products used. The protection lasts from four to nine years, depending on soil and weather conditions. Timber elements should be impregnated before use. The timber surface is protected only if sprayed with insecticide prior to painting. Cracks, joints and cut surfaces must be protected with special care, as termite attacks always start in such locations.

Slab-on-the-ground construction: First, the construction site must be carefully cleaned and all termite colonies tracked down, broken and poisoned with 50–200 litres of chemical emulsion. Second, after the topsoil has been removed and any excavation is completed, poison should be applied at a rate of 5 litres per square metre over the entire area to be covered by the building.

The soil used as backfill along the inside and outside of the foundation, around plumbing and in the wall voids, is treated at a rate of 6 litres per metre run and, before casting the floor slab, any hardcore fill and blinding sand should also be treated. Existing buildings can be given some protection by digging a 30 cm wide and 15 cm to 30 cm deep trench around the outside of the foundation. After having sprayed the trench with poison, the excavated soil is treated and replaced.

It is advisable to carry out soil poisoning when the soil is fairly dry and when rain is not imminent, otherwise there is risk of the chemical being washed away instead of being absorbed by the soil.

It is also advisable to cover the poisoned band of soil with concrete or with a substantial layer of gravel. This protects the poison barrier and helps to keep the wall

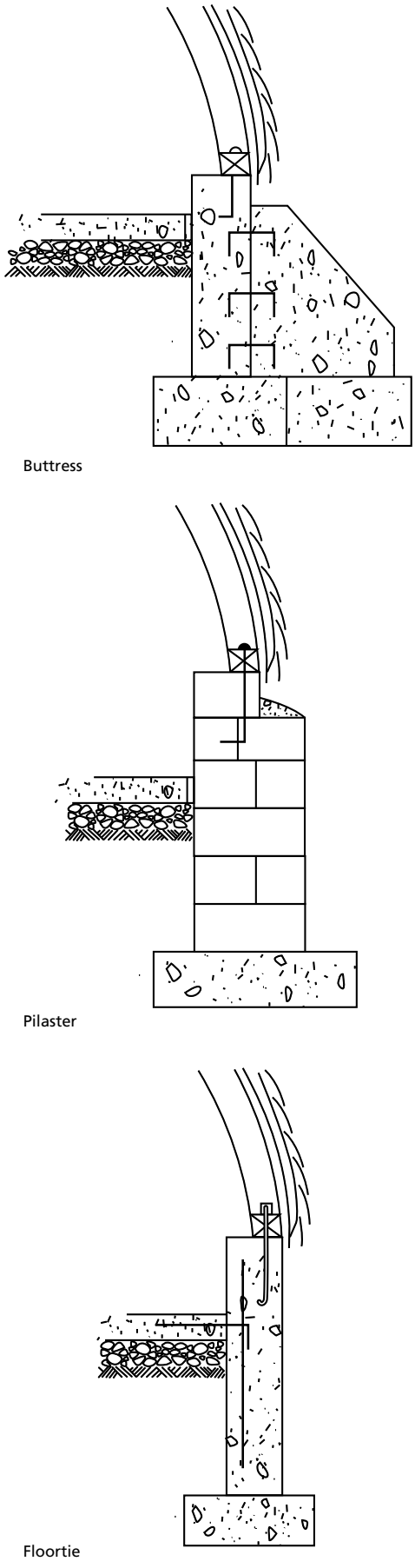


Figure 8.16 **Methods of strengthening foundations**

clean and free of mud splashes. If the wall is rendered, it is preferable to poison any rendering that is applied within 30 cm or so of the ground. To poison concrete or sand–cement mortar, simply use a 0.5–1.0 percent dieldrin emulsion instead of the usual mixing water. This has no effect on the amount of water required or the binding strength of the cement.

All preservatives are toxic and should be handled with care. Some are extremely toxic if swallowed or allowed to remain in contact with the skin. Insist on a recommendation for first aid from the supplier of the preservative. When using dieldrin, aldrin or chlorodane, children and animals should be kept away from the area where treatment is to be carried out.

Termite shields: The termite shield should be continuous around the foundation, irrespective of changes in level, and should be made of 24-gauge galvanized steel. The edge of the shield should extend horizontally outwards for 5 cm beyond the top of the foundation wall, and should then bend at an angle of 45° downwards for another 5 cm. There should be a clearance of at least 20 cm between the shield and the ground. All joints in the shield should be double-locked and properly sealed by soldering or brazing, or with bituminous sealer. Holes through the shield for anchor bolts should be coated with bituminous sealer and a washer fitted over the bolt to ensure a tight fit.

Protection of existing buildings: A building should be regularly inspected inside and out, and especially at potential hiding places. The outside should be checked for such things as staining on walls below possibly blocked gutters, accretion of soil, debris or add-on items, such as steps, that might bridge the termite shield. Ground-floor window and door frames and timber cladding should be probed to discover decay or termite damage. All timber, whether structural or not, should be inspected, paying special attention to places that are infrequently observed, such as roof spaces, undersides of stairs, built-in cupboards and flooring under sinks where there may be plumbing leaks.

Extensively damaged wood should be cut out and replaced with sound timber pretreated with preservative. In the case of decay, the source of moisture must be found and corrected and, where subterranean termites are found, their entry point must be traced and eliminated. Termites within the building must first be destroyed. The treatments to be applied include some measure of soil poisoning, the provision of barriers and the surface treatment of timber and wood-based materials.

In the case of drywood termites, fumigation is the only reliable method of extermination, and this should be carried out by trained personnel under proper supervision.

WALLS

Walls may be divided into two types:

(a) Load-bearing walls that support loads from floors and roof in addition to their own weight and resist side-pressure from wind and, in some cases, from stored material or objects within the building.

(b) Non-load-bearing walls that carry no floor or roof loads.

Each type may be further divided into external or enclosing walls, and internal dividing walls. The term 'partition' is applied to walls, either load-bearing or non-load-bearing, that divide the space within a building into rooms.

Good-quality walls provide strength and stability, weather resistance, fire resistance, thermal insulation and acoustic insulation.

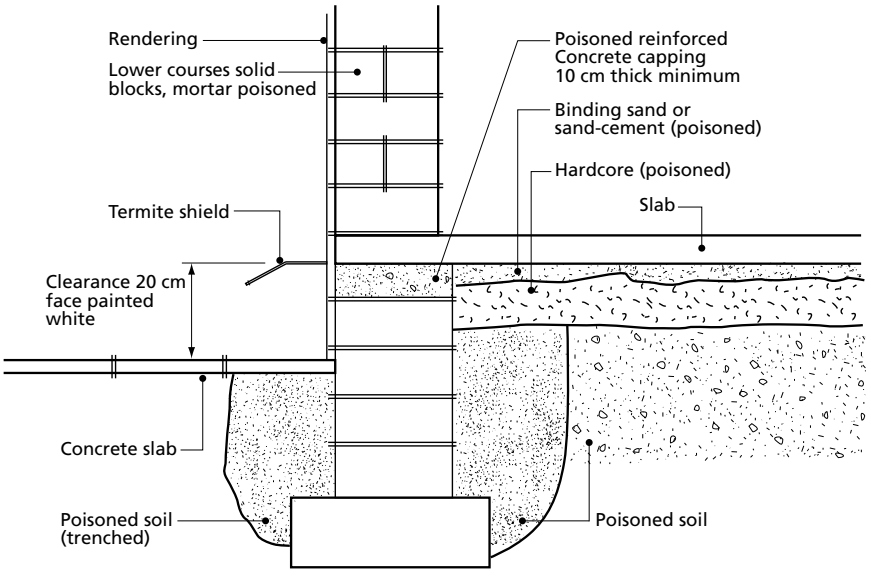


Figure 8.17 **Termite protection**

Types of building wall

While there are various ways to construct a wall and many different materials can be used, walls can be divided into four main groups.

Masonry walls, where the wall is built of individual blocks of materials such as brick, clay, concrete block or stone, usually in horizontal courses bonded together with some form of mortar. Several earth-derived products, either air-dried or fired, are reasonable in cost and well suited to the climate.

Monolithic walls, where the wall is built of a material placed in forms during construction. The traditional earth wall and the modern concrete wall are examples. Earth walls are inexpensive and durable if placed on a good foundation and protected from rain by rendering or wide roof overhangs.

Frame walls, where the wall is constructed as a frame of relatively small members, usually of timber, at close intervals, which, together with facing or sheathing on one or both sides, form a load-bearing system. Offcuts are a low-cost material to use for a frame-wall covering.

Membrane walls, where the wall is constructed as a sandwich of two thin skins or sheets of reinforced plastic, metal, asbestos cement or other suitable material bonded to a core of foamed plastic to produce a thin wall element with high strength and low weight.

Another form of construction suitable for framed or earth buildings consists of relatively light sheeting secured to the face of the wall to form the enclosed element. These are generally termed 'claddings'.

Factors that determine the type of wall to be used are:

- the materials available at a reasonable cost;
- the availability of craft workers capable of using the materials in the best way;
- climate;
- the use of the building and functional requirements.

The height of walls should allow people to walk freely and work in a room without knocking their heads on the ceiling, beams, etc. In dwellings with ceilings, 2.4 metres is a suitable height. Low roofs or ceilings in a house create a depressing atmosphere and tend to make the rooms warmer in hot weather.

Masonry walls

Apart from certain forms of stone walling, all masonry consists of rectangular units built up in horizontal layers called courses. The units are laid up with mortar in specific patterns, called 'bonds', in order to spread the loads and resist overturning and, in the case of thicker walls, buckling.

The material in the masonry units can be mud or adobe bricks, burnt clay bricks, soil blocks (stabilized or unstabilized), concrete blocks, stone blocks or rubble. Blocks can be solid or hollow.

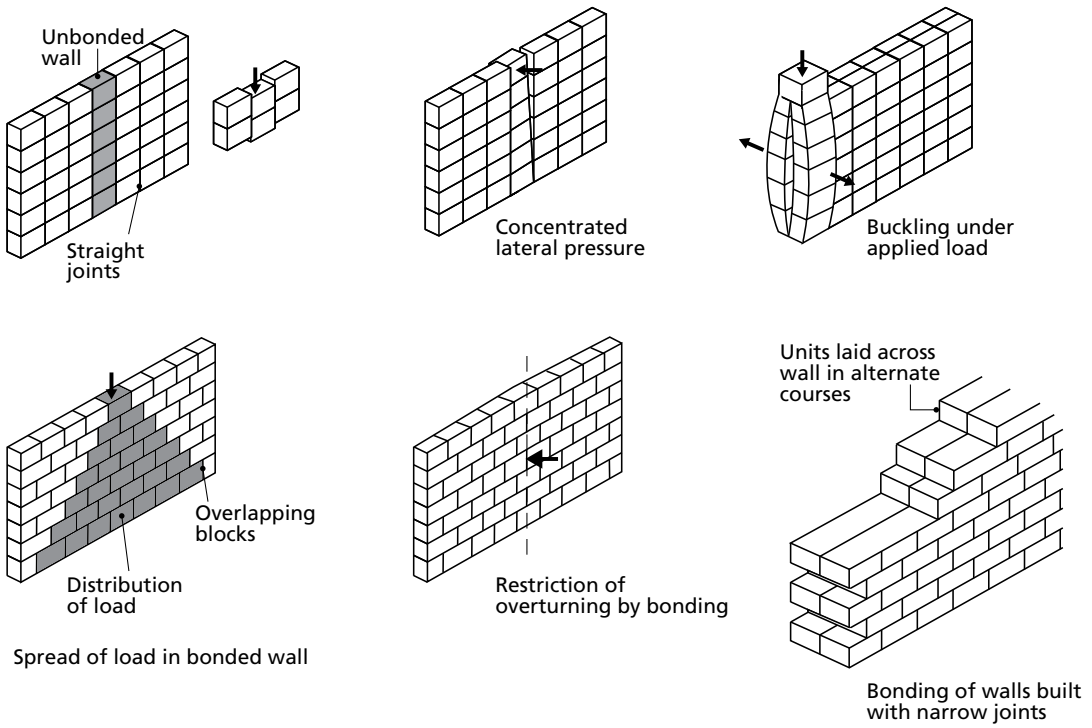


Figure 8.18 **Examples showing why bonding is necessary**

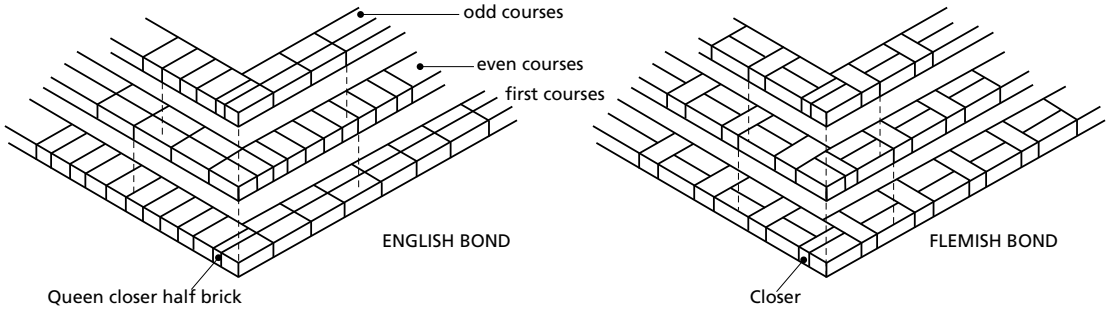


Figure 8.19 **English and Flemish bonding of brick walls**

Bricks

In brickwork, the bricks laid lengthwise in the wall are called 'stretchers' and the course in which they occur, a 'stretching course'. Bricks laid across the wall thickness are called 'headers' and the course in which they occur, a 'heading course'.

Bricks may be arranged in a variety of ways to produce a satisfactory bond, and each arrangement is identified by the pattern of headers and stretchers on the face of the wall. These patterns vary in appearance, resulting in characteristic 'textures' in the wall surfaces, and a particular bond may be used for its surface pattern rather than for its strength properties. In order to maintain the bond, it is necessary, at some points, to use bricks cut in various ways, each of which is given a technical name according to the way it is cut.

The simplest arrangements, or bonds as they are called, are the stretching bond and the heading bond. In the stretching bond, each course consists entirely of stretchers laid as in Figure 8.20 and is suitable only for half-brick walls, such as partitions, facing for block walls and the leaves of cavity walls. Thicker walls built entirely with stretchers are likely to buckle, as shown in Figure 8.18. The heading bond is ordinarily used only for curved walls.

The two bonds most commonly used for walls of one brick or more in thickness are known as 'English bond' and 'Flemish bond'. A 'one-brick thickness' is equal to the length of the brick. These bonds incorporate both headers and stretchers in the wall, which are arranged with a header placed centrally over each stretcher in the course below in order to achieve a bond and minimize straight joints. In both bonds, 120 bricks of standard size are required per square metre of 23 cm wall. This figure allows for 15–20 percent breakage and 1 cm mortar joints. Figure 8.19 illustrates English and Flemish bonding.

Bricks are sometimes used in the construction of cavity walls because the airspace provides greater thermal resistance and resistance to rain penetration than a solid wall of the same thickness. Such a wall is usually built up with an inner and outer leaf in a stretching bond, leaving a space or cavity of 50 mm to 90 mm between the leaves. The two leaves are connected by metal wall ties spaced 900 mm horizontally and 450 mm vertically, as shown in Figure 8.20.

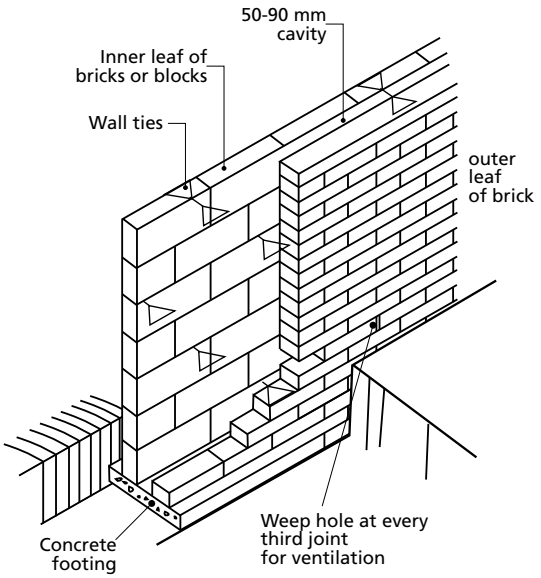


Figure 8.20 **Brick cavity wall**

Concrete blocks

Much of the procedure for the construction of concrete block walls has been discussed under the heading 'Foundations'. However, there are a few additional factors to be considered.

It is best to work with dry, well-cured blocks to minimize shrinking and cracking in the wall. Except at quoins (corners), load-bearing concrete-block walls should not be bonded at junctions as in brick and stone masonry. At junctions, one wall should butt against the face of the other to form a vertical joint, which allows for movement in the walls and thus controls cracking.

Where lateral support must be provided by an intersecting wall, the two can be tied together by 5 mm × 30 mm metal ties with split ends, spaced vertically at intervals of about 1 200 mm. Expansion joints should be allowed at intervals not exceeding two-and-a-half times the wall height. The two sections of wall must be keyed together or stabilized by overlapping jamb blocks, as shown in Figure 8.21. The joints are sealed with flexible mastic to keep water from penetrating the wall.

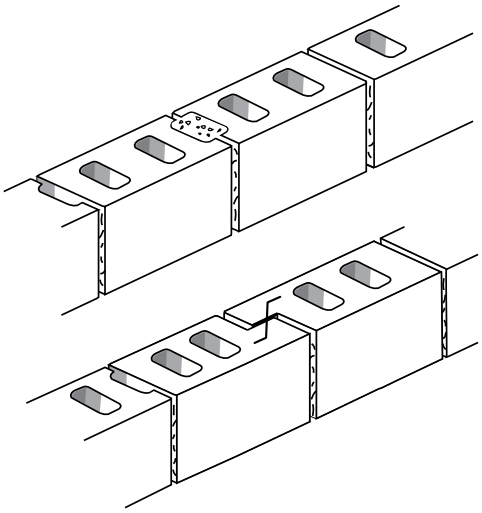


Figure 8.21 **Lateral support for walls at expansion joints**

Many walls in the tropics are required to let in light and air while acting as sunbreaks. To meet this need, perforated walls are popular and are designed in a variety of patterns, some load-bearing, others of light construction. Hollow concrete blocks may be used to good effect for this purpose. Horizontal or vertical slabs of reinforced concrete (slats) can be used to act as sunbreaks. These are usually built at an inclined angle in order to provide maximum shelter from the sun.

Stones

Quarried stone blocks, either rough or dressed to a smooth surface, are laid in the same way as concrete or stabilized-soil blocks. Random rubble walls are built using stones of random size and shape, either as they are found or straight from the quarry. Walls using laminated varieties of stone that split easily into reasonably straight faces of random size are called 'squared rubble walling'.

In these walls, as in all masonry, the longitudinal bond is achieved by overlapping stones in adjacent courses, but the amount of overlap varies because the stones vary in size. Rubble walls are essentially built as two skins, with the irregular space between filled solidly with rubble material (small stones), with a transverse bond or tie provided by the use of long header stones known as 'bonders'.

These extend not more than three-quarters through the wall thickness to avoid the passage of moisture to the inner face of the wall, and at least one is required for each square metre of wall face. Large stones, reasonably square in shape or roughly squared, are used for corners and the jambs of door and window openings to provide increased strength and stability at these points.

Random rubble walls may be built as uncoursed walling in which no attempt is made to line the stones into horizontal courses, or they may be brought to courses in which the stones are roughly levelled at 300 mm to 450 mm intervals to form courses varying in depth with the quoin and jamb stones.

Rough squaring of the stones has the effect of increasing the stability of the wall and improving its weather resistance because the stones bed together more closely, the joints are thinner and therefore there is less shrinkage in the joint mortar. External load-bearing stone walls should be at least 300 mm thick for one-storey buildings.

Openings in masonry walls

Openings in masonry walls are required for doors and windows. The width of opening, the height of the wall above the opening and the strength of the wall on either side of the opening are major design factors. They are particularly important where there are many openings quite close together in a wall.

The support over an opening may be a lintel of wood, steel or reinforced concrete, or it may be an arch constructed of masonry units similar or identical to

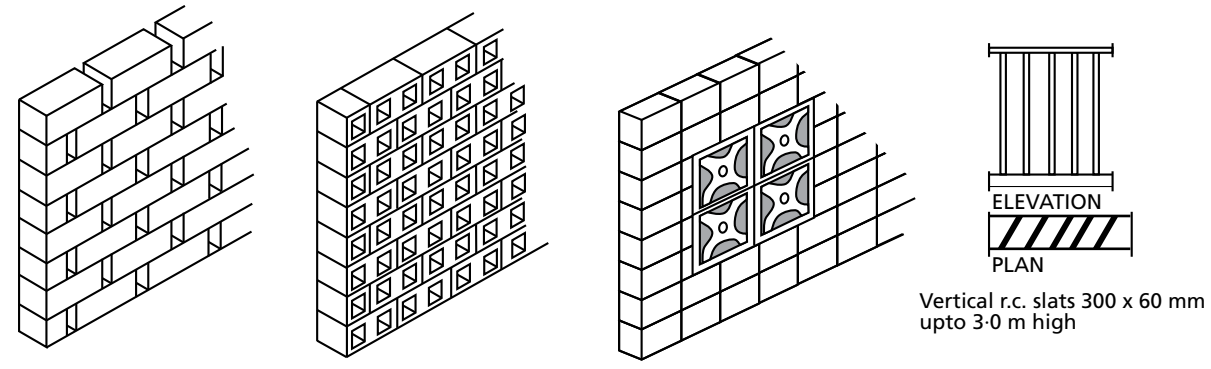


Figure 8.22 **Block walls for ventilation**

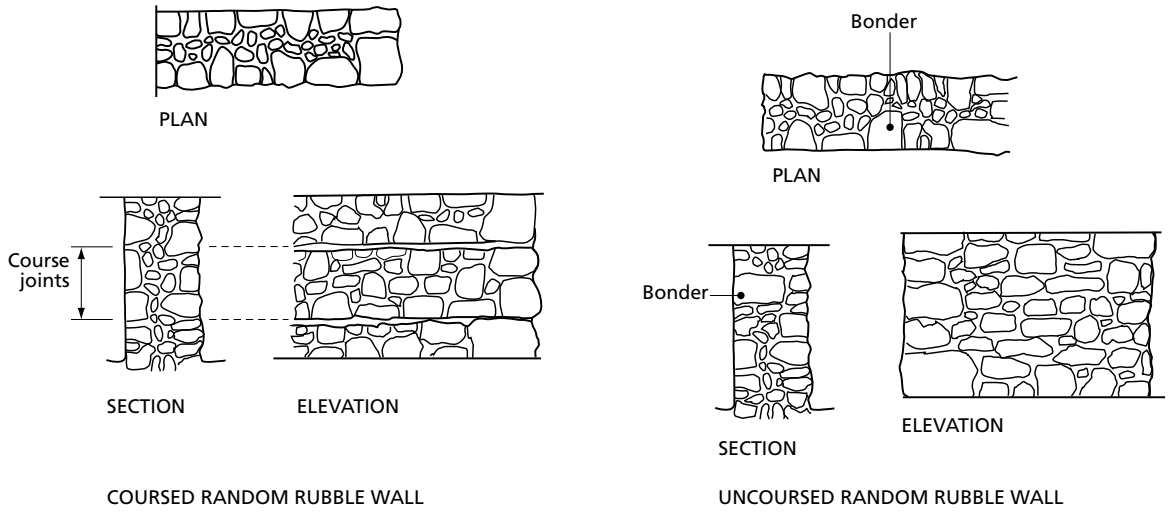


Figure 8.23 **Coursed and uncoursed random rubble walls**

those used in the adjoining wall. Lintels impose only vertical loads on the adjoining sections of walls and are themselves subjected to bending loads, shear loads and compression loads at their support points. Concrete lintels may be either cast in place or prefabricated and installed as the wall is constructed.

Arches are subjected to the same bending and shear forces but, in addition, there are thrust forces against both the arch and the abutting sections of the wall.

It is not difficult to determine loads and choose a wood or steel lintel to install, or to design the reinforcing for a concrete lintel. However, the design of an arch always involves assumptions, followed by verification of those assumptions.

Lintels made of wood are suitable for light loads and short spans. Timber that has been pressure-treated with a preservative should be used.

Steel angles are suitable for small openings and Table 8.8 presents size, span and load information for several sizes. Larger spans require universal section I-beams and a specific design analysis. Steel lintels should be protected from corrosion with two or more coats of paint.

TABLE 8.8
Allowable uniformly distributed loads on steel angle lintels (kg)

Angle size (mm) V × H × Th	Weight kg/m	Safe load (kg) at span length (m)				
		1	1.5	2	2.5	3
90 × 90 × 8	10.7	1 830	1 200	900	710	
125 × 90 × 8	13.0	3 500	2 350	1 760	1 420	1 150
125 × 90 × 13	20.3	5 530	3 700	2 760	2 220	1 850
125 × 102 × 10	18.3	6 100	4 060	3 050	2 440	2 032

V = vertical leg; H = horizontal leg; Th = thickness

Reinforced concrete is very commonly used for lintels. Concrete lintels are made of 1:2:4 concrete mix (with an ultimate strength of 13.8 MPa) and are normally reinforced with one steel bar for each 100 mm of width. For reasonably short spans over door and window openings, the 'arching' action of normal well bonded bricks or blocks owing to the overlapping of the units may be taken into account. It may be assumed that the lintel will carry only that part of the wall enclosed by a 45° equilateral triangle, with the lintel as its base.

For wide spans, an angle of 60° is used. For spans up to 3 metres, the sizes of lintels and the number and sizes of reinforcement bars shown in Table 8.9 may be used. The steel bars should be covered with 40 mm of concrete, and the bearings on the wall should be preferably 200 mm, or at least equal to the depth of the lintel. Lintels with a span of more than 3 metres should be designed for the specific situation.

Long-span concrete lintels may be cast *in situ* in formwork erected at the head of the opening. However, precasting is the usual practice where suitable lifting tackle or a crane is available to hoist the lintel into position, or where it is light enough to be put into position by two workers.

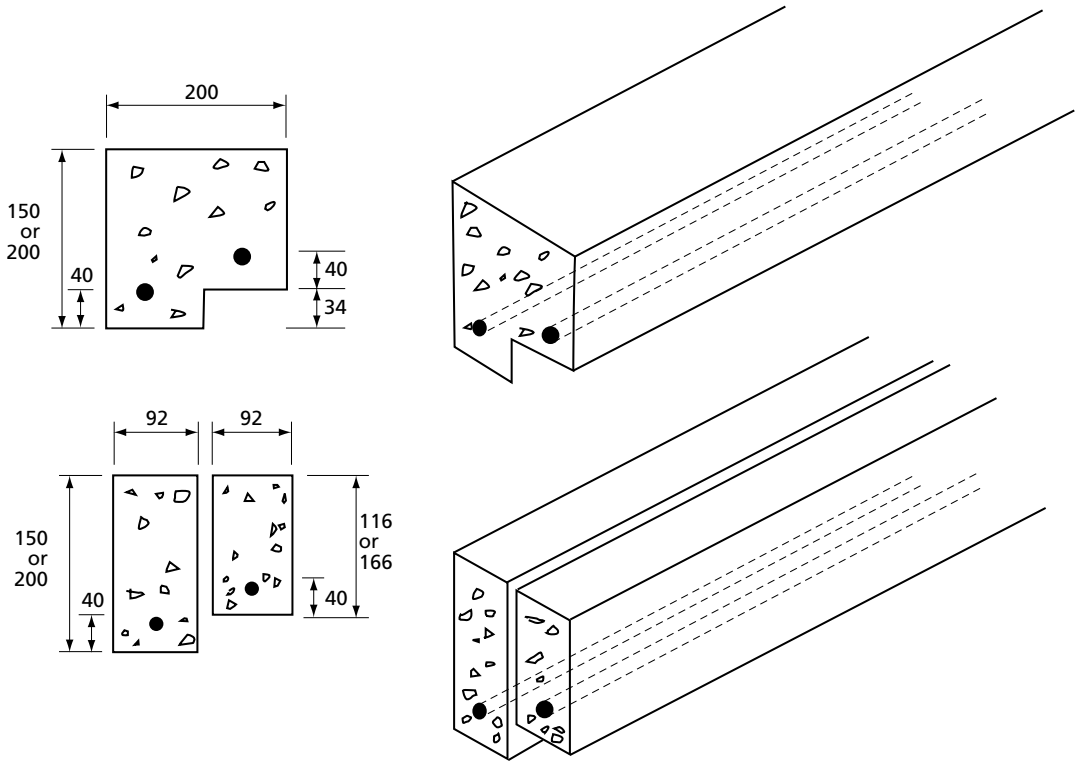
Stone is generally used as a facing for a steel or concrete lintels. Unless they are reinforced with mild steel bars or mesh, brick lintels are suitable only for short spans up to 1 metre but, like stone, bricks can also be used as a facing for a steel or concrete lintel.

The arch is a substructure used to span an opening made with components smaller in size than the width of the opening. It consists of mutually-supporting blocks placed over the opening between the abutments on each side. It exerts a downward and outward thrust on the abutments, which must be strong enough to ensure the stability of the arch.

Jointing and pointing

Jointing and pointing are terms used for the finishing given to both the vertical and horizontal joints in masonry,

TABLE 8.9
Reinforced concrete lintels



Size of lintel (millimetres)		Clear span	Bottom reinforcement	
H	W	M	Number of bars	Size of bars
		Split lintels with wall load only		
150	200	<2.0	2	10 mm, round, deformed
200	200	2.0–2.5	2	10 mm, round, deformed
200	200	2.5–3.0	2	16 mm, round, deformed
		Split lintels with wall load only		
150	200	<2.0	1 each	10 mm, round, deformed
200	200	2.0–2.5	1 each	10 mm, round, deformed
200	200	2.5–3.0	1 each	16 mm, round, deformed

Safe bearing at each end = 200 mm

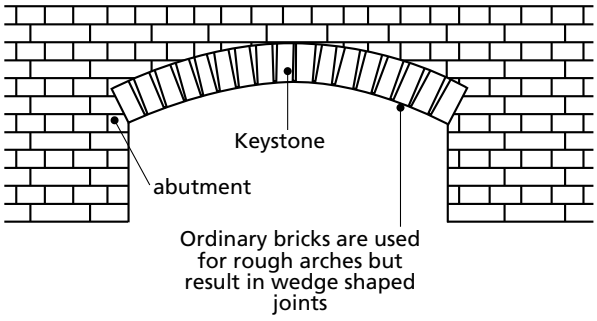


Figure 8.24a **Rough arch**

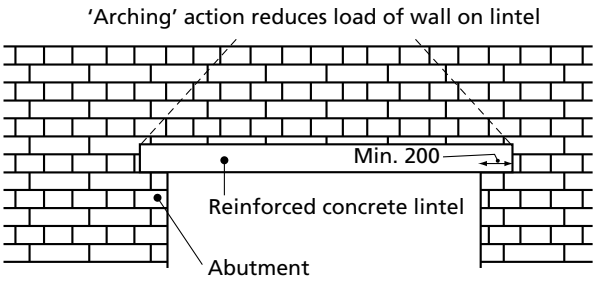


Figure 8.24b **Opening spanned by a reinforced concrete lintel**

Figure 8.24 **Openings in masonry walls**

irrespective of whether the wall is made of brick, block or stone. Jointing is the finish given to the joints as the work proceeds. Pointing is the finish given to the joints by raking out the mortar to a depth of approximately 20 mm and refilling the face with a hard-setting cement mortar, which may contain a colour additive. This process can be applied to both new and old buildings. Typical examples of jointing and pointing are given in Figure 8.25.

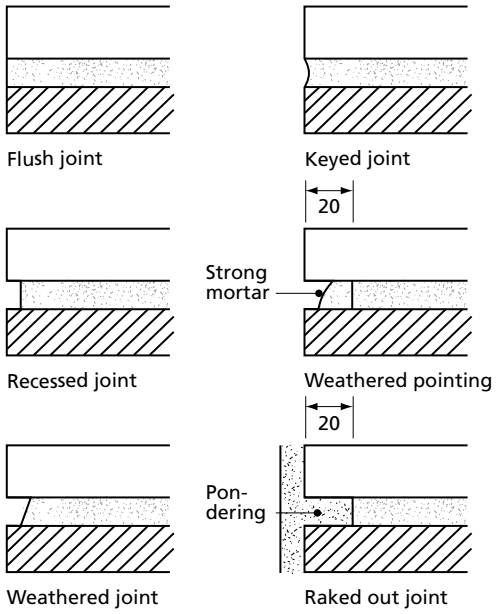


Figure 8.25 **Examples of jointing and pointing**

Monolithic earth walls

Earth wall construction is widely used because it is an inexpensive building method and materials are usually abundantly available locally. As the earth wall is the only type many people can afford, it is worthwhile to employ methods that will improve its durability. Its susceptibility to rainfall erosion and general loss of stability through high moisture can be eliminated if simple procedures are followed during site selection, building construction and maintenance.

Earth walls are affected mainly by:

- erosion through rainfall hitting the walls directly or splashing up from the ground;
- saturation of the lower part of the wall by rising capillary water;
- earthquakes.

For one-storey earth-walled houses, structural considerations are less important because of the light roofing generally used. A badly designed or constructed earth-walled building may crack or distort, but sudden collapse is unlikely. Durability, not strength, is the main problem, and keeping the walls dry after construction is the basic solution. Methods of stabilizing earth can be found in Chapter 5.

Key factors for improving the durability of earth-walled buildings include:

- Selection of a site with adequate drainage and a free-draining and non-swelling soil. Construction of earth buildings on and with swelling soils may lead to foundation and wall distortion during the rainy season.
- Construction of a foundation wall either from blocks or stones set in cement or mud mortar. The foundation minimizes the effects of all types of water damage to the base of the wall.
- Stabilization of the soil used for the construction of walls. Stabilized earth walls are stronger and more resistant to moisture, rain and insects, especially termites. Avoid the use of pure black cotton soil for construction because it shrinks significantly on drying, leading to cracking and distortion. Clay soils should be stabilized with lime because cement has shown poor results for these soils.
- Impregnating a stabilized earth wall with a waterproof coating.
- Plastering the wall to protect it from water and insects.
- Provision of an adequate eave width (roof overhang) to reduce wall erosion. However, eave width is limited to approximately 0.6 metres because of the risk of wind damage. Verandas can be useful for wall protection.
- Maintenance of the wall and protective coating.
- Provision for free evaporation of capillary moisture by clearing away any low vegetation near the building walls.

Soil is a material that can be used in many ways for wall construction. Hand-rammed or machine-compacted, stabilized-soil blocks and sun-dried mud (adobe) bricks are used in the same manner as masonry units made of other materials. While masonry constructions have already been described, it should be noted that the somewhat poorer strength and durability of soil blocks and adobe bricks may make them less suitable for some types of construction, e.g. foundation walls. Special care must be taken when designing lintel abutments to ensure that the bearing stresses are kept within the allowable limit.

Rammed-earth walls

A method for the construction of a monolithic earth wall is shown in Figure 8.26. The use of soil mixed with a suitable stabilizer at a proper ratio will increase the strength and durability of the wall, provided the wall is properly cured. However, perhaps the single most important factor when constructing a rammed-earth wall (using stabilized or natural soil) is thorough compaction of each layer of soil as it is filled in the mould. The formwork must be strong enough to resist the lateral forces exerted by the soil during this operation. The distance between lateral supports

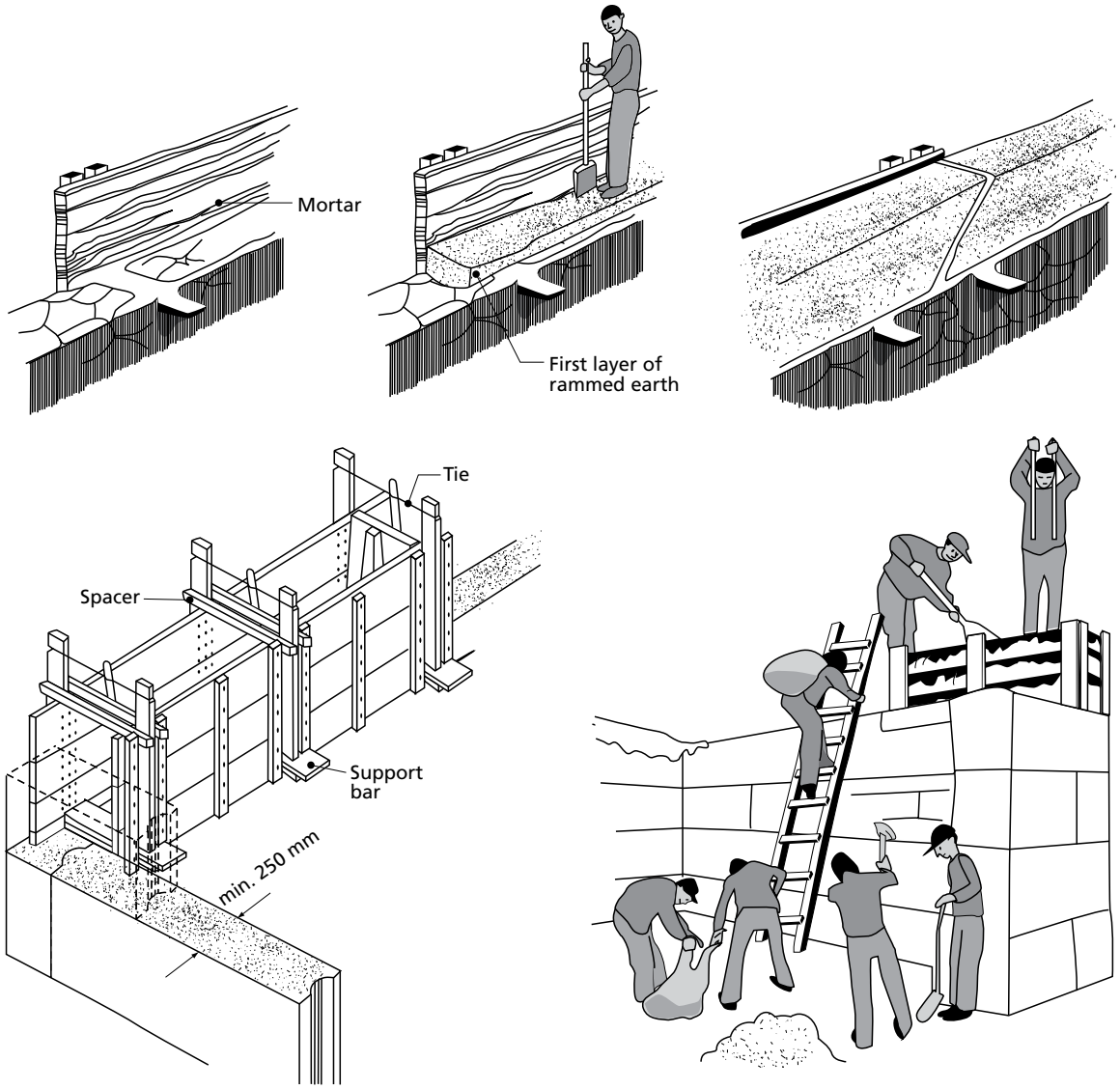


Figure 8.26 **Construction of a rammed-earth wall**

(crosswalls, etc.) should not exceed 4 metres for a 300 mm thick rammed-earth wall

Finish the foundation wall with a sand–cement mortar cap. A mould is then constructed, supported on horizontal brackets running across the wall. The brackets, as well as draw wires above the mould, act as ties and must be sufficiently strong, in conjunction with the rest of the mould, to resist the pressure of the earth during the ramming operations. Fill the earth in thin layers and compact it thoroughly before the next layer is placed.

After the mould has been filled, it is removed and placed on top of the already finished wall. Because the mould is only 500 mm to 700 mm deep, it will have to be moved several times before the finished height of the wall is reached. Notching of the sections will increase the stability of the wall. A workforce that is large enough to allow several operations, such as soil preparation, transport, filling and ramming to be carried out simultaneously, will ensure swift construction.

Gliding formwork for rammed-earth walls

The foundation wall is built to 50 cm above the ground level with stones and lime mortar. Reinforcement in the walls consists of poles or bamboos that are set in the trench when the stones of the foundation wall are laid. The earth panel in the gliding formwork is tamped, layer after layer, until the form is full. The form is then moved and a new panel started. Finally, the upper ring beam is tied to the reinforcement sticks. After finishing the panels, the joints are filled with earth mortar.

Mud-and-pole walls

The construction of mud-and-pole walls is discussed at the end of the section dealing with earth as a building material, along with some other types of mud-wall construction. A pole-frame wall can be built using either thick earth construction (25 cm or more), or thin earth cladding (10 cm or less). As soil-block walls and rammed-earth walls are usually superior to mud-and-

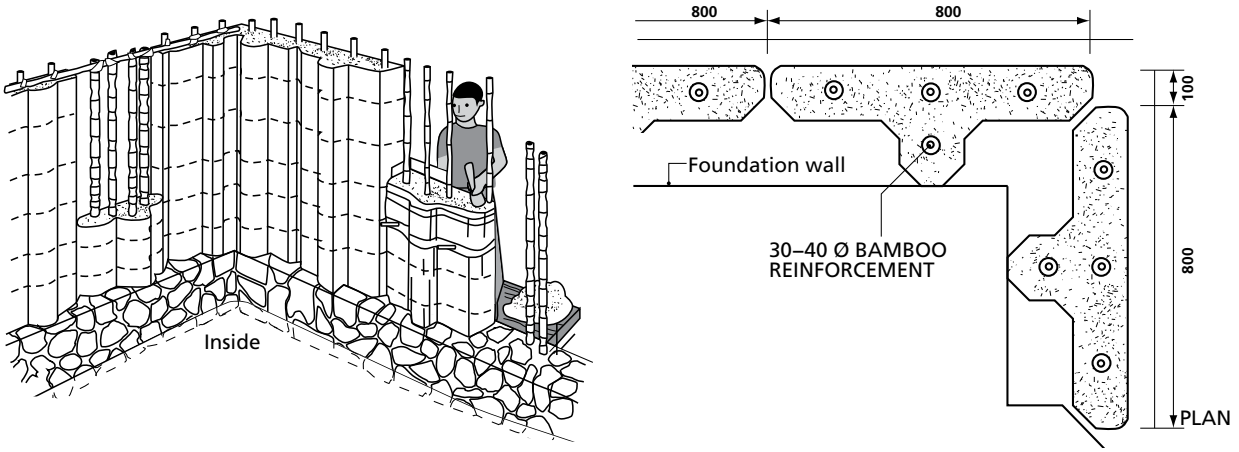


Figure 8.27 **Construction of a rammed-earth wall with a gliding form**

pole walls, the latter should be used only when a supply of durable poles is available and the soil is not suitable for block making. Regardless of the type of wall, the basis for any improvement is to keep the wall dry after construction.

Install a damp-proof course on top of the foundation wall, about 50 cm above ground level. Prefabricate ladders out of green bamboo or wooden poles about 5 cm in diameter. The outside wooden or split bamboo battens are nailed or tied to the ladders as the soil is filled in successive layers. The corners must be braced diagonally. Earthquake resistance is improved by securing the base frame to the foundation with a layer of lime-soil or cement-soil mortar.

Frame walls

Frame walls consist of vertical timber members, called 'studs', framed between horizontal members at the top and bottom. The top member is called the 'plate' and the bottom member the 'sole' or 'sill'. Simple butt joints are used, which are end-nailed or toe-nailed. As a result, the frame is not very rigid and requires bracing in order to provide adequate stiffness.

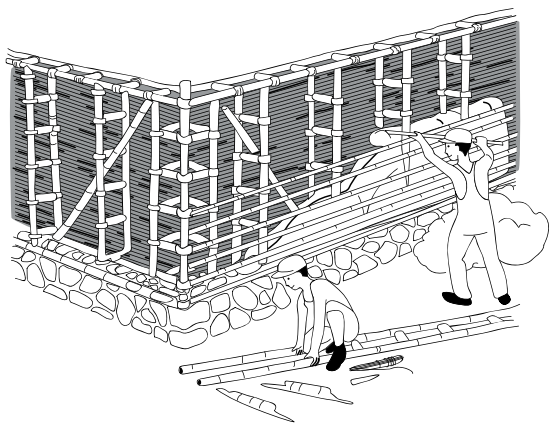


Figure 8.28 **Construction of a mud-and-pole wall**

Although diagonal braces can be used for this purpose, a common method, which is quicker and cheaper, is to use building board or plywood sheathing to stiffen the structure. The studs are commonly spaced on 400 mm or 600 mm centres, which relates to the standard 1 200 mm width of many types of building boards used for sheathing. The load-bearing members of this type of wall are wood, so it is not recommended for use in termite areas, especially if both faces of the frame are finished or covered, making it difficult to detect a termite attack.

Frame construction using timber must be raised out of contact with ground moisture and protected from termites. This is accomplished by construction on a base wall or foundation beam rising to a damp-proof course, or on the edge of a concrete slab floor. As a base for the whole structure, a sill is set and carefully levelled on the damp-proof course, before being securely anchored to the foundation. To maintain the effectiveness of the damp-proof course, it must be sealed carefully at all bolt positions.

A continuous termite shield should be installed between the damp-proof course and the sill, and great care taken to seal around the holes required for the anchor bolts. The sill-plate may be 100 mm by 50 mm when fixed to a concrete base, but should be increased in width to 150 mm on a brick base wall.

Instead of timber, bamboo or round wooden poles can be used as studs and then clad with bamboo mats, reed mats, grass, palm leaves, etc. An alternative is to fix mats to the studs and then plaster the mats with cement plaster or other material. Some structures of this type have a short life owing to damage by fungi and termites. They are also difficult to keep clean and pose a serious fire risk. Figure 8.30 gives brief information on bamboo wall panels that can be made by skilled craftsmen.

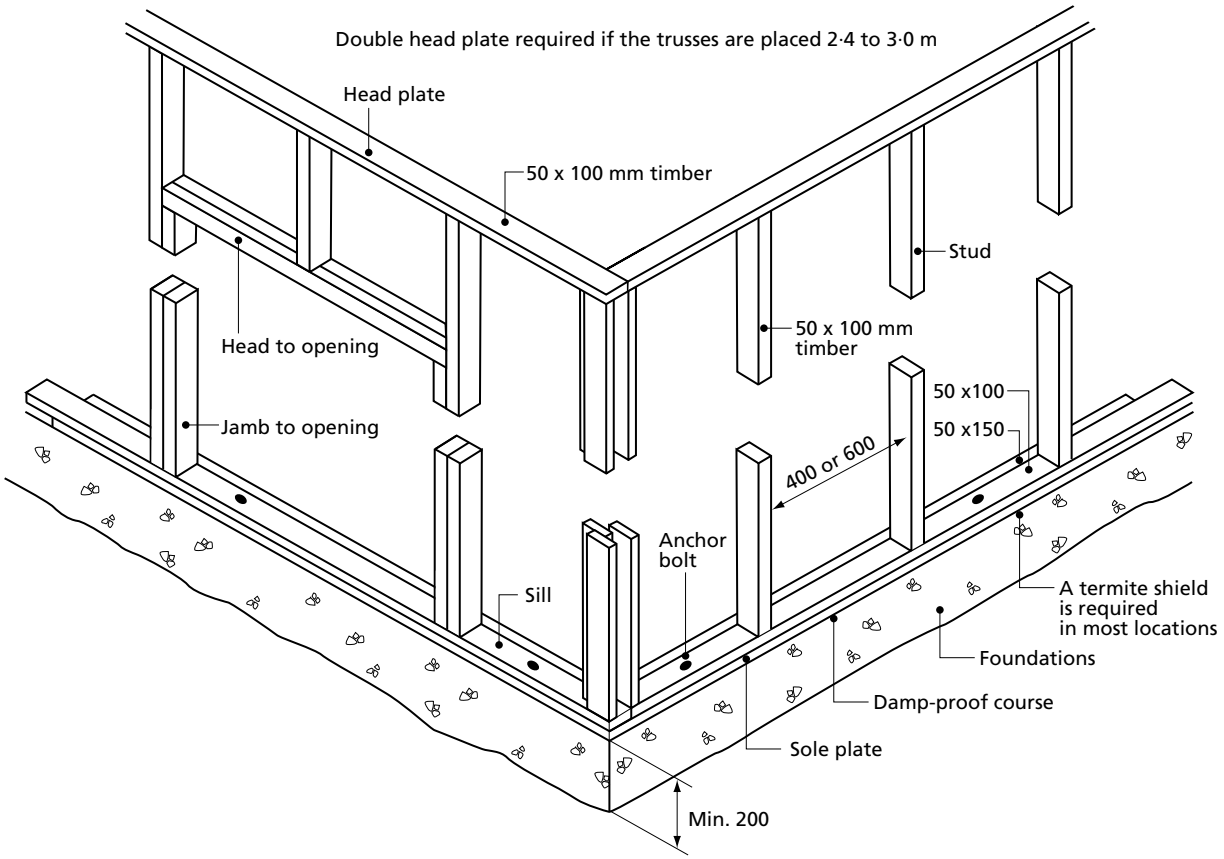


Figure 8.29 **Frame-wall construction**

Facings and claddings

Facings and claddings refer to panels or other materials that are applied as external coverings on walls, to provide protection from the elements or for decorative effect. Facings or claddings are particularly useful for protecting and improving the appearance of the walls of earth structures, which by themselves may be eroded by rain and become quite unsightly.

Facings generally have little or no structural strength and must be attached to a smooth, continuous surface. Plaster or small tiles are examples.

Cladding differs from facing in that the materials have some structural strength and are able to bridge the gaps between the battens or furring strips on which they are mounted. Various types of shingles, larger-sized tiles and both vertical and horizontal timber siding and building boards, such as plywood and asbestos-cement board, are suitable for cladding. Corrugated steel roofing is also satisfactory. The cladding materials must be able to transfer wind loads to the building structure and to absorb some abuse from people and animals. The spacing of the furring strips will influence the resistance of the cladding to such forces.

The spacing for shingles and tiles is determined by the length of the units. The spacing for horizontal timber siding should ordinarily be about 400 mm, while vertical timber siding can safely bridge 600 mm. Plywood of at least 12 mm thickness can bridge 1 200 mm edge to edge if supported at 800 mm intervals in the other direction.

Metal roofing used as cladding can be mounted on furring strips spaced 600 mm apart. It is common for manufacturers of building materials to provide installation instructions, including the distance between support members.

FLOORS

Building floors may be as simple as compacting the soil present on the site before the building is constructed, or as complex as attractively finished hardwood parquet. A well chosen, well-built floor offers protection from vermin and rodents, is easy to clean, and is dry, durable and a valuable asset to a building. For special circumstances, it may be designed to be washable, particularly attractive, thermally insulated, sloped to a drain or perfectly smooth and level.

For farm buildings, including homes, simple floors offering hard, durable surfaces at ground level (grade) are probably adequate for the vast majority of situations. Floors may be built at ground level, i.e. on the soil within the building, in which case they are called 'solid' or 'grade' floors, or they may be supported on joists and beams, in which case they are called 'suspended' or 'above-grade' floors. The finished level of a solid floor

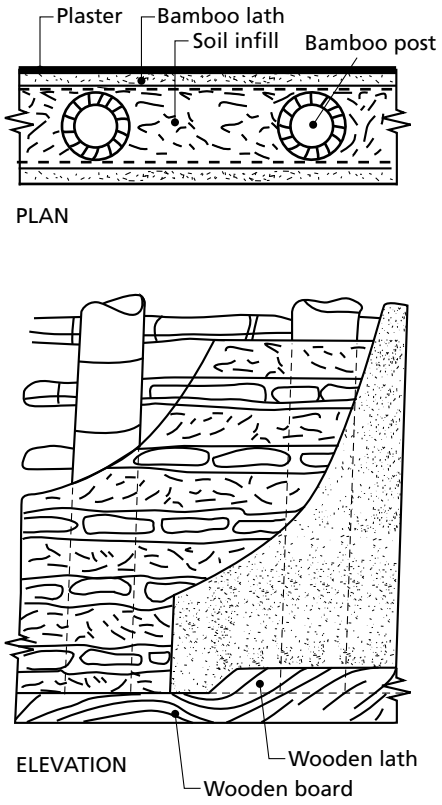


Figure 8.30a **Bamboo and wall**

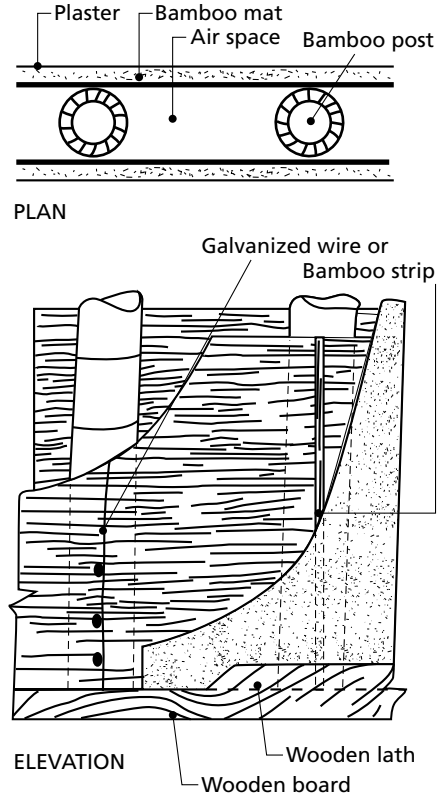


Figure 8.30b **Plastered bamboo wall mats**

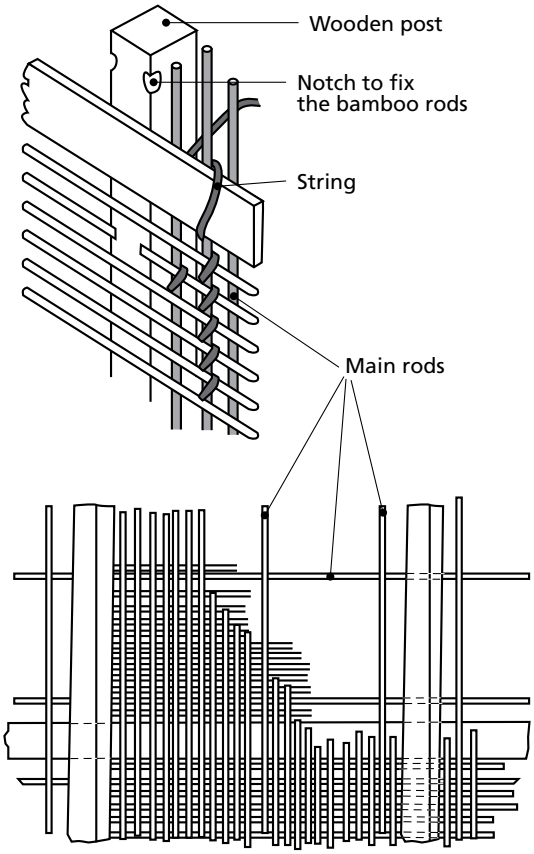


Figure 8.30c **Woven bamboo panels (Japanese wall panels)**

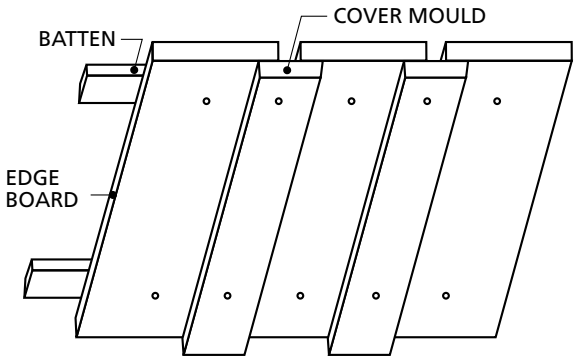
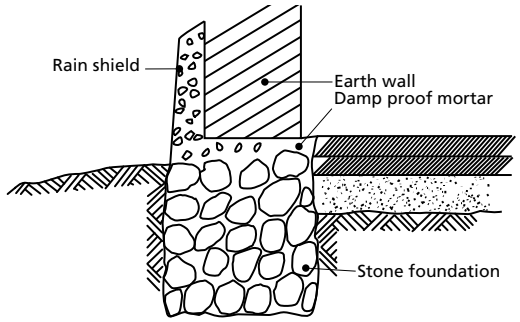


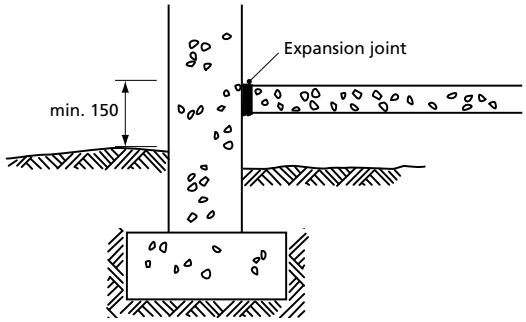
Figure 8.31 **Vertical timber siding. (Note the single nails near the centre of each board and batten to allow for shrinking and swelling.)**

should be at least 150 mm above the outside ground level as a protection against flooding. The topsoil should be removed and replaced with coarse material before the actual floor slab is constructed.



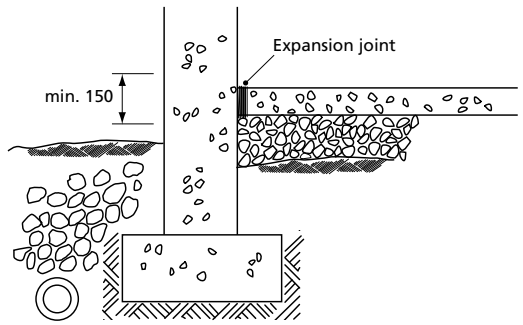
Floor
- Two layers of tamped, stabilized soil (50 mm).
- Tamped sand.
- Existing subsoil (topsoil removed)

Figure 8.32a **Well-drained site**



Floor
- Concrete slab (minimum 75 mm).
- Tamped sand (100–150 mm).
- Existing subsoil.

Figure 8.32b **Well-drained site**



Floor
- Concrete slab (minimum 75 mm).
- Polythene sheet (750 gauge).
- Sand (50 mm) or mortar (25 mm).
- Coarse aggregate (150–200 mm).
- Existing subsoil (eu. compacted).

Figure 8.32c **Site that is poorly drained or where a very dry floor is required**

Figure 8.32 **Construction of solid floors built at ground level**

Solid or grade floors

Tamped soil is often satisfactory for the floors of animal shelters and, perhaps, the homes of subsistence farm families. They should be designed a little above the ground level outside the building and will be improved by being stabilized with anthill clay, cow dung, lime or portland cement.

A discussion of stabilizing materials to use in different circumstances can be found in Chapter 5.

Concrete makes a more durable, harder and cleaner floor. Properly constructed, concrete floors can be made dry enough to make them usable for grain storage or for the farm home. Figure 8.32 shows cross-sections of stabilized soil and concrete floors. Figure 8.32a shows an earth floor suitable for a well drained site, while Figure 8.32b shows a concrete floor that needs to be moderately dry. The single-size coarse aggregate shown in Figure 8.32c is used to prevent the capillary movement of water to the underside of the floor. The polythene sheet prevents moisture from reaching the concrete slab, and the layer of sand or mortar protects the sheet from being punctured.

The concrete mixture chosen for a solid floor will depend on the severity of use and type of loading. For a deep-litter building or a subsistence farm dwelling, a mix of 1:3:6 by weight may be satisfactory for the light service to which it will be subjected. Floors that will be exposed to heavy loads, such as a bag-grain store or a farm repair shop, will need to be stronger. A 1:2:4 mix should be adequate over a good firm base. The floors in a creamery or slaughterhouse are subject to acid erosion and require a richer mix of concrete (1:2:3) to give a durable surface.

Pouring concrete floors

Solid concrete floors should be laid on a level and tamped base of hardcore or gravel. On well-drained sites, sand, or even laterite, can also be satisfactory. The base layer should be at least 100 mm thick. While it is desirable for the finished floor level to be at least 150 mm above the surrounding ground, some fill may be required under the base course. However, fill needs to be thoroughly compacted to provide the required stability and, generally, it is therefore more satisfactory to increase the thickness of the base course.

Any material used for fill or for the base course must be free of organic matter. Hence, the excavated topsoil must be rejected as fill. If a damp-proof barrier (polythene or a 3 mm-thick hot bitumen layer) is to be installed, a layer of sand should be spread over the base. Sand can also be used as blinding on a hardcore base, to reduce the amount of concrete that 'disappears' in the gaps between the stones.

Finally, 75 mm to 150 mm timber screeds are put in place to be used as guides in striking off and levelling the concrete, and reinforcement bars, if required, are put in position. The thickness of the slab will depend on the expected loads, the quality of the concrete used,

the reinforcement and the bearing characteristics of the ground.

A floor area that is larger than about 10 square metres should be divided into bays for concreting. This will help to prevent the development of shrinkage cracks during the curing process, and will allow for each bay to be cast, levelled and finished within a manageable time. Square bays are best and 2.5 metre to 4 metre sides allow a slab to be cast in a single operation.

The concrete can then be mixed and placed. Regardless of the mix chosen, the concrete should be kept as stiff as possible, and the size of the coarse aggregate should not exceed one-quarter of the thickness of the slab. The bays are concreted alternately, as shown in Figure 8.33. When the first set of bays has hardened, the timber screeds are carefully removed and the remaining bays can be cast.

Once the concrete is placed, it is levelled by moving a straight timber along the screeds (or, in the case of the second set of bays, the already-hardened concrete in adjoining bays), using a sawing action. The concrete can then be 'floated' slightly to smooth the surface. After the initial light floating, the bay can be left for a few hours before the final floating to give it a smooth surface. If a non-slip floor is desired, the concrete can be 'broomed' soon after it is placed, to give a rough surface. It should not be touched again until it sets. Once the concrete has set, it should be kept moist for a week.

Suspended or above-grade floors

Timber floors

Suspended timber ground-level floors are useful on sloping sites where a great deal of filling would be required to level the ground for a solid floor.

Timber ground-level floors must be well protected against moisture, fungus and termites, and must therefore be raised above the ground. The space under such a timber floor should be high enough to ensure good ventilation and to allow a person to crawl underneath to inspect the floor. Termite protection is more likely to be effective if the floor is raised above the ground by at least 45 cm.

The supporting piers are frequently built of timber but are better if made of stone, concrete or steel. Hollow concrete blocks, reinforced and filled with concrete, make a strong support. Metal termite shields should be fitted to the top of the foundation wall and to steeper walls and piers.

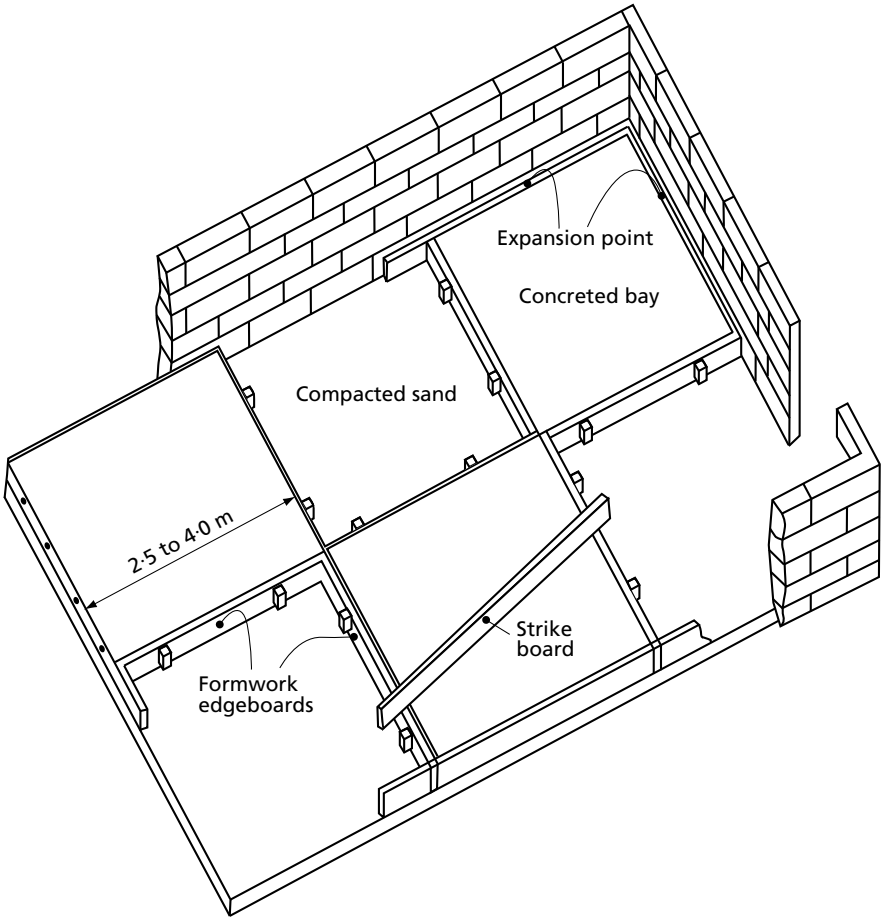


Figure 8.33 **Concrete-floor construction**

The foundation wall beneath a timber ground-level floor must be fitted with ventilation openings to ensure good air exchange in the crawl-space below the floor. The openings should be covered with 10 mm mesh screen to keep rodents out.

When the span is more than 5 metres, joists may be supported by cross-walls built with 150 mm solid concrete blocks laid about 80 mm apart in a honeycomb pattern to allow the free passage of air.

Beams of steel, timber or concrete may be used to support upper floors when the span is over 5 metres.

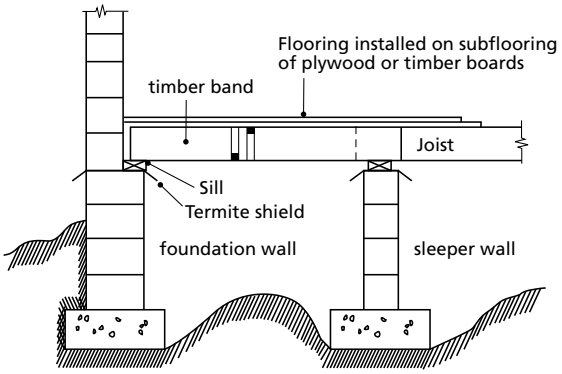


Figure 8.34 **Suspended timber floor construction**

Suspended concrete floors

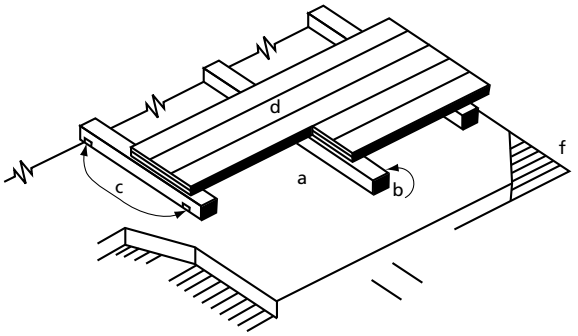
The main advantage of a reinforced concrete suspended floor is that its fire resistance and acoustic insulation are better than that of a timber floor, but it is generally too expensive for use in farm buildings.

In its simplest form it consists of a one-way span slab cast *in situ*, with the reinforcement acting in one direction only between two supports placed not more than 5 metres apart. The reinforcement may be either mild steel main rods with distribution bars wired together at right angles, or reinforcing mesh consisting of main bars and distribution bars electrically welded at the crossings. The reinforcement must be designed by a qualified structural engineer or obtained from a reliable standard design.

Floor finishes

In rural areas, the extra cost of a floor finish is often considered unnecessary, as the durability of the surface of a slab of concrete or stabilized soil is satisfactory for most purposes. However, a floor finish can enhance the appearance of the room, reduce noise or make the floor easier to clean, depending on the type of finish used.

A cement-sand screed or a granolithic finish (one part cement and three parts hard stone chippings laid about 30 mm thick) may be used where an extremely durable finish is needed. Sheet materials and slab tiles are likely to be very expensive, but slab tiles are installed in farm buildings in exceptional cases because of their durability. Figure 8.35 shows a typical wood floor over a solid slab. It is important for the space between the concrete slab and the wood flooring to be ventilated.



a = Cured and dried-out concrete or stabilized-soil slab, preferably with a damp-proof course between slab and hardcore.
b = Joists 50 × 50 mm.
c = Bulldog floor clips.
d = Wood flooring or chipboard.

Figure 8.35 **Wood floor on a solid concrete floor**

ROOFS

A roof is an essential part of any building, in that it provides the necessary protection from rain, sun, wind, heat and cold. The integrity of the roof is important for the structure of the building itself, as well as for the occupants and the goods stored within the building.

The roof structure must be designed to withstand the dead load imposed by the roofing and framing, as well as the forces of wind and, in some areas, snow or drifting dust. The roofing must be leakproof and durable and may have to satisfy other requirements such as fire-resistance, good thermal insulation or a high thermal capacity.

There is a wide variety of roof shapes, frames and coverings from which to choose. The choice is related to factors such as the size and use of the building, its anticipated life and appearance, and the availability and cost of materials. Roofs may be classified in three ways, according to:

1. The plane of the surface, i.e. whether it is horizontal or pitched.
2. The structural principles of the design, i.e. the manner in which the forces set up by external loads is resolved within the structure.
3. The span.

Flat and pitched roofs: A roof is called a flat roof when the outer surface is within 5° of horizontal, whereas a pitched roof has a slope of more than 5° in

one or more directions. Climate and covering material affect the choice of a flat or pitched roof. The effect of climate is less marked architecturally in temperate areas than in areas with extremes of climate. In hot, dry areas, the flat roof is common because it is not exposed to heavy rainfall and it forms a useful outdoor living room. In areas of heavy rainfall, a steeply pitched roof drains off rainwater more rapidly.

Two-dimensional roof structures have length and depth only, and all forces are resolved within a single vertical plane. Rafters, roof joists and trusses fall into this category. They fulfil only a spanning function, and volume is obtained by using several two-dimensional members carrying secondary two-dimensional members (purlins) to cover the required span.

Three-dimensional structures have length, depth and also breadth, and forces are resolved in three dimensions within the structure. These forms can fulfil a covering, enclosing and spanning function and are now commonly referred to as 'space structures'. Three-dimensional or space structures include cylindrical and parabolic shells and shell domes, multicurved slabs, folded slabs and prismatic shells, grid structures such as space frames, and suspended or tension roof structures.

Long- and short-span roofs: Span is a major consideration in the design and choice of a roof structure, although functional requirements and economy have an influence as well.

Short spans of up to 8 metres can generally be covered with pitched timber rafters or lightweight trusses, either pitched or flat. Medium spans of 7–16 metres require truss frames made of timber or steel.

Long spans of more than 16 metres should, if possible, be broken into smaller units. Otherwise these roofs are generally designed by specialists using girder, space deck or vaulting techniques.

In order to reduce the span and thereby reduce the dimensions of the members, the roof structure can be supported by poles or columns within the building, or by internal walls. However, in farm buildings, a free-span roof structure might be advantageous if the farmer eventually wants to alter the internal arrangement of the building. The free space without columns allows greater convenience in manoeuvring equipment as well.

Ring beam: In large buildings that have block or brick walls, such as village stores, a 150 mm^2 reinforced concrete beam is sometimes installed on top of the external walls instead of a wall plate. The objective of this ring beam, which is continuous around the building, is to carry the roof structure in the event of part of the wall collapsing in an earth tremor. It also provides a good anchorage for the roof, to prevent it lifting and to reduce the effects of heavy wind pressure on the walls and unequal settlement.

Types of roof

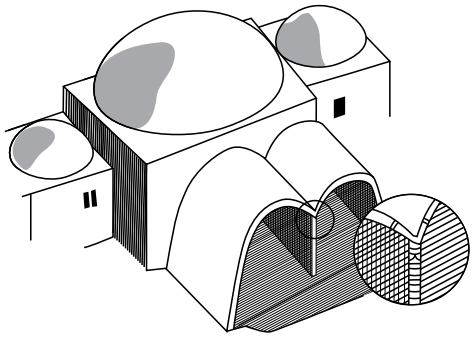
Flat roof

The flat roof is a simple design for large buildings in which columns are not a disadvantage. Although simple beams can be used for spans up to about 5 metres, with longer spans it is necessary to use deep beams, web beams or trusses for adequate support. As farm buildings often need large areas free of columns, it is not common to find flat roofs with built-up roofing. Flat roofs are prone to leaks. To prevent pools of water from collecting on the surface, they are usually built with a minimum slope of 1:20 to provide drainage.

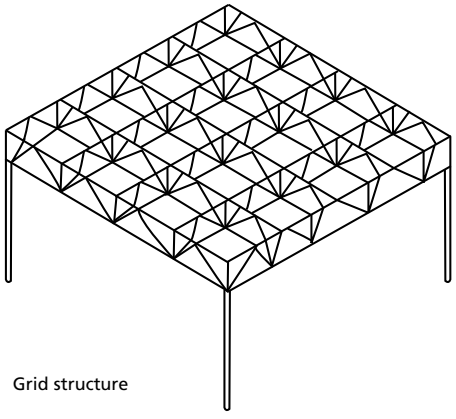
The roof structure consists of the supporting beams, decking, insulation and a waterproof surface. The decking, which provides a continuous support for the insulation and surface, can be made of timber boards, plywood, chipboard, metal or asbestos-cement decking units or concrete slabs.

The insulation material improves the thermal resistance and is placed either above or below the decking.

The most common design for a waterproof surface is the built-up roof using roofing felt. This material consists of a fibre, asbestos or glass fibre base that has



Earth dome and vault



Grid structure

Figure 8.36 **Three-dimensional roof structures**

been impregnated with hot bitumen. The minimum pitch recommended for built-up roofs is 1:20 or 3°, which is also near the maximum if creeping of the felt layers is to be prevented.

For flat roofs, two or three layers of felt are used, the first being laid at right angles to the slope commencing at the eaves. If the decking is made of timber, the first layer is secured with large flathead felting nails and the subsequent layers are bonded to it with layers of hot bitumen compound. If the decking is of a material other than timber, all three layers are bonded with hot bitumen compound. While it is still hot, the final coat of bitumen is covered with layers of stone chippings to protect the underlying felt, to provide additional fire resistance and to increase solar reflection. An application of 20 kg/m² of 12.5 mm chippings of limestone, granite or light-coloured gravel is suitable.

Where three layers of roofing felt are used and properly laid, flat roofs are satisfactory in rainy areas. However, they tend to be more expensive than other types and require maintenance every few years.

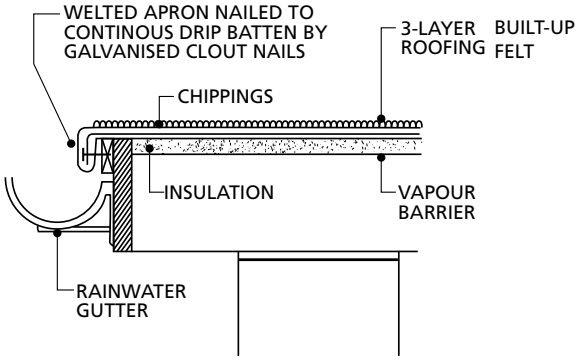


Figure 8.37 **Built-up roofing felt**

Earth roof

Soil-covered roofs have good thermal insulation and a high capacity for storing heat. The traditional earth roof is subject to erosion during rain, and requires regular maintenance to prevent leakage. The roof is laid rather flat, with a slope of 1:6 or less.

The supporting structure should be generously designed of preservative-treated or termite-resistant timber or poles, and should be inspected and maintained periodically because a sudden collapse of this heavy structure could cause great harm. The durability of the mud cover can be improved by stabilizing the top layer of soil with cement, and it can be waterproofed by placing a plastic sheet under the soil. Figures 8.38 and Figure 8.39 show two types of earth roof.

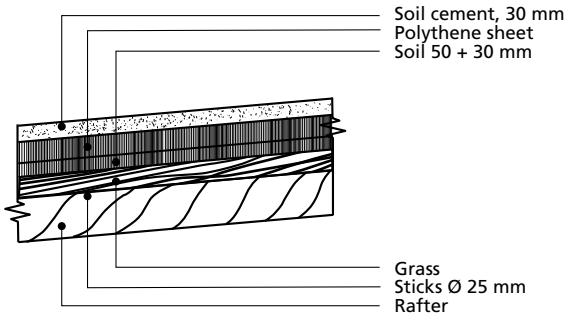


Figure 8.38 **Cross-section of an improved earth roof**

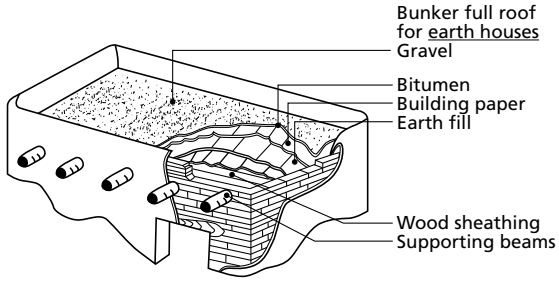


Figure 8.39 **Earth roof with bitumen waterproofing**

However, the introduction of these improvements adds considerably to the cost of the roof. Therefore the improved earth roof is a doubtful alternative for low-cost roofing and should be considered only in dry areas where soil roof construction is known and accepted.

Monopitch roof

Monopitch roofs slope in only one direction and have no ridge. They are easy to build, comparatively inexpensive and recommended for use on many farm buildings. The maximum span with timber members is about 5 metres, so wider buildings will require intermediate supports. Also, wide buildings with this type of roof will have a high front wall, which increases the cost and leaves the bottom of the high wall relatively unprotected by the roof overhang. When using corrugated steel or asbestos-cement sheets, the slope should be not less than 1:3 (17° to 18°). A lower sloping angle may cause leakage, as strong winds can force water up the slope.

The rafters can be made of round or sawn timber or, when wider spans are required, of timber or steel trusses, which can be supported on a continuous wall or on posts. The inclined rafters of a pitched roof meet the wall plates at an angle and their load tends to make them slide off the plate. To reduce this tendency and to provide a horizontal surface through which the load can be transferred to the wall without excessively high compressive forces, the rafters in pitched roofs are notched over the plates. To avoid weakening the rafter,

the depth of the notch (seat cut) should not exceed one-third the depth of the rafter. When double rafters are used, a bolted joint is an alternative. The rafters should always be properly fixed to the walls or posts to resist the uplift forces of the wind.

Double-pitched (gable) roof

A gable roof normally has a centre ridge with a slope to either side of the building. With this design, the use of timber rafters provides for a greater free span (7–8 metres) than a monopitch roof. Although the monopitch design may be less expensive for building widths up to 10 metres, the inconvenience of many support columns favours the gable roof. The gable roof may be built in a wide range of pitches to suit any of several types of roofing material. Figure 8.41 shows a number of the elements associated with a gable roof. The following description refers to Figure 8.41:

- The bottom notch in the rafter that rests on the plate is called the 'seat cut' or 'plate cut'.
- The top cut that rests against the ridge board is called the 'ridge cut'.
- The line running parallel with the edge of the rafter from the outer point of the seat cut to the centre of the ridge is called the 'work line'.
- The length of the rafter is the distance along the work line from the intersection with the corner of the seat cut to the intersection with the ridge cut.
- If a ridge board is used, half the thickness of the ridge board must be removed from the length of each rafter.
- The 'rise' of the rafter is the vertical distance from the top of the plate to the junction of the workline at the ridge.
- The 'run' of the rafter is the horizontal distance from the outside of the plate to the centreline of the ridge.
- The portion of the rafter outside the plate is called the 'rafter tail'.
- The 'collar beam' or 'cross-tie' prevents the load on the rafters from forcing the walls apart, which would allow the rafter to drop at the ridge. The lower the collar beam is placed, the more effective it will be. Occasionally, small buildings with strong walls are designed without collar beams. The only advantage of this design is the clear space all the way to the rafters. Scissor trusses, as shown in Figure 8.51, at the same time allow some clear space.
- The right-hand rafter shows purlins spanning the rafters and supporting a rigid roofing material, such as galvanized steel or asbestos-cement roofing.

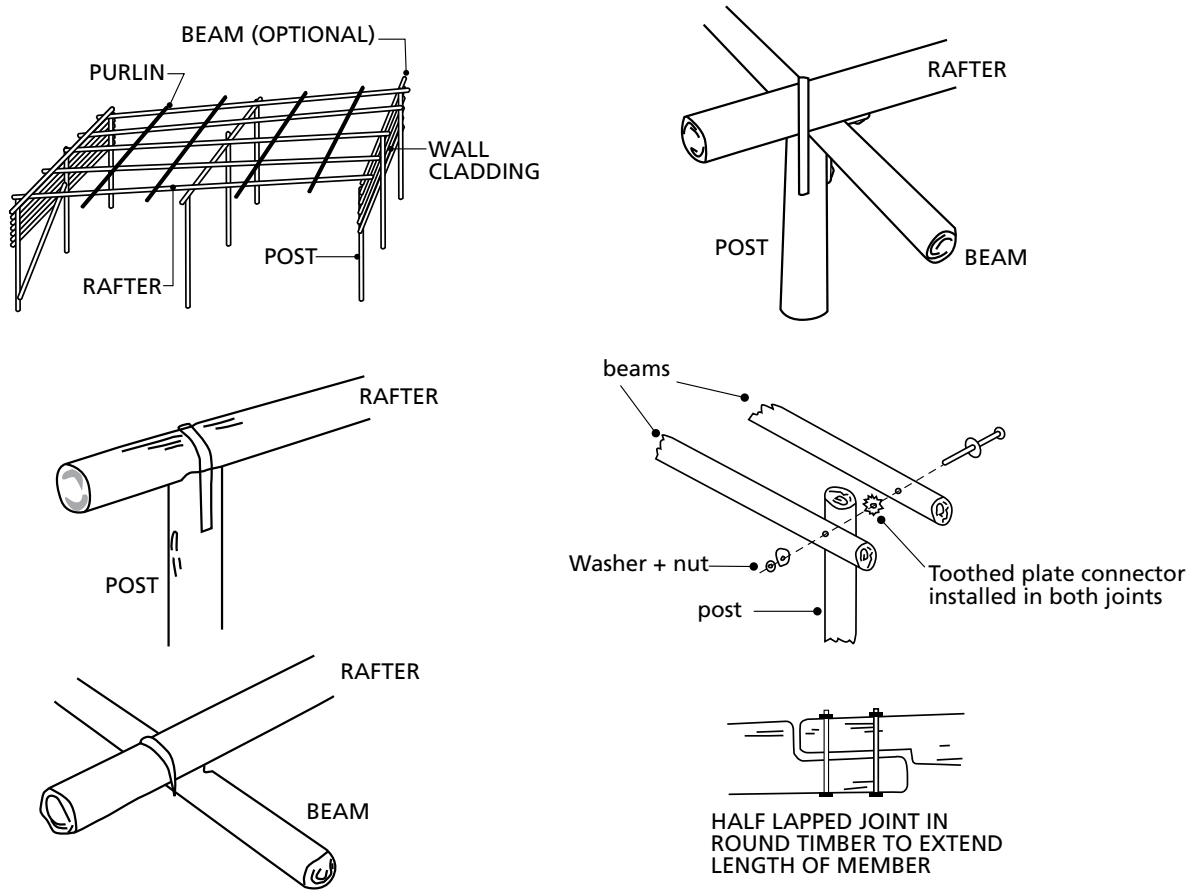


Figure 8.40 **Pole framing for a monopitch building**

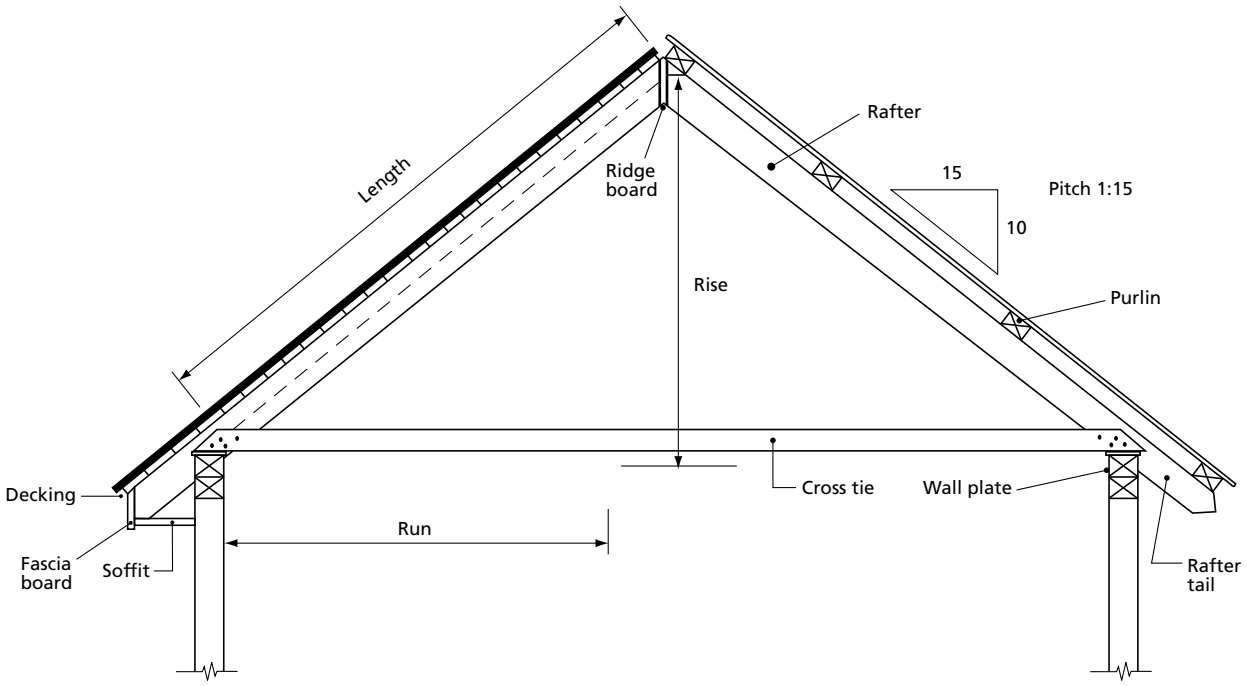


Figure 8.41 **Gable-roof design**

- The left-hand rafter is covered with a tight deck made of timber boards, plywood or chipboard. It is usually covered with a flexible roofing material such as roll asphalt roofing.
- The left-hand eave is enclosed with a vertical 'fascia' board and a horizontal 'soffit' board.
- The pitch is shown on the small triangle on the right side.

The angle of the ridge and seat cuts can be laid out on the rafter with a steel carpenter's square and the appropriate rise and run values, using either the outside of the blades or the inside of the blades of the square (30 cm and 20 cm in the example in Figure 8.42). The length may be found by applying the Pythagoras theorem using the rise and run of the rafter. The length is measured along the workline.

When a gable roof is required to span more than 7 metres, trusses are usually chosen to replace plain rafters. For large spans, trusses will save on the total material used and provide a stronger roof structure. For solid roof decks, the trusses are usually designed to be spaced approximately 600 mm on centre, while for rigid roofing mounted on purlins, a truss spacing of 1 200 mm or more is common.

The agricultural extension service may be able to provide designs for the spans, spacings and loads that are commonly found on farms. Chapter 7 discusses the theory of truss design. Figure 8.43 illustrates a simple truss design.

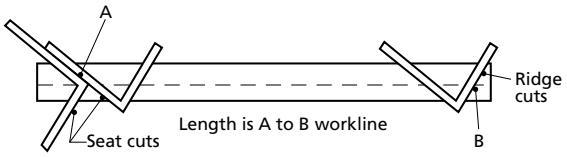


Figure 8.42 **Laying out a common rafter**

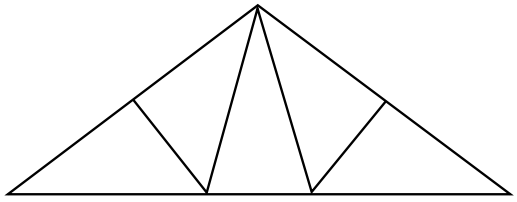


Figure 8.43 **A 'W'-truss design**

As a result of large negative wind loads, roofs are in danger of being blown off. Therefore it is important to anchor the roof trusses properly to the wall plates. This can be done with strips of hoop iron, with one strip tying the wall plate to the wall every 90 cm and the other tying the trusses to the wall plate (see Figure 8.44). In coastal areas, it is advisable to use galvanized strips. If the walls have been plastered, the strips can be recessed in the wall by cutting a channel and covering the strip with mortar.

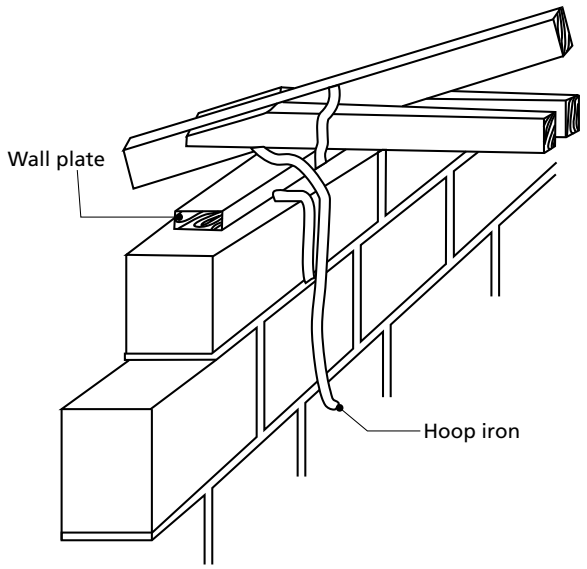


Figure 8.44 **Anchoring trusses to a wall**

For stores or other buildings where tractors and trucks may be driven inside, considerable free height is necessary. Rigid frame structures are well suited for this purpose. A simple frame can be built of gum-poles or sawn timber connected with bolts, as shown in Figure 8.45.

Rigid frames are also factory-manufactured in steel and reinforced concrete.

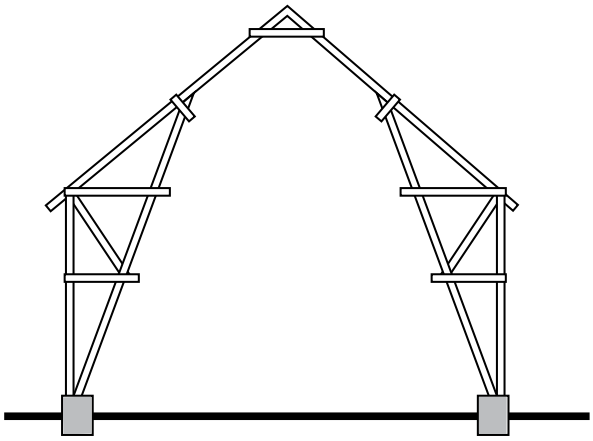


Figure 8.45 **Timber rigid frame**

Hip roof

A hip roof has a ridge in the centre and four slopes. Its construction is much more complicated, requiring compound angles to be cut on all of the shortened rafters and provision for deep hip rafters running from the ridge to the wall plate to carry the top ends of the jack rafters. The tendency of the inclined thrust of the hip rafters to push out the walls at the corners is overcome by tying the two wall plates together with an angle tie. At the hips and valleys, the roofing material has to be cut at an angle to make it fit. The valleys are prone to leakage, and special care has to be taken in the construction.

Four gutters are needed to collect the rainwater from the roof, but this does not necessarily mean that there will be an increase in the amount of water collected. As this is an expensive and difficult way to roof a building, it is only recommended in cases where it is necessary to protect mud walls or unplastered brick walls against heavy driving rain and, for wide buildings, to reduce the height of the end walls.

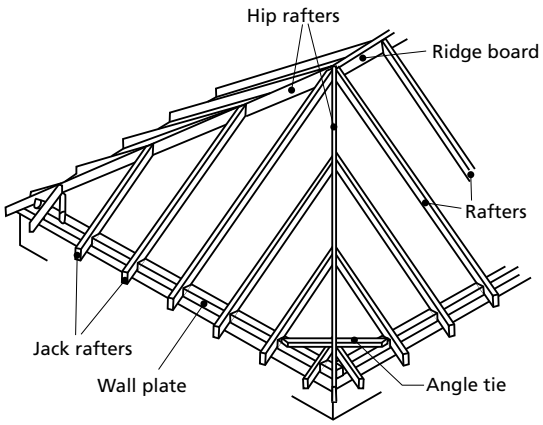


Figure 8.46 **Hip roof framing**

Conical roof

The conical roof is a three-dimensional structure that is commonly used in rural areas. It is easy to assemble and can be built with locally available materials, making it inexpensive. It must be constructed with a slope appropriate to the roofing materials to prevent it from leaking. The conical roof design is limited to rather short spans and to either circular buildings or to small, square buildings. It does not allow for any extension. If modern roofing materials are used, there is considerable waste because of the amount of cutting needed to secure a proper fit.

A conical roof structure requires rafters and purling and, in circular buildings, a wall plate in the form of a ring beam. This ring beam has three functions:

1. To distribute the load from the roof evenly to the wall.
2. To supply a fixing point for the rafters.
3. To resist the tendency of the inclined rafters to press the walls outwards radially by developing tensile stress in the ring beam. If the ring beam is properly designed to resist these forces and secondary ring beams are installed closer to the centre, a conical roof can be used on fairly large circular buildings.

In the case of square buildings, the outward pressure on the walls from the inclined rafters cannot be converted to pure tensile stress in the wall plate. This makes it more like the hip roof structure and it should be designed with angle ties across the wall plates at the corners.

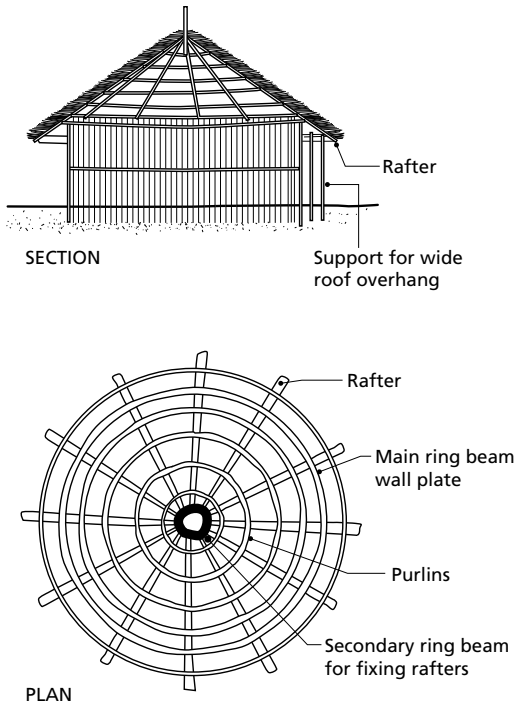


Figure 8.47 **Conical roof design**

Roofing for pitched roofs

Desirable characteristics for roof surfacing materials are:

1. Resistance to the penetration of rain, snow and dust, and resistance to wind effects (both pressure and suction).
2. Durability under the effects of rain, snow, solar radiation and atmospheric pollution, in order to minimize maintenance over the lifetime of the roof.
3. Light in weight, but with sufficient strength to support imposed loads, so that economically sized supporting members can be used.
4. Acceptable fire resistance.
5. Reasonable standard of thermal and acoustic insulation.
6. Acceptable appearance.
7. Reasonable cost over the lifetime of the roof.

The roof shape, type of structure and slope determine the types of roofing material that are suitable. The minimum slope on which a material can be used depends on exposure to the wind, the type of joint and overlap, porosity and the size of the unit.

When considering the cost of various roofing materials, it should be noted that those requiring steeper slopes will need to cover a greater area. Table 8.11 provides a guideline for the relative increase in roofing area as the slope increases. The area for a flat roof has been taken as 100.

The weight of the roof-covering material influences greatly the design of the roof structure and the purling. Table 8.12 shows some examples.

TABLE 8.10
Minimum pitch requirements for roofing materials

Roof covering	Angle	Slope	Rise in mm/m
Built-up bitumen felt	3°	1:20	50
Corrugated metal sheets (minimum 150 end laps)	12°	1:5	200
Corrugated metal sheets (minimum 100 end laps)	18°	1:3	300
Corrugated asbestos-cement sheets (with 300 mm end lap)	10°	1:5.7	180
Corrugated asbestos-cement streets (with 150 mm end lap)	22.5°	1:2.4	410
Single-lap tiles	30°	1:1.7	580
Plain tiles in burnt clay	40°	1:1.2	840
Slates (minimum 300 mm wide)	25°	1:2.1	470
Slates (minimum 225 mm wide)	35°	1:1.4	700
Shingles (wood)	35°	1:1.4	700
Thatch of palm leaves (makuti)	34°	1:1.5	670
Thatch of grass	45°	1:1	1 000
Stabilized soil	9°	1:6	170
In situ mud (dry climates only)	6°	1:10	100
Fibre-cement roofing sheets	20°	1:2.8	360
Concrete tiles (interlocking)	17.5°	1:3.2	320

Purlins

The spacing of the purlins that support the roofing depends on the size and rigidity of the roofing material. The size of the purlins depends on the spacing of the rafters and purling, the weight of the roofing material and the loading on the roof from wind, people working on roof construction or maintenance and, in some areas, snow. Round or sawn timber is the most common material used for purlins because roofing material can be attached easily by nailing. When the spacing of trusses is greater than 2.5–3.0 metres, timber purlins are not feasible and steel profiles are used instead. The profile can be an angle iron or a Z-profile made from plain iron sheets.

Small units, such as slates, tiles and shingles, are fixed to closely spaced battens of rather small section, which means that the rafters must be closely spaced.

TABLE 8.11
Relative areas of roofs of various slopes

Angle	Slope	Relative area of roofing
0°	-	100
10°	1:5.7	102
15°	1:3.7	104
20°	1:2.7	106
25°	1:2.1	110
30°	1:1.7	115
35°	1:1.4	122
40°	1:1.2	131
45°	1:1.0	141
50°	1:0.8	156
55°	1:0.7	174
60°	1:0.6	200

TABLE 8.12
Weights of roofing materials

Material	Weight kg/m²
Corrugated aluminium sheet	2.5–5 depending on gauge
Corrugated steel sheets	6–9 depending on gauge
Corrugated steel sheets, laid	8–12 depending on gauge
Asbestos-cement sheets	14
Asbestos-cement sheets, laid	16
Slates, laid	40
Tiles, laid	65

Thatch

Thatch is a very common roofing material in rural areas. It has good thermal insulation qualities and helps to maintain reasonably uniform temperatures within the building, even when outside temperatures vary considerably. The level of noise from rain splashing on the roof is low but, during long, heavy rains, some leakage may occur. Although thatch is easy to maintain, it may also harbour insects, pests and snakes.

A number of different plant materials, such as grass, reeds, papyrus, palm leaves and banana leaves, are suitable and inexpensive when locally available. Although the materials are cheap, thatching is rather labour-intensive and requires some skill.

The durability of thatch is relatively low. In the case of grass, major repairs will be required every two to three years, but when thatch is laid well by a specialist and properly maintained, it can last for 30 years or more. Although the supporting structure of wooden poles or bamboo is simple, it must be strong enough to carry the weight of wet thatch.

The use of thatch is limited to rather narrow buildings because the supporting structure would otherwise be complicated and expensive, and the rise of the roof would be very high owing to the need for a very steep slope. Palm leaves should have a slope of at least 1:1.5 (but preferably 1:1) and grass thatch should have a minimum of 1:1 (but preferably 1:0.6). Increasing the slope will improve durability and reduce the risk of leakage. The risk of fire is extremely high but may be reduced by treating the thatch with a fire-retardant, as described later.

Grass thatch

Grass for thatching should be:

- hard, fibrous and tough, with a high content of silicates and oils and a low content of easily digestible nutrients, such as carbohydrates, starches and proteins.
- free of seeds and harvested at the right time.
- straight, with thin leaves at least 1 metre long.

Proper thatching requires stems that are parallel and densely packed, with the cut-side pointing outwards. A steeply sloping roof frame of 45° or more should be used. The eaves should be low to offer protection for the walls. For best results, the roof shape should be conical, pyramidal or hipped in shape, rather than double-pitched where the verges present weak points.

For easy handling, the grass should be tied into bundles. The thatching is started from the eaves, in widths of about 1 metre. A number of grass bundles are placed next to each other on the roof, with the base of the stems to the bottom. The grass is tied to the purlins with bark fibre or, preferably, tarred sisal cord. In subsequent layers, the bundles are laid to overlap the layer underneath by half to two-thirds of their length, which means that there will be two to three layers in the finished thatch.

A long needle is used to push the string through and tie the bundles of grass onto the roof laths. Then the bundles themselves are untied and, with the hands, the grass is pushed into the right position to give a smooth surface to the roof. Then the string is pulled to fix the grass securely in place. Another method leaves the bundles of grass as they are, giving the roof a stepped surface. The thickness of the new thatch layers varies between 15 cm and 20 cm but later it will become somewhat thinner as a result of settling.

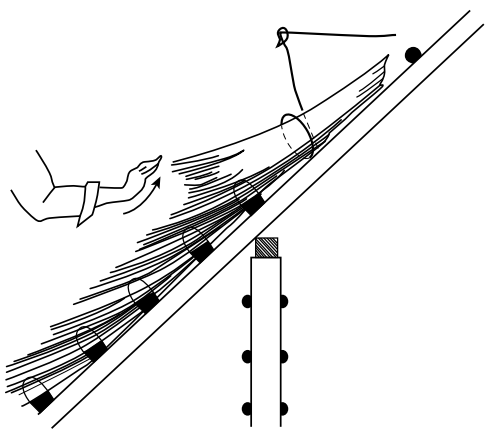


Figure 8.48 **Thatching with grass**

The bottom of the first thatch has to be stitched onto the lowest batten. The second layer must overlay the stitching of the first row and include the top section of the layer below in the actual stitch. It is best to have each layer held by three rows of stitching. The stitching of each row must be completely covered by the free ends of the next layer above it.

The grass or straw is bound in bundles to the battens, forming thatch boards. These boards are manufactured on the ground and bound to the rafters beginning at the eaves and continuing to the ridge. Each board covers the board underneath with its free ends.

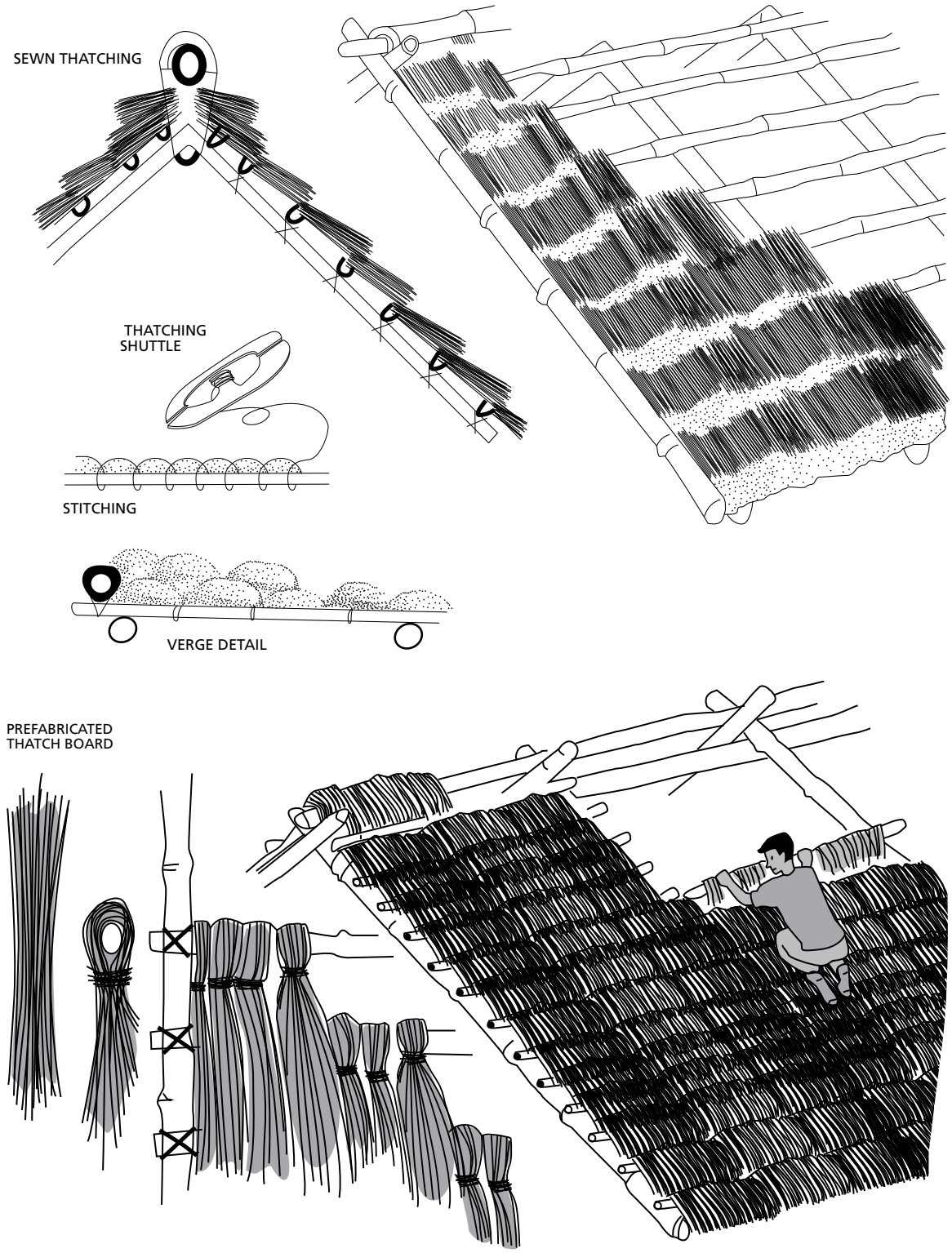


Figure 8.49 **Methods of grass thatching**

Palm leaf thatch (makuti)

Palm leaves are often tied into makuti mats, which are used for the roof covering. They consist of palm leaves tied to a rib (part of the stem of the palm leaf) using the dried fibre of doum palm leaves or sisal twine.

The mats are laid on the rafters (round poles) and the stems tied to the rafters with sisal twine. The mats are usually produced to a standard size of 600 mm × 600 mm and laid with a 100 mm side lap, requiring rafter spacing of 500 mm. An average of 75 blades will be required to make a good-quality mat measuring 600 mm wide. Spacing up the roof slope, i.e. the distance between the ribs of the makuti mats, is usually 150 mm to 100 mm, forming a four- to six-layer covering 5 cm to 8 cm thick.

Figure 8.51 shows three types of ridge caps that can be used on thatched roofs.

Papyrus thatch

First a papyrus mat is placed on top of the purling, second a layer of black polythene and, last, another one or two papyrus mats to complete the roof. These materials are fixed to the purlins with nails and iron wire. Nails are fixed to the purlin with a spacing of 15 cm to 20 cm, after which the iron wire is stretched over the top of the papyrus mat and secured to the nails. The papyrus has a life span of about three years but it can be extended by treating the papyrus with a water-repellent paint.

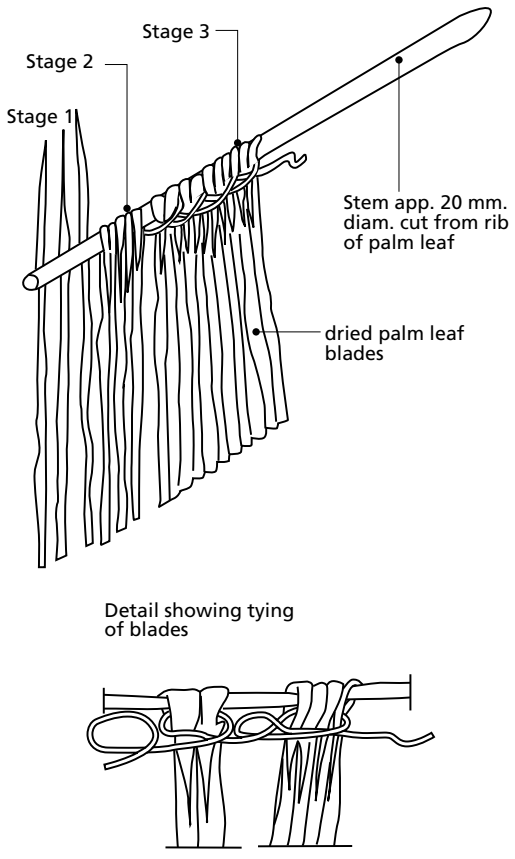


Figure 8.50 **Assembling makuti mats**

Fire-retardant for bamboo and thatch

Fire-retardant paints are available as oil-based or water-based finishes. They retard ignition and the spread of flame over surfaces. Some are intumescent, which means that they swell when heated to form a porous insulating coating.

A cheap fire-retardant solution can be prepared from fertilizer-grade diammonium phosphate and ammonium sulphate. The solution is made by mixing 5 kilograms of diammonium phosphate and 2.5 kilograms of ammonium sulphate with 50 kilograms of water. The principal disadvantage is that it is rendered less effective by leaching with rain. Therefore the fire-retardant impregnation must be covered with a water-repellent paint. The entire roof construction, i.e. bamboo trusses, strings, wooden parts and thatch, should be treated with the fire-retardant. The following procedure is recommended.

Impregnation of thatch

1. Dry the thatching materials, such as reeds, palmyra leaves, bamboos or ropes, by spreading them out in the sun.
2. Prepare the solution of fertilizer grade diammonium phosphate, ammonium sulphate and water as recommended.
3. Immerse the material in the chemical solution and allow it to soak for between 10 hours to 12 hours. A chemical loading of between 10 percent to 14 percent by weight of the thatch (dry basis) is adequate.
4. Take out the material, drain any excess solution, and dry it in the sun once more.
5. Prepare the roof thatch in the conventional manner using the impregnated material and similarly treated framing material.

Such roofs do not catch fire easily and fire spreads very slowly.

Galvanized corrugated steel sheets

Galvanized corrugated steel sheets (GCS) are the cheapest of the modern corrugated sheeting materials and are widely used as roofing material for farm buildings. While uprotected steel would have a very short life, a zinc coating (galvanizing) adds substantial protection at a relatively low cost. Alternative coatings for steel sheets are bitumen, polyvinyl chloride (plastic) on zinc, asbestos, felt and polyester. If the coating is damaged, the steel will rust. When the first signs of rust appear, the sheet should be coated with a lead-based paint to stop the rusting.

The main advantages of galvanized corrugated steel are:

1. Its relatively light weight makes the sheets easy to transport and flexible so they are not easily damaged during transport.
2. It is easy to install and handle. However, the edges of the sheets are often very sharp and can

cause cuts in clothing and skin. The sheets may be cut to any required length, and the roofing nails can be driven through the sheets directly without drilling holes.

3. The supporting structure can be relatively simple. Owing to the flexibility of the sheets, minor movements of the supporting structure can occur without causing damage.
4. The sheets are quite durable if they are maintained and are not attacked by termites or fungus. They are watertight and non-combustible.
5. They can be dismantled and reused, provided that the same nail holes are used.

The main disadvantages of GCS are its poor thermal properties and the noise caused by heavy rainfall and thermal movements. The thermal and acoustic properties are improved by using an insulated ceiling.

Most corrugated steel sheets have corrugations with a 76 mm pitch and 19 mm depth. Thickness varies between 0.3 mm and 1.6 mm. Thicknesses of 0.375 mm to 0.425 mm are recommended for farm buildings.

The standard widths normally marketed are 610 mm, 762 mm and 1 000 mm. Lengths range from 2–4 metres (see Figure 8.53 and Tables 8.13 and 8.14).

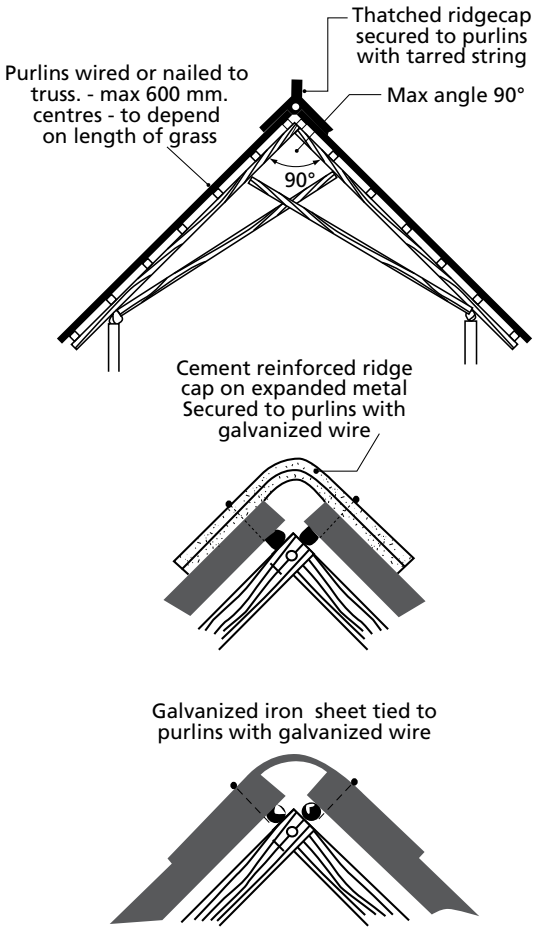


Figure 8.51 **Alternative ridge caps for thatch roofs**

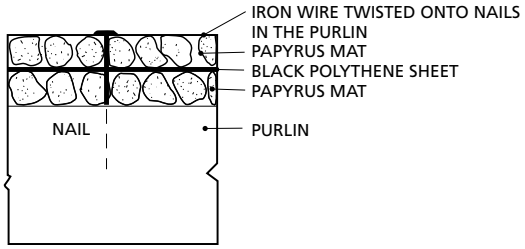


Figure 8.52 **Papyrus–polythene roof**

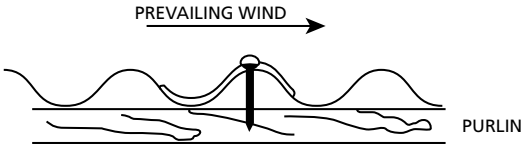


Figure 8.53 **Corrugated roofing with overlap**

TABLE 8.13
Recommendations for the slope, end lap and side lap of corrugated steel roofing

Type of position	Minimum slope	Minimum end lap	Minimum side lap
Sheltered site	1:5	150 mm	1.5 corrugation
	1:3	100 mm	1 corrugation
Normal site	1:3	100 mm	1.5 corrugation
Exposed site	1:3	150 mm	2 corrugation

TABLE 8.14
Covering width for different side lap and type of corrugated iron sheet

			Covering width (mm)		
			Number of corrugations for the side lap		
Type	Number of corrugations	Overall width (mm)	1	$1^1/_2$	2
Corrugated sheet nominal 8/76	8	610	533	495	457
Corrugated sheet nominal 10/76	10	762	686	645	610

Laying the sheets

The spacing of the purlins will depend on the thickness of the sheets used. As a guide, the maximum spacing of purlins for 0.475 mm sheets is 1 500 mm. The purlins should be at least 50 mm wide to make nailing easy.

Laying of the sheets should start from the eave and away from the prevailing wind. The side laps will then be away from the wind, preventing water from being forced into the lap.

It is very important for the first sheet to be laid at right angles to the eave and the ridge, as this means that all the rest will also be perpendicular to the ridge. The first row of sheets is laid with a 50 mm overhang beyond the fascia board.

Special roofing nails are used to fix the sheets to timber purling. They are 67 mm long and average about 100 nails per kilo. Under average conditions, the nails should be placed at every second corrugation on the purlin at the eave, and then at every third corrugation on other purling. A stretched string along the purlin makes it easier to nail the sheets. Extra nails are needed along the verge (gable-end overhang). The nails should always be placed at the ridge of the corrugation to avoid the risk of leakage. Roofs in exposed positions require closer nailing. All end laps must occur over purling.

Ridging is normally available in pieces 1 800 mm in length. They should be fitted with a 150 mm overlap. Other accessories, such as close-fitting ridges, eave-filler pieces and gutters, are available from some suppliers.

The number of sheets to be purchased for a roof can be calculated using the following formula:

Number of sheets = (Length of roof × width of roof)
/ (Length of sheets × covering width)

Note that the length of the sheets in the formula is the nominal length minus the end lap. When making the bill of quantities for a building, the calculated number of sheets should be increased by about 10 percent to allow for waste during transport and installation.

Asbestos-cement sheets

The advantages of asbestos-cement sheets (A-C) compared with GCS sheets are:

1. Longer life if properly fitted.
2. Less noise from heavy rain and thermal movements.
3. More attractive.
4. Better thermal insulation properties.

The disadvantages are:

1. They are heavier (the weight per square metre is more than twice that of GCS), therefore it is more expensive to transport and requires a stronger roof structure.
2. Brittleness causes a high rate of wastage from breakage during transport and installation. A more rigid roof structure is necessary, as the sheet does not allow for more than very small movements of the supporting structure without cracking. Walking on the roof may also cause cracking.
3. They are labour-intensive because of weight and brittleness.
4. The corners of the sheets must be mitred prior to fitting, and holes for the fixing screws must be drilled.

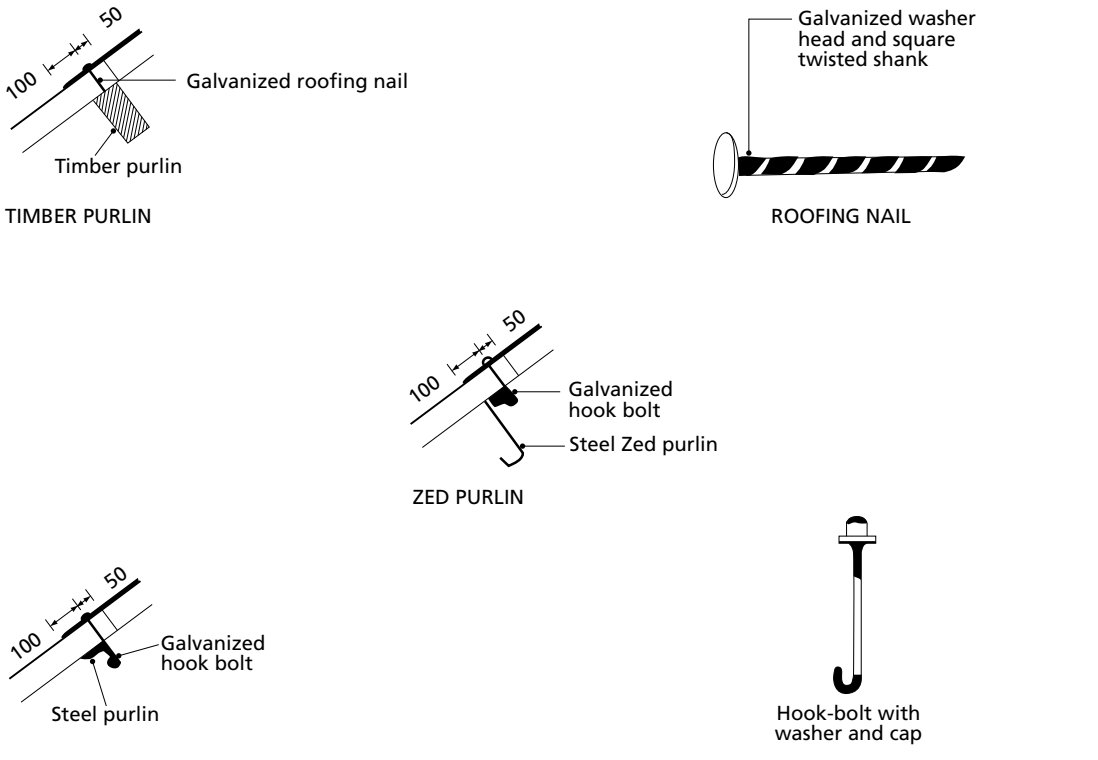


Figure 8.54 **Methods of fastening corrugated roofing to purling**

5. They become discoloured easily with dust and algae.
6. The manufacture and processing of asbestos products presents hazards to health.

Corrugated asbestos-cement sheets are normally marketed in a variety of corrugations and sizes. However, the most common corrugation used for farm buildings has a pitch of 177 mm and a depth of 57 mm. The sheet width is 920 mm. It is supplied in lengths ranging from 1.5 metres to 3 metres. The effective coverage width is 873 mm.

Storage and handling

At the building site, the sheets should be stacked on timber bearers levelled with each other at not more than 1 metre centres on firm, level ground. The sheets can be stacked to a height of approximately 1.2 metres without risk of damage. The sheets should be handled by two people – one at each end.

During installation, roof ladders or crawl boards must be used to ensure safety and to avoid possible damage to the sheets. Under no circumstances should anyone walk on the sheets between two purlins.

Laying the sheets

Corrugated A-C roofing should be installed with a slope of 1:2.5 (22°), with an end lap of at least 150 mm under normal conditions. Under exposed conditions a 200 mm end lap is better. The sheets are designed for a side lap of half a corrugation in all situations.

Purlins must be of sawn timber in order to provide a flat support for the sheets, and must be designed with a minimum of deflection. For the type of sheets described here, a maximum purlin spacing of 1.5 metres is recommended. If used as wall cladding, the spacing can be increased to 1.8 metres.

Sheets should be laid from left to right, or right to left, depending on the direction of the prevailing wind. Side laps must always be sheltered from the main wind direction.

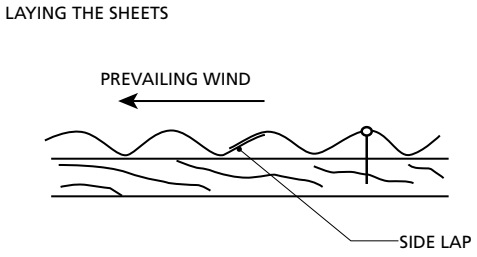


Figure 8.55 **Lapping the roofing against the prevailing wind**

Mitring the corner of the sheets at the overlaps is essential to ensure correct positioning and to allow the sheets to lie flat. The smooth surface of the sheet should be laid uppermost. Laying of the sheets should commence at the eaves (or from the lowest course for cladding). The necessary mitring is shown in Figure 8.56.

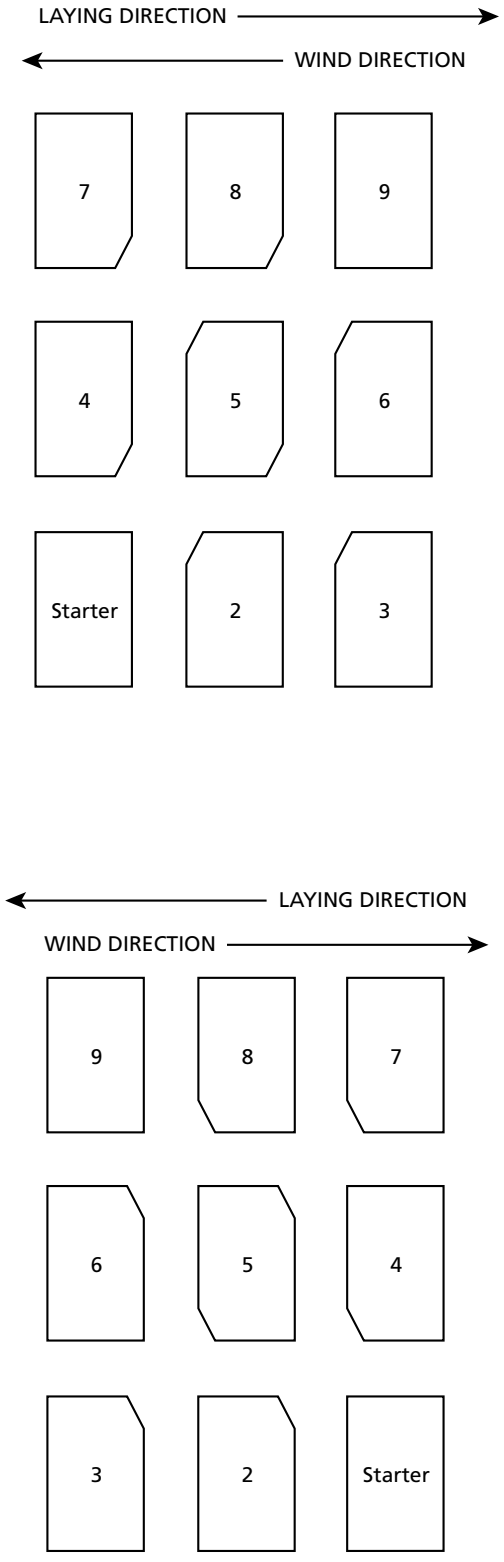


Figure 8.56 **Mitring asbestos-cement sheets**

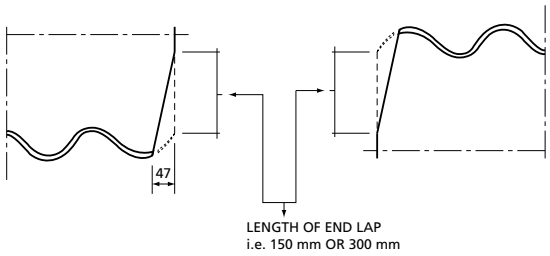


Figure 8.57 **Mitre dimensions**

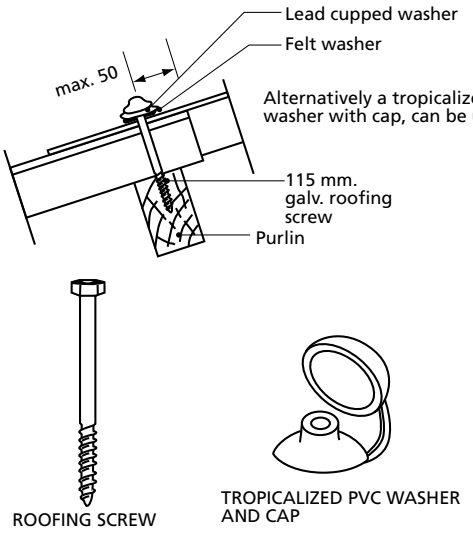


Figure 8.58 **Screws and caps for asbestos-cement roofing**

Mitring

The correct mitre is most important. It should be made from a point along the edge of the sheet equivalent to the end lap, i.e. either 150 mm or 200 mm, to a point along the end of the sheet equivalent to the side lap 47 mm. The gap between the mitres should be at least 3 mm, but should not exceed 6 mm. The sheets can be cut with a handsaw or a sheet hacksaw.

Fixing the sheets

Holes must be drilled 2 mm to 3 mm larger than the diameter of the roofing screws to be used to allow for movement within the framework of the building and the sheets themselves. All holes must be on the crown of the corrugation. It is important to remove all drilling dust before washers are put in position, otherwise water may be able to penetrate. Screws should be finger-tight until the correct alignment of the sheets in relation to the purlin has been checked. They should then be tightened until some resistance is felt. Screws should be located in the crown of the second and fifth corrugation of a sheet of seven corrugations. All end laps must occur over the purlins.

Sisal-cement roofing sheets

These sheets are normally heavier and more brittle than asbestos-cement sheets, which means that they will require a stronger roofing structure and even more caution during handling and laying. In all other respects they are similar to asbestos-cement sheets, and are used for construction in the same way.

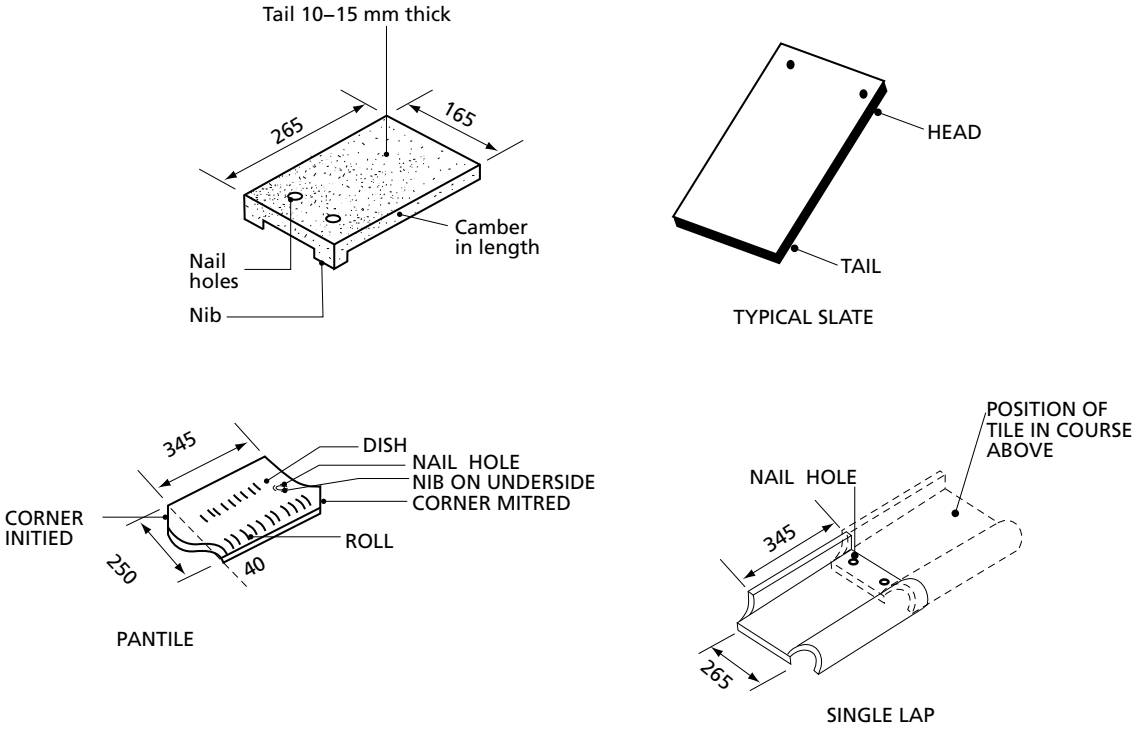


Figure 8.59 **Examples of single-lap tiles and slate**

Corrugated aluminium sheets

Corrugated aluminium (CA) sheets are lighter and more durable than GCS sheets, but are more expensive. When new, the sheets have a bright, reflective surface but, after a year or more, oxidation of the surface will reduce the glare. There is never any need to paint aluminium sheets for protection.

The reflective surface will keep the building cooler than with GCS sheets but, because aluminium is softer, the roof is more likely to tear away in a heavy wind storm. Aluminium also has greater thermal expansion than steel, resulting in noisy creaks and more stress on fasteners.

Corrugated aluminium sheets are normally supplied with the same corrugation and in the same sizes as GCS. For use in farm buildings, a thickness of 0.425 mm is recommended. The sheets are laid and fixed in the same manner as GCS.

Fibreglass-reinforced plastic sheets

These sheets are shaped like those of steel, asbestos cement or aluminium and are used to replace some of the sheets in a roof to give overhead light. They are translucent and give good light inside large halls, workshops etc. They are long-lasting, simple to install and provide inexpensive light, although the sheets themselves are expensive. They are combustible and must be cleaned occasionally.

Roof tiles and slates

Tiles were originally handmade using burnt clay, but now they are manufactured by machine from clay, concrete and stabilized soil in several sizes and shapes. Plain tiles are usually cambered from head to tail so they do not lie flat on each other. This prevents capillary movement of water between the tiles. The shaped side lap in single-lap tiling takes the place of the double end lap and bond in plain tiles or slates. Many types of single-lap tile are available, examples of which are shown in Figure 8.59.

Slates were originally made from natural stone, but now they are also manufactured from asbestos-cement and sisal-cement. As plain tiles and slates have similar properties and are laid and fixed in the same manner, they will be discussed together.

Tiles and slates are durable, require a minimum of maintenance and have good thermal and acoustic properties. The units themselves are watertight, but leaks may occur between the units if they are not laid properly. However, handmade tiles tend to absorb water, and stabilized-soil tiles may erode in heavy rains. While they are fairly easy to lay and fix, being very heavy, they require a very strong supporting roof structure. However, the weight is advantageous in overcoming uplifting wind forces. The dead weight of the covering will normally be enough anchorage for the roofing, as well as the roof structure.

When rainwater falls on a pitched roof, it will fan out and run over the surface at an angle determined by the pitch of the roof. Normally, the convention is the steeper the pitch the narrower the angle, and the lower the pitch the wider the angle. Wider slates will be required for low-pitch roofs.

Water running off tile *A* runs between *B* and *C* and spreads between tiles *B* and *D* and *C* and *D* as shown by the hatched area (see Figure 8.60). It then runs because of the lap, onto tiles *E* and *F* close to their heads. Note that tiles are normally laid close together at the sides.

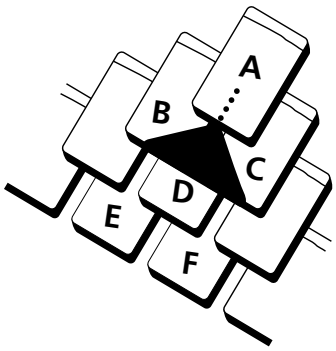


Figure 8.60 **Water drainage on tiles**

TABLE 8.15
Slate and tile size, pitch and lap

Unit	Minimum	Minimum	Minimum lap (mm)	
Size	Pitch	Slope	Normal sites	Exposed sites
Slates				
305 mm × 205 mm	45°	1:1	65	65
330 mm × 180 mm	40°	1:1.2	65	65
405 mm × 205 mm	35°	1:1.4	70	70
510 mm × 255 mm	30°	1:1.7	75	75
610 mm × 305 mm	25°	1:2.1	90	100
610 mm × 355 mm	22.5°	1:2.4	100	N/A
Plain Tiles*				
Concrete and machine pressed	35°	1:1.4	65	75
Stabilized soil	45°	1:1	65	75

* Standard size 265 mm × 165 mm, laid with a 32 mm side lap

Although plain tiling and slating provides an effective barrier to rain, wind and dust penetrate through the gaps between the units. Therefore boarding or sheeting may be placed under the battens on which the tiles or slates are to be hung. Roofing felt is the material most commonly used for this purpose.

In laying plain tile or slate, there must always be at least two thicknesses covering any part of the roof, butt-jointed at the side and placed so that no vertical joint is immediately over another vertical joint in the course below. To ensure this, shorter-length units are

required at the eaves and the ridge, and each alternate course is commenced with a tile or slate of one-and-a-half units in width. The ridge is capped with special units bedded in cement mortar.

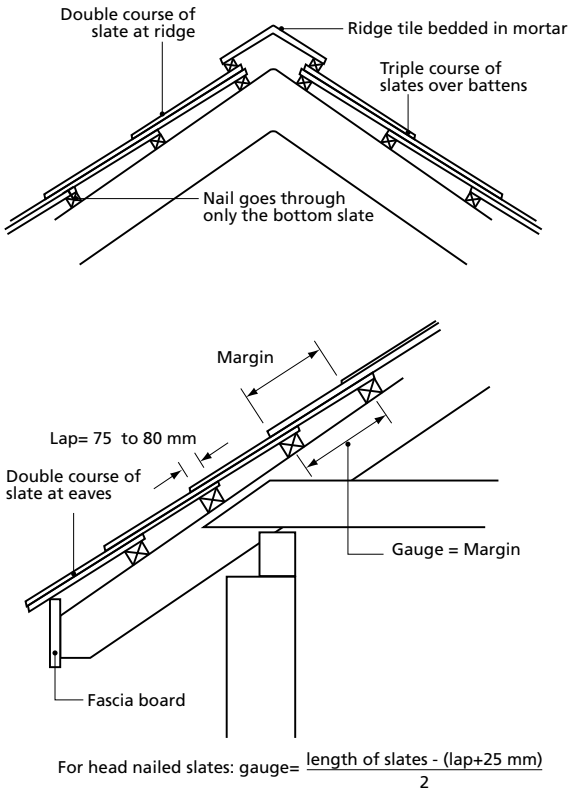


Figure 8.61 **Installation of slates**

The hips can be covered with a ridge unit, in which case the plain tiling or slating is laid underneath and mitred at the hip. Valleys can be formed using special units.

Plain tiles are ordinarily fixed with two galvanized nails in each tile at every fourth or fifth course. However, in very exposed positions every tile should be nailed.

Slates, which do not have nibs securing them to the battens, should be nailed twice in every unit. Plain tiles and small slates are nailed at the head, while long slates are sometimes nailed at the centre to overcome vibrations caused by the wind. Centre-nailing is mainly used for pitches below 35° and in the courses close to the eave.

The battens upon which the slates or plain tiles are fixed should not be less than 40 mm wide and of sufficient thickness to prevent undue springing back as the slates are being nailed to them. The thickness of the battens will therefore depend upon the spacing of the rafters and, for rafters spaced 400 mm to 460 mm on centres, the battens should be 20 mm thick.

The distance from centre to centre of the battens is known as the gauge, and is equal to the exposure of the slate or tile.

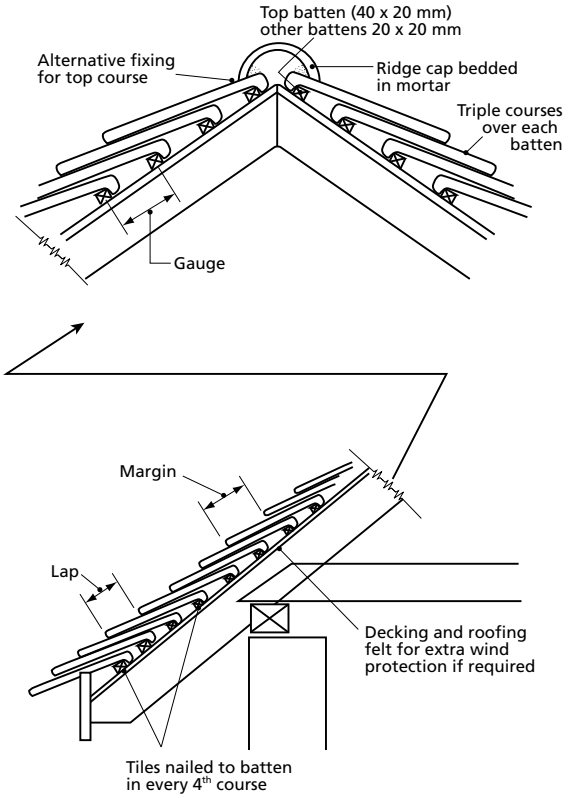


Figure 8.62 **Plain-tile roof**

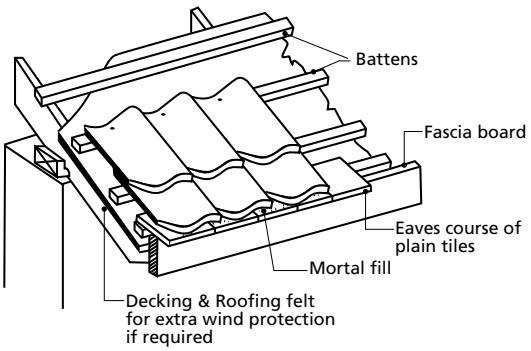


Figure 8.63 **Single-lap tiles**

Wood shingles

Wood shingles are pleasing in appearance and, when made from decay-resistant species, will last for between 15 and 20 years, even without preservative treatment. Cedar and cypress will last 20 years or more. Wood shingles have good thermal properties and are not noisy during heavy rain. The shingles are light and not very sensitive to movements in the supporting structure, which means that a rather simple roof frame made of round timber can be used.

The shingles are laid starting at the eaves, touching on the sides and doubled lapped. This means that there are three layers of shingle over each batten. Each

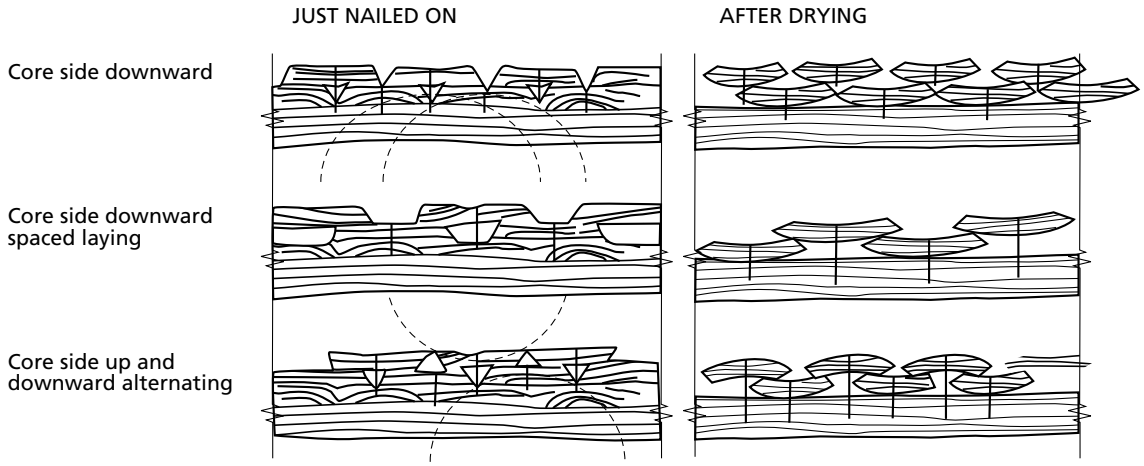


Figure 8.64 **Core-side effect on wood shingles**

shingle is fastened with one galvanized nail to the batten. No nail should go through two shingles. The shingles can be laid either with the core side of the timber alternating up and down in the successive rows, or with the core side down in all rows, thereby using the cupping effect of timber after drying to produce a roof cover less prone to leakage.

Bamboo shingles

The simplest form of bamboo roof covering is made of halved bamboo culms running full length from the eaves to the ridge. Large-diameter culms are split into two halves and the cross-section at the nodes removed. The first layer of culms is laid side by side with the concave face upwards. The second is placed over the first with the convex face upwards. In this way, the

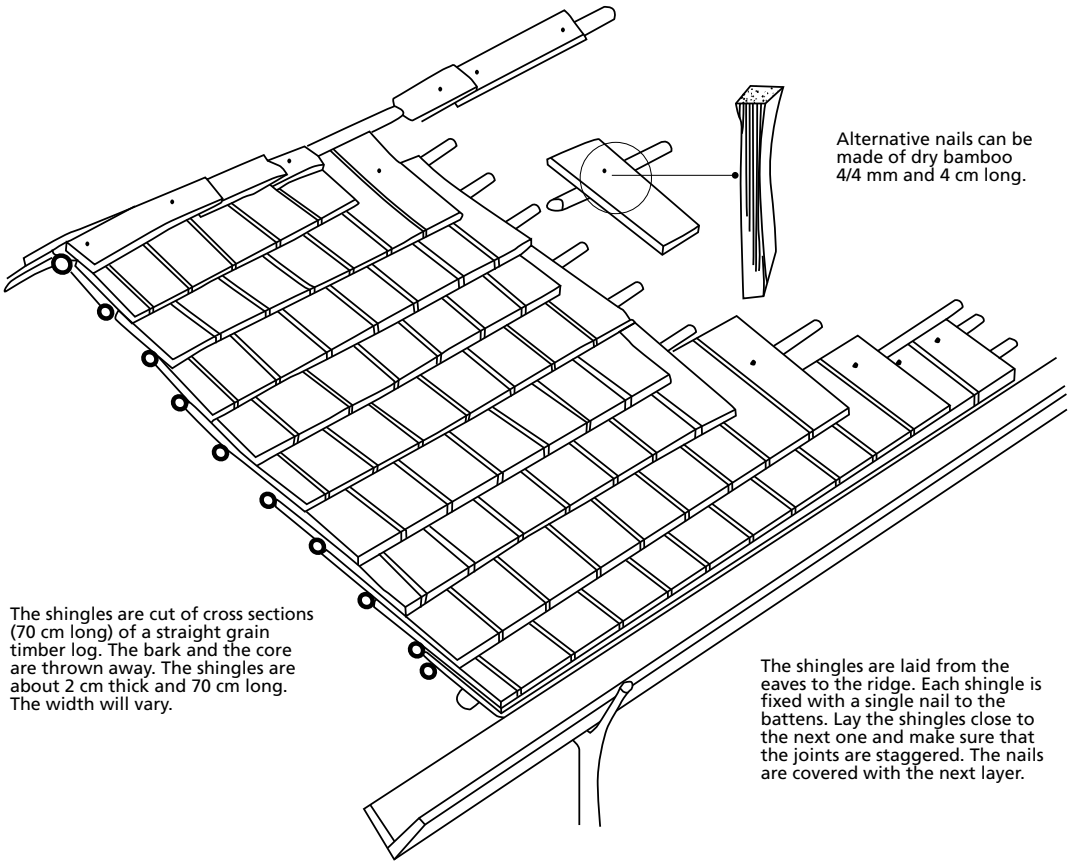


Figure 8.65 **Roofing with wood shingles**

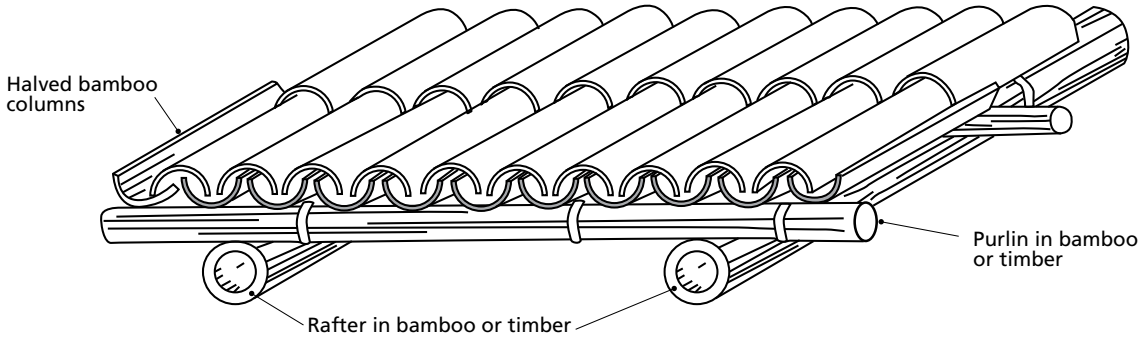


Figure 8.66 **Core-side effect on wood shingles**

bamboo overlaps in the same way as in a tile roof, and can be made completely watertight. Several types and shapes of bamboo shingle roofing may be used where only smaller sizes of bamboo culm are available.

Rainwater drainage from roofs

The simplest method is to let the roof water drop onto a splash apron all around the building. This method also protects the walls from surface groundwater. The water is then collected in a concrete ground channel, or allowed to flow onto the ground surrounding the building to soak into the soil. This method can only be recommended for very small buildings because the concentrated flow from a larger building may cause considerable soil erosion and damage to the foundation. The water from ground channels is drained into a soakaway or collected and stored. Blind channels are frequently used. These are simply trenches filled with stones that act as soakaways, either for a ground channel or for a splash apron.

Pitched roofs are often provided with eave gutters to collect and carry the rainwater to downpipes that deliver the water to ground drains or a tank. Flat roofs are usually constructed with a slight fall to carry rainwater directly to a roof outlet.

The sizing of gutters and downpipes to effectively remove rainwater from a roof will depend upon the:

1. Area of the roof to be drained.
2. Anticipated intensity of rainfall.
3. Material of the gutter and downpipe.
4. Fall along the gutter, usually in the range of 1:150 to 1:600.
5. Number, size and position of outlets.
6. Number of bends: each bend will reduce the flow by 10–20 percent.

Pitched roofs receive more rain than their plan area would indicate, owing to the wind blowing rain against them. An estimate of the effective area for a pitched roof can be made by multiplying the length by the horizontal width, plus half the rise.

In order to find the flow, the area is multiplied by the rainfall rate per hour. The rainfall intensity during heavy rain will vary between areas, and local data should be used where available. As a guide, rainfall values of 75 mm to 100 mm per hour may be used. Gutters should be installed with very little fall, 0.3 percent being recommended. Falls that are too steep cause difficulties because the water flows too rapidly, leaving trash behind. Also, gutters with more than a slight fall do not look right.

TABLE 8.16
Flow capacities in litres per second for level half-round gutters

Gutter size (millimetres)	Flow (litres/second)
75	0.43
100	0.84
112	1.14
125	1.52
150	2.46

There is always a possibility that unusually heavy rain, or a blockage in a pipe, will cause gutters to overflow. With this in mind, it is always advisable to design a building with a roof overhang so that, in the event of overflow, the water will not flow down the facade or make its way into the wall, where damage may result.

Common materials for gutters and downpipes are galvanized steel, aluminium and vinyl. Galvanized steel is the least expensive. Aluminium is long-lasting but easily damaged. Vinyl is both durable and resistant to impact damage.

Two major types of gutter bracket are normally available. One is for fixing the gutter to a fascia, as illustrated in Figure 8.67. The other is used when there is no fascia board and the gutter is fixed to the rafters. The roof cover should extend 50 mm beyond the ends of the rafters or the fascia board in order to let the water fall clear.

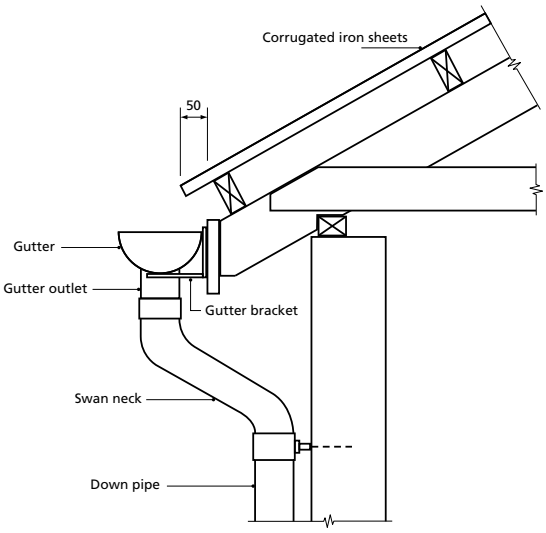


Figure 8.67 **Gutter and downpipe fastening**

DOORS

Doors are essential in buildings to provide security and protection from the elements, while allowing easy and convenient entry and exit. Farm buildings may be served adequately with unframed board doors, while homes will need more attractive, well-framed designs that close tightly enough to keep out dust and rain and allow only minimal air leakage. Large openings are often better served by rolling doors, rather than the side-hinged type.

General characteristics of doors

Size: Doors must be of adequate size. For use by people only, a door 70 cm wide and 200 cm high is adequate. However, if a person will be carrying loads with both hands, e.g. two buckets, between 100 cm and 150 cm of width will be required. If head loads will be carried, door heights may need to be increased to 250 cm. Shop or barn doors need to be considerably larger to give access for tools and machinery.

Strength and stability: Doors must be built of material heavy enough to withstand normal use and to be secure against intruders. They should be constructed of large panels, such as plywood, or designed with sturdy, well-secured braces to keep the door square, thereby allowing it to swing freely and close tightly. A heavy, well-braced door mounted on heavy hinges fastened with 'blind' screws and fitted with a secure lock will make it difficult for anyone to break in.

Door swing: Edge-hung doors can be hung at the left or at the right, and operate inwards or outwards. Careful consideration should be given to which edge of the door is hinged to provide the best control and the least inconvenience. An external door that swings out is easier to secure, wastes no space within the building, and egress is easier in an emergency. However, unless it is protected by a roof overhang or a verandah, it may be damaged by rain and sun. An inward-swinging door is better protected from the weather.

Weather resistance and durability: It is desirable to use materials that are not easily damaged by weathering, and to further improve the life of the door by keeping it well painted.

Special considerations: Under some circumstances, fireproof doors may be desirable or even mandatory. In cooler climates, insulated doors and weather-stripping around the doors will help to conserve energy.

Types of door

Unframed doors: Very simple doors can be made from a number of vertical boards held securely by horizontal rails and a diagonal brace installed in such a position that it is in compression. These are inexpensive doors and entirely satisfactory for many stores and animal buildings. As the edge of the door is rather thin, strap or tee hinges are usually installed over the face of the rails.

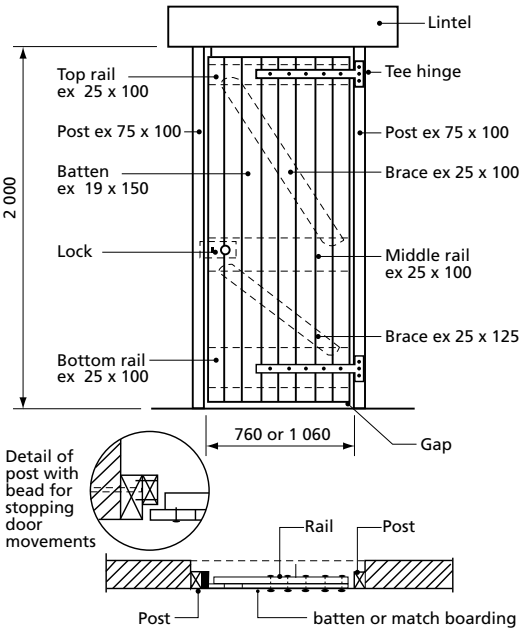


Figure 8.68 **A simple unframed door**

Framed doors: A more rigid and attractive assembly includes a frame around the outer edge of the door held together at the corners with mortise and tenon joints. The framed door can be further improved by rabbeting the edge of the frame rails and setting the panels 10 mm to 20 mm into the grooves. The door can be hung on strap or tee hinges but, as there is an outer frame, the door can also be hung on butt hinges with hidden screws. If the inner panel is made of several boards, braces are needed, but, if only one or two panels are made of plywood, no braces will be required. Large barn or garage doors will need bracing regardless of the construction of the centre panels.

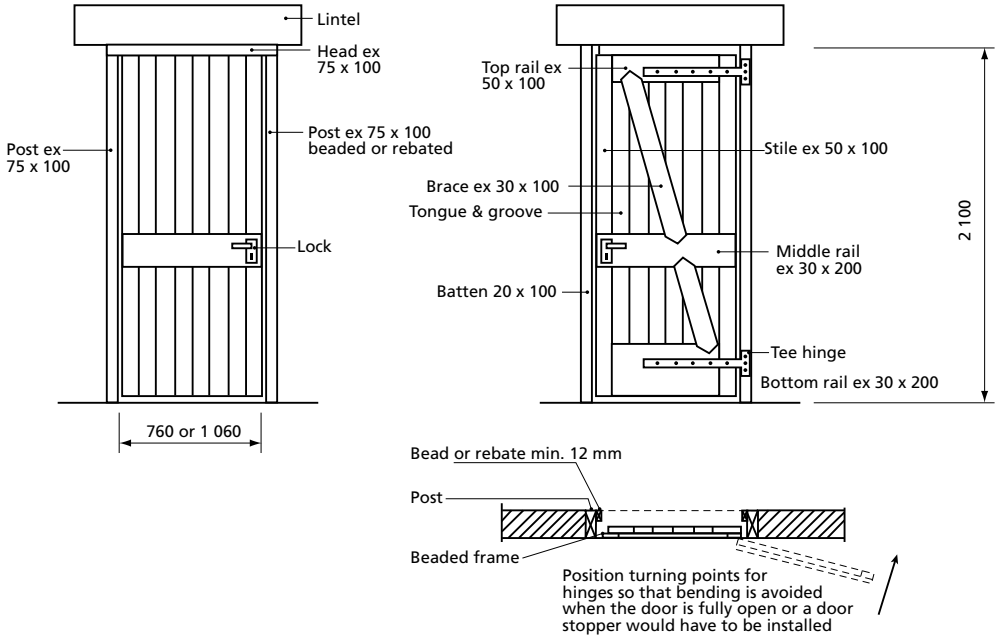


Figure 8.69 **Framed door**

Flush Doors: Flush-panel doors consist of a skeleton frame clad with a sheet facing, such as plywood. No bracing is necessary and the plain surface is easy to finish and keep clean. Flush-panel doors are easily insulated during construction if necessary.

Double Doors: Large door openings are often better served by double doors. If hinged doors are used, smaller double doors are not as likely to sag and bend and they are much less likely to be affected by wind. Usually opening only one of the double doors will allow a person to pass through. Figure 8.70 shows how the meeting point of the two doors can be covered and sealed with a cover fillet.

When doors are large and heavy and need to be opened only occasionally, it is desirable to place a small door either within, or next to, the large door. Figure 8.71 shows typical locations for a small door for the passage of people.

Rolling Doors: An alternative to double-hinged doors for large openings is one or more rolling doors. They often operate more easily, are not as affected by windy conditions and are not as subject to sagging and warping as swinging doors. Rolling doors are usually mounted under the eave overhang and are protected from the weather when either open or closed. It is true that they require space at the side of the doorway when they are open, but there are several designs to suit a variety of situations. For example:

1. One large door rolling one way from the doorway.
2. Two doors rolling in opposite directions from the doorway.
3. Two doors on separate tracks rolling to the same side.

In all cases it is desirable to have guides at the base to prevent wind interference and to make the building more secure from intruders. For security reasons, the door hangers should be of a design that cannot be unhooked but only roll on or off the end of the track. The most secure place to mount the door hangers is on the stiles (end frame pieces). See Figure 8.72 for details.

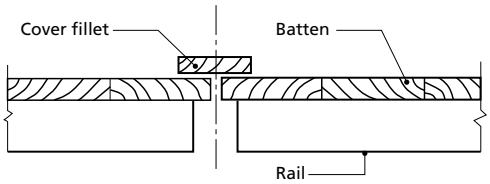


Figure 8.70a **Unframed door**

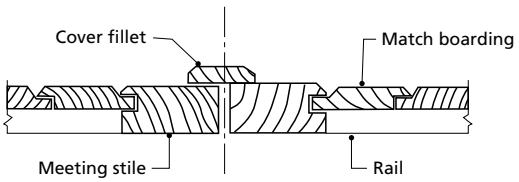


Figure 8.70b **Framed door**

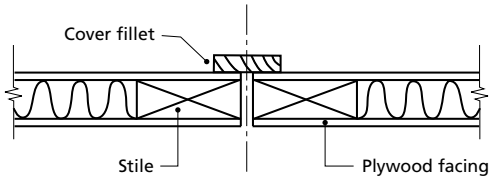


Figure 8.70c **Flush door**

Figure 8.70 **Sealing the meeting point of double doors**

Half-door or Dutch door: Doors that are divided in half horizontally allow the top section to be opened separately to let in air and light while at the same time restricting the movement of animals and people.

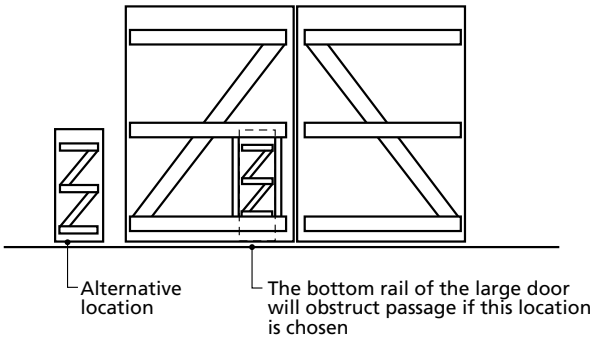


Figure 8.71 **Alternative locations of a small door for the passage of people**

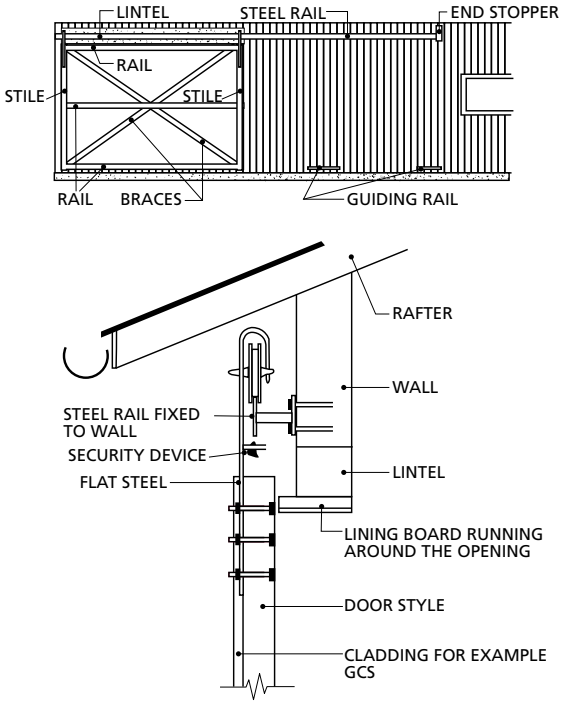


Figure 8.72 **Rolling door details**

Door frames

A timber door frame consists of two side posts or jambs, a sill or threshold, and a head or soffit. For simple buildings not requiring tight-fitting doors, the two jambs shown in Figure 8.73 may be all that is required. However, if a tightly fitting door is needed, a complete frame is required, including strips or stops around the sides and top against which the door closes. As the door jambs are installed against the wall and the fit may not be precise, the doors of dwellings are often hung in an inner frame that can be plumbed and levelled by inserting shims between the inner and outer frames, as shown in Figure 8.74.

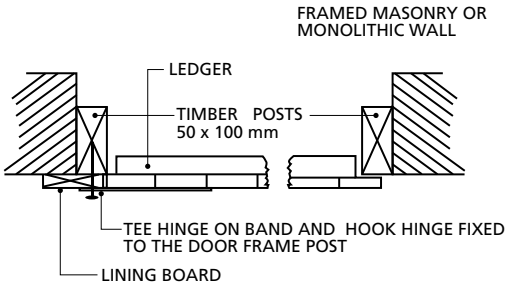


Figure 8.73 **Simple timber door-frame installation**

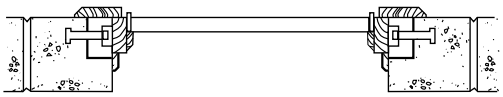


Figure 8.74 **Framed timber door in concrete block wall with jamb blocks**

This figure also shows the use of concrete jamb blocks, which are often available for concrete masonry walls. They have a corner cut out, so that when the wall is laid up there is a recessed area in which to install the jamb rigidly. A door frame may be anchored in an opening where square end blocks are used, as shown in Figure 8.75.

The simplest doors do not close tightly because they have no threshold or head. A threshold allows the door to close with a relatively tight fit at the bottom, while at the same time allowing the door to swing open with adequate clearance from the floor. The head permits the top of the door to close tightly.

Simple locks for barn doors

Large double doors are normally secured by locking them at both the top and the bottom. Four sliding bolt locks are required, and should be installed close to where the doors meet. In small double doors, top and bottom locks are required for only one of the doors. Figure 8.77a illustrates a simple wooden handle, locking with a wedge nailed to the lintel. It can be used at the top of an unframed door. Note that the top rail must be placed far enough down to allow movement of the top of the handle. For example, in barn doors, where movements of the door can be tolerated, often only a lock at the top is provided.

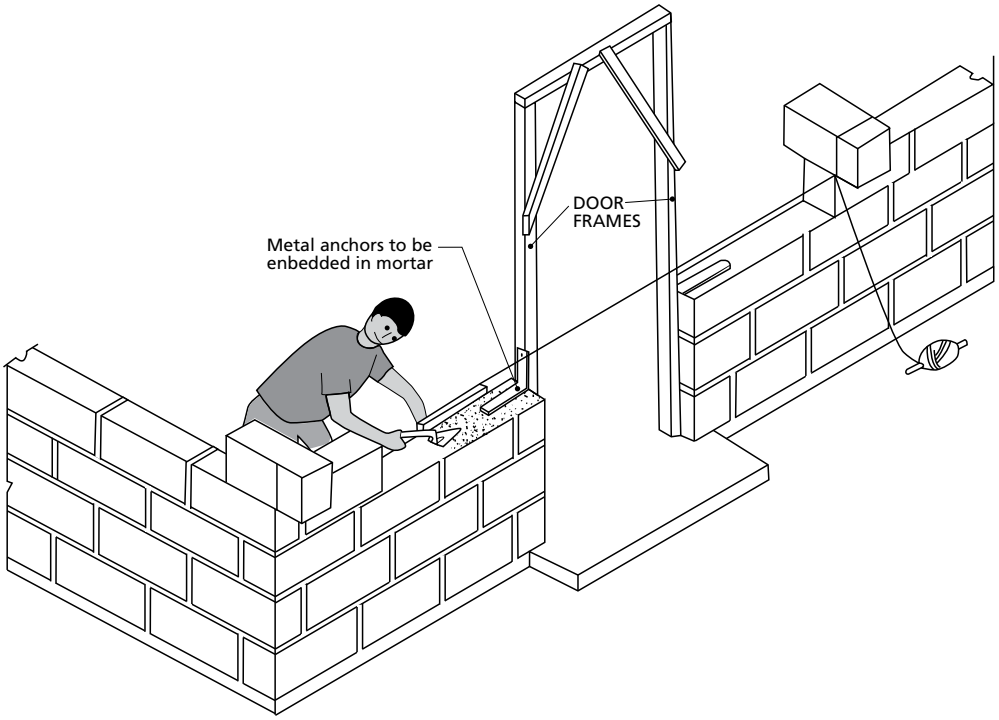


Figure 8.75 **Anchoring a doorframe in a masonry wall without jamb blocks**

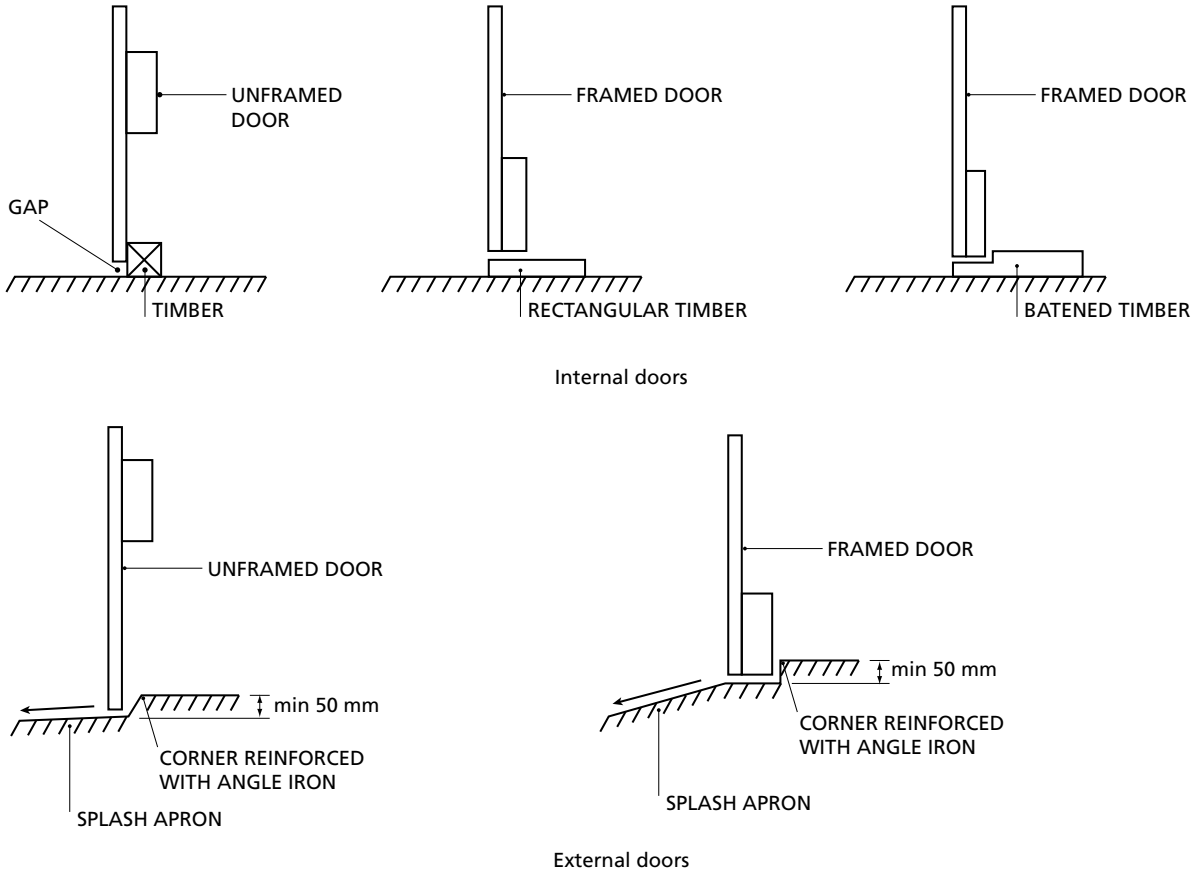


Figure 8.76 **Types of threshold**

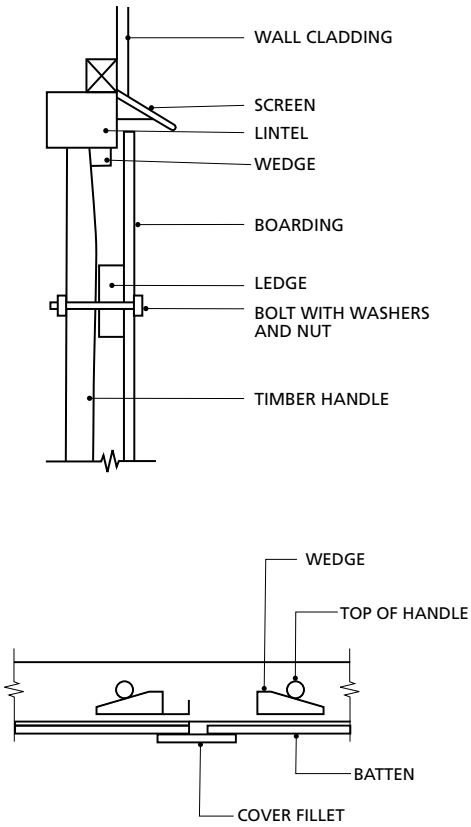


Figure 8.77a

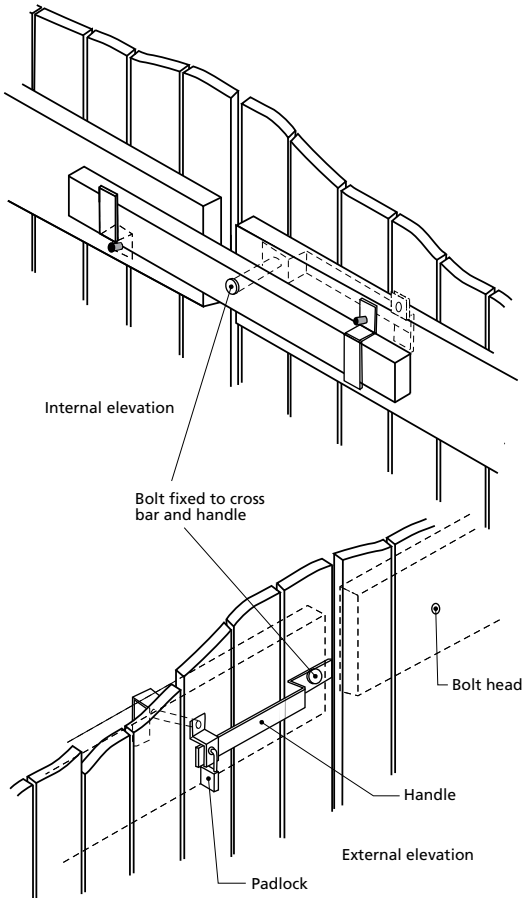


Figure 8.77b

Figure 8.77 **Simple barn-door lock**

Alternatively, the lock shown in Figure 8.77b can be used. This lock, which is located at the middle rail, has a bolt running through the door. The bolt is secured to a crossbar on the inside and a handle on the outside. When the handle is pressed down, the crossbar rotates out of the hooks. A padlock can be fitted to secure the handle in the locked position.

WINDOWS

Windows provide light and ventilation in a building and allow the people inside to view the surrounding landscape and observe the activities in the farmyard. In sitting rooms and work rooms where good light and ventilation are important, the window area should be 5–10 percent of the floor area of the room. Windows sometimes need to be shaded to reduce heat radiation, or closed to keep out driving rain or dust. In addition, screening may be needed for protection from insects. Shutters, either top- or side-hinged, are commonly used to provide the required protection. Side-hung glazed windows, fly screens and glass or timber louvres are also used.

Shutters: These are basically small doors and are constructed as unframed, framed or flush shutters. Owing to the smaller size, only two rails are required and the timber can be of smaller dimensions. The principles of construction are the same as for doors.

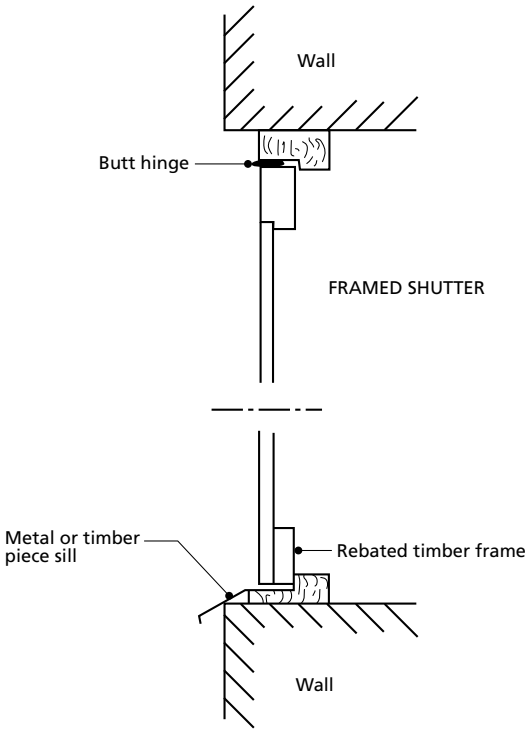


Figure 8.78 **Recessed window or shutter**

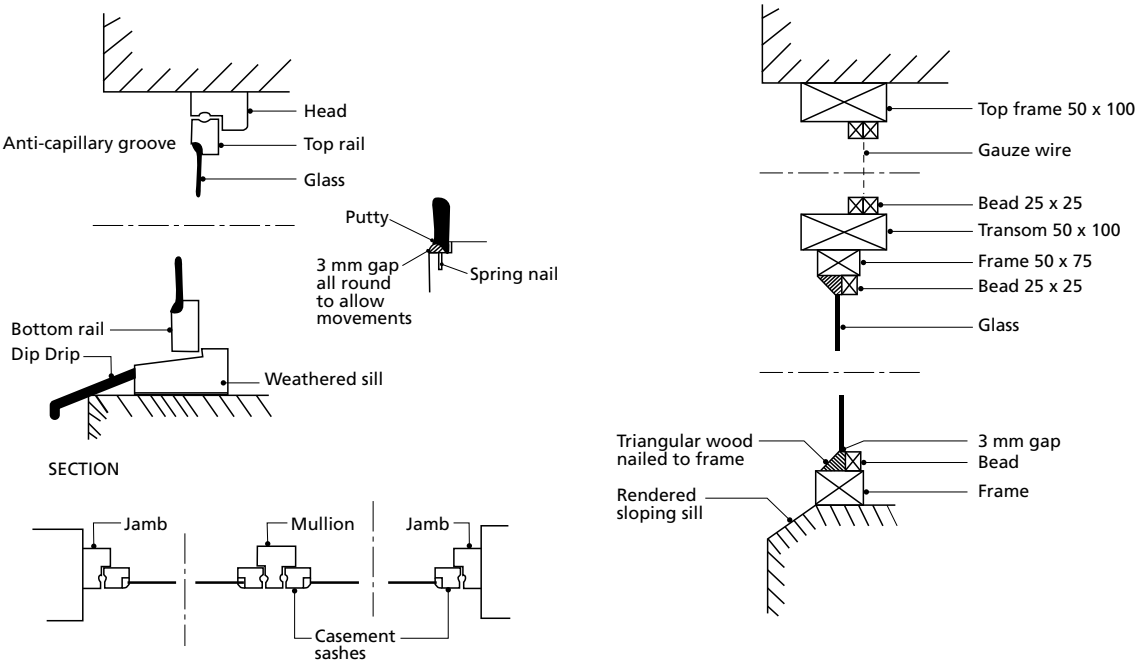


Figure 8.79 **Window installations**

However, when the frame for the shutter is recessed in the wall, the sill must be sloped and extend out from the wall to let the water drip clear of the face of the building. The window shutter can be side-hinged or top-hinged. A top-hinged shutter has the advantage of shading the opening when kept open, as well as allowing ventilation while preventing rain from entering.

Glazed windows: Glazed windows are relatively expensive but are most practical in cold areas. When temperatures are low, the window can be shut while still allowing daylight to enter the room. Frames for glazed windows are available in wood and metal, metal being more expensive. Glazed windows with frames are usually marketed as a unit, but Figure 8.79 illustrates various methods of frame construction and installation.

STAIRS AND LADDERS

The angle, which is governed by the height and the horizontal distance available, will determine the most suitable means of moving from one level to another.

- For a slope up to 1:8 (7°), a ramp is suitable for both walking and pushing a wheelbarrow.
- For walking alone, a 1:4 (14°) slope is satisfactory provided that it remains permanently dry.
- For slopes between 1:3 and 1:0.8 (18° to 50°), stairways are possible, although 30° to 35° is preferred. Angles steeper than 50° require a ladder or ladder-stairway.
- Temporary ladders should be set up at 60° to 75°, while a fixed ladder may be vertical if necessary.

Ramps: Ramps may be made of tamped earth or concrete. An earth ramp should be made of a mixture of fine gravel and clay: the gravel to give texture for a nonslip surface and the clay to serve as a binder. The surface of a ramp constructed of concrete should be 'broomed' across its slope after having been poured and struck off.

Stairs: Stairs can be designed as one straight flight, with a landing and a 90° turn, or with a landing and a 180° turn. The straight flight is the simplest, the least expensive and the easiest for moving large objects up or down. However, stairs with a landing are considered safer because a person cannot fall as far.

Definitions and descriptions of terms relating to stairways (see Figure 8.80):

Angle block: A glued angle block in the junction between the tread and riser to reduce movements and creaking.

Balusters: The vertical members between the stringer and the handrail.

Going: The horizontal distance between the nosings, or risers, of two consecutive steps. This is sometimes called the 'run' or the 'tread'.

Handrail: A safety rail, parallel to the stringers and spanning between newels at either end. This can be attached to the wall above, and parallel to, a wall stringer. The vertical distance between the stringer and handrail should be 850 mm to 900 mm.

Headroom: The vertical distance between the treads and any obstruction over the stairway, usually the lower edge of a floor. The headroom should be at least 2 metres.

Housing: The treads and risers can be housed in grooves in the stringers, or supported on beads that are nailed and glued to the stringers. In both cases they should be secured with wedges and glue.

Newel post: The post supporting the handrail at the bottom, turn and top of a staircase.

Pitch: Usually 30°–35°.

Rise: The vertical distance between two consecutive treads.

Risers: The vertical members between consecutive treads. Sometime the riser is omitted (open riser) for simplicity and economy. In that case, the treads should overlap by 25 mm to 35 mm.

Steps: The combined treads and risers.

Stringers: The inclined beams supporting the steps. The strength required for the stringers will depend on the load and method of support. They may be supported only at the ends or continuously along the wall.

Treads: The members that are stepped upon as a person climbs the stairs. The treads must be strong enough to carry and transfer the imposed load to the stringers without excessive deflection. They should have a non-slippery surface. The treads can be housed in grooves in the stringers or supported on beads that are nailed and glued to the stringers. In both cases they are secured with wedges nailed and glued to the stringer.

Width: Sufficient width for two people to pass requires a width of 1.1 metre. A minimum width of 600 mm can be used for traffic of people not carrying anything.

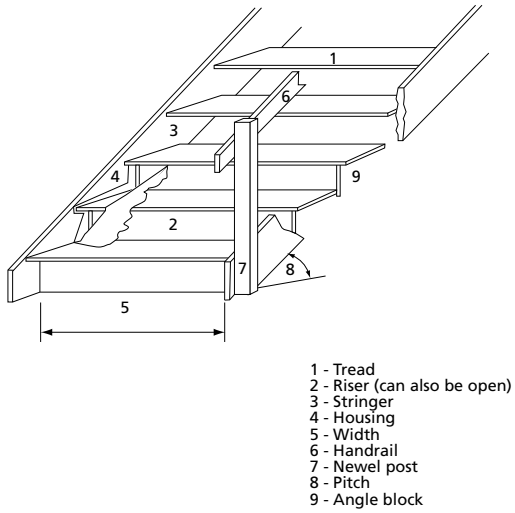


Figure 8.80 **Stairway construction**

The pitch for most stairs should not exceed 42° nor be less than 30° and, for stairs in regular use, a maximum of 35° is recommended. For most stairs, a minimum going of 250 mm and a maximum of 300 mm should be adopted, although in domestic stairs a minimum of 200 mm is acceptable for stairs that are used infrequently. A rise of between 150 mm and 220 mm is usually satisfactory.

Comfort in the use of stairs depends largely on the relative dimensions of the rise and going of the steps. Rules for determining the proportion are based on the assumptions that about twice as much effort is required to ascend as to walk horizontally, and that the pace of an average person measures about 585 mm. Thus, the fact that a 300 mm going with a rise of 140 mm or 150 mm is generally accepted as comfortable, results in the rule that the going plus twice the rise should equal 580 mm to 600 mm.

It is essential to keep the dimensions of the treads and risers constant throughout any flight of steps, to reduce the risk of accidents caused by changing the rhythm of movement up or down the stairway.

Stairs are constructed by gluing and wedging the treads and risers into the housing grooves in the stringers to form a rigid unit, as shown in Figure 8.80.

Stairs are designed to be either fixed to a wall with one outer stringer, fixed between walls, or freestanding, with the majority of stairways having one wall stringer and one outer stringer. The wall stringer is fixed directly to the wall along its entire length or is fixed to timber battens plugged to the wall. The outer stringer is supported at both ends by the posts. The posts also serve as the termination point for handrails that span between them.

The space between the handrail and the tread may be filled with balusters, balustrade or a solid panel to improve both the safety and the appearance of the stairway.

Reinforced concrete is better suited for outdoor stairs than timber. The number, diameter and spacing of the main and distribution reinforcement for each stairway must always be calculated by an experienced designer.

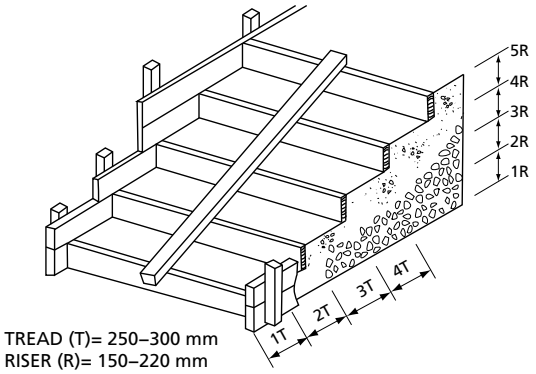


Figure 8.81 **Typical formwork for casting concrete stairs**

Ladder-stairway: The recommended pitch for this type of steep, narrow stairway is 60°. The width is usually roughly the minimum of 600 mm. The size of the going (tread) is dependent on the pitch. Table 8.17 gives recommended values.

TABLE 8.17
Measurements of tread and rise at different pitches of the stairway

	Pitch degrees					
	50	55	60	65	70	75
Tread (mm)	220	190	160	130	100	70
Rise (mm)	262	272	277	278	275	262

Timber ladders are basically of two types:

1. those having round rungs fixed in holes in the stringers;
2. those having square, or slightly rectangular, treads cut into and nailed on the forward side of the stringers.

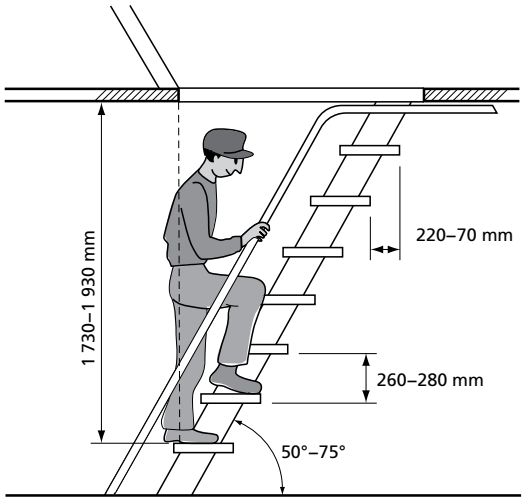


Figure 8.82 **Ladder-stairway**

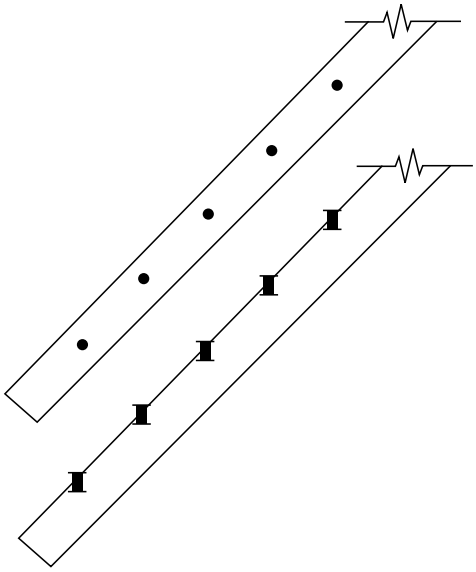
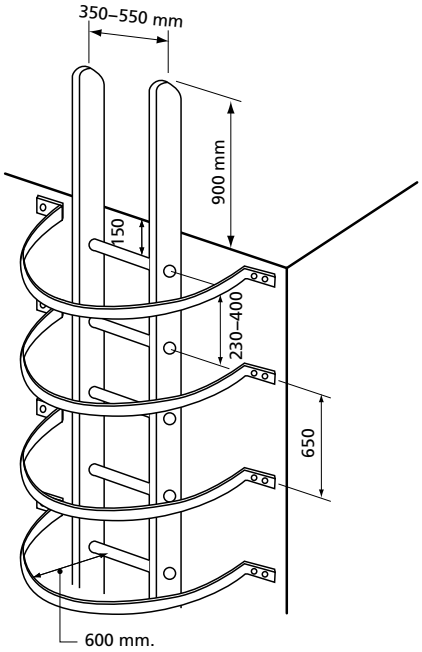


Figure 8.83 **Two basic types of ladder**



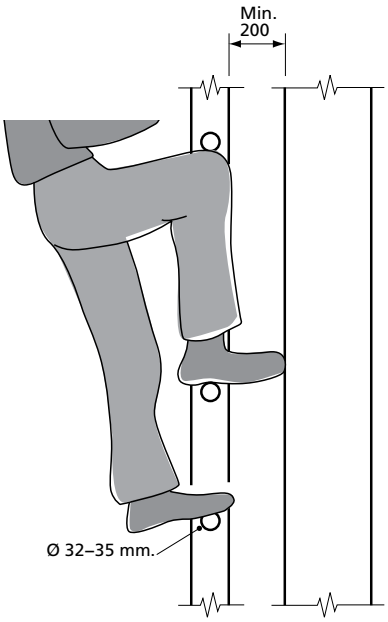


Figure 8.84 **Ladder guard**

The width of the ladder should be 350 mm to 500 mm and the rise should be 230 mm to 400 mm, with 300 mm as the recommended value.

Ladders that are moved from place to place should have hooks and dowels so that they can be thoroughly stabilized at the bottom and top. Ladders mounted permanently should be firmly secured in their position and, if necessary, provided with handrails. If the total length is more than 5 metres and the pitch steeper than 70°, the ladder should be provided with a guard to prevent the climber from falling backwards. If the ladder is taller than 2.5 metres and starts from a small platform, it too should have a guard.

ELECTRICAL INSTALLATIONS

Electrical energy can be put to many uses, and an increasing number of farms will benefit from electrification as the electrical supply network expands into the rural areas or generators are installed at farms. Although few farms, in particular small farms, are connected to an electrical supply at present, everyone concerned with the design and construction of farm buildings will need to have an appreciation of the general layout and function of electrical installations.

For most types of farm building, the electrical layout can be drawn on a copy of the plan view using the symbols shown in Figure 3.8. The layout should indicate where outlets, lighting points, switches, motors, heaters and other appliances are to be fitted, and the accompanying specifications should describe the chosen wiring system and fixing heights, and detail each appliance. Detailed wiring plans and installation designs prepared by a specialist will only be necessary for large and complex buildings, such as plants for processing agricultural produce.

Electricity supply

Electricity supply to a farm will normally reach it overhead from a local transformer substation, where the voltage has been reduced to a three-phase, 415/240 volt (V) supply. Four wires are required for a three-phase supply: one for each of the lines and one common return or neutral. The neutral is connected to earth at the substation. The voltage between any phase wire and the neutral is 240 V, while it is 415 V between any two phase wires.

If nearly equal loads are connected to each of the phases, the current in the neutral will be kept to a minimum. To achieve this, most appliances that consume large amounts of electricity, notably electrical motors and larger heating and air-conditioning units, are designed for connection to a three-phase supply.

Lighting circuits, socket outlet circuits and appliances of low power rating are served by a single-phase supply, but the various circuits are connected to different phases to balance the overall loading. However, sometimes small farms or domestic houses are served with a single-phase, 240 V supply. In this case, only two wires are required in the supply cable: one live and one neutral. The load balancing takes place at the substation, where the lines from several houses are brought together.

The intake point for the main supply to a farm should be at a convenient place to allow for the possible distribution circuits. The intake point must provide for an easily accessible area that is protected from moisture and dust and where the main fuse, the main switch and the meter can be fitted. Circuit fuses and

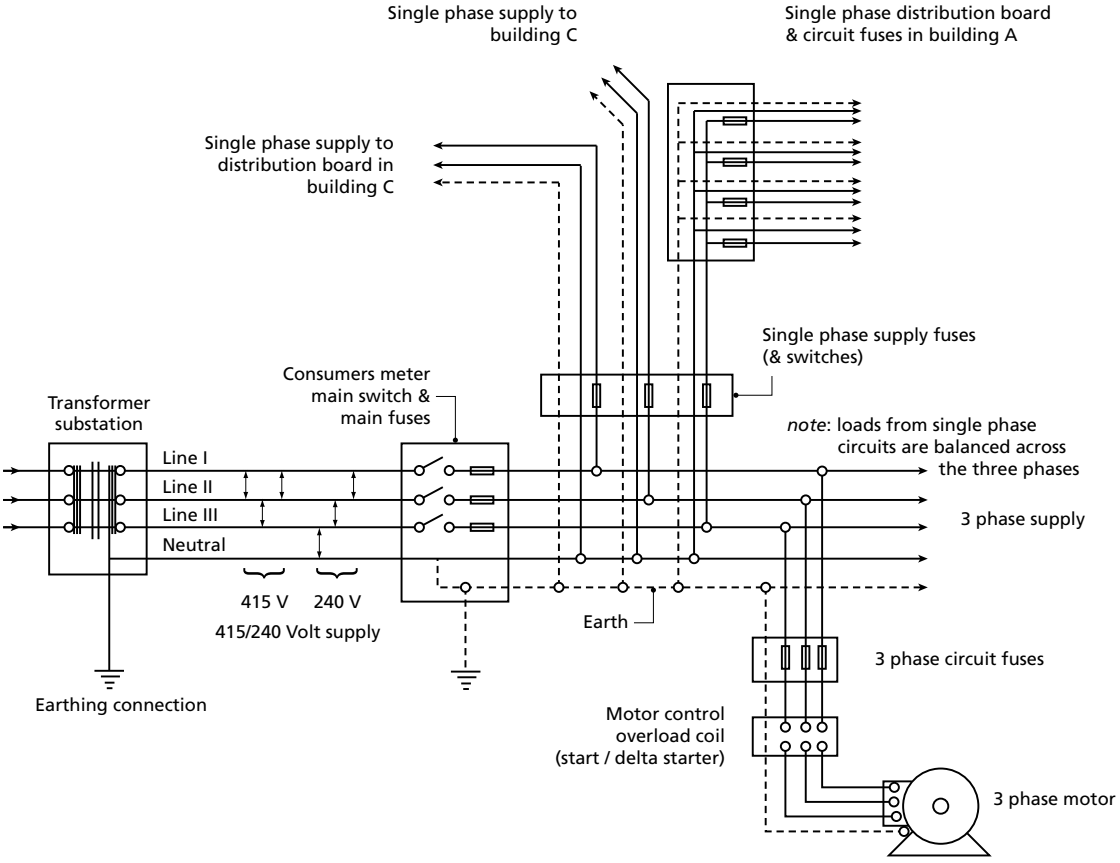


Figure 8.85 **Typical electrical distribution system**

distribution gear may be installed at this location, or in each building at the farmstead that is to be served with electricity.

Electricity tariffs are the charges that are passed on to the consumer. The charges commonly consist of two elements: a fixed cost that often depends on the size of the main fuse and a running cost that depends on the amount of electrical energy consumed. The required amp rating for the main fuse will depend on the maximum total power required for the appliances to be connected at any one time, and is also influenced by the type of starter used for electrical motors. Usually the motor with the highest power rating will be the determining factor at a farmstead.

Earthing and bonding

Should a base live wire touch, or otherwise become connected to, the metal framework of an appliance, a person touching it would receive an electric shock. As a precaution against this, connect any exposed metalwork to an earth wire that takes the form of an extra conductor in the power cable connected to an earthing connector, which consists of a number of copper rods driven well into the ground.

An earthing wire will therefore be carried as a third conductor in a single-phase supply cable and as a fourth or fifth conductor in a three-phase supply cable, depending on whether the cable includes a neutral wire. The neutral should not be used for earthing. Some appliances are protected by enclosure in an insulating cover instead of being earthed.

Bonding is a low-resistance connection between any two points of an earthed system, used to prevent any difference of potential that could produce a current, thereby providing additional protection. If, for example, the metal appliances in a milking parlour are electrically connected to the reinforcement bars of the concrete floor, the cows will be protected from electrical shocks should the appliance become charged by an earth-leaking current that is not large enough to blow a fuse, because the floor will receive the same electrical potential.

Distribution circuits

Electricity is distributed within buildings in cables, which consist of one or several conductors made of copper or aluminium, each surrounded separately by an insulating material, such as plastic, and then enclosed in an outer sheet of plastic or rubber. The size of a cable is given by the cross-section area of its conductors. All cables are assigned a rating in amperes (A), which is the maximum load the cable can carry without becoming overheated. Large conductors are usually divided into strands to make the cable more flexible.

Surface wiring is normally used in farm buildings. This implies sheathed cables fixed to the surface of walls, ceilings, etc. and fixed with clips. Care must be taken to ensure that cables are not sharply bent, are protected when passing through a wall and are installed well away from water pipes. Conduit wiring, where the cables are drawn through concealed tubing, is too expensive and complex to be employed in farm buildings.

Lighting circuits normally have 5 A fusing and wiring (1.0 mm² cables). While a suitable arrangement of one-way and two-way switches will allow lamps to be switched on and off individually or in groups, each such circuit can serve ten 100 W lamps without danger of overloading. If all 10 lamps are on at the same time, they have a power requirement of 1 000 W, according to the relationship:

$$W = V \times A$$

where:
W = power
V = voltage
A = current

The lamps would produce a 4.2 A current in a 240 V circuit, i.e. leaving a suitable safety margin before overloading the fuse and wiring.

Power circuits normally use 2.5 mm² wiring and are arranged as ring circuits that are supplied from the mains at both ends through 10 amp to l5 amp fuses. In domestic installations, a power circuit can carry any number of outlets, provided it does not serve a floor area greater than 100 m². However, when designing power circuits for farm buildings, such as a workshop, it is wise to calculate the current consumed by all appliances that are expected to be connected at any one time, to avoid overloading.

A range of lamp fittings, switches and outlets is available, offering varying degrees of protection against dust and moisture penetration. Although more expensive, those offering a higher level of protection will normally be required in farm buildings, as well as for fittings installed outdoors.

No socket outlets are permitted in bathrooms and showers, and should be avoided in rooms such as dairies and washrooms because of the presence of water.

Fixed electrical appliances with a single-phase supply, such as water heaters, air-conditioners and cookers, should have their own circuits with individual fuses.

Three-phase electrical motors and appliances require power supply cables with four or five conductors, including the earthing wire. Each appliance should have its own power supply and the phase lines must be fused individually. Movable three-phase motors are supplied from special three-phase power outlets, via a rubber sheathed flexible cord that is fixed to the motor at one end and fitted with a three-phase plug at the other. All flex cords must be protected from damage and should be hung clear of the ground wherever possible. Under no circumstances may flex cords be connected by twisting the conductors together.

Artificial lighting

In tropical countries with strong natural light, even relatively small windows can provide sufficient indoor lighting. Artificial lighting will therefore be required mainly to extend the hours of light.

Where electrical energy is available, the two most commonly used artificial light sources are incandescent bulbs and fluorescent tubes. Tubes, and fittings for tubes, are more expensive than bulbs and bulb fittings, but tubes produce three to five times as much light per unit of electrical energy, have up to 10 times the life and generate less heat. Fluorescent light is therefore normally the cheapest option, despite the higher initial cost.

However, in small rooms where the light is switched on and off frequently, bulb fittings are usually preferred, as in this case the installation cost is more important than the energy cost. Mercury vapour and sodium lamps are often used for outdoor lighting. Although they have higher efficiency in terms of the light produced than fluorescent tubes, their light covers only a limited spectrum and tends to distort colours.

Various types of fitting are normally available for both bulbs and tubes. While a naked bulb or tube may be sufficient in some circumstances, fittings that protect the lamp from physical damage and moisture penetration will often be required in farm buildings. From an optical point of view, the fitting should obscure the lamp and present a larger surface area of lower brightness to reduce the glare caused by excessive luminance contrast. This is particularly important if the lamp is positioned where it will be viewed directly.

A lighting point must also be positioned to avoid reflected glare and unwanted shading of a work area. While light colours on interior surfaces will create a bright room, shades of blue or green produce a feeling of coolness. The dusty conditions in many farm buildings require the use of fittings that are easy to clean. Accumulated dust can reduce the light emitted by more than 50 percent.

Although most agricultural production operations carried out in buildings can be performed quite satisfactorily using natural light, where artificial light is to be installed the standard of illumination should be suited to the activities carried out. While the installation of 2.0 W to 3.0 W of fluorescent light per square metre of floor area will be sufficient for general illumination, work areas need more light (say 5 W/m² to 8 W/m²), and a desk or workbench where concentrated or exacting tasks are performed may need 10 W/m² to 15 W/m², or more. Where bulbs are to be installed instead of tubes, the above values will have to be at least tripled.

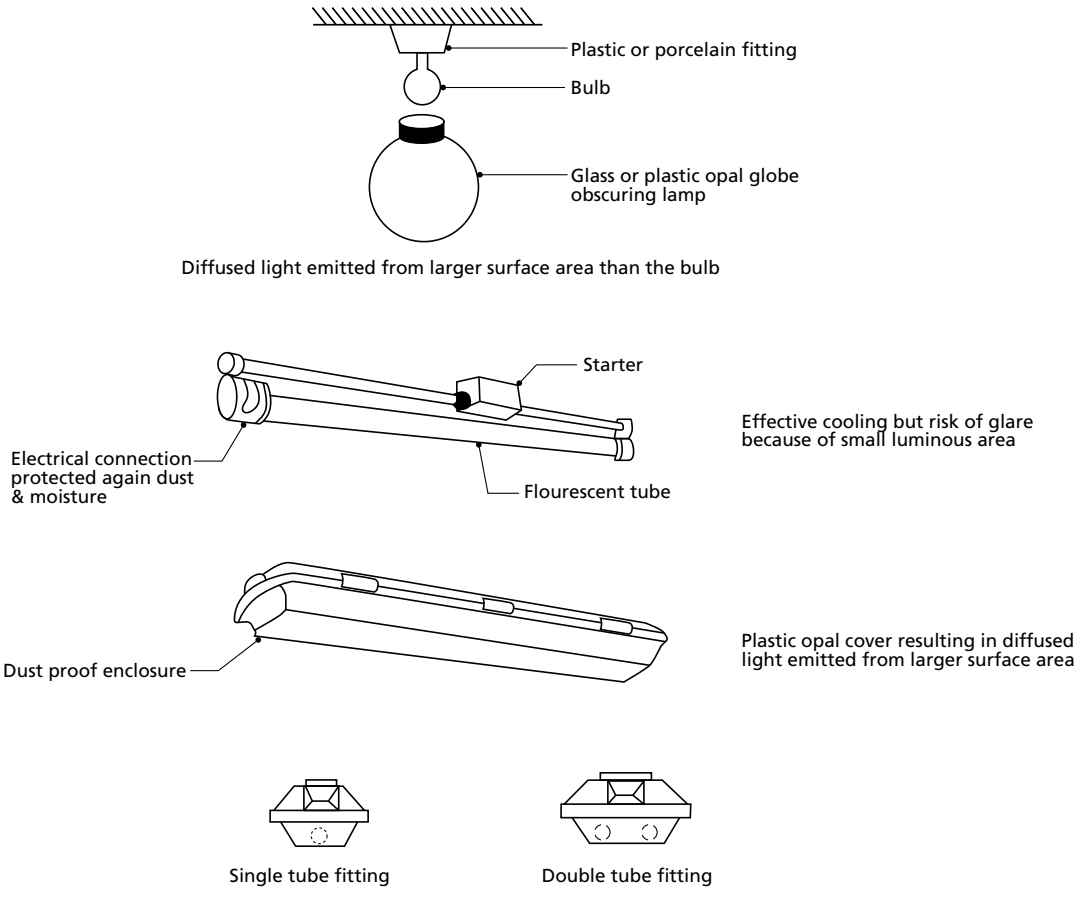


Figure 8.86 **Examples of light fittings for farm buildings**

Electrical motors

Single-phase motors in sizes up to about 1 kilowatt have a wide range of applications, particularly for use in domestic appliances. The most common type, the single-phase series motor or universal motor, produces good starting torque and can be run on either alternating current (AC) or direct current (DC). While it has the advantage of being able to connect to an ordinary socket outlet, generally it cannot compete with the performance and efficiency of a three-phase motor.

The three-phase induction motor is the most common electrical motor at farms, where it is used to power fans, transport devices, mills, etc. Modern electrical motors are manufactured in a wide range of power ratings and types. Types of enclosure range from screen protection to total enclosure. Motors used in farm buildings should normally have an enclosure that is dust-tight and splash-proof, i.e. it should not be damaged by exposure to water splashing from any direction. However, sometimes even better protection is required, such as dust-proofing and flush-proofing, and submersible motors must be totally enclosed and completely waterproof.

Inherent features of the induction motor are its poor starting torque and heavy starting current – up to six times the full load current. To prevent an excessive voltage drop in the supply network, the electricity company usually allows only small induction motors to be started direct on line. A star/delta starter is commonly fitted to motors above 2 kW to 3kW, to reduce the starting current to about twice the full load current. Unfortunately it also reduces the already poor starting torque still further, so that the motor cannot start against heavy load. Other types of motor and starter are available for situations where starting against load cannot be avoided.

The starter for any motor rated above about 0.5 kW must incorporate an overload cut-out that switches off the current if it exceeds a safe value for longer than the time required to start the motor. In many installations it is also desirable to include a release mechanism that prevents an unexpected restart after a power failure. A wide range of sensors, timers and other devices are available for automatic supervision and control of electric-motor operation.

Lightning conductors

Lightning striking a building can cause substantial structural damage and may start a fire. Buildings with thatched roofs located in prominent positions present the worst risk, while concrete and steel frame buildings run a low risk. A lightning protection installation has three major parts – an air termination, a down conductor and an earth termination – and its function is to provide a simple and direct path for the lightning to discharge to the ground.

The air termination consists of one or several pointed copper rods fixed above the highest point of the roof. One down conductor (e.g. 25 mm × 3 mm copper tape) can serve a building of up to 100 m². The earth termination consists of a 10 mm to 12 mm copper-plated rod driven into the ground to a depth of at least 2 metres. If the soil tends to become very dry at any time during the year, additional ground rods driven 2.5 metres deep will offer greater protection.

REVIEW QUESTIONS

1. What is the role of foundations and footings?
2. Why is it necessary to excavate the topsoil before laying the foundation?
3. Briefly describe six types of foundation that may be used in the building of a rural structure.
4. Describe five types of protective material for foundations.
5. Outline the factors that determine the type of walls used for a building.
6. Briefly describe four types of floor and roof.
7. Outline three types of roofing material, describing their advantages and disadvantages.
8. What are the general characteristics of doors?
9. Why is earthing and bonding important in electrical supply?

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Chapter 9
Building production

INTRODUCTION

Building production is the organization and management of the plans, equipment, materials and labour involved in the construction of a building, while at the same time complying with all codes, rules and contractual stipulations. The procedure should be designed to run efficiently to keep costs low and to allow returns on the investment to be realized as early as possible.

While many topics included in this chapter, such as standardization, organization of building works carried out by a contractor, tendering, contracting, inspection and control and progress charts, may have limited relevance for small-scale building projects on African farms, it is felt that an engineer will need some knowledge of these topics when tackling work involving the construction of communal and central facilities for agricultural production and services and medium- to large-scale rural buildings.

The costs of rural buildings such as animal housing and stores for produce can be expected to be repaid in terms of increased production, improved animal health, reduced storage losses, increased quality of produce and more efficient work performance. Other buildings such as dwellings are expected to be worth their costs mainly in terms of the standard of space, environment, convenience, construction and appearance they provide.

The term 'costs' in this context means costs over the whole life of the building, including operating and maintenance costs, as well as an annual portion of the initial cost of construction. It also includes the costs of building materials and construction labour, and fees paid to consultants, architects and legal advisors, as well as interest on capital and any loss of production incurred during the construction phase.

Building planning is thus concerned with economic building rather than with cheap building, i.e. with providing the required standard of facilities at the lowest cost. It should be noted that costs include not only cash payments but also the value of materials and work provided by the farmer and the family, because these are resources that could have been used for alternative activities at the farm to generate income or produce food.

Most methods for construction costing and economic feasibility studies assume that resources employed for the construction, as well as the benefits of the finished structure, can be valued in a convenient monetary unit. Subsistence farmers are part of the monetary economy to only a limited extent, so it is difficult to put a fair price on material and work supplied by them for construction at their farms, or to correctly value the benefits of the structure.

There is a national interest in the efficient use of the resources invested in buildings. Governments express their minimum demands in the form of building regulations, codes and laws.

A farmer employing an engineer to design a building, a contractor to construct it and suppliers to deliver materials will expect delivery of work and goods to the standard and price stipulated in the agreement. For later reference it is common to formalize the agreement in a contract that makes reference to drawings and specifications for the structure and to general specifications. Inspections and controls are carried out to ensure compliance with the agreement.

THE BUILDING PRODUCTION PROCESS

The building production process begins when the farmer starts to seriously consider investing in a structure and ends only when the finished building is in use. The process is divided into stages that follow in logical sequence. Each stage is terminated by a decision. Table 9.1 gives an outline plan of work for the building production process.

In small projects where the farmer performs virtually all tasks involved, it may not be necessary to follow the chart in detail. Nevertheless the same procedural basics and logical order should be followed. During the initial planning stages, the costs are low compared with the importance of the tasks involved. The high costs involved in correcting errors once site operations and construction are under way can be avoided if time is spent working out a good, functional design that is technically and economically sound.

METHODS OF CONSTRUCTION

The methods of constructing rural buildings refer to the way in which units and components of the building structure are produced and assembled. The manner of organizing this process differs from region to region and depends on the level of technology and the materials available. The operations involved in the construction of rural buildings of traditional designs are familiar to most rural people in Africa, and small buildings on farms are usually constructed by the farmers and their families.

TABLE 9.1
The building production process

Stage	Substage	Tasks to be done	People directly involved	Result of work	Decision to be reached
Briefing	Inception	Investigate different alternatives for investments and development of the farm now and in the future. Alternatives to finance the investment. Suitability of conditions for different enterprises	Client, agricultural economist, various specialists as required for technical briefing	Investment plan Development plan	Choice of investment alternative. Appoint farm building engineer
	Feasibility	Carry out studies of user requirements, site conditions, requirements from authorities, functional and technical requirements and cost	Client, farm building engineer, various specialists as required for technical briefing	Feasible, alternative sets of functional and technical requirements with indication of their cost	Choice of functional and technical requirements
Sketch plans Alt. A	Outline proposals	Develop brief further. Roughly sketch alternatives for the general approach to layout, functional planning, design and construction. Approach authorities	Client, farm building engineer, various specialists as required to develop the brief	Alternative rough sketches for general outlines with indication of their cost	Choice of general outline
	Scheme design	Complete the brief. Complete the functional planning of the layout. Preliminary construction design and cost calculation. Obtain outline decision from authorities	Client Farm building engineer	Alternative outline proposals for construction design with indication of cost. Complete brief and functional layout	Choice of construction design. Preliminary decision to produce the building
Sketch plans Alt. B	Standard drawings	Develop and complete the brief. Collect drawings from reliable sources. Study the drawings and evaluate them regarding the functional and technical requirements	Client Farm building engineer	Alternative standard layouts	Choice of drawing set. Preliminary decision to produce the building
Brief should not be modified after this point					
Final design	Detail design	Full design of every part and component of the building. Complete cost checking of designs. Final decisions from authorities	Farm building engineer. Assistance from specialist engineers might be required in large and complex projects	Complete set of drawings, technical specifications, functional instructions and an accurate cost estimate	Final decision to produce the building
Any further change in location, size, shape or cost after this point will result in abortive work					
Working drawings	Production information	Preparation of final production information i.e. drawings, schedules and specifications regarding production methods and assembly and installation instructions. Prepare a time schedule for the production of the building	Farm buildings engineer. Assistance from a specialist might be required in large and complex projects	Production information. Time schedule	Detailed decision to carry out work
Purchase	Bills of quantities	Preparation of bill of quantities and tender documents	Farm building engineer (sometimes specialist assistance required)	Bill of quantities Tender documents	Select persons and firms to be invited for tendering
	Tender action	Evaluate and compare tenders and quotations after having put costs to exceptions and additions in the tenders and quotations. Draw up and sign contracts	Client Farm building engineer Contractor	Contract with contractor and suppliers	Select contractor and suppliers. Contractor may contract subcontractors

TABLE 9.1 *(continued)*
The building production process

Stage	Substage	Tasks to be done	People directly involved	Result of work	Decision to be reached
Site operations	Project planning	Hire labour, provide tools, prepare access road to site, put up temporary stores and sheds, clear the site, prepare stockpile areas and set out the building	Contractor	Site prepared for actual construction activities	
	Operations on site	Construction activities. Delivery of materials. Technical controls and inspections. Site meetings, accounts and economic control	Contractor Farm building engineer Client	Finished building	Decision on alternatives, when operations do not or cannot proceed according to the plans
	Completion	Technical inspection on completion. Correction of errors, defects and shortcomings. Final technical inspection	Contractor Client Farm building engineer	Complete building Responsibility for the building transferred to client	Acceptance of the quality of the work carried out by the contractor
Post-construction	Entry into service	Study instructions and learn how to operate equipment and installations in the building. Develop smoothly running production work routines	Client Farm workers	Effective agriculture production involving the building	
	Guarantee	Investigate and inspect hidden defects, errors and shortcomings as they show. Inspection at the end of the guarantee period. Action for measures as required following the above inspections. Calculate final investment cost	Contractor Client Farm building engineer Farm workers	Building without hidden defects and shortcomings	Acceptance of work at the guarantee inspection. Responsibility for defects
	Feedback	Analyse technical and functional performance of the project. Analyse job records from site operations. Analyse costs	Farm building engineer Contractor Client	Recommendations for the design of similar future projects	

However, where new methods of construction, materials or layouts have been adopted, as well as where there is an increase in the size of the project, the assistance of trained artisans will usually be required. Self-help projects for the construction of communal facilities such as village stores must be accompanied by a training programme for the people involved. Where most of the construction is done by employed building workers, three different contemporary building methods can be distinguished – traditional; post traditional and system building.

The traditional method of constructing farm buildings is increasingly being replaced by post-traditional methods and, to some extent, by system-building methods. This rapid adoption stems from the marketing of modern building products by the materials manufacturing industry. The change has also been promoted by a rapid rise in population, which has led to a scarcity of traditional materials such as thatch.

Traditional buildings

In traditional buildings, the forms of construction have been developed by the traditional building trades, particularly walling, roofing, plastering, carpentry and joinery. This method is a process of combining many small units. Most of the fabrication and assembly takes place at the site and usually at the position that the completed structure is to be located.

Within each tribal culture, traditional buildings result in structures that are similar but differ slightly, depending on the specific requirements and site. Owing to the limited range of materials and forms of construction used, the craftsmen are familiar with the content and order of operations in their own trade and know their relationship to operations in other trades so well that they carry it out with a minimum of detailed information.

The traditional craft-based building method is flexible and able to accommodate variations in market demand for the work of craftsmen more readily and inexpensively than methods based on highly mechanized factory production. This is because production is carried out by the craftsmen and there is little investment in equipment, especially mechanical equipment, and factory buildings. However, the proportion of skilled labour required at the site is fairly high.

Post-traditional building

The post-traditional or conventional method of building mixes traditional and new forms of construction, involving both the old crafts and newly developed techniques based on new materials. To some extent traditional building has always been in a state of change, but the introduction of Portland cement and mild steel has made it feasible to construct large and complex buildings, and this has led to the need to organize the construction process efficiently.

The amount of on-site fabrication has been reduced by the introduction of prefabricated, factory-produced components, especially in the field of joinery and carpentry (windows, doors, cupboards, roof trusses, etc.). Reinforced concrete and preformed steel lend themselves to off-site fabrication of parts, followed by their assembly on site. Post-traditional building differs from traditional building mainly in terms of the scale of the work carried out and the use of expensive machinery for many operations.

The use of prefabricated, standardized components reduces the amount of skilled labour, but at the same time reduces the freedom of the designer in meeting varying design requirements. The scale of operation makes it necessary to pay greater attention to planning and organization of the work to ensure that material and labour are available in a continuous flow, that the mechanical equipment is used efficiently, and that the construction can proceed smoothly. It is therefore necessary to consider production operations during the design stage.

System building

System building is a method under which most of the building's component parts are factory-produced and site-assembled. The main advantages of system building are the possibilities for efficient factory production of large numbers of similar building elements and the reduced period of time necessary for assembly at the site. A disadvantage of this method is the high level of accuracy required for setting out and for foundation work because the nature of the components and the principles of the system are such that mistakes are difficult to correct during the assembly process.

The components (e.g. wall, floor, ceiling and roof elements) are usually related to a specific building type, such as houses, schools or warehouses, or to a restricted range of types. The design of buildings produced by this method is inflexible and limits the possibility of adjusting to specific requirements at a certain site or to a local building tradition. The building components may, for example, be produced for only specific dimensional measurements. For example, if prefabricated wall elements are 3.6 metres long, then the building length must be a multiple of 3.6 metres.

Components of one system will not ordinarily fit with components of other systems, a situation referred to as a 'closed system'. On the other hand, an 'open system' allows each component to be interchanged and assembled with components produced by other manufacturers. In order to keep the variety within acceptable limits for mass production, such a system must operate within a framework of standardization of the main controlling dimensions, e.g. floor-to-ceiling height of wall elements.

PREFABRICATION

Prefabrication is the manufacture of building components either on-site (but not *in situ*) or off-site in a factory. The use of prefabricated components can reduce the need for skilled labour at the site, simplify construction by reducing the number of separate operations, and facilitate continuity in the remaining operations. However, prefabrication is not necessarily time-saving or economical in the overall construction project. For example, the use of prefabricated lintels may save formwork and result in continuity in the bricklaying work, but could be uneconomical if a lifting crane is required at the site to place them, when it is not required for any other purpose on the job.

On-site prefabrication

On-site prefabrication may be an advantage where a number of identical components such as roof-trusses, doors, windows, gates and partitions are required. Once a jig, mould or prototype has been made by a skilled craftsman, a number of identical components can be produced by less-skilled labour, e.g. the farmer could do this job when there is time available during the off-season. Prefabrication of such items as roof-trusses also makes for more convenient and effective production than construction *in situ*.

It is advantageous to prefabricate some concrete components. Components for elevated positions require simpler formwork if cast on (or in) the ground so that the soil can be used to support the formwork. Although prefabrication eliminates the waiting time for concrete components to harden sufficiently for subsequent on-site operations to continue, the weight and size of concrete parts may make prefabrication impractical.

Local production by farmers of adobe bricks, burnt bricks, soil blocks, etc. is not normally referred to as prefabrication, although similar planning and organization are required for the production of these units as for the production of prefabricated building components.

Off-site prefabrication

Factory production of components requires capital investment in machinery and premises, a high degree of work organization, standardization and a steady demand for the products. Building components that can be produced economically in a factory essentially fall into three categories:

1. Those that have a high degree of standardization and are in great demand, making mass production,

utilizing the greater efficiency of modern factory production, feasible, e.g. bricks, blocks, pipes, windows, doors and building hardware.

2. Those that incorporate materials or finishes that are exclusively or more efficiently produced using factory-based techniques, e.g. metal components, plastic items, galvanized items and baked-paint finishes.
3. Those that make use of new factory-based techniques and machines, e.g. laminated-wood beams, pre-stressed concrete beams and insulated sandwich panels.

Factory production is relatively inflexible because large runs of any one component are essential for economical operation. The mere transfer of a simple operation from a site to a factory will not in itself reduce costs; on the contrary, it may increase them. This is particularly true for components for rural buildings because the demand for them originates from a large number of scattered construction projects, resulting in high transportation and distribution costs. Therefore many factory-made components used in rural buildings will have been designed primarily for other purposes.

DIMENSIONAL COORDINATION AND STANDARDIZATION

In order to limit variety in the size of similar components, to facilitate their assembly at the site and to make them interchangeable between different manufacturers, building components are manufactured in standardized dimensions based on an accepted system of dimensional coordination. Such preferred dimensions are given in standards, together with specifications for minimum technical performance requirements.

As the experience gained in factory production of components increases, the technique will be applied to components of increasing size and complexity (e.g. wholly finished wall elements) and this will increase the need for dimensional coordination. One system of dimensional coordination uses the international basic building module of 100 millimetres. The reference system establishes a three-dimensional grid of basic modules, or very often multimodules of 300 millimetres, into which the components fit.

The modular grid does not give the size of the component but does allow space for it. In order for the component to fit correctly, it will always be slightly smaller than the space allowed for it. The system must allow for some inaccuracy in the manufacturing process

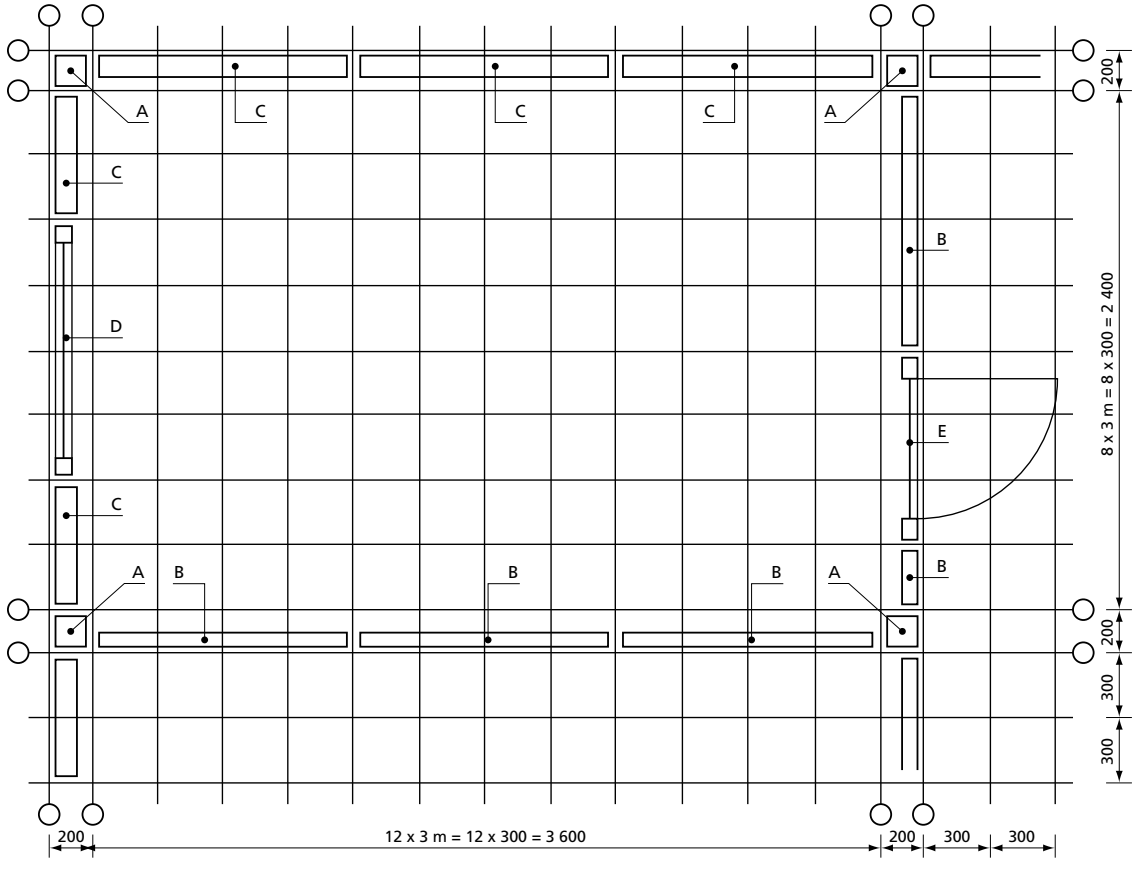


Figure 9.1a **Grid of 3M multimodules between zones of 200 mm allowed for load-bearing columns (A). Building components such as partition components (B), external wall components (C), windows (D) and door sets (E) are manufactured in sizes that are multiples of the 3M multimodule.**

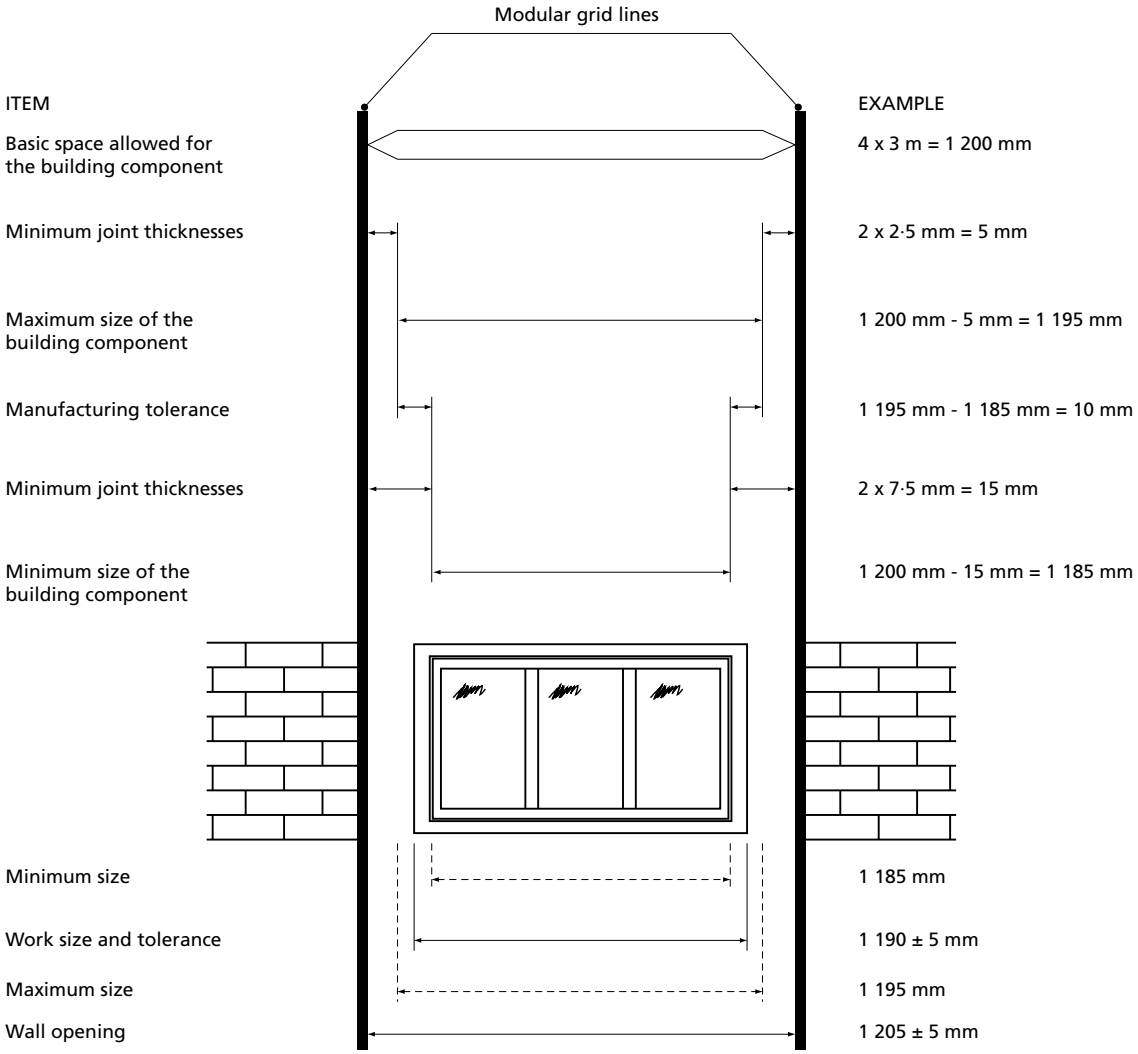


Figure 9.1b **Relationship of basic size, work size, manufacturing tolerance and joint thickness (***Note that tolerance and joint thickness are not to scale.***)**

and changes in size owing to changing temperature and moisture conditions.

This is expressed as a *tolerance* in size. For example, a window that is allowed a basic size of 1 200 mm for its width is produced with a working size of 1 190 mm and a manufacturing tolerance of 5 mm, which is expressed as 1 190 ± 5 mm. The actual dimension of a window delivered to the site would be somewhere between 1 185 mm and 1 195 mm. The joint would be designed to take these deviations into account.

Modular-size concrete blocks are 290 mm long and modular format bricks are 190 × 90 × 40 or 90 mm actual size to allow for 10 mm mortar joints and plaster. The actual size of openings will then be 1 220 mm. In this process the designer has a responsibility to specify tolerances that can be achieved with available craftsmen and factories.

It will be easier to fit factory-produced window and door casements, which are made to standard modular sizes, if these sizes are also used when bricks and blocks are manufactured locally. The common brick size of 215 × 102.5 × 65 mm allows for laying four courses to 300 mm vertically and four brick lengths to 900 mm horizontally, if 10 mm joints are used.

BUILDING LEGISLATION

In urban areas, government authorities issue building regulations to ensure the safety, security and welfare of those who use the buildings and to make maximum use of the scarce resources available for building construction. Typically, building regulations cover subjects such as building materials, structural integrity, fire precautions, thermal and acoustic insulation, ventilation, window openings and stairways, as well as drainage and sewage disposal. Building regulations may state minimum functional requirements, such as room height and space, for specific types of rooms.

Additional legislation applicable to buildings may be found in the public health act and public roads act. The building regulations and other legislation are statutory,

i.e. they must be followed as far as they apply. The local authority ensures that the legislation is complied with through its building inspector, health inspector, etc. However, the authorities will sometimes issue guidelines for building, in addition to the regulations. These are mere recommendations and the designer may diverge from them if there are good reasons.

Building regulations do not normally apply to buildings outside urban areas, but there may be instances where other legislation is applicable, for example, where a farmer wants to connect to a main water supply or a main sewer or to run a drain under a public road. Therefore it is wise to contact the local authorities about any new building proposal or major alteration to an existing building. If local authority approval is necessary, copies of drawings and specifications will have to be submitted for its advice and approval.

CONSTRUCTION COSTING

Throughout the building production process, costs will have a major influence when choosing between alternative designs. An excessively high cost may even cause the whole project to be abandoned. In the initial stages, when rough sketches are evaluated, general guideline costs based on building area or volume may be sufficient. In the final design stage, when the farmer has to decide whether or not to proceed with construction, a more detailed cost estimate based on a simplified bill of quantities is usually prepared.

A contractor will need the most accurate cost estimate based on a bill of quantities, as the quotation should be low enough to be competitive but still generate a profit. On large projects, the bill of quantities is also used to determine interim payments for work that has been completed.

Quantity surveying

The objective of quantity surveying is to provide an accurate bill of quantities, which is a list of the amounts of all materials and labour necessary to complete a construction project. In the simplified version, supplied by the designer with the final design documents, the labour requirement is not detailed. Sufficient accuracy for the purposes of this bill can be obtained by including labour as a lump sum, or as the number of hours or days of work, or as a percentage of the building material cost.

A bill of quantities for a standard drawing often excludes such operations as site clearance, excavation and fill, and external works, because such quantities may vary greatly from one site to another and can therefore be difficult to assess accurately at the time the drawing is completed. Indeed, the bill for a standard drawing may be a mere list of materials, perhaps with a rough estimate of labour added.

To avoid mistakes or the omission of any item, sophisticated methods have been developed for quantity surveying of large-scale projects. As rural buildings are normally smaller and far less complex, a simplified procedure will be adequate. Many rules of thumb or conversions have been developed to take into account such factors as cutting waste, differences between nominal and actual sizes, and breakages.

Taking-off

The objective of taking-off is to produce a detailed list of all materials and work. The quantities are assessed on the basis of detailed project drawings and specifications and listed, as far as possible, in the order that building construction will proceed. The first items are site clearing, excavation and foundations and final items are finishings and external works.

The dimensions of each item are obtained from the drawings and then the quantity is calculated in the units in which the item is customarily sold or priced. For example, excavation or fill, concrete, mortar and water would be in cubic metres, aggregates in cubic metres or tonnes, cement and lime in numbers of bags, and many things such as bricks and blocks, windows and doors, building boards and roofing sheets in numbers of units. Sawn timber is listed as the number of pieces of a specific size or, where that is unnecessary, total linear or volume quantities. Round timber is listed as the number of units of a specific cross-section and length.

A particular item that occurs in several places in a building can be noted each time it occurs or the number of units can be totalled in one place. One way of ensuring completeness is to tick off each item on the drawing as it is listed.

Assessment of labour

Detailed labour requirements to complete the type of construction commonly used in farm buildings may be difficult to find in published sources. This is because the contractors, who have the best knowledge of such data, use them as a means to compete for tenders. Also, most construction companies involved in rural building are too small to employ a quantity surveyor who could collect the data. Data published by quantity surveyors' or building contractors' associations tend to emphasize urban types of construction.

Rough estimates of the labour requirement needed by the designer of rural structures must be obtained through experience and by analysing a number of projects similar to the one at hand. Where the farmer and the farm labourers construct a building, it is to be expected that the labour requirement will be higher than when skilled construction workers are used. However, farm labour is available without any extra cash payment and there may be few alternative uses for it during the off-season.

Bill of quantities

The items for a bill of quantities are normally grouped together under headings for either the main operations (excavation, foundations, walling, flooring, roof

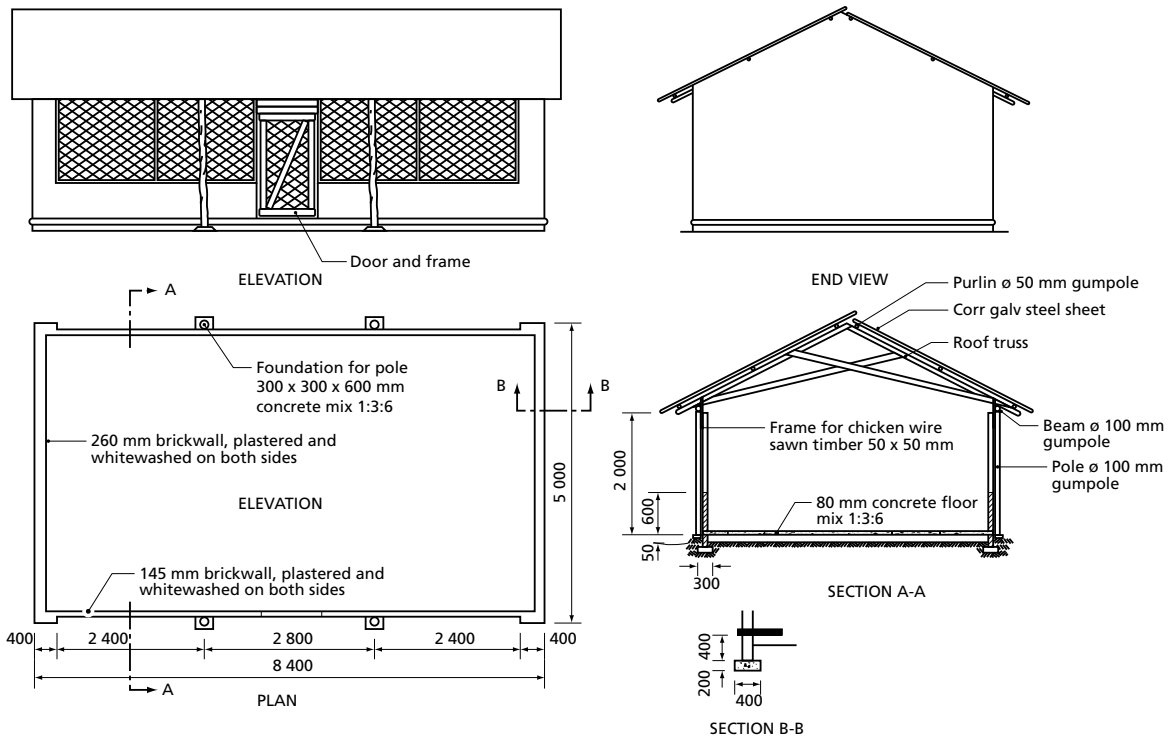


Figure 9.2 **Main drawing for a poultry house**

structure, roofing, finishing and external works) or the trades involved (earthwork, masonry, concrete work, carpentry and painting). Work normally carried out by subcontractors (wiring, plumbing, installation of equipment and furnishing) is listed separately.

The total quantity of each material or volume is transferred from the taking-off sheets to the appropriate heading in the bill of quantities and, while doing so, a percentage allowance for waste and breakage is normally added. The percentage added will depend on the type of material or volume but is often taken to be between 5 percent and 15 percent.

To keep a record of the items, they should be ticked off on the taking-off sheets as they are transferred to the bill of quantities. Labour may be listed under each operation or trade but, in the simplified bill, it is given as a lump sum at the end.

Example:
Prepare a bill of quantities for the poultry house illustrated in Figure 9.2. Start with taking-off.

Footing and foundation for poles, concrete 1:3:6

Footing, end walls	2 × 5.8 × 0 4 × 0.2	0.93 m³
Footing, side walls	2 × 7.6 × 0.3 × 0.15	0.68 m³
Foundation for poles	4 × 0.3 × 0.3 × 0.6	0.22 m³
Waste and spill 10%		0.18 m³
		2.01 m³

The amount of ingredients can be calculated using the figures in Table 5.13.

Floor

Base layer of gravel	8.4 × 5.0 × 0.15	6.30 m³
Sand for blinding	8.4 × 5.0 × 0.02	0.84 m³
Concrete (5% waste)	8.4 × 5.0 × 0.08 × 1.05	3.53 m³

Bricks

Area of sidewalls,

(0.6 + 0.2) × (2.4 + 2.8 + 2.4) × 2	12.16 m²
minus door opening 0.6 × 1.00	0.6 m²
	11.56 m²

Number of standard bricks
(0.215 + 0.010) × (0.065 + 0.010) = 0.017 m² per brick
11.56 × 1/0.017 = 680 bricks

Area of gable walls	0.40 × (2.0 + 0.4) × 4	3.84 m²
	5.0 × (2.25 + 0.4) × 2	26.50 m²
	5.0 × 0.5 × 1.34 × 2	6.70 m²
		37.04 m²

Number of standard bricks
(0.1025 + 0.010) × (0.065 + 0.010) = 0.0084 m²/brick,
37.04 × 1/0.0084 = 4 410 bricks

Number of bricks, 680 + 4 410	5 090
Waste and breakage 15%	765
Total number of bricks	5 855

Mortar, composition 1:1:6

Sidewalls 11.56 m² × 0.025	0.29 m³
End-walls 37.04 m² × 0.051	1.89 m³
Waste and spill 15%	0.32 m³
	2.50 m³

Plaster, cement plaster 1:5
Plaster thickness 10 mm

(11.56 + 37.04) × 2 × 0.01	0.97 m³
Waste and spill 15%	0.15 m³
	1.12 m³

The amount of cement and sand for the mortar and plaster can be calculated using the values in Table 5.17.

Wooden posts

Gum-poles 3.0 m, diameter 100 mm	4 pieces
Wood preservative	2 litres

Trusses

Gum-poles 4.0 m, diameter 100 mm	4 pieces
Bolts 110 mm long, diameter 8 mm	10 pieces
Bolts 200 mm long, diameter 8 mm	2 pieces

Purlins

Gum-poles 3.0 m, diameter 50 mm	18 pieces

Roofing
Corrugated steel sheets are laid in two rows on each side and the covering width is 533 mm per sheet. The length of the roof is 9 metres.

9 000/533 = 16.9

i.e. 17 sheets are required per row, or a total of 68.

Roofing nails
6 nails per m² × 68 m² = 408. As each kilogram of nails holds about 97, the requirement will be 4.5 kilograms.

Netting wall

Frame, timber 50 × 50 mm , including 10% waste	51.8 m
Chicken wire 1 800 mm wide	16.0 m

Door

Casement, timber 75 × 75 mm, including 10% waste	5.5m
timber 25 × 100 mm	2.0 m
Door frame, timber 25 × 100 mm	7.7 m
subtotal timber 25 × 100 mm	9.7 m
10% waste	1.0 m
Total timber 25 × 100 mm	10.7 m

Nails

Staples for fixing the chicken wire	1 kg
Wire nails 75 mm	1 kg
Wire nails 100 mm	1 kg

Whitewash
Whitewash is required for 97 m²

When all requirements are calculated, the amounts are included in the bill of quantities as follows:

TABLE 9.2
Bill of quantities for poultry house (see Figure 9.2)

Item	Description	Unit	Quant.	Rate	Total
1.	Foundation, 2.01 m³ concrete, mix 1:3:6 (10 percent waste)				
	Cement	50 kg	9.0		
	River sand (0.88 m³)	tonne	1.3		
	Crushed stone (1.8 m³)	tonne	2.9		
2.	Floor, gravel (6.3 m³)	tonne	10.1		
	Sand (0.84 m³)	tonne	1.2		
	3.53 m³ concrete, mix 1:3:6 (5 percent waste)				
	Cement	50 kg	14.0		
	River sand (1.6 m³)	tonne	2.3		
	Crushed stone (3.2 m³)	tonne	5.0		
3.	Bricks (215 × 102.5 × 65 mm)	number	5 910		
4.	Mortar, 2.5 m³, mix 1:1:6 (15 percent waste)				
	Cement	50 kg	13.0		
	Lime	kg	250.0		
	Building sand (2.8 m³)	tonne	4.0		
5.	Plaster, 1.13 m³, mix 1:5 (15 percent waste)				
	Cement	50 kg	7.0		
	Building sand (1.3 m³)	tonne	1.8		
6.	Posts, gum-poles (3.0 m × ϕ 100 mm)	number	4		
	Wood preservative	litres	2.0		

TABLE 9.2 *(continued)*
Bill of quantities for poultry house (see Figure 9.2)

Item	Description	Unit	Quant.	Rate	Total
7.	Roof structure, gum-poles (4.0m × ϕ 100 mm)	number	4		
	Gum-poles (3.0m × ϕ 50 mm)	number	18		
	Bolts (110 mm × ϕ 8 mm)	number	10		
	Bolts (200 mm × ϕ 8 mm)	number	2		
8.	Roofing, corrugated galvanized iron sheets				
	(CS 8/76 × 2.0 m, 0.018 mm)	number	68		
	Roofing nails	kg	4.5		
9.	Netting wall				
	Sawn timber (grade 3) 50 × 50 mm	running metre	51.8		
	Chicken wire, width 1 800 mm,	metre	16.0		
10.	Door, sawn timber (grade 2)				
	75 × 75 mm	running metre	5.5		
	Sawn timber (grade 2)				
	25 × 100 mm	running metre	10.7		
	Hinges	number	2		
	Latch	number	1		
11.	Nails, staples	kg	1.0		
	Wire nails 75 mm	kg	1.0		
	Wire nails 100 mm	kg	1.0		
12.	Whitewash (97 m²)				
	Lime	kg	50.0		
	Sand	kg	10.0		
	Cement				
13.	Furnishings, feed troughs	number	4		
	Drinkers	number	4		
TOTAL MATERIAL COST					
14.	Transport cost for material				
15.	Earthworks, excavation to level	m³			
	Remove top soil	m³			
	Excavation for foundation	m³			
16.	Construction	man-days			
17.	External works				
18.	Contingencies				
19.	Supervision and contractors' overhead costs				
TOTAL COST					

Costing

As mentioned in the introduction to this section, it is necessary to continuously assess the building costs for a proposed structure throughout the planning stages of the building production process. Three levels of accuracy can be distinguished: general guidance cost, specific guidance cost and accurate costing.

In addition, costing is carried out during construction to ascertain how the project is progressing from a financial point of view and to determine any interim payments to the contractor.

In the post-construction stage, the actual cost of the project should be calculated so that a record can be produced that will enable future building work to be accurately costed.

Unfortunately this is often neglected by designers and builders of rural structures.

General guidance cost

In this case rough estimates, simply giving the scale of costs, are derived by experience and analysis of a number of other similar projects. For example, if the

costs of a number of grain stores are assessed and in each case compared with the capacity of each store in tonnes, then a rough cost for grain stores can be estimated in terms of cost per tonne stored.

Hence an estimate can be given for a proposed new grain store if the capacity is known. Similarly, a building for dairy animals can be estimated if an average cost per cow is known from a number of different units.

Furthermore, for particular types of construction, it is possible to obtain average figures in terms of floor area. This type of estimate is based on a number of projects, some of which may not be directly comparable.

Specific guidance costs

By comparing similar projects, it may be possible to obtain reasonably accurate estimates before taking time to design the building and work out the bill of quantities. In this case, the costs of other buildings should be assessed in three components:

1. *Established costs*: costs that either have a fixed value or a uniform-unit value regardless of the size of the building. Examples are windows and doors.
2. *Variable costs*: costs that vary with the size of the building. As the length of a building grows, its total cost will grow but, at the same time, the unit cost may decrease so that even though a building is 50 percent longer the cost increase may be only 40 percent.
3. *Additional costs*: costs such as fees for consultants, architects, lawyers and accountants. Interest, insurance, fitting costs and losses should also be included.

Therefore, if a number of similar buildings are analysed, good estimates of each of these types of costs may be obtained and reliable specific guidance costs can be determined.

Accurate costing

This is done in conjunction with the bill of quantities. An accurate total cost of a job can be derived from the rate column in the final bill of quantities, together with the cost rate for each item. This requires each individual item of material, volume or labour to be costed.

However, for convenience and to facilitate the calculation of a quotation, many building contractors derive a cost per quantity of common types of construction. For example, a cost per square metre of concrete block wall will include the cost of the blocks, the labour to mix mortar, the cost of mortar materials and the labour required to lay the blocks. It may even incorporate a factor taking into consideration the average requirement of window and door openings and scaffolding.

However, costing with this degree of detail requires considerable information that can only be gained from experience and data that have been collected and analysed over a number of building projects. The unit costs will have to be reviewed continuously or be corrected with an index for building costs.

ECONOMIC FEASIBILITY

In addition to the actual cost of constructing a building, which must be considered in relation to the financial capacity of the farmer, the total annual cost of the building should be determined. When the annual cost is then compared with the expected increase in income or the saving in storage costs, it forms the basis for deciding whether or not the new building is a worthwhile investment, i.e. it determines the economic feasibility of the building.

To derive the true annual cost of a building, a number of factors must be considered. These include the estimated life of the building, annual repairs and maintenance, interest on the investment, insurance and, in some countries, real estate taxes. With the possible exception of repairs and maintenance, these are 'fixed' costs that occur whether or not the building is used. Consequently it is important to plan carefully both the use of the building and the construction.

The building may be considered as a production cost, and the potential income from the enterprise housed in it must be sufficient to justify the cost of building. It should be stressed, however, that there may well be reasons other than economic ones for constructing a building. For instance, a dwelling cannot be justified in terms of profitability alone as aspects such as amenity and welfare considerations may outweigh other factors.

Building life (depreciation period)

Physical life

All building components have a limited life. After a time, materials will deteriorate to a point where they can no longer fulfil their function. While repair, replacement and maintenance can extend the life, eventually the overall deterioration becomes excessive.

The life span of a building is influenced by its design and construction. In general, more costly materials such as steel and concrete are likely to last longer than timber and other organic materials. The physical life of rural buildings may range from two to five years for the simplest structures and as much as fifty years or more for substantial ones. An average figure is between 10 and 20 years.

Economic life

Although a building may last for many years, it may cease to be economically sound at an earlier time for any of several reasons. It may be that the design has become obsolete and is not suitable for new mechanization; or perhaps it is too small because the farm has grown; or a new enterprise requires a new layout or interior partitions, but supports simply cannot be moved to accommodate the new requirements. General purpose buildings will therefore have a longer economic life than those built for a specific enterprise.

Write-off life

It is impractical to expect any enterprise to pay the full cost of a new building in the year immediately following construction. Therefore the capital cost of the building is allocated or depreciated over several years. The number of years is determined by the write-off life, that is to say, the number of years over which it seems feasible to spread the original cost, but never fewer than the duration of a loan. In addition, the write-off life must not exceed the estimated physical or economic life to avoid being in possession of a useless building for which the original cost has not yet been fully paid.

As economic conditions change rapidly, the risk of a large investment is reduced considerably if the depreciation can take place over a relatively short write-off period. Ten years is considered short, 15 to 20 years medium, and 20 to 30 years a long period. This means that a building that is still physically sound and economically practical after the depreciation has been completed can be considered an economic bonus for the farm.

For cost estimation, depreciation is usually calculated on a 'straight-line' basis, that is to say, equal annual amounts over the write-off life. The annual straight-line depreciation cost is the original cost of the building divided by the years of write-off life. There are a number of alternative methods for assessing depreciation, most of which result in higher costs in the early years and decreasing costs over the life of the building.

Interest

The cost of the money used to construct a building must be considered, whether the financing is by means of a loan or by cash at hand. If money is borrowed, the interest cost is obvious. However, if farmers invest their own money, they are foregoing interest income from a bank or the possibility of other investments. Consequently, interest is still a real expense and should be included as an annual building cost.

The interest rate used is either the rate actually being paid or the prevailing rate for mortgage loans in the area. The interest charge is assessed during the years of depreciation and, during that period, the amount invested (principal) is gradually written off, from the full cost at the start to zero at the end.

Therefore the annual interest charge is usually based on the rate, multiplied by the average investment (original cost divided by two, or the original cost and half the rate). It should be pointed out that both a long-term mortgage with equal monthly payments (interest plus principal) and compound bank interest will result in higher interest costs.

Repairs and maintenance

Although all buildings will require some maintenance, the cost will vary with the type of building, the climate and environment, the materials used in construction and the use of the building. Although the cost for repairs and maintenance will vary from one year to the next and generally increase with the age of the building, it is common practice to assume a uniform annual allowance throughout the life of the building.

It is typical to allow between 1 percent and 3 percent of the initial construction cost for repairs and maintenance. While this is true in a monetary economy, it may not apply in a subsistence economy.

Insurance and taxes

If an owner carries insurance on buildings to cover the risk of fire and other hazards, then the cost of that insurance is included as an obvious annual cost. On the other hand, if farmers choose not to take out insurance, they are in reality carrying the risk themselves and should still include an annual charge for insurance. Insurance will ordinarily range between 0.5 percent and 1 percent of the original cost.

In countries where an annual real estate tax is levied, the taxes must also be included as an annual building cost. Taxes will range from zero, where there are none, up to 1 or 2 percent of the original cost of the building.

Annual cost

The five principal components of the annual cost of a building have been discussed in some detail. A variety of situations produce a rather wide range in the annual cost figures. The greatest variation occurs in the write-off period. This is influenced by the life of a loan, the life of the building and, in some cases, simply the arbitrary decision of the farmer.

In the following examples, all the low-range values are combined, as are all the high-range values. It should be pointed out, however, that they may occur in any combination. A high depreciation cost and low maintenance or low interest is perfectly possible.

	Low	Medium	High
Depreciation	3.5 (29 years)	6.25 (16 years)	10 (10 years)
Interest*	3	5	7
Maintenance and repairs	1	2	3
Taxes	0	1	2
Insurance	0.5	0.75	1
Total annual cost as a percentage of the original cost	8%	15%	23%

*Note: The interest rate is halved, as ordinarily interest is based on the average value or one-half of the original cost.

Having determined a write-off life and the corresponding depreciation percentage, as well as prevailing values for the other costs, the total percentage is multiplied by the original cost of the building to

obtain the annual cost. Next an estimate is made of the net income from the enterprise to be housed and the result compared with the annual building cost. The income should more than cover the building cost, allowing for a reasonable profit.

It should be noted that an existing building already has annual costs and that it is the *increased* cost of a replacement building that is compared with an *increased* income. If the plan is for an entirely new building to house a new enterprise, then the *total* annual building cost is compared with the *total* net income from the enterprise.

Cash flow and repayments

The annual cost for a building, as illustrated in the previous section, includes the capital cost in the form of depreciation as well as the carrying cost or interest.

If the farmer is fortunate enough to be able to pay all or most of the original cost of the building, then a comparison of annual building costs with income indicates the length of the period over which the farmer can expect to recover the investment. However, if the building project has to be financed largely by a loan, then cash flow and the ability to repay both capital and interest charges must be considered.

Any grantor of a loan will usually demand that repayments start immediately but, owing to the problems commonly experienced by farmers in starting up production in a new building, the earnings at this stage may be lower than expected. In the case of animal housing, the capital needed to purchase animals, feed and equipment is often larger than anticipated. The result may be insufficient cash during the first few years after the building has been constructed.

Even where a careful analysis has shown the enterprise to be profitable, that is to say, it has shown the expected average annual cost to be lower than the expected average income, the combined interest and principal payments on a long-term loan are likely to exceed the estimated average annual costs.

This makes it important to determine not only whether the cost of a new building can be justified, but also whether the necessary cash flow can be generated to cover both interest and capital repayments. While this is more of a business-management problem than a farm-structures problem, it is no less important to a farmer contemplating a new building.

ORGANIZATION FOR CONSTRUCTION OF SMALL BUILDINGS

In the case of farm structures, the future proprietor – the farmer – is normally much more directly involved in any repair or construction process than would be the case with a building in an urban area. Although the farmer may appoint an advisor to help with planning and design, employ a contractor or local craftsmen and take out a loan to finance the construction, the family's participation at all stages will normally be of great importance and serve to reduce the amount of cash necessary for the project.

Depending upon the level of self-involvement by the farmer, the family and any farm labour, and the way in which the construction is administered, four forms of organization can be distinguished: personal management; divided contract; general contract and turnkey contract.

Forms of organization

Personal management is a very common form of organization for repair work and construction of small- to medium-size rural buildings. The work is carried out by the employer (the farmer and the family), with the assistance of farm labourers and temporarily employed craftsmen. The employer may simply administer the work or participate in the construction work.

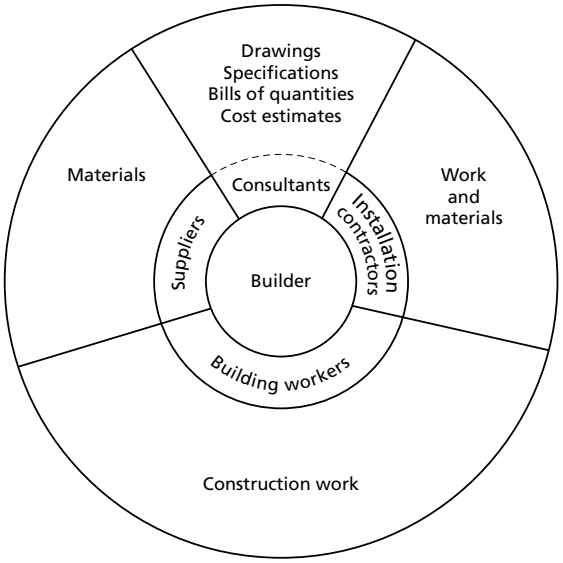


Figure 9.3 **Personal management**

A divided contract implies that the employer engages different contractors for the construction work and for installation and fitting work. This form of organization differs from personal management mainly in that the building construction work is carried out on a contract.

Self-involvement by the farmer can be arranged either by excluding some operations from the contract, such as earthwork and external work, or by giving the farmer some form of 'employee' status with the contractor. The latter is more easily arranged when a running-account payment system is used for the contract (see section entitled 'Forms of payment'). Building materials may be purchased by either the employer or the contractor. The contractor for the building construction work may be appointed to act as a coordinator for the various contracts.

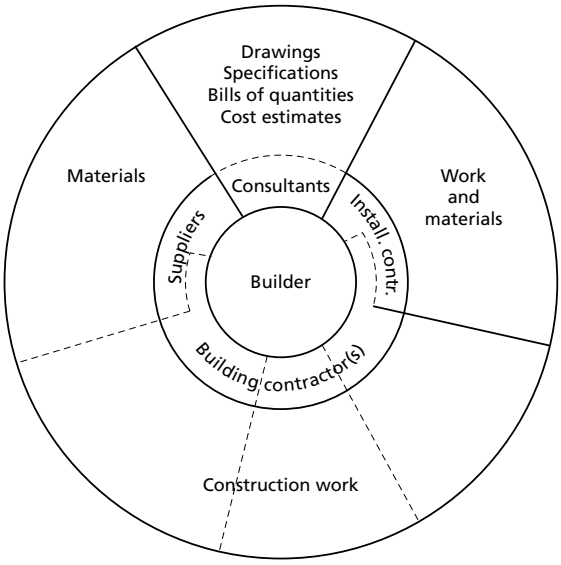


Figure 9.4 **Divided contract**

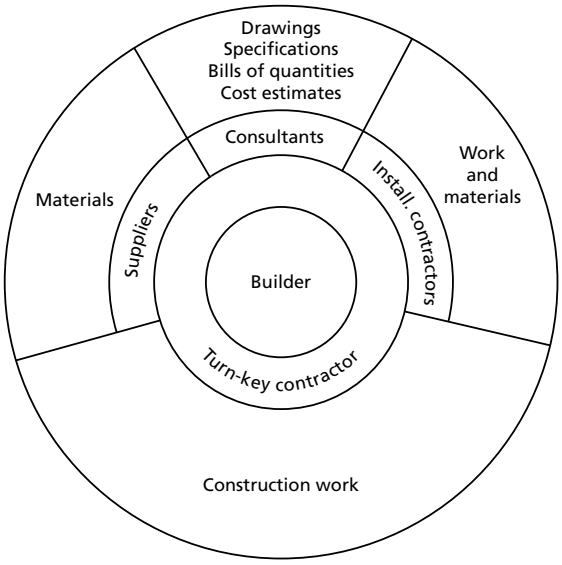


Figure 9.6 **Turnkey contract**

A general contract implies that the employer engages one contractor to carry out all the building construction operations. The contractor may in turn engage subcontractors to carry out work, such as fittings and installations, which the contractor lacks the skills or capacity to undertake. This form is uncommon for farm building construction, except for large projects.

A turnkey contract differs from the general contract in that the planning and design of the building is also included in the building contract. This form is very rare for rural building construction, except perhaps for completely prefabricated buildings in which the manufacturer serves as the contractor for erection.

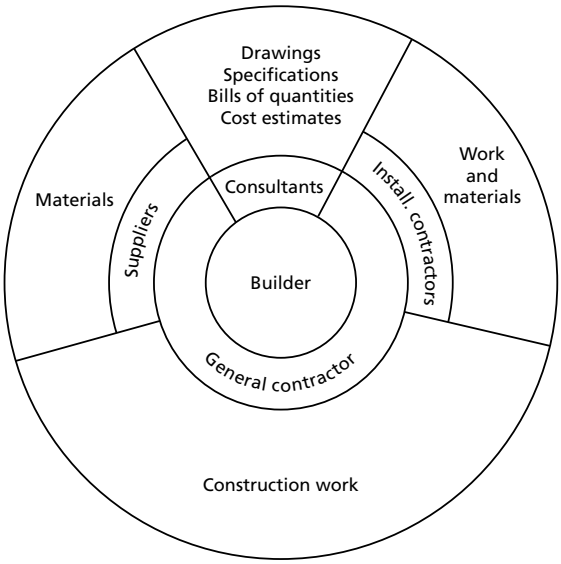


Figure 9.5 **General contract**

Forms of payment

The contract or agreement between an employer and a contractor may state that the payments for the contracted work will be made at a fixed price, with or without instalments for work completed, or on a cost-plus basis up to a ceiling figure, or with a running account for cost of materials purchased, plus an agreement on labour costs.

A fixed price is common for general and turnkey contracts, and is often used for divided contracts. The advantage of a fixed price to the employer is that the cost of the construction is known at an early stage. However, the contractor will require comprehensive documentation in the form of drawings and specifications to be able to give a quotation for a fixed-price contract.

Incomplete documentation will cause problems and frequent negotiations to decide on details and variations, usually involving additional expenditure. Therefore a running account is frequently used in cases where the documentation is insufficient or where it is difficult to make a satisfactory description of the work beforehand, as with repair and maintenance work. If a ceiling is placed on the running account, the employer will be guaranteed a maximum cost and will benefit, compared with a fixed price contract, should the work be less costly than the stated maximum.

TENDERING

The objective of tendering is to obtain proposals for construction work from different contractors and quotations for building materials from different suppliers. Competition between suppliers to submit the most favourable offer should result in a less expensive building for the farmer.

The tender procedure

When the farmer has decided to proceed with the proposed structure, the farmer and the advisors will prepare the tender documents, which usually comprise a letter of instructions, the necessary drawings and specifications and perhaps a bill of quantities, and will send them to various contractors and suppliers.

A contractor, or an estimator, will cost all building materials, volumes and labour and, after adding an allowance for supervision, overheads, insurance, contingencies and profit, will prepare a tender that is sent to the prospective employer in a sealed envelope.

During preparation of the tender, the contractor will visit the proposed building site to consider possible difficulties, in particular: access to the site and the need for temporary roads; storage of materials; type of ground; arrangements for siting any temporary office or welfare buildings; availability of labour in the area; arrangements for protecting the works against theft and vandalism. The contractor may also request fuller written documentation from the employer and, where subcontractors are to be employed, obtain tenders for their work.

A supplier of building materials or equipment will require less documentation and usually will not have to visit the site in order to prepare a quotation. The offer may or may not include transport to the site.

When the reply period specified in the tender instruction has expired, all the sealed envelopes containing the offers from the contractors and suppliers are opened. The contractors/suppliers may be invited to attend the opening of bids and be given names, prices and other relevant information contained in the offers. After careful evaluation of the offers, the most favourable, which will not necessarily be the cheapest, is accepted and a contract is prepared.

Methods of tendering

Open tendering: The prospective employer advertises in the press, giving brief details of the work, and issues an open invitation to contractors to apply for the necessary documents. The advertisement should state that the employer is free to select any or none of the bids that may be tendered. Tenderers are normally required to submit references and to pay a deposit for the documents, which will be returned on receipt of a serious tender. Open tendering is uncommon for rural construction work.

Selective tendering: Competitive tenders are obtained by drawing up a list of three to five serious contractors or suppliers in the area and inviting them to submit quotations. Normally the farmer and the advisor will know of a sufficient number of contractors who have the skill and experience to construct farm buildings and are also known for their integrity. Hence the lowest tender can usually be accepted.

Negotiated contracts are obtained by contacting one or two contractors or suppliers who have been found satisfactory in the past. The price for carrying out the work or delivering the material is negotiated until an agreement is reached. Negotiated contracts are also commonly used where the magnitude of the contract is not known at first, such as repair work, excavation in unknown ground, or where the tender documents are insufficient.

In such cases, the negotiation will normally aim at establishing reasonable task rates for a contract, with a running account. With a fixed contract, a contractor would have to safeguard against the unexpected and a large allowance for unforeseen expenditure would lead to a high contract price.

Evaluation of tenders

Quotations submitted to the prospective employer are likely to contain reservations, exceptions, additions and other conditions for the work or delivery of materials. A contractor may also suggest an alternative design or building method. If the letter of instructions for tender states that all such divergences from the tender documents should be priced separately, it will be quite simple to recalculate the tenders so that they are comparable. In other cases they will have to be costed by the employer.

The letter of instruction will normally ask the contractor to submit references from similar projects constructed in the past. For large projects, a bank reference and a performance bond are advisable. These should be examined to establish the contractor's practical and financial ability to undertake the proposed work.

CONTRACTS

A contract is a legal document signed by both parties before witnesses. The essence of a contract for construction work is the promise of a contractor to erect the building as shown on the drawings, and in accordance with the detailed specifications, in return for a specified amount of money known as the contract sum. A variety of standard forms are available for building construction contracts, but it would be desirable to develop a standard contract form specifically applicable to rural building construction.

If a bill of quantities is included in the documents attached to the contract, the employer will be responsible for any errors of measurement or shortcomings that occur in the bill. However, the selected contractor can be asked to check the bill and accept responsibility for it as being final. In the case of contracts without a bill of quantities, the bill is prepared by the contractor and any errors are then his responsibility.

A standard contract form may include the following information, but each clause in it should be studied prior to signing, and any clause that fails to meet the specific requirements of the project should be modified or deleted:

1. Names and addresses of employer and contractor.
2. List of all attached documents, i.e. drawings, specifications and bill of quantities.

3. Amount of the contract sum.
4. Starting date and completion date.
5. Weekly penalty to be paid should the contractor fail to complete the work on time. (Not always included.)
6. Directions for the employer to make a fair and reasonable extension of time for completion should the work be delayed through any cause beyond the contractor's control.
7. Directions for the contractor to comply with all applicable rules and regulations issued by local authorities.
8. Directions for the contractor to arrange regular site meetings between the contractor and the employer and to keep a diary detailing progress of the work. (Not always applicable.)
9. Directions for the contractor to obtain the employer's approval before any work is executed that diverges from the drawings or specifications, in particular where the variations involve additional expenditure.
10. Reference to a list of any building materials and equipment that will be supplied by the employer.
11. The extent of the contractor's responsibility for any liability, loss or claim arising during the execution of the contract work, whether for personal injury or loss or damage to property.
12. Insurance requirements for the contractor.
13. Statement requiring the contractor to pay, at his own expense, for any defects or faults arising from materials or workmanship that are not in accordance with the drawings and specifications.
14. Statement requiring the contractor to pay, at his own expense, for any hidden defects or faults that may appear during a specified guarantee period, usually 3 to 12 months, after the contract work has been completed.
15. Payment schedule, describing the percentage of the contract price to be paid on completion of each step.
16. Guarantee amount: normally about 10 percent of the contract sum is withheld until the guarantee period has expired or all defects are corrected, whichever is later.
17. Procedure for resolving disputes between the contractor and employer, e.g. that they shall be referred to arbitration for a binding decision.
18. The signatures of the contractor, the employer and witnesses.

SPECIFICATIONS

The specifications document supplements the drawings. The drawings should describe the geometry, location and relationships of the building elements to one another. The specifications set out quality standards for materials, components and workmanship that cannot be written on the drawings.

For example, if the drawing states that concrete Type 1 should be used for a floor, the specifications may set out a mixing ratio, quality standards for aggregate and water, compaction and curing practices, and quality standards for joints and finish.

Minimum requirements for capacity and reliability of equipment, as well as calculations relating to design, insulation, ventilation, etc., may be included as appendices. While in small projects, which are typical of numerous rural structures, many of the specifications may be included on the drawings, in large-scale projects the specifications may run to scores of pages.

General specification

As much of the information in the specifications will be similar from one project to another, it can be generalized to apply to most buildings. In many countries, the building industry or government agencies have therefore developed a 'General specification for building works'. This normally covers the majority of materials, types of construction, fittings, furnishings, etc. for the types of buildings and other structures built in urban areas. While some of the information included may also apply to rural structures, in general a list of specifications will need to be developed for the particular structure.

The advantages of using a general specification are that all parties are expected to have access to a copy and that they are familiar with the quality standards required in the various sections. Any planner/designer preparing specifications for a building may refer to the section numbers in the general specification without repeating the text of those sections. In addition, particular specifications that supplement, amplify or amend the provisions of the general specification will be required for each specific project.

To avoid confusion arising from discrepancies between the various building documents, the drawings normally prevail over the general specification, particular specifications override both drawings and the general specification and building code regulations override all other documentation.

Occasionally, when the government is the employer or when buildings are financed with government loans or subsidies, the general specification is considered statutory, but in all other cases its provisions can be used and amended as and when required.

PROGRESS CHART

A progress chart is a schedule, used to coordinate the sequence and timing of the operations in a building production process. It helps to ensure a timely supply of manpower, materials, equipment, machinery and subcontracted services by providing information on which dates and in which quantities they will be required, so that they can be ordered in good time. It can also be used to monitor the progress of the work and ensure compliance with the schedule.

The chart is often divided into three parts:

- The first part is produced by the farmer or an advisor and covers all work up to the time site operations start. It includes the sketches, any applications to authorities, final working drawings, tendering and ordering.
- The second part is normally produced by the contractor and includes all site improvements and construction operations (see Figure 9.7).
- The third part covers the start-up of production in the building and is developed by the farmer and advisors.

The preparation of a progress chart starts with listing all operations and their expected duration and identifying operations that *must* follow each other in sequence.

In the second step, a chart is developed showing the input of labour, machinery and equipment for various operations until the completion date is met. While doing this, it will be noticed that there is a sequence of operations called *critical operations* that must follow each other in a specific order and together determine the total time required to carry out the work.

In the third step, the requirements in terms of resources, in particular labour, and to a lesser extent machinery, are adjusted so that a fairly uniform workforce can be maintained. This is done by amending the timing and sequence of operations that can take place partly or wholly at the same time as the critical operations.

The fourth step consists of monitoring the work, in particular the critical operations, and revising the progress chart as problems or delays arise, e.g. delayed replies from authorities, contractors or suppliers; delayed delivery of materials and subcontracted services; delays in site operations owing to prolonged bad weather.

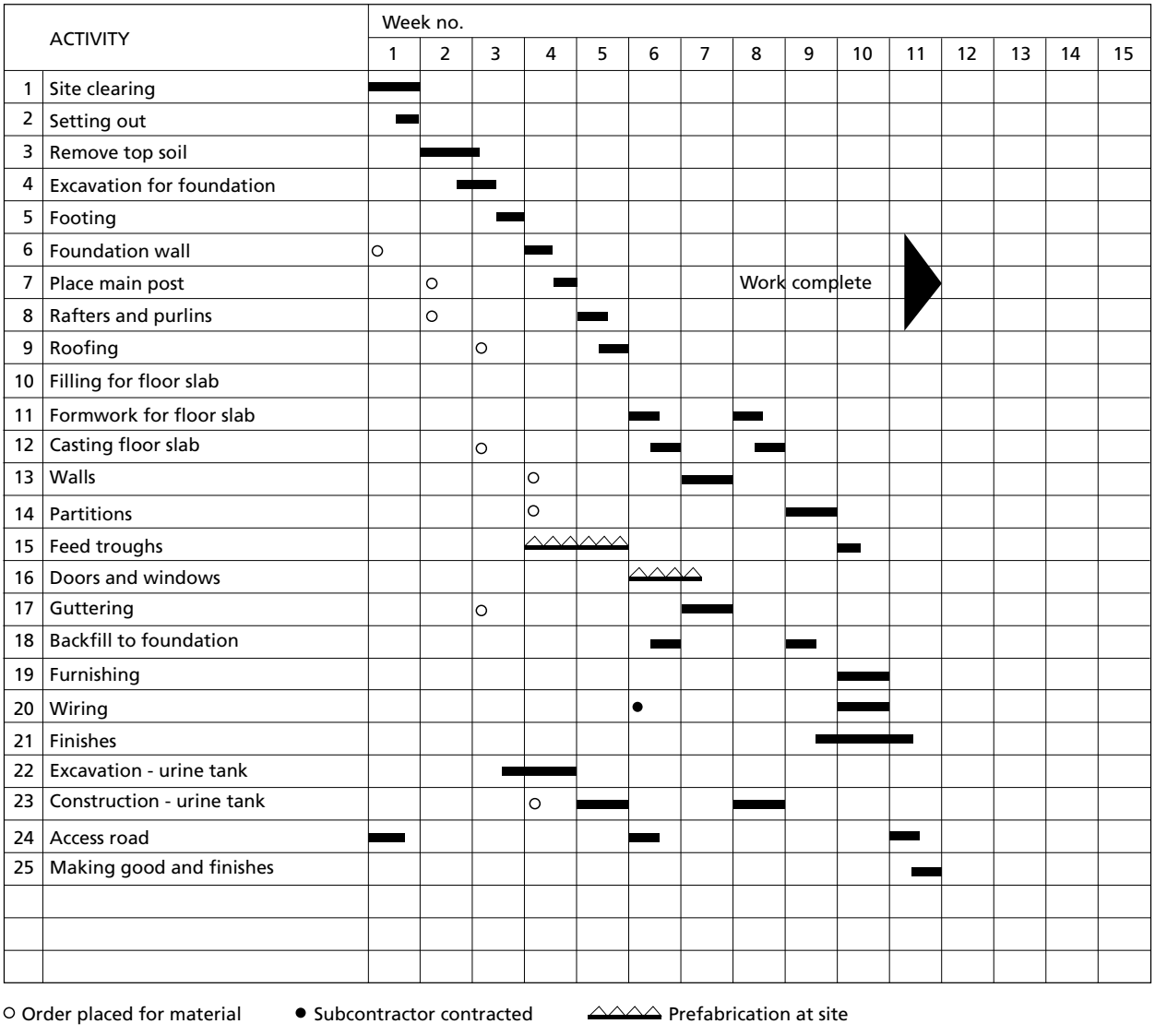


Figure 9.7 **Progress chart**

INSPECTION AND CONTROL

Whenever a building is constructed, it is likely that faults and defects will occur as a result of such factors as deficiencies in the building materials, negligence by workmen and mistakes in the drawings and specifications. Occasionally a contractor may be tempted to increase the profit by knowingly producing inferior work. To avoid this as far as possible, the employer or a person experienced in building construction (appointed by the employer) should act as an inspector during site operations. Control is normally carried out continuously as the construction work proceeds. In addition, more formal inspections are required upon completion of a contract and at the end of any guarantee period to determine whether the contracted payment should be made.

The duties of the inspector include the following:

1. To ensure that the contractor complies with the drawings, specifications and contractual provisions for the project.
2. To ensure that the project progresses according to schedule.
3. To inspect and control all materials delivered to the site and to reject any that fail to meet the specified quality.
4. To reject work that does not comply with the contractual quality and to stop work when continuation would result in substandard work.
5. On behalf of the employer, to interpret drawings, specifications and contractual provisions, and to act on the employer's behalf concerning variations.

SAFETY AT BUILDING SITES

Accidents may be caused by falling objects, falls resulting from unstable scaffolding or ladders or inadequate guard rails. Unguarded machinery, hazardous materials, carelessly maintained electrical wiring and equipment can also result in injury. Excessive haste may contribute to accidents and to wasteful, poor-quality work.

Most accidents can be avoided and safety standards improved considerably with little or no expense if the following basic safety precautions at the building site are observed:

1. Storing materials and tools in an organized fashion, with none left scattered around the building site.
2. Ensuring that tools, machinery and equipment are well maintained, with all guards covering moving parts in place.
3. Maintaining a clean and tidy building site with the removal of all waste, particularly scrap timber with protruding nails.
4. Making sure that all operators have been carefully instructed in the use of machinery and the handling of hazardous materials.
5. Insisting that all workers wear suitable clothing and protective gear, such as hard hats, hard-toe shoes and safety glasses.
6. Using properly designed, supported and braced scaffolds, ladders and platforms.
7. Establishing and enforcing rules as to where people can work while elevated members are being installed.
8. Making sure that all temporary wiring and electrical equipment is well maintained and grounded, and is properly used.
9. Having a good safety programme and making workers aware of hazards and how to avoid accidents.
10. Maintaining suitable first-aid equipment and supplies, and making sure workers know how to use them, to minimize the effects of any accidents that do happen.

BUILDING MAINTENANCE

Buildings deteriorate as a result of age, weathering and use. This necessitates maintenance and repair to ensure that the building retains its appearance and remains in a serviceable condition. Cleaning, repainting, reroofing and replacing or repairing broken parts, such as window panes and roof tiles, help to maintain the original value of the building.

Maintenance costs can be kept down by using materials that are suitable for the climatic conditions and with which local builders are accustomed to working. Furthermore, the building should be simple in detail, have easily replaceable parts and be free of unnecessarily complex or sensitive technical installations.

The fabric of a building should be thoroughly inspected once or twice a year to assess the performance of the different elements of the building. The inspection will result in a list of repair and maintenance jobs that should be carried out promptly, because insufficient or delayed measures will accelerate deterioration. Although maintenance work is usually carried out by the farmer, in the case of large repairs it may be carried out by hired building workers or a contractor. When a contractor is engaged, payment is often made on the basis of time and materials used according to an agreed schedule of prices.

REVIEW QUESTIONS

1. Define building production.
2. When does the building production process begin?
3. Briefly describe the various types of prefabrication.
4. Outline the role of a quantity surveyor in the building production process.
5. Describe the terms 'take-off' and 'bill of quantities'.
6. Briefly describe the building costing process for rural structures.
7. Differentiate between the 'physical life' and the 'economic life' of a building.
8. Briefly describe the tendering process in building production.

9. Outline the three types of tendering that are used in building construction.
10. Describe the progress chart as used in building production.
11. Explain the role of inspection and control in building production.
12. Describe some of the safety standards that should be observed on a building site.
13. Why is it necessary to maintain a building?

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Chapter 10
Livestock housing

INTRODUCTION

The main purpose of livestock production is to convert the energy in feed into products that can be utilized by human beings, such as milk, eggs, meat, wool, hair, hides and skins, draught power and manure (fertilizer). Traditional, extensive livestock production involving indigenous breeds and low-cost feeding will usually have low performance and can therefore only justify minimal, if any, expenditure for housing. However, where improved breeds, management and feeding are available it will usually be economically beneficial to increase the production intensity.

Although this can be facilitated by, among other things, the construction of buildings and other livestock structures to provide for some environmental control, reduced waste of purchased feedstuffs and better control of diseases and parasites, this rule is not invariable. For example, it is difficult to identify an economic benefit in sheep production arising from the use of anything but the least expensive buildings. At the other end of the scale, a relatively expensive farrowing house, providing a high level of environmental control, may improve the survival rate in piglets sufficiently to justify the cost and add to the profitability of the production unit.

The planning and design of any structure for a livestock production system involves many alternatives for each of numerous variables and can therefore be turned into a complex and theoretical subject, but is usually far simpler in reality. However, every facet of the design, including the production system, equipment, building materials, layout and location, will play a part in determining the profitability of production and any variation in one of them may significantly affect the profitability of the whole.

One special difficulty when designing livestock structures for tropical climates is that, up to now, most research and development has been concerned with the conditions in temperate or cold climates. Any recommendations derived from such experiments and applied uncritically in warm climates may result in an adverse environment for the animals and in very high building and operating costs.

ANIMAL BEHAVIOUR

Introduction

A basic understanding of domestic animal behaviour and the relationship between human beings and farm animals can contribute greatly to increased economic benefit in animal husbandry and to easier handling of the animals. The importance of animal behaviour aspects in the design of animal housing facilities generally increases with the intensity of production and the degree of confinement. Many modern farming systems greatly reduce the freedom of animals to choose an environment in which they feel comfortable. Instead they are forced to resort to an environment created by humans.

Animals that can exercise their natural species-specific movements and behaviour patterns as far as possible are less likely to be stressed or injured and will therefore be more productive. However, in the practical design of an animal production system and any buildings involved, many other factors, such as feeding, management, thermal environment, construction and economics, can be equally or even more important. The animals can, to some extent, adapt their behaviour to suit a bad design and, on a long-term basis, they can be changed by breeding and selection, but generally it will be much easier to tailor the husbandry and building design to the animals.

The lifespan of a building is usually 5 to 15 years, which makes it clear that even a small increase in production or decrease in the frequency of injury and disease, feed waste or labour requirements for animal handling will repay all the thought and care that has been put into the design, layout and construction of the building. Furthermore, it may cost as much to construct a building that is poorly designed and equipped for the animals as one that works well.

Behaviour patterns

Farm animals are born with certain fixed behaviour patterns, such as pecking in chickens and nursing in mammals, but most behaviour patterns develop through play and social contact with other animals of their kind and under the influence of environmental stimulation and genetic factors. Although behaviour variation within a species is caused mainly by differences in the environment and between the sexes, breed, strain and individual variance also have an influence. Domestic animals show great ability to modify their behaviour patterns in relation to environments and to learn from experience.

Animals often form a daily cycle of habits caused by the uniformity of husbandry; for example, the regular variation in light during night and day relate to internal physiological rhythms. This is why cows gather around the barn just before milking time. Some behaviour

patterns change from season to season, partly in response to the changing weather. Cows tend to be more active during the night in the hot season and, if outside, spend less time lying down during the wet season. Many domestic animals show a slight seasonal breeding pattern.

Domestic animals under conditions of close captivity frequently display abnormal behaviour such as stereotyped movements or inappropriate sexual behaviour, particularly if they are unable to escape from, or adapt to, the situation. However, many disturbed behaviours have more complex causes. For example, tail and ear biting in pigs may be associated with boredom, breakdown of social order, an excessively high stocking rate, insufficient fibre content in the feed, malnutrition, poor ventilation leading to high humidity and overheating, lack of bedding, inadequate trough space and watering points, skin disease, parasites, teething problems, etc.

Social rank order

Domestic animals are highly sociable and naturally form groups. Males and females form separate groups, except during the breeding season, and the young tend to form small groups in the proximity of the female group. When strange adult animals meet for the first time they are likely to fight to establish dominant/subordinate relationships. The resulting pecking order, or social rank order, in which one or two animals are invariably dominant is usually formed quickly. While physical age and weight are the main factors determining social rank, sex, height and breed can also be an influence. The group can live in relative harmony as long as each animal knows its place and gives way to animals of higher rank. However, the order is seldom strictly hierarchic or static. Some animals of low rank may dominate others whose positions are normally higher, and fast-growing and maturing animals may move up the ladder.

The introduction of new animals into a group or the mixing of groups will normally lead to fighting until a new social order is established, and this may cause a growth check as well as injury.

The normal response to aggressive behaviour in a group with an established social order is for the subordinate animal to move away. The building layout must allow space for this and therefore narrow passages and corners where one animal can be trapped by another should be avoided in pens and yards. The order usually remains stable provided the group is small to ensure that all animals in it can remember the positions of the others, i.e. fewer than 80 cows, between 12 and 15 pigs or about 100 chickens.

Animal behaviour studies

Experiments intended to improve the design of animal housing, its furnishing and equipment, usually employ one of the following methods:

(a) A choice of environment is provided for the animals and their preference for the different facilities is recorded.

(b) The behaviour of animals in an experimental environment is studied and the result is compared with the behaviour of animals in a reference system, on a free range, or that of their wild relatives. Often the study is confined to activities such as resting, eating, standing/walking, but sometimes the frequency of other behaviour patterns, such as investigative, agnostic, sexual, care-giving, care-soliciting or eliminative behaviour is also included.

In addition, productivity and the frequency of injuries and disease outbreaks are recorded.

Animal behaviour and building design

Animal behaviour can influence the design of structures, as demonstrated in the examples given below. More examples will be given when housing facilities for the various species are described later in this chapter.

Cattle normally live in herds but, when giving birth, cows attempt to find a quiet, sheltered place away from the disturbance of other cows and humans. The cow needs to be alone with her calf for some time after birth for the cow/calf bond to be established. When a cow that is confined in a loose housing system is approaching calving, it should be removed from the herd and placed in an individual pen.

Hens spend considerable time in the selection of a nest, which is on the ground. Nesting is characterized by secrecy and careful concealment. Hens in deep-litter systems therefore, sometimes lay eggs on the floor instead of in the nest boxes, especially if the litter is quite deep or there are dark corners in the pen.

To avoid this, plenty of fresh litter is provided in the nests, and they are kept in semidarkness and fitted with a rail in front so that birds can inspect the nests prior to entry. An additional measure is to start with nest boxes on the floor and slowly raise them to the desired level over a period of days.

Sows are nest-builders and should be transferred to clean farrowing pens one to two weeks before giving birth, and given some bedding with which they can build a nest. Oestrus, especially in gilts, is increased by the smell, sight and physical presence of a boar. Gilts and sows awaiting mating should therefore be kept in pens adjoining the boar pen.

Cattle prefer to be able to see while drinking, therefore more animals can drink at once from a long, narrow trough than from a low round one. With cattle (and hens), feeding is typically a group activity, therefore space at the feed trough must be provided for all the animals at one time. At pasture, undersized feed or water troughs can result in inadequate feeding and watering of the animals that are lowest in rank because these animals could well be excluded from the trough but, despite this, they still tend to leave with the rest of the herd after feeding or watering.

To prevent wasting feed, a trough should be designed

to suit the particular behaviour pattern that each species exhibits while feeding, i.e. pecking in hens; rooting with a forward and upward thrust in pigs; and wrapping their tongue around the feed (grass) and jerking the head forward in cattle.

Artificially reared calves bunt the bucket instead of the cow's udder, and this requires a sturdy holder for the bucket. The habit of suckling each other is a problem in dairy calves. The problem can be reduced by making the calves suckle harder and longer for their feed by using a rubber teat rather than a bucket and by giving them access to dry feed. Assuming intersuckling is not a problem, a group pen for calves is more natural than individual pens, and helps to ensure normal activity and resting.

Sheep are vigilant and tight-flocking, and respond to disturbances by fleeing. When designing handling facilities, these characteristics should be taken into account. A race should be straight, level, fairly wide, have no blind ends, and preferably have close-boarded sides. Sheep that are following should be able to see moving sheep ahead, but advancing sheep should not see the sheep behind as they will tend to stop and turn around.

Sheep move best from dark into light areas and dislike reflections, abrupt changes in light contrast and light shining through slats, grates or holes. Handling facilities should be examined from the sheep's eye level, rather than from human eye level to detect flaws in the design.

ANIMAL ENVIRONMENTAL REQUIREMENTS

The capacity of an animal to produce differs between species, breeds and strains as a result of genetic factors. However, a complex set of interrelated animal husbandry factors will influence the animal's ability to utilize that capacity for growth, development and production.

Progress in breeding and feeding to further increase production and efficiency can be limited by environmental factors. Research into these factors has therefore been increasing in recent years, especially in countries with intensive animal production systems.

Animal housing design is mainly concerned with the physical environment, in particular climatic and mechanical factors. However, all other factors should also be considered in order to create a good layout, where healthy, high yielding animals can be provided with correct feeding, can be easily handled and can produce without stress or suffering physical harm.

Heat regulation

All domestic livestock are *homeotherms,* that is to say, they maintain a relatively constant internal body temperature, usually within a 1–2 °C range. The normal body temperatures of some domestic animals and humans are given in Table 10.1.

TABLE 10.1
Normal body temperatures of domestic animals and humans

	Temperature (°C)	
Animals	**Average**	**Range**
Dairy cow	38.6	38.0–39.3
Beef cow	38.3	36.7–39.1
Pig	39.2	38.7–39.8
Sheep	39.1	38.3–39.9
Goat		38.7–40.7
Horse	37.9	37.2–38.2
Chicken	41.7	40.6–43.0
Human	37.0	

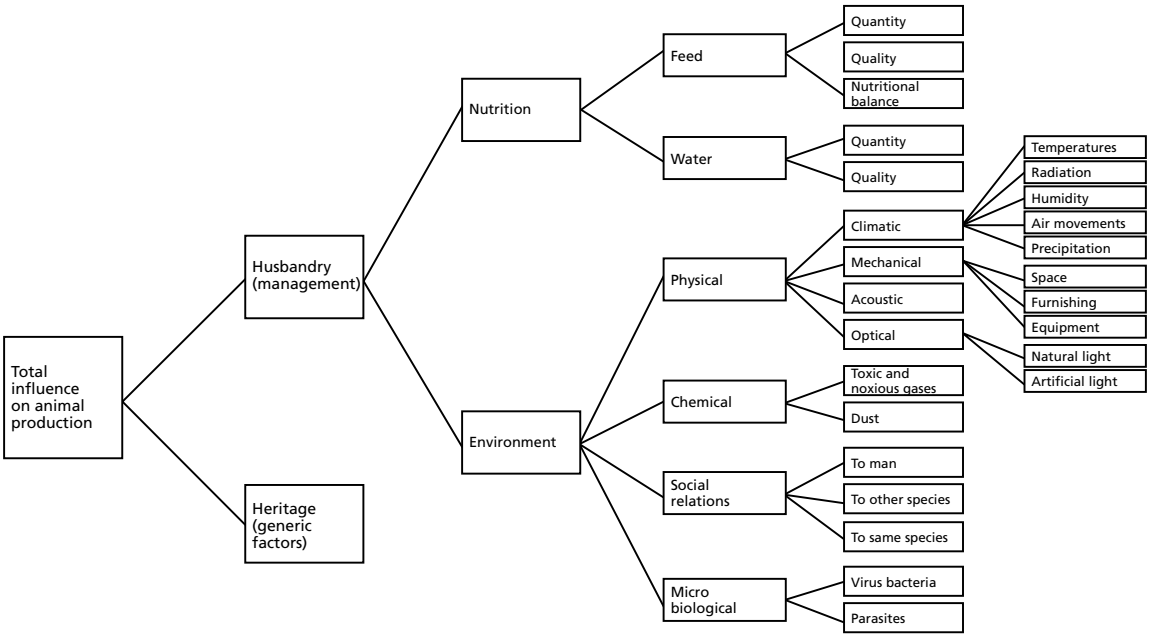


Figure 10.1 **Classification of factors influencing livestock production**

The body temperature of most domestic animals is considerably higher than the environmental temperature to which they are exposed most of the time. They maintain their body temperature by balancing internal heat production and heat loss to the environment. The *hypothalamus gland* acts as a body thermostat by stimulating mechanisms to counteract either high or low ambient temperatures. For example, increased conversion of feed-to-heat energy is used to counteract low ambient temperatures, while increased respiration (rate and volume) and blood circulation in the skin counteracts high ambient temperatures.

Varying the temperature also results in changed behaviour. Most animals reduce their level of activity in a hot environment and, for example, pigs lie clustered in a heap at low temperatures, while they lie spread out with extended limbs at high temperatures. This would suggest an increased space requirement for pigs in a warm, tropical climate. The body can tolerate short periods of heat stress but if the ambient temperature exceeds the body temperature for an extended period, it may prove fatal.

When feed is converted by the animal's metabolism for the production of milk, eggs, meat, offspring, etc., heat is produced as a by-product. An increased production level (and hence feed requirement) will therefore result in increased internal heat production. High-yielding animals are consequently more likely to suffer from heat stress in a hot climate than low-yielding ones.

Feeding fibre-rich, low-digestible feedstuffs, such as hay, will result in high heat-production because of increased muscular activity in the alimentary tract and, in ruminants, increased micro-organism activity in the rumen. An increased share of concentrates in the feed may therefore reduce heat stress in an animal under hot climatic conditions.

Animal moisture and heat production

Heat is produced centrally in the deep body. The surplus is conducted to the skin surface where it is transferred to the atmosphere as sensible heat by means of convection, conduction and radiation, and as latent heat through the evaporation of moisture from the lungs and skin. Increasing the ambient temperature, resulting in a smaller temperature difference between the body surface and the air, will decrease the amount of heat that can be emitted as sensible heat. Instead, a larger proportion is given off as latent heat, that is to say, heat employed to vaporize moisture.

Table 10.2 lists values for animal heat and moisture production at various temperatures. The heat and moisture produced by the animals confined in a structure must be removed by ventilation. In the tropics, sufficient air flow is usually provided by the use of open-sided structures.

However, if an enclosed building is used, a range of ventilation flow rates must be provided for in the building design. The minimum ventilation rate should remove the moisture produced, but retain as much sensible heat as possible during cold periods. The maximum ventilation rate should remove enough of the sensible heat produced so that a small temperature difference, usually 2–4 °C, can be maintained between inside and outside. It should be noted that ventilation alone can maintain the building at only slightly above ambient temperature. Ventilation is discussed in more detail in Chapter 13.

Climatic factors

Temperature

The overriding environmental factor affecting the physiological functions of domestic animals is temperature. For most farm animals, a mean daily temperature in the range 10–20 °C is referred to as the 'comfort zone'. In this range, the animal's heat exchange can be regulated solely by physical means, such as the constriction and dilation of blood vessels in the skin, ruffling up the fur or feathers and regulation of the evaporation from lungs and skin.

At the upper and lower critical temperatures, physical regulation will not be sufficient to maintain a constant body temperature and the animal must, in addition, decrease or increase its metabolic heat production A further decrease or increase in temperature will eventually bring the temperature to a point beyond which not even a change in heat production will be sufficient to maintain *homeothermy*.

A very young animal, lacking fully developed temperature-regulating mechanisms, particularly the ability to increase heat production by increased metabolism, is much more sensitive to its thermal environment and requires higher temperatures.

Humidity

Poultry do not have sweat glands, so all evaporative heat loss must originate from the respiratory tract. Other livestock species have varying abilities to sweat and, in descending order, they are as follows: horse, donkey, cattle, buffalo, goat, sheep and pig.

In a hot, dry climate evaporation is rapid but, in a hot humid climate, the ability of the air to absorb additional moisture is limited and inadequate cooling may result in heat stress.

Excessively low humidity in the air will cause irritation of the mucous membranes, while excessively high humidity may promote the growth of fungus infections. High humidity may also contribute to decay in structures. If possible, keep the relative humidity in the range of 40 percent to 80 percent.

Radiation

The heat load on a grazing animal can be increased considerably by direct solar radiation and radiation reflected from clouds or the ground. A white hair coat will absorb less radiant energy than a dark one, but the heat penetrates deeper into a white, loose

coat. Air movements will dispel the heat and reduce the differences. Solar radiation may also adversely affect the animal's skin, in particular breeds with unpigmented skin.

Heat gain by radiation can be effectively reduced by the provision of a shaded area. It must, however, be sufficiently large to allow space between the animals to avoid reducing heat loss by other means. Grass-covered ground in the surroundings of the shade will reflect less radiation than bare soil.

Air movements

Air movements assist heat loss by evaporation and by conduction/convection, as long as the air temperature is lower than the skin temperature. When the air temperature approaches skin temperature, rapid air movements are experienced as comfortable but, at low temperatures, they lead to excessive cooling of unprotected skin areas (cold draught).

In addition, air movements are required to remove noxious and toxic gases and to supply the animal with fresh air for breathing. A wind velocity of 0.2 m/s is generally regarded as a minimum requirement, but it can be increased to 1.0 m/s when the temperature is nearing the upper critical level, or more when it rises beyond that.

Precipitation

Heavy rain may penetrate the fur of an animal and decrease its insulation value. In such circumstances, a strong wind can lead to excessive cooling. However, a naturally greasy hair coat will resist water penetration and with the provision of a shelter for the animals the problem may be avoided altogether.

TABLE 10.2
Animal heat and moisture production

Livestock	Weight (kg)	Ambient temperature* (°C)	Moisture (g/h–animal)		Sensible heat (W/animal)		Total heat[1] (W/animal)	
			*°C	25 °C	*°C	25 °C	*°C	25 °C
Dairy cow	400	12	410	835	685	395	960	960
	500	12	445	910	745	430	1 045	1 045
	600	12	485	985	805	465	1 130	1 130
	700	12	515	1 045	855	495	1 200	1 200
Dairy calf	50	12	70	105	70	75	115	145
	75	12	185	365	220	120	345	365
	150	12	205	365	280	170	420	420
	200	12	160	330	270	155	380	380
	300	12	220	450	370	215	520	520
	400	12	275	565	460	265	645	645
Swine	5	27	30	-	20	-	40	-
	10	24	35	40	35	35	60	60
	20	20	60	70	55	50	95	95
	30	16	65	90	80	65	125	125
	50	16	75	120	125	85	175	165
	70	16	100	150	145	105	215	205
	90	16	115	170	165	120	245	235
Dry sow	180	12	85	165	210	135	270	245
Sow one week prior to birth	180	12	120	220	285	185	365	335
Sow with piglets	180	16	175	300	340	245	460	450
+W36 pullets	0.04	32	0.35	-	0.1	-	0.3	-
	0.8	21	3.5	-	4.1	-	6.4	-
Laying hen	1.4	24	5.6	-	5.5	-	9.1	-
	1.5	20	5.2	6.5	6.6	5.7	10.1	10.1
	2.0	20	6.0	7.6	7.6	6.6	11.7	11.7
Broilers	0.1	32	3.1	-	0.9	-	3.0	-
	1.0	20	5.0	6.5	6.6	5.6	10.0	10.0
	1.5	20	6.2	8.0	8.1	6.9	12.3	12.3

* Referring to temperature stated in the column 'ambient temperature';
[1] Total heat equals sensible heat plus latent heat (latent heat equals moisture in g/h × 0.675 Wh/g);
+ Data adapted from Chepete *et al*., 2004 – ASHRAE Transactions.

Effect of climatic factors on livestock performance

In tropical and subtropical countries, an animal may often be under heat stress. When the environmental temperature exceeds the upper critical level (18 °C to 24 °C, depending on the species) there is usually a drop in production or a reduced rate of gain. Furthermore, when the temperature falls outside the comfort zone, other climatic factors assume greater significance. Humidity becomes increasingly important, as do solar radiation and wind velocity.

Dairy cattle show a reduced feed intake under heat stress, resulting in lower milk production and reduced growth. Reproduction is also adversely affected. There are, however, important differences between breeds. European cattle (*Bos taurus*) produce well at temperatures ranging from 4 °C to 24 °C, even at high humidity. Much lower temperatures (-10 °C) have little effect, provided that fluctuations are not too rapid or frequent.

On the other hand, a drop in milk production results when temperatures exceed 25 °C. The drop may be as much as 50 percent at temperatures of 32 °C or higher. In contrast, zebu cattle (*Bos indicus*), which are native to warm climates, have a comfort zone of 15–27 °C and milk production begins to drop only when temperatures rise above 35 °C.

It is important to note some of the physical differences between these two types of cattle that make each suited to its climate of origin. The zebu is characterized by a hump, large ears and loose, thin skin with a prominent dewlap. These characteristics promote heat loss by convection and evaporation and thus efficient body temperature regulation under hot climatic conditions. In addition, the zebu has less subcutaneous fat, a lower body volume for the surface area, and short, smooth hair, all of which contribute to the animal's comfort under hot conditions.

On the other hand, the European breeds have thick skin held tightly to the body, long hair and a large amount of fat, which serve as insulators and are desirable traits for cold or temperate climates. Although there is a considerable range in size within each breed, the zebu is a relatively small animal (a fully grown bull rarely exceeds 700 kg), while the European cattle are large, reaching 1 000 kg live weight. Figure 10.2 illustrates the configurations of the two types of cattle. Calves seem most sensitive to cold draughts and poor ventilation, but are quite tolerant of a wide range of temperatures.

Beef cattle make their best weight gains at temperatures below 25 °C. They can easily tolerate temperatures below 0 °C if they have a good supply of feed.

Pigs require a change in ambient temperature as they age and grow and, like cattle, they show a decreased feed intake when under heat stress. Piglets survive and develop best at 30–32 °C initially, followed by a gradual reduction to 20 °C over the first three weeks. Feeder pigs (weighing 30–65 kg) make good gains in the temperature range 10–25 °C, with 24 °C reported to be optimum. The optimal ambient temperature for pigs weighing 75–120 kg is 15 °C.

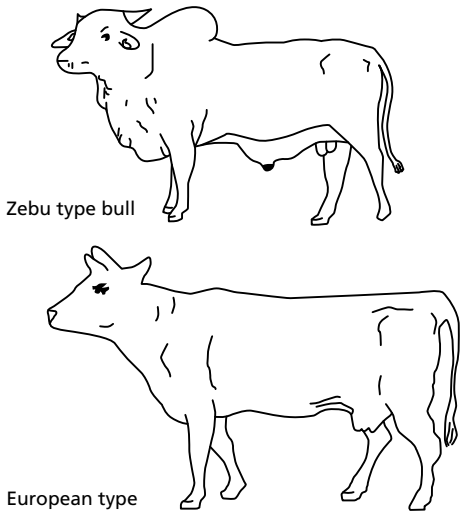


Figure 10.2 **Characteristic appearances of zebu and European-type cattle**

Brood sows do well at 15 °C but suffer badly at 25 °C and above because they do not perspire when hot. Reproduction rates fall under heat stress, and sows are more apt to trample their baby pigs during the discomfort of hot weather.

Sheep can tolerate a wide range of temperatures but should be protected from wind and rain. However, a long period of high ambient temperatures inhibits reproduction. Heat stress also reduces the lambing percentage, decreases the incidence of twinning, and decreases the birth weight of lambs. When temperatures are below 7 °C at breeding time, ewes show improved reproductive efficiency.

Goats are affected by temperature, humidity and rain. In hot , goats need shelter from intense heat during the day. In humid areas, they need protection from prolonged heavy rain. Excessive wetting from rain can cause pneumonia and an increase in parasitic infestation.

Poultry environmental requirements vary with age. Chicks should be started at 35 °C. As from one week, the temperature is reduced gradually to 24 °C by the fifth week. Broilers and young turkeys reared at ambient temperatures below 18 °C are heavier than similar stock reared within the 18–35 °C range, but their feed conversion efficiency will be lower. Laying birds produce the greatest number of eggs and the largest-sized eggs at 13–24 °C. The best feed conversion efficiency is achieved between 21 °C and 24 °C.

An increase in the ambient temperature will result ina decrease in feed intake and in behaviour alterations. Within the temperature range 5–30 °C, there is a reduction of about 1.6 percent in feed intake for every

10 °C increase in ambient temperature. Above 24 °C, there is a reduction in egg production and egg size. A continued rise in temperature to 38 °C or more may prove lethal. High humidity at high temperatures creates conditions that are more likely to be lethal because of a breakdown in body-cooling through respiration.

Rabbits are affected the most by sun and heat, wind, rain and draughts. Sunlight is of benefit to breeding stock and to the growing young, but it will also fade the coat of coloured rabbits and discolour a white one. While rabbits enjoy the sun but they must be given the opportunity to keep out of the direct rays. Owing to their thick fur coats they tolerate cold better than extreme heat, but they are susceptible to chilling from draughts. Rabbits also need protection from rain and dampness.

Horses do not require warm surroundings, but they do not easily tolerate draughts, dampness and high humidity. When exposed to high temperatures and vigorous exercise, horses sweat, and the evaporation of this perspiration cools the skin and helps to maintain normal body temperature.

Humans: The subject of rural housing is covered elsewhere in the book, so human comfort zones will be discussed briefly here. Humans have the ability to become acclimatized to a constant temperature. Thus people living in cold climates easily tolerate low temperatures, just as people living in tropical climates do not mind the heat.

In temperate climates, most sedentary people dressed in light clothing find optimum comfort at approximately 26 °C. However, relative humidity of over 70 percent may produce discomfort. At 22 °C people may feel cool, regardless of humidity. Above 26 °C they are likely to feel warm and, as the relative humidity rises above 45 percent, discomfort increases. People who are dressed warmly and doing active work can be comfortable in temperatures as low as 0 °C and below.

Microbiological environment

Disease remains a major profit-limiting factor in animal production in many tropical countries. Sanitary control measures should be incorporated into any building design, so that a good hygienic standard can be easily maintained. An animal that is well fed and watered, as well as being in good condition, will have high resistance to disease. Good management can do much to remove or reduce the effects of adverse environmental factors, such as climatic stress, which would otherwise weaken the body's natural defences.

Newborn stock should always receive colostrum (first milk), which contains antibodies. It takes time for an effective immune system to develop in an animal and therefore good hygiene is of special importance in facilities for young animals. Pens, in particular those for calving and farrowing, should be constructed of easily cleaned and disinfected materials and be free from corners and recesses where manure and dirt can accumulate.

The whole building should be cleaned and disinfected periodically, and any pen that is emptied should be thoroughly cleaned before other animals are transferred to it. Rearing and fattening of young animals should be organized so that the building can be emptied, cleaned and disinfected between batches. This 'all-in, all-out' policy is particularly beneficial for disease control, where the animals are bought from outside the farm, and in finishing units for pigs, as well as broiler and layer houses.

Diseases are transmitted in many ways, including direct contact between animals, airborne micro-organisms, biting insects and ticks, manure, soil, contaminated feed and water, birds and rodents, as well as the stockperson's boots. Direct contact between animals can be reduced by decreasing the number of animals in each group and by constructing solid partitions between pens. However, solid walls may obstruct air movement and thus contribute to heat stress. Ideally, the waste handling system should prevent animals of different groups from coming into contact with one another's manure. Young animals, in particular, must be protected from contact with manure from adult animals.

Good husbandry includes regular observation of the animals to detect any change in behaviour that could indicate disease. Sick animals should be separated from the herd immediately to prevent further spread of infectious disease and to allow them to rest. The sick animal should be isolated in a pen kept especially for this purpose, which should ideally be in a separate building.

Newly acquired animals, and animals returning from a market or any other place where they may have been exposed to the risk of infection, must be quarantined for an adequate length of time to detect any disease that they may be carrying before they are allowed into the herd.

Other environmental factors

As far as we know, *acoustic factors* have only a marginal effect on the animal's development and production. Nervous animals may, however, react adversely to intermittent sudden noises. Pig squeals prior to feeding can become a hazard to the stockperson's hearing. Soft radio music in a milking parlour may have a soothing effect on the cows.

Day length or photoperiod varies with latitude and season and has a direct influence on animal performance, especially on the breeding season for sheep and poultry egg production. Under natural conditions, there is a correlation between the length of day and the rate of laying. Artificial light is used in the temperate zone to equalize egg production throughout the year. Additional hours of light before dawn and after dusk are recommended in hot climates to encourage the hens to eat during the cooler hours.

Dust can carry micro-organisms, which may cause an outbreak of disease.

Toxic and noxious gases are produced by manure that accumulates in buildings or storage facilities, especially

during the agitation of manure slurry stored in a pit in a building, when harmful amounts of gas can be released. However, problems with gases are not likely to arise in the open-sided buildings used in the tropics.

CATTLE HOUSING

Cows play an extremely important role in most African cultures. The ownership of cattle will often be the deciding factor in a person's social position in the community because the herd may be the only practical way of accumulating wealth. However, of greater importance is the fact that cattle represent a source of high-protein food, in the form of both milk and meat.

This section focuses on housing requirements for cattle kept primarily for milk production. Little or no housing is required for herds maintained only for beef production, and special handling and support facilities are discussed separately.

Much of the dairy farming in east and southeast Africa occurs at elevations of 1 500 metres or more. European breeds have been successfully established under these circumstances. However, European bulls crossed with zebu cows have produced animals that are more tolerant of high temperatures than the European breeds and are significantly better producers than zebu.

Whether purebred or crossbred, they will not provide a profit to the farmer if they are left to find their own feed and water and are milked irregularly. Experience has shown that cattle respond favourably to good management, feeding and hygiene, all of which is possible in a system with suitable housing.

Herd profiles

The composition and management of cattle herds varies considerably. At one extreme, nomadic herdsmen graze their entire herd as one unit. Smallholders with only a few head may keep their heifer calves for replacements or sell them. Commercial dairy producers typically have about four-fifths of their cows milking and one-fifth waiting to calve, while heifers of 10 months to calving age, plus calves of various ages, will approximately equal the number of milkers. Mature dairy cows are bred annually and are milked for 300–330 days after calving.

On closer examination, several factors will be found to influence the number of animals of various categories found in a dairy herd. In a herd of say, 24 cows, with calving evenly distributed throughout the year and a 12-month calving interval, an average of two calves will be born per month. The calves are normally kept in individual pens for two to three months. There is therefore a requirement for four to six pens in a herd of 24 cows. However, the need for calf pens is halved in herds where the bull calves are sold or otherwise removed from the herd at one to three weeks of age. A longer calving interval and high mortality among the calves will decrease the required number of calf pens, while concentration of the calving season in the herd will increase the pen requirements. If all calving is concentrated in six months of the year, the requirement for calf pens will be doubled.

A number of cows in a dairy herd will be culled each year because of low milk yield, infertility, disease, old age, etc. These cows are best replaced with young stock from their own herd, because any animals acquired from outside the farm may bring disease to the herd. Cows are commonly culled after three to five lactations, corresponding to a replacement rate of 20 percent to 30 percent per year.

In herds with very intensive production there is a tendency towards a higher replacement rate, but it cannot exceed 40 percent if the heifers are obtained exclusively from the herd itself. This is due to the fact that only about half of the calves born are female, and some of these will die or be culled before first calving as a result of disease, infertility or other factors.

The number of maturing heifers will increase in line with an increase in the age of heifers at first calving, a higher replacement percentage and a shorter calving interval. Concentrated calving may slightly increase the number of animals during some periods of the year, and will greatly affect the distribution of animals in the different age groups. The age at first calving of heifers of European breeds is typically 24–27 months, while heifers of the slower-maturing zebu cattle are often aged 36 months or more.

Maturing heifers require little or no housing facilities in the tropics. Knowledge of their exact number and distribution in various age groups during different months is therefore not as important to a building designer as to the manager of the herd.

Heifers should be introduced into the dairy herd at least a couple of months prior to their first calving, to enable them to learn and become adjusted to the handling and feeding routines. In loose housing systems with free stalls (cubicles), or in tie-barns, this may slightly increase the need for stalls, but normally the heifer will simply take over the stall used by the culled cow that it replaces.

In herds where cows are taken to a special calving pen during calving, one such pen per 30 cows is sufficient, because the cow and her calf will spend only a few days there. However, in herds where calving is concentrated in a short period, the requirement can increase to one calving pen per 20 cows. The pen should be at least 3.3 metres by 3.3 metres.

General housing requirements

As has already been pointed out, cattle will produce milk and reproduce more efficiently if they are protected from extreme heat, i.e. temperatures of 25–30 °C, and particularly from direct sunshine. Thus in tropical and subtropical climates, providing shade becomes an important factor.

If cattle are kept in a confined area, it should be free from mud and manure in order to reduce hoof infection to a minimum. Concrete floors or pavements are ideal

where the area per cow is limited. However, where ample space is available, an earth yard, properly sloped for good drainage, is adequate.

Shade from the sun

With these needs in mind, a shade structure allowing 2.5–3 square metres per animal will give the minimum desirable protection for cattle, whether for one animal belonging to a smallholder or many animals in a commercial herd. A 3 metre by 7 metre roof will provide adequate shade for up to eight cows. The roof should be a minimum of 3 metres high to allow air circulation.

If financially feasible, the entire area that will be shaded at some time during the day should be paved with good-quality concrete. The size of this paved area depends on the orientation of the shade structure. If the longitudinal axis is east to west, then part of the floor under the roof will be in shade all day. Extending the floor by approximately one-third of its length on the east and on the west, as shown in Figure 10.3, results in a paved surface being provided for the shaded area at all times.

If the longitudinal axis is north to south, the paved area must be three times the roof area i.e. one-third to the east, one-third to the west and one-third underneath. Obviously this means an increase in the cost of paving. When deciding on which orientation to use, the following factors should be considered:

1. With the east-west orientation, the feed and water troughs can be under the shade, which will allow the cows to eat and drink in shade at any time of the day. However, the shaded area should be increased to 3–4 metres per cow. By locating the feed and water in the shade, feed consumption will be encouraged, but more manure will be dropped in the shaded area, which in turn will lead to dirty cows.
2. With the north-south orientation, the sun will strike every part of the floor area under and on either side of the roof at some time during the day. This will help to keep the paved area dry. A shaded area of 2.5–3 metres per cow is adequate if feed and water troughs are placed away from the shaded area.
3. If paving is considered to be too costly, the north-south orientation is the best choice in order to keep the area as dry as possible.
4. In regions where temperatures average 30 °C or more for up to five hours per day during some period of the year, the east-west orientation is the most beneficial.

Figure 10.3 shows shade patterns at various times and orientations at a location at latitude 10 degrees. A gable roof shade is shown in Figure 10.4. The gable roof is more wind resistant than a single pitch roof and allows for a centre vent. A woven mat of local materials can be installed between the rafters and the corrugated iron roof to reduce radiation from the steel and to reduce temperatures just below the roof by 10 °C or more.

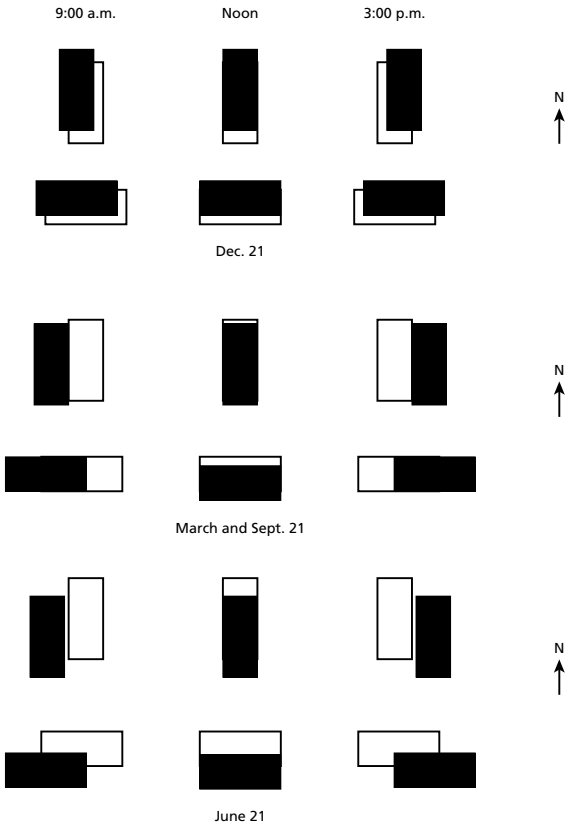


Figure 10.3 **Shadows cast at various times and dates at latitude 10 degrees south**

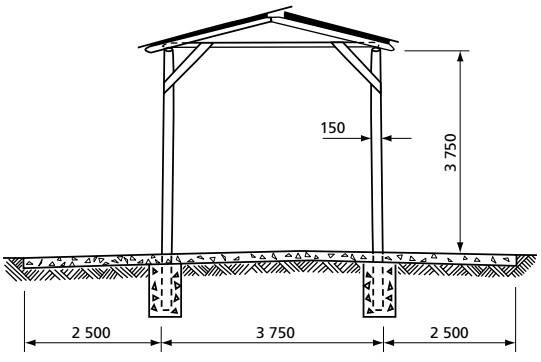


Figure 10.4 **Sunshade with insulated corrugated steel roof**

Yards

If space is severely limited and only 4–5 square metres per cow is available, then concrete paving is highly desirable. If 40–60 square metres per cow is available, then unpaved yards should be quite satisfactory, provided that the feed and shade areas are paved and the yard is graded for good drainage.

If the smallholder is unable to afford an improved structure, such as a shade or a paved area for feeding, then conditions can be prevented from becoming intolerable by building mounds of earth in the yard with drainage ditches between them, as shown in Figure 10.5. Between 20 square metres and 30 square metres per cow will keep the animals out of the worst of the mud. The soil in the mounds can be stabilized by working chopped straw, or straw and manure, into the surface. A number of trees in the yard will provide sufficient shade.

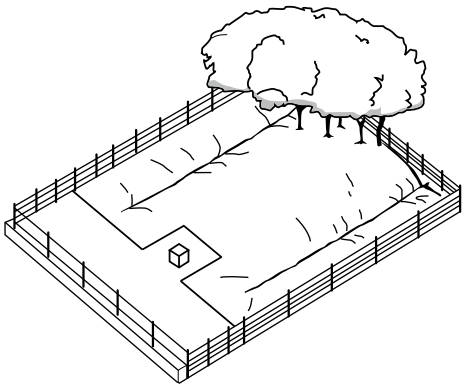


Figure 10.5a **Yard with fence-line feed trough, paved feed area and earth mound**

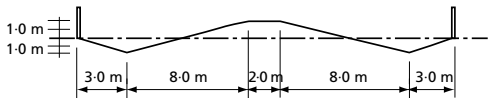


Figure 10.5b **Dimensions for an earth mound**

Deep-bedded sheds

In a deep-bedded system, straw, sawdust, shavings or other bedding material is periodically placed in the resting area so that a mixture of bedding and manure builds up in a thick layer. Although this increases the bulk of manure, it may be easier to handle than wet manure alone. This system is most practical when bedding is plentiful and cheap.

Table 10.3 gives the space requirements for various ages of animals when there is access to a yard. By designing the building to be partially enclosed on the east and west, the shading characteristics can be improved. Where a well-drained earth floor is quite adequate, such a building will compare favourably in cost with a paved shaded area.

Loose housing with free stalls (cubicles)

Although simple yard and shade, or yard and bedded-shed, systems are entirely satisfactory in warm climates, particularly in semi-arid areas, some farmers may prefer a system with somewhat more protection. A loose housing yard and shed with free stalls will satisfy this need. Less bedding will be required and less manure will have to be removed. Free stalls must be of the right size in order to keep the animals clean and to reduce injuries to a minimum.

When stalls are too small, injuries to teats will increase and the cows may also tend to lie in other areas that are less clean than the stalls. If the stalls are too large, cows become dirty from manure dropped in the stall and more labour will be expended in cleaning the shed area. A bar placed across the top of the free stalls will prevent the cow from moving too far forward in the stall for comfortable lying down movements, and it will encourage her to take a step backwards when standing so that manure is dropped outside the stall.

However, the bar must not interfere with her normal lying and rising movements. Table 10.3 lists recommended dimensions for stalls. The floor of the stall must be of a non-slippery material, such as soil. A good foothold is essential during rising and lying-down movements to avoid injury. A 100 mm ledge at the back edge of the free stall will prevent any bedding from being pulled out into the alley.

The number of stalls should ordinarily correspond with the number of animals housed, except that in large

TABLE 10.3
Area for bedded sheds and dimensions of free stalls (cubicles)

Animal	Age (months)	Weight (kg)	Bedded shed area per animal (m^2)		Free stalls Dimensions (m)	
			A	B	Length	Width
Young stock	1.5–3	70–100	1.5	1.4	1.2	0.6
Young stock	3–6	100–175	2.0	1.8	1.5	0.7
Young stock	6–12	175–250	2.5	2.1	1.8	0.8
Young stock	12–18	250–350	3.0	2.3	1.9	0.9
Bred heifers and small milking cows		400–500	3.5	2.5	2.1	1. 1
Milking cows		500–600	4.0	3.0	2.2	1.2
Large milking cows		> 600	5.0	3.5	2.3	1.2

A = enclosed and fully covered bedded shed. B = bedded shed in conjunction with exercise yard.

herds (80 or more) only about 90 percent of the animals need to be accommodated at one time. Figure 10.6 shows two free-stall designs. Young stock may be held in yards with shade, or in sheds with either free stalls or deep bedding. The alley behind the free stalls (cubicles) must be wide enough to allow the cows smooth passage, and the minimum widths applicable are shown in Table 10.4.

TABLE 10.4
Alley widths in conjunction with free stalls (cubicles)

Alley between a row of free stalls and a trough (increase to 4.0 metres if there are more than 60 cows in the group)	2.7–3.5 metres
Alley between a row of free stalls and a wall	2.0–2.4 metres
Alley between two rows of free stalls	2.4–3.0 metres
Alley between a feed trough and a wall	2.7–3.5 metres

Tie-stall sheds

Only in the case of purebred herds, where considerable individual attention is given to cows, can a tie-stall system be justified in tropical areas. If such a system is chosen, stalls and equipment may be purchased, in which case floor plans and elevations may be available from the equipment supplier. However, if equipment is to be manufactured locally, Table 10.5 provides some typical dimensions.

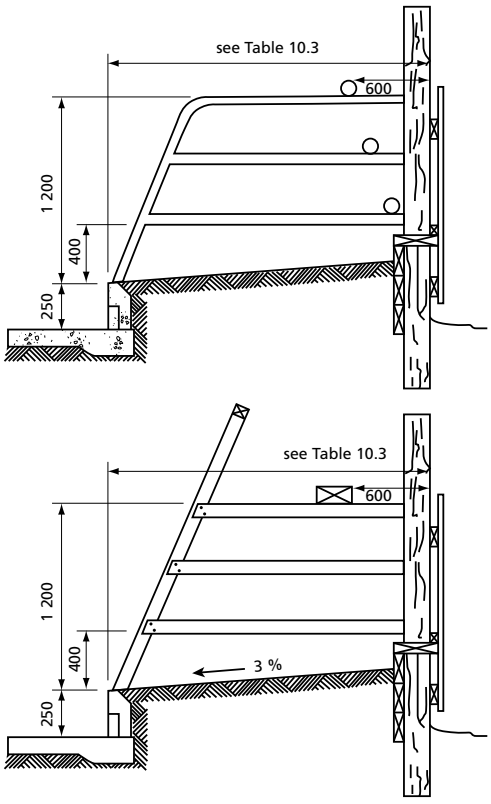


Figure 10.6 **Free-stall cubicle designs**

TABLE 10.5
Tie-stall system dimensions (metres)

	Cow live weight		
Stall section	**450 kg**	**550 kg**	**650 kg**
Platform width	1.1	1.2	1.3
Platform length[1]	1.6	1.7	1.8
Manger width	0.5	0.6	0.65
Platform slope		2–4%	
	Nose-out system		Nose-in system
Flat-manger feed alley	1.7–2.0		1.6–2.0
Feed alley (excluding step manger)	1.2–1.4		1.2–1.4
Service alley width		1.4–2.0	
Manure gutter width		0.4–0.7	
Depth		0.25–0.35	

[1] If cows are allowed to lie with their heads over the trough, otherwise add 0.4–0.5 metres to the length

The tie-and-feed-barrier construction must allow the cow free head movements while lying down as well as standing up. However, it should prevent the cow from stepping forward into the feed trough. Most types of yoke restrict the cow's movements too much. A single neck rail, set about 1 metre high and 0.2 metres over the manger may bruise the cow's neck when it pushes forward to reach the feed.

The feed barriers that best meet the requirements are shoulder supports and the comfort stall, shown in Figure 10.7. Note the fixing rods for the cross-tie, which allows for vertical movement of the chain. Stall partitions should be used at least between every second cow to prevent cows from trampling each other's teats and to keep the cow standing straight so that the manure falls in the gutter (Figure 10.7c).

Bull pens

A bull pen should have a shaded resting area of 12–15 square metres and a large exercise area of 20–30 square metres. The walls of the pen must be strong. Eight horizontal rails made of minimum 100 mm round timber or 50 mm galvanized steel tubes to a total height of 1.5 metres, fixed to 200 mm timber posts not more than 2 metres apart, will be sufficient.

The gate must be designed so that the bull cannot lift it off its hinges, and there should be at least two exits where the herd worker can escape. A service stall where the cow can be tethered prior to, and during, service is usually provided close to the bull pen. The stall can have ramps at the sides to support the bull's front feet.

Calf pens

Calf mortality is often high in tropical countries, but proper management and suitable housing that protects the calf from climatic stress, infections and parasites can reduce this. Individual pens for calves from birth to two

to three months of age are often built with an elevated slatted floor. This floor, which is best constructed from sawn timber boards measuring 37–50 mm by 75–100 mm, leaving a 25–30 mm slit between each board, will ensure that the calf is always dry and clean.

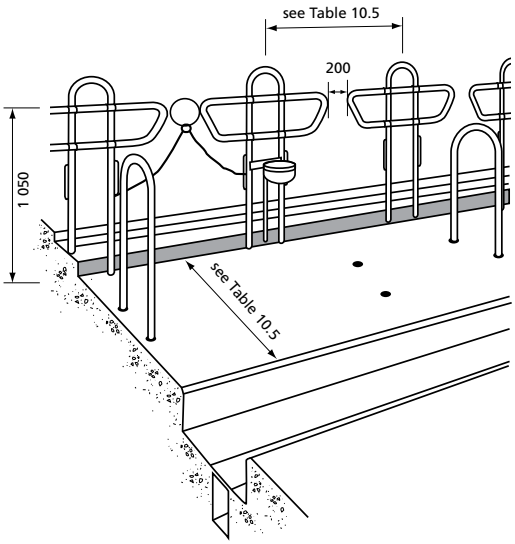


Figure 10.7a **Shoulder support system**

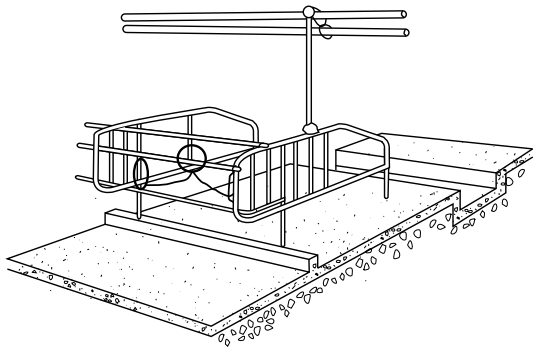


Figure 10.7b **Comfort stall**

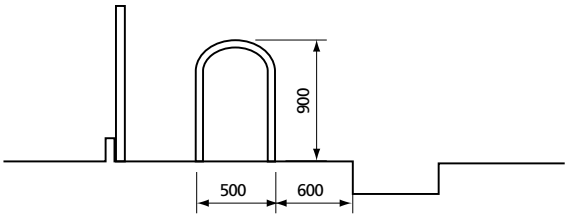
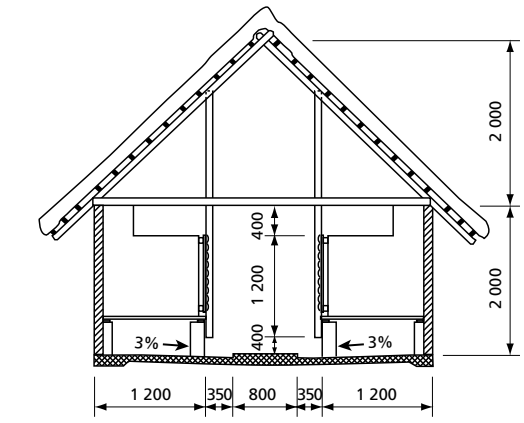
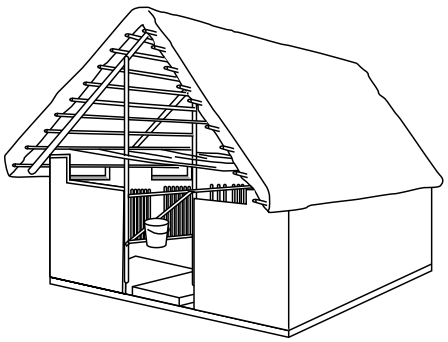
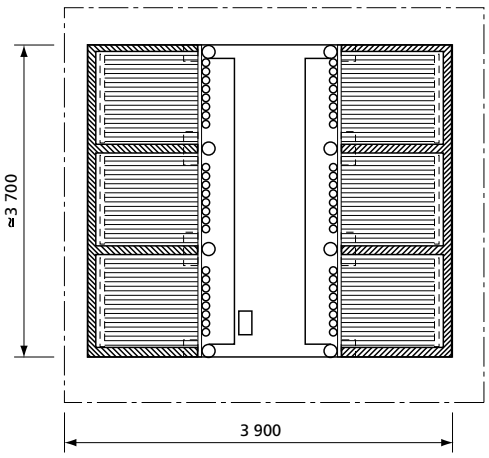


Figure 10.7c **Stall partitions**







Description:

Floor: Concrete floor, 80 mm on firm ground, sloping towards the centre line with an elevated pavement along the same line. Slotted wooden floor in the pens elevated 400 mm, made of 25 × 100 mm sawn timber with spacing of 25 mm.

Walls: The pens can be made of gum-poles and offcuts, bricks or concrete blocks plastered on both sides, or any other locally available material.

Roof: The structure in this case is made of treated gum-poles and thatched grass

Figure 10.8 **Calf shed**

The required minimum internal dimensions for an individual calf pen are 1 200 mm by 800 mm for a pen where the calf is kept to two weeks of age, 1 200 mm by l 000 mm where the calf is kept to six to eight weeks of age; and 1 500 mm by 1 200 mm where the calf is kept from 6 to 14 weeks of age. Three sides of the pens should be enclosed to prevent contact with other calves and to prevent draughts.

Draughts through the slatted floor may be prevented by covering the floor with litter until the calf is at least one month of age. The front of the pen should be made so that the calf can be fed milk, concentrates and water easily from buckets or a trough fixed to the outside of the pen, and so that the calf can be moved out of the pen without lifting. The milk or milk substitute fed to the calf will not provide it with enough liquid and therefore it should be given fresh, clean water daily, or preferably have continuous access to water in a drinking nipple.

All calves, but especially those that are weaned early, should have access to good-quality forage as soon as possible to stimulate rumen development. Forage can be supplied in a rack placed above the side wall of the pen. Figure 10.8 shows a thatched shed with six slatted-floor calf pens. This construction, with a feed alley, will be rather expensive but can be cheaper if calves are fed from outside. Calf pens are recommended where the cows are kept in a semizero-grazing or zero-grazing system.

Another system that works well is the use of individual hutches, as shown in Figure 10.9. The hutch must be thoroughly cleaned and set up in a new location every time a new calf is housed in it. Plenty of litter is placed directly on the ground inside the hutch. Protection from wind, rain and sun is all the calf requires, but the key to success is to always move the hutch to clean ground.

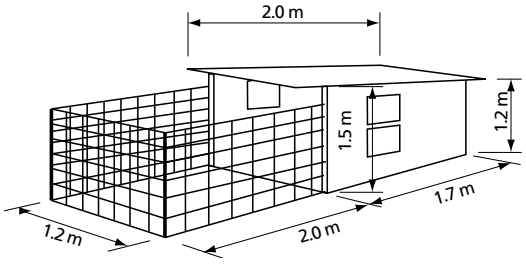


Figure 10.9 **Calf hutch**

Housing for the small herd

For the smallholder who wants to make the very best use of his crop land and to provide his cattle with good housing that will encourage high production, a zero-grazing system is recommended.

Figure 10.10 shows perspective, elevation and plan views of a zero-grazing unit for three cows, two heifers and a young calf. Additional stalls can be added up to a total of about 10. For any more than that, consideration should be given to two milking places and a larger feed store.

Gum-poles may be used instead of the cedar posts and sawn rafters, but any wood in contact with, or within 50 cm of, the ground should be well treated with wood preservative. It is desirable to pave the alley but, if that is not possible, the distance between the free stalls (cubicles) and the feed trough should be doubled or tripled.

A concrete pit or sloping slab in which to accumulate manure is essential. If the alley is paved, the pit can also collect urine. In fact, paving the alley not only saves space, but the value of the urine will help to pay for the paving.

The circular manure tank shown in Figure 10.10 has a volume of 10 cubic metres. This will be adequate to store the manure produced during one month, plus any rainfall collected in the alley. If more stalls are added, the capacity of the tank will need to be increased or the interval between emptying shortened.

A water tank to collect water from the roof can be very useful unless there is an abundant supply of water nearby.

Housing for medium to large herds

For the farmer with up to about 30 cows, a yard with a paved shade and feed area would be suitable. The yard and feeding area may alternatively be combined with an open-sided barn designed for deep bedding or equipped with free stalls and, where the herd consists of high-yielding cows, the milking shed may be equipped with a bucket milking machine. Some farmers with up to 30 cows may even consider using an open-sided tie-stall shed.

In general a medium- or large-scale dairy unit may include the following facilities:

1. Resting area for cows:
   (a) paved shade; or
   (b) deep bedding in an open sided barn; or
   (c) free stalls in an open-sided barn.
2. Exercise yard (paved or unpaved).
3. Paved feed area:
   (a) fence-line feed trough (shaded or unshaded); or
   (b) self-feeding from a silage clamp.
4. Milking Centre:
   (a) milking shed or parlour; and
   (b) collecting yard (part of the exercise yard); and
   (c) dairy, including milk store; and
   (d) motor room.
5. Bull pen with a service stall.
6. Calving pen(s).
7. Calf accommodation.
8. Young stock accommodation (yard with paved shade and feed area).
9. Bulk feed store (hay and silage).
10. Concentrate feed store.

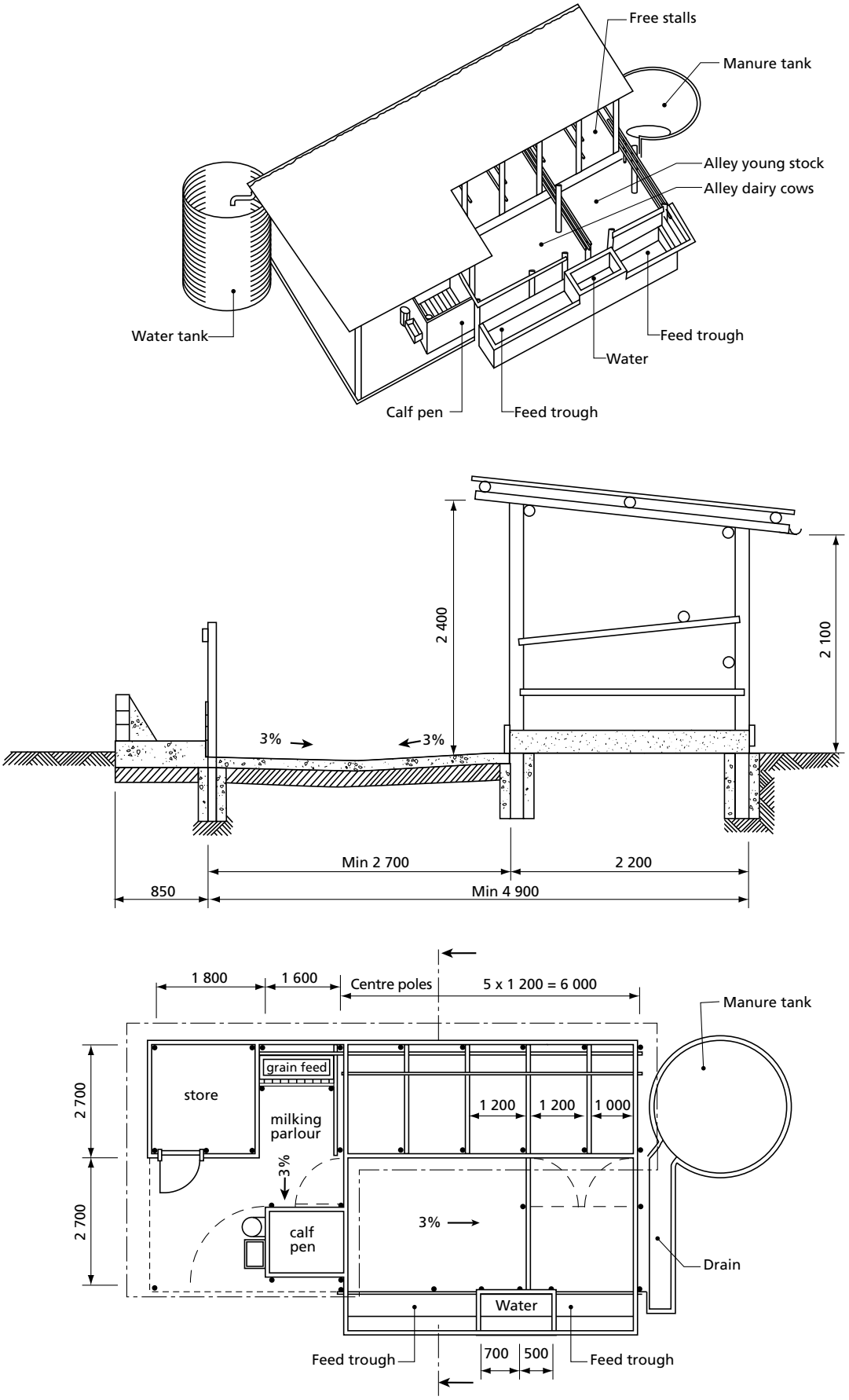


Figure 10.10 **Zero-grazing system for the smallholder**

11. Veterinary facilities:
    (a) diversion pen with artificial insemination stalls; and
    (b) isolation pen.
12 Waste store:
    (a) slurry storage; or
    (b) separate storage of solids and effluents.
13 Office and staff facilities.

Each of the parts of the dairy unit may be planned in many different ways to suit the production management system and the chosen method of feeding. Some requirements and work routines to consider when the layout is planned are:

1. Movement of cattle for feeding, milking and perhaps to pasture.
2. Movement of bulk feed from store to feeding area, and concentrates from store to milking shed or parlour.
3. Transfer of milk from milking shed or parlour to dairy and then off the farm. Clean and dirty activities, such as milk handling and waste disposal, should be separated as far as possible.
4. The diversion pen, with artificial insemination stalls and any bull pens, should be close to the milking centre because any symptoms of heat or illness are commonly discovered during milking, and cows are easily separated from the rest of the herd when leaving the milking area.
5. Easy and periodical cleaning of accommodation, yards, milking facilities and dairy, and transfer of the waste to storage and then to the fields.
6. Movements of herd workers. Minimum travel to move cows in or out of the milking area.
7. Provision for future expansion of the various parts of the unit.

Milking and milk handling

Hand milking versus machine milking

In developed countries, where labour is scarce and expensive, machine milking has become very widespread and it is also practiced on many large commercial dairy farms in the tropics. Milking machines not only reduce labour requirements and eliminate the drudgery of hand milking but, in most cases, perform a better quality milking operation than would be done by hand.

However, most of the many small dairy farms in developing countries have a surplus of cheap labour, and the number of cows milked at each of them is not sufficient economically to justify the installation of a machine. Furthermore, machines require power and are more expensive to purchase than the few pieces of equipment needed for hand milking. In many developing countries there is an irregular supply of spare parts and a lack of skilled mechanics.

Machine milking gives good quality and operates with a uniform vacuum of 275–350 mm of mercury,

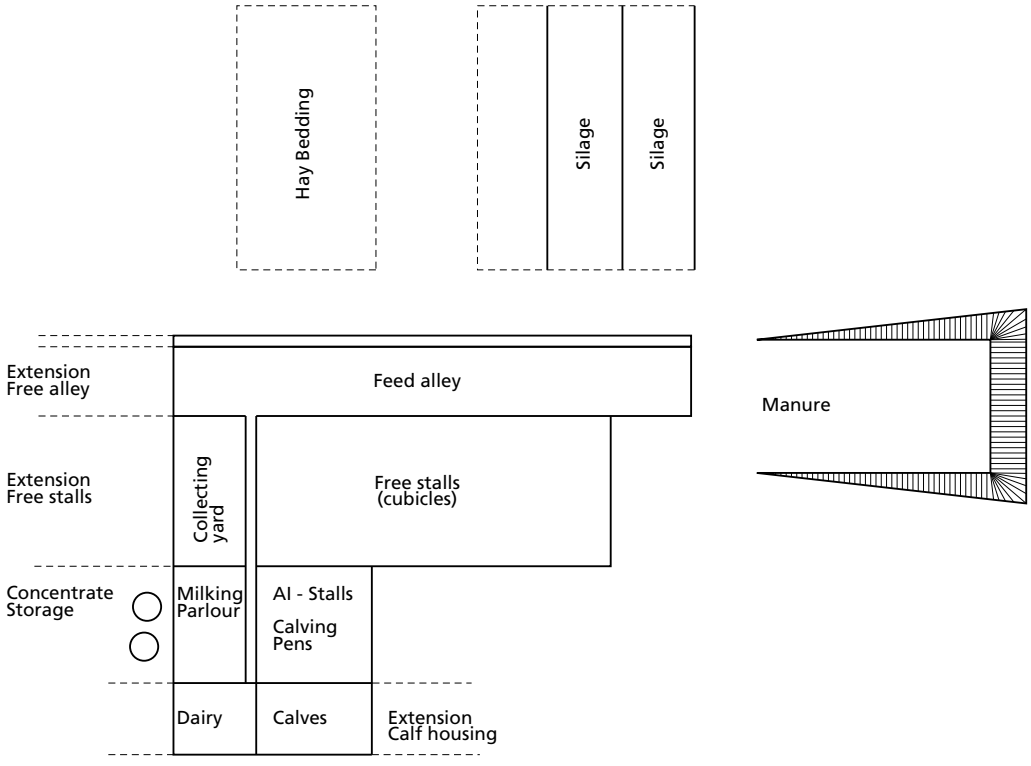


Figure 10.11 **Basic sketch of a layout for a medium- to large-scale dairy unit, showing the relative location of the various parts and a suggestion for extension (not to scale)**

provides a massaging effect on the teats, and is easy to clean. The milking machine simulates nursing by the calf. Two vacuum lines lead to the teat cups. A pulsator supplies an intermittent vacuum to one line at the rate of 45–60 pulses per minute.

The line, connected to the shell of the teat cup, causes the teat inflation (rubber liner) to alternately expand and collapse. This massaging action promotes normal blood circulation in the teat. The second line maintains a continuous vacuum on the teat and carries the milk either to a stainless steel bucket or through a pipeline directly to the milk cooler.

A *bucket milking machine* as shown Figure 10.12 is the simplest and least expensive to install, but the milk must be carried by hand to the cooler. This type of system is often chosen for the small- and medium-size herd and where the cows are milked on a level floor of a stable or milking shed.

The labour of carrying the milk to the cooler can be avoided by installing a transfer system. This consists of a 30-litre receiving tank, including a built-in filter, mounted on wheels so that it can be moved around the stable. It is connected to the cooler with a plastic hose and the milk is drawn to the cooler by vacuum from the milker pump. The hose is reeled in or out as necessary as the cart is moved around the stable.

A *pipeline milking plant* transports the milk through a pipe direct from the cow's udder to the milk cooler. Figure 10.13 illustrates such a system. Pipeline milking systems are usually installed in milking parlours, where the operator stands below the level of the cows.

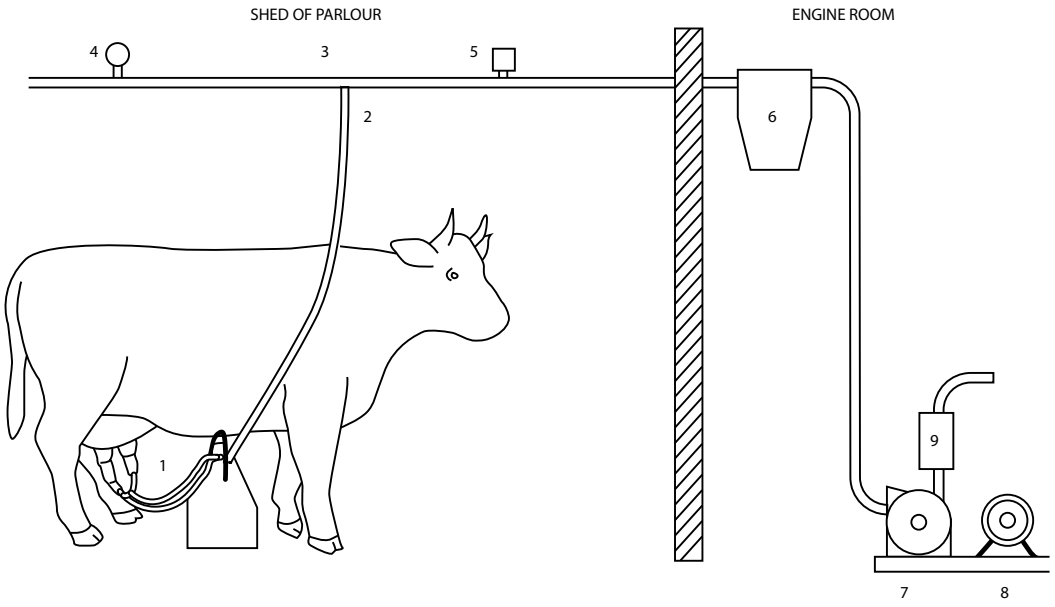
Although they are expensive, they reduce the backbreaking tasks and are usually designed to be cleaned in place, a feature that not only saves labour but also helps to ensure good sanitation. They may also be installed in stanchion or tie-stall barns but the extra pipeline needed makes the system even more expensive.

Milk room and cooler

Sanitation is the primary consideration in the handling of milk, whether it is from one or two cows belonging to a smallholder or from a commercial herd supplying milk for the city. In either case, an adequate supply of potable water is essential for cleaning the milking equipment immediately after use. Hot water (85 °C), mixed with a chemical detergent, is required for effective cleaning, and cold water is used for rinsing.

Milk should be handled in a separate area that is easy to clean and is free of insects, birds, rodents and dust. A smallholder producing milk only for the household may be able to process, curdle, or consume the milk within a short time so that cooling is not necessary.

Selling milk to the public requires higher standards of sanitation and more elaborate facilities. Whether the cows are hand- or machine-milked, a separate milk room adjacent to the milking stalls or milking parlour is needed. This room should be well ventilated and designed with a concrete floor with a slope of 20 mm/m to a drain and masonry walls with a smooth, water-resistant surface that can be easily and thoroughly cleaned.



1 Milking Unit with Bucket and Pulsator
2 Vacuum Tube
3 Vacuum Pipe Line
4 Vacuum Gauge
5 Vacuum Regulator
6 Moisture Trap
7 Pump
8 Motor
9 Silencer

Figure 10.12 **Bucket milking machine**

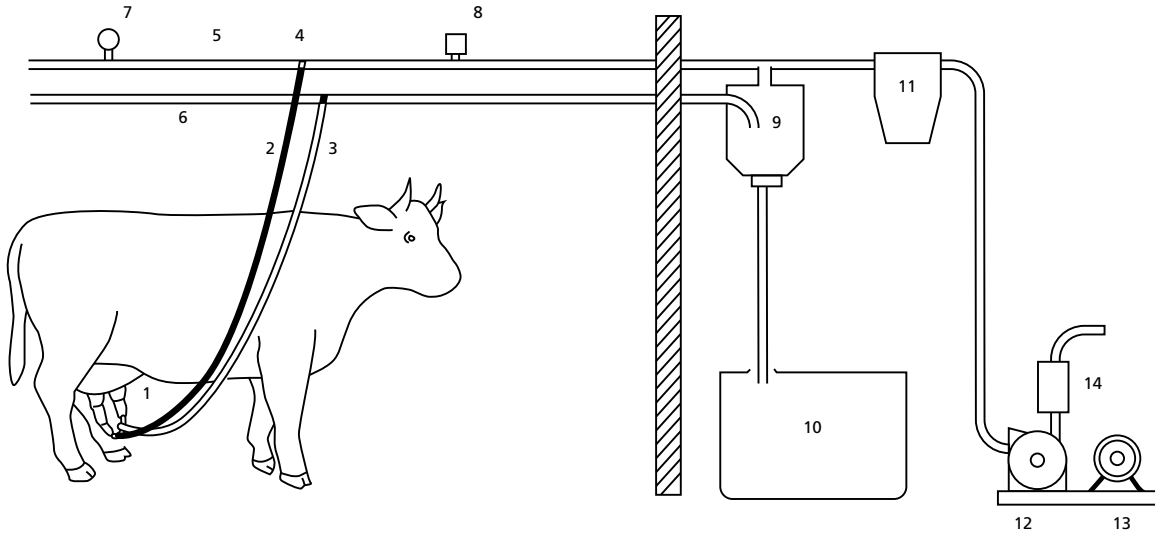


Figure 10.13 **Pipeline milking system**

TABLE 10.6
Minimum water requirements for parlour and milk-room washing

	Hot water (at 85 °C) (litres)	Warm water (at 40 °C) (litres)	Cold water (at 4–10 °C) (litres)
Hand milking equipment	10/wash		20/wash
Bucket milking equipment	20/wash		40/wash
Pipeline milking equipment	30/wash		60/wash
Cooling of milk in			2–3 times the
Plate-type milk cooler			amount of milk
Parlour floor wash		1/m^2 per day	3–6/m^2 per day
Milk-room floor wash		1/m^2 per day	1–3/m^2 per day
Car wash	3/car		60/car
Bulk tank wash	25–40/wash	20–30/wash	25–35/wash
Miscellaneous	20–50/day		30–100/day

Milk is strained and cooled in this room in preparation for selling. As soon as the cow has been milked, the bacteria in the milk start to multiply, but cooling the milk to about 4 °C within two hours will drastically reduce bacterial growth. However, proper cooling is a very difficult problem for the small-scale producer. The only practical solution for individual farmers in an area may be to bring their milk to a central collection depot for cooling immediately after milking (see Figure 10.14).

On dairy farms of sufficient size and where power is available, the milk can be cooled by cold water circulated between an evaporative water cooler and a milk cooler (plate heat exchanger), through which the milk is passed until it is adequately cooled. Where milk is stored and transported in cans, cooling can be accomplished by immersing the full cans in a water-filled refrigerated cooler or by passing cold water through a coil, which is immersed in the can. Large-scale dairy farms with a pipeline milking system and milk collection by road tanker require a refrigerated cooler and holding tank.

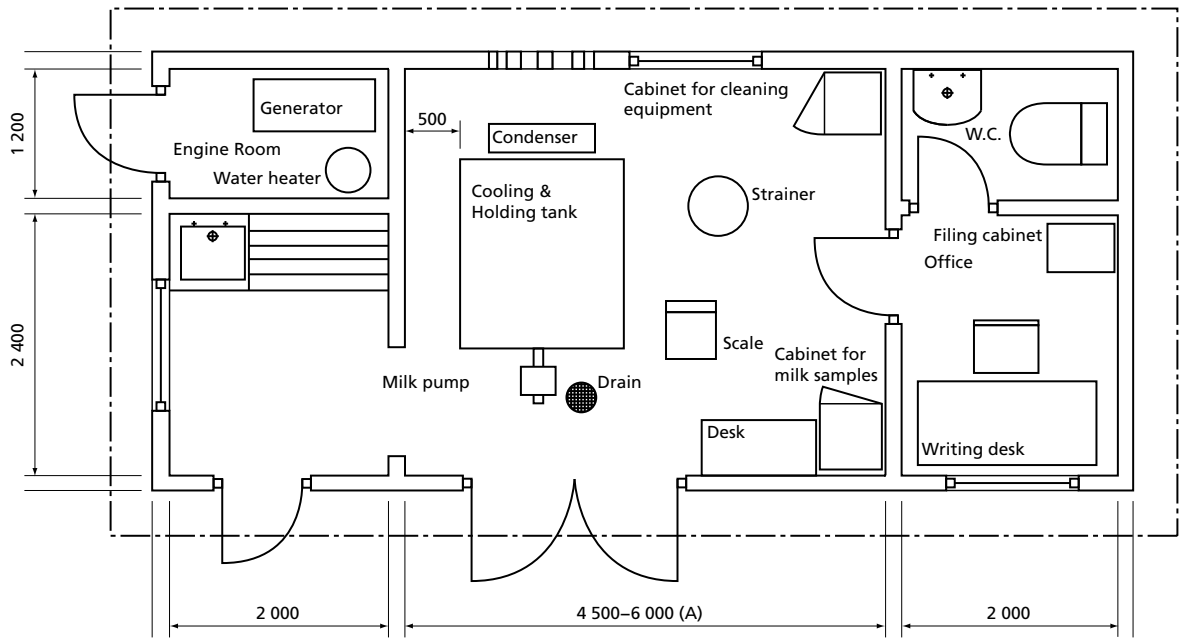


Figure 10.14 **Milk collection centre. The dimensions (A) will vary depending on the capacity of the cooling and holding tank**

Milking parlour for a medium-size herd

For farmers with between 10 and 30 cows and a yard with a paved shade and feed area, the milking parlour shown in Figure 10.15 provides a suitable design. Two stands will be sufficient where the herd numbers 8 to 14, but more stands should be added as indicated when the herd number increases. Hand milking would probably be used for an operation of this size.

If machine milking is installed, the vacuum pump and the engine that powers it can be placed in the engine room, which is indicated in outline in the plan view. This is arranged by closing off a portion of the store room with a simple partition.

A milk cooler will be necessary to cool and hold the milk for pick-up. The milk cooler and facilities for washing and storing the milking equipment will be accommodated in the milk room, while concentrates are kept in the store room.

A milk room should face the prevailing wind to ensure good ventilation and to keep it as cool as possible, but any openings should be screened with insect mesh.

Milking parlour

On commercial farms where several cows are milked at the time, a milking parlour becomes a feasible investment. Several types of milking parlour are in use in dairy regions throughout the world. Figures 10.16a, 10.16b, 10.16c and 10.16d, illustrate some of the most common types.

Any type of parlour should have a high quality concrete floor and metal railings for durability and ease of cleaning. Walls are not required but, if supplied, they should at least be plastered masonry walls. The pit where the milker stands should have a floor level 900 mm below that of the cattle stands to ensure the most comfortable work position.

The number of stands is determined by the allowable milking time of the herd or the time taken to eat the concentrate ration.

Abreast parlour

The abreast parlour allows cows to enter and leave individually. The variation of this parlour shown here, in which the front of the stands can be opened to allow the cows to proceed forward out of the parlour after milking, has proved effective. The main drawback with the abreast parlour is the relatively long distance to walk between milking points, and cows obstructing the herd worker, as they share the same floor space.

The stands should be 1.0 metres to 1.1 metres wide when a bucket milking machine is used or when hand milking is practiced, while 0.7 metres to 0.8 metres is adequate when a pipeline milking system is installed. In both cases, the width for the milker should be 0.6 metres to 0.8 metres. A two-level abreast parlour, in which the milker works at a lower level than the cows, is more difficult to construct and has no great advantage over the single-level type. The abreast parlour has been common in east Africa for herds of more than 40 cows, but its use is decreasing and giving way to the double herringbone parlour.

Tandem parlour

The tandem parlour also allows for individual care of the cows. It is used mostly for smaller commercial

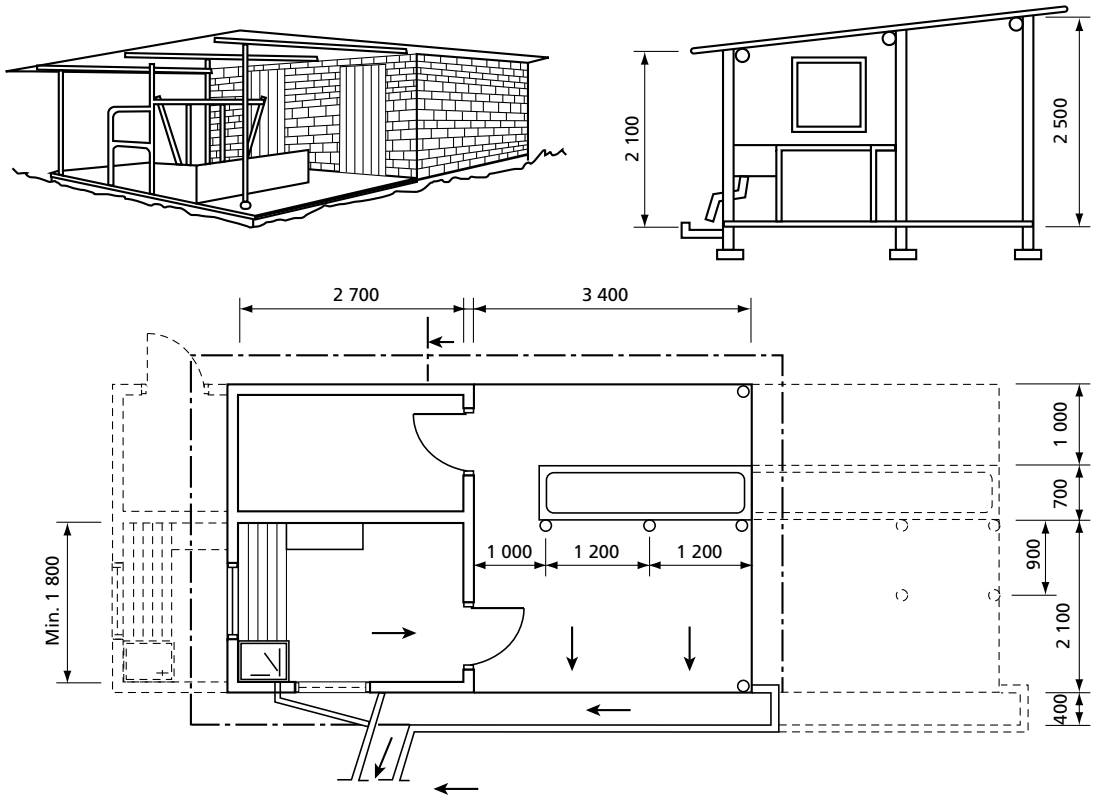


Figure 10.15 **Milking parlour for a medium-size herd**

herds and, in particular, for herds with high-yielding cows. The main drawbacks with this type of parlour are its larger space requirement and more expensive construction when compared with other types of parlour of similar capacity. The parlour capacity in terms of cows milked per hour and labour efficiency compares with that of a small herringbone parlour.

Walk-through parlour

In walk-through or chute parlours, cows enter and leave in batches. They have been used mainly for small herds. Their narrow width can be an advantage where a parlour is to be fitted in an existing building, but it is inferior to other types in most other respects. However, it is cheaper to construct than a tandem parlour.

Herringbone parlour

The herringbone parlour layout results in a compact working area and allows feeders to be fixed to the side walls. Four stands on each side of the pit, as shown in Figure 10.16c, is the minimum size for this type of parlour to ensure high labour efficiency. If the herd has fewer than 80 cows, then a double-three parlour will keep the investment lower, with only a small decline in labour efficiency.

The popularity of the herringbone parlour stems mainly from its simplicity and its high capacity measured in the number of cows milked per staff-hour. (A staff-hour is the equivalent of one person working for one hour). However, the risk of cows kicking the herd worker is greater in the herringbone parlour than in parlours where the person stands alongside the cow.

Double 6-, 8-, 10- and even 12-stand parlours are used for very large herds. Although these larger parlours allow more cows to be milked per hour, because of the need for more workers and the increased waiting time to allow all cows on one side to finish before they are released, the output per staff-hour is usually lower.

Grain feeders

It is advantageous to equip milking parlours with grain feeders that allow each cow to be fed in proportion to her production. As cows are more likely to enter the parlour when they expect to be fed, some labour will be saved. Manual distribution of the concentrates with a measuring scoop is recommended, except in the largest herds. Semiautomatic and automatic systems are expensive to install and require spare parts and mechanics for their maintenance, and these may not be available when needed.

Collecting yard

The cows are normally assembled in a collecting yard (holding area) before milking. This may be a portion of the yard that is temporarily fenced off with chains. The collecting yard should have a minimum size of 1.1 metres to 2.0 metres per cow. Large horned cows

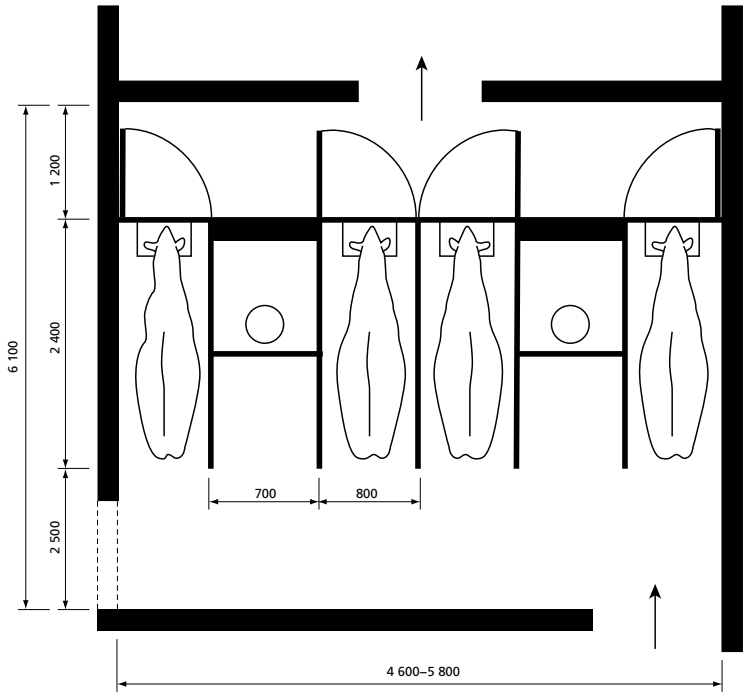


Figure 10.16a **Abreast parlour**

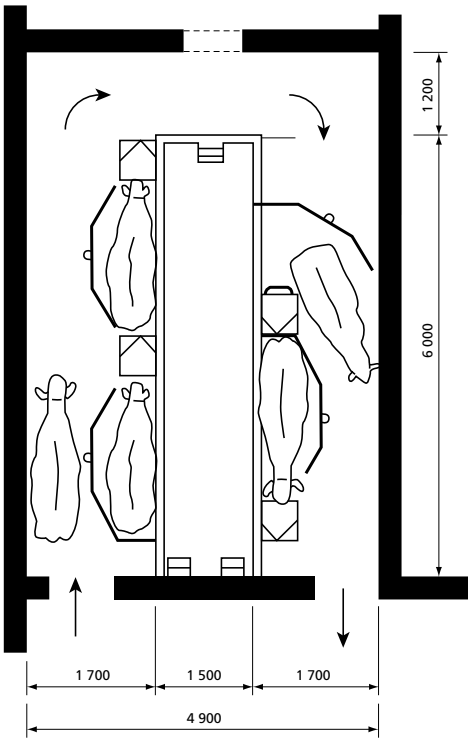


Figure 10.16b **Tandem parlour**

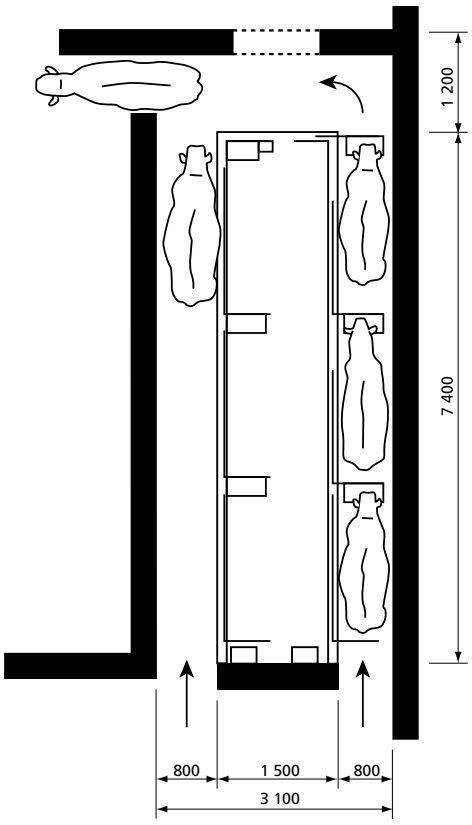


Figure 10.16c **Walk-through parlour**

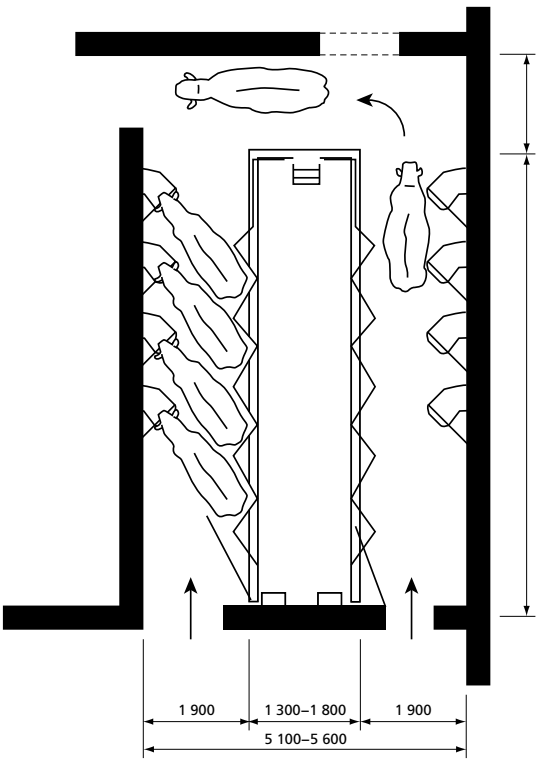


Figure 10.16d **Herringbone parlour**

and a low herd number will require the largest space per cow. Water must be provided for cows waiting their turn to enter the parlour.

The area should slope away from the parlour with an incline of 20–100 millimetres per metre. This not only improves drainage but also encourages the cows to face the entrance. The collecting yard should be paved for easy cleaning and to ensure sanitary conditions in the parlour. A roof is desirable for shade and to avoid wet cows entering the parlour in the rainy season. It will also reduce the amount of rainwater that has to be stored in the manure pit.

Entrance and exit

A straight entrance into the parlour (no turns) ensures smooth and convenient operation. Once trained, cows and heifers will walk readily into the parlour. A single step of about 100 mm will help to keep manure from being carried into the parlour.

An exit leading into an area that is not crowded will facilitate animal flow. A straight exit is desirable but not as important as a straight entry. If exiting alleys are needed they should be narrow (700 mm to 900 mm, depending on cow size), to prevent the cows from turning around.

Feeding equipment

One advantage of loose housing of cattle is the opportunity to construct the feed trough in the fence to allow easy access for filling. The simplest type of manger consists of a low barrier with a rail fixed above. The drawback is that cattle have a tendency to throw feed forward while eating, but a wall in front, as shown in Figure 10.18, will reduce this problem.

The dimensions of the trough must be chosen to conform with the required height, reach and width of the feeding space for the animals to be fed, while providing enough volume for the amount of feed distributed at each feeding time (as shown in Figures 10.17, 10.18 and 10.19).

Although timber construction is simple to install, concrete should be considered because of its greater durability. When timber is used, the base should be well treated with wood preservative. However, the preservative should not be used on any surface that cattle can reach to lick, as some preservative materials are toxic to animals.

When concrete is used, the grade should be at least C20, or a nominal mix of 1:2:4, because a lower grade concrete would soon deteriorate as a result of chemical attack by feedstuffs and the cow's saliva. The cows will press against the barrier before and during feeding, so the head rail must be firmly fixed to the vertical posts, which are set immovably in the ground.

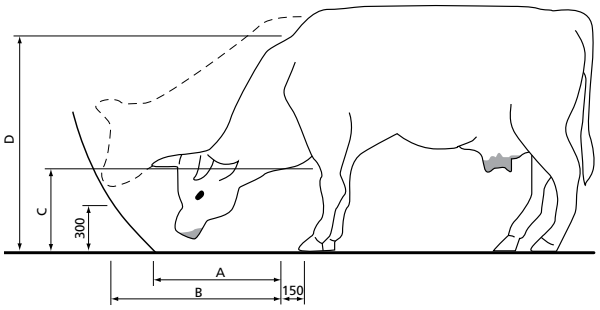
A 2.5 metre-wide concrete apron along the feed trough will reduce the accumulation of mud. A narrow step next to the trough will help to keep the trough free from manure, as animals will not back onto such a step. The bottom of the feed trough should be at a level 100 mm to 400 mm above the level at which the cow is standing with her front feet.

A slightly more elaborate feed trough separates the cattle by vertical rails or tombstone barriers, as shown in Figure 10.19, to reduce competition during eating. The tombstone barrier may also reduce fodder spillage because the cow has to lift her head before withdrawing it from the trough.

A simple roof constructed over the feed trough and the area where the cows stand to eat will provide shade and encourage daytime feeding in bright weather, while protecting the feed from water damage in rainy periods.

Watering equipment

Drinking-water for cattle must be clean. Impurities may disturb the microbiological activities in the rumen. Table 10.7 shows the drinking-water requirement, but a hot environment may considerably increase it. In dairy cows, the need for water will increase with milk yield.



		Calves	Heifers	Mature cows
A	Reach at ground level	550	650	700
B	Reach at 300 mm above ground level	700	850	900
C	Trough height	350	500	600
D	Height to the withers	1 000	1200	1 300
—	Width of feeding space: when all animals feed at once	350–500	500–650	650–750
	Feed always available	100	150	220
—	Level of feed trough bottom above level of stand	50–200	100–300	100–400

Figure 10.17 **Dimensions for feed trough design for cattle**

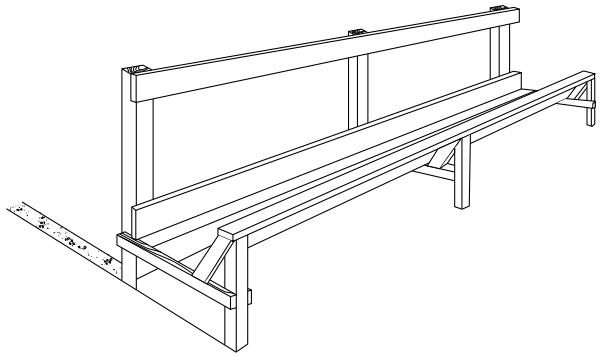


Figure 10.18a **Perspective view of timber feed trough**

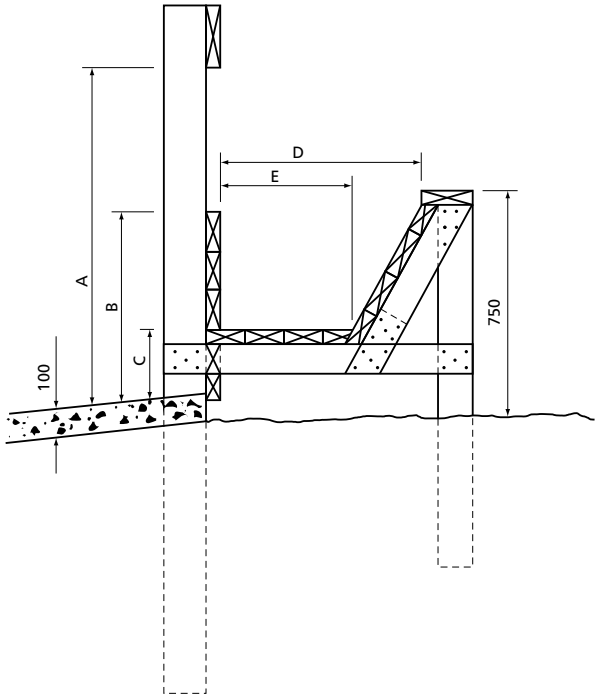


Figure 10.18b **Timber trough**

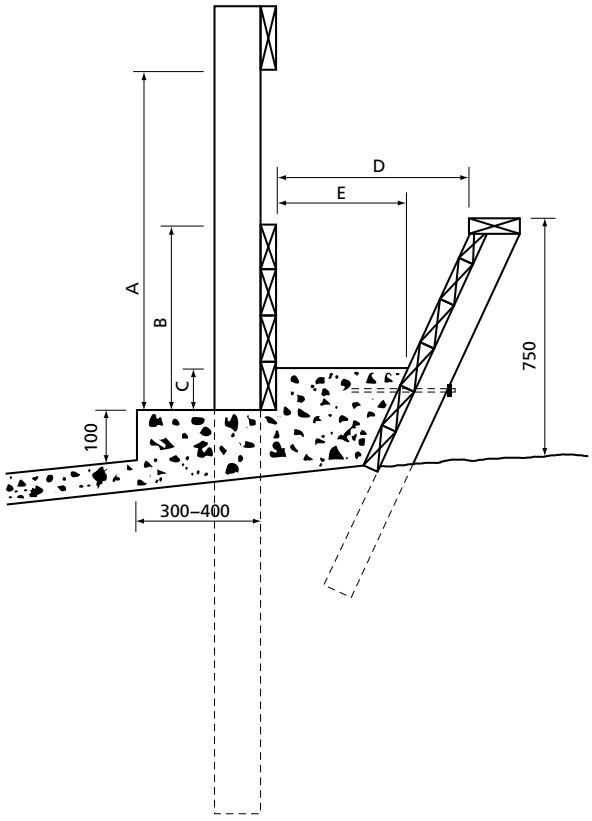


Figure 10.18c **Concrete trough with a step in front of the trough**

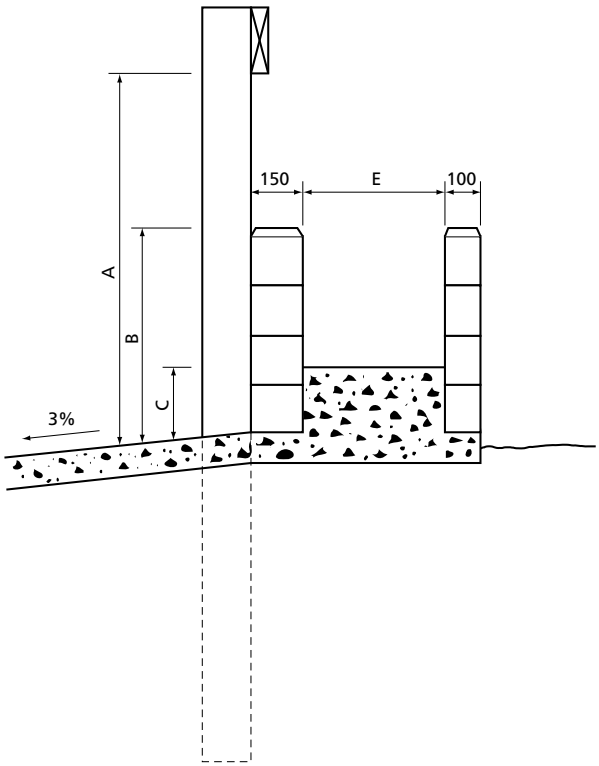


Figure 10.18d **Masonry walls in the trough**

Dimension	Calves	Heifers	Mature cows
A	800–900	900–1 000	1 000–1 200
B	300	400	500
C	50–200	100–300	100–400
D	500–700	650–850	700–900
E	300–550	400 –650	450–700

Figure 10.18 **Simple feed trough**

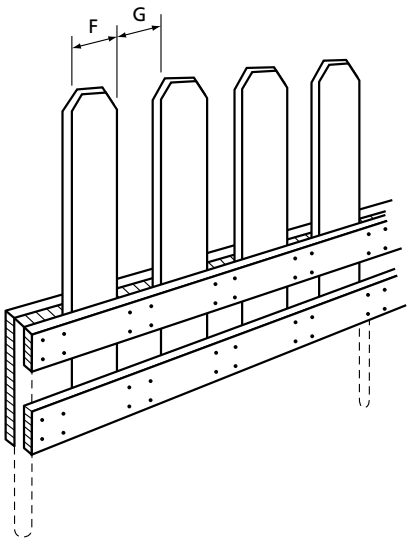


Figure 10.19a **Perspective view**

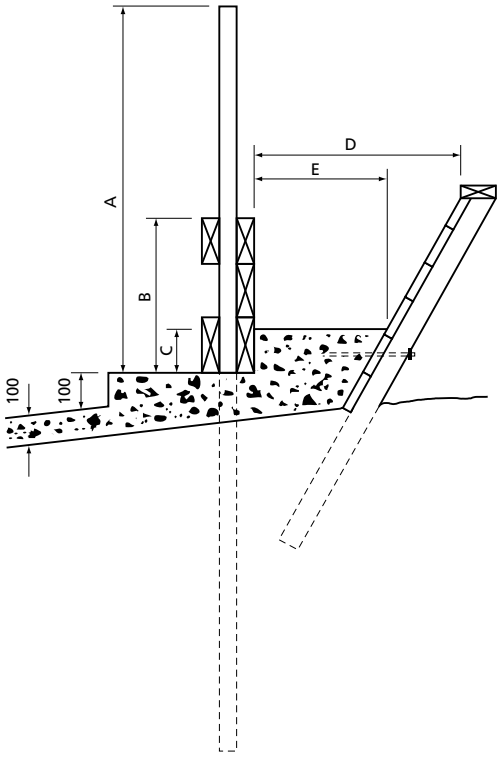


Figure 10.19b **Section**

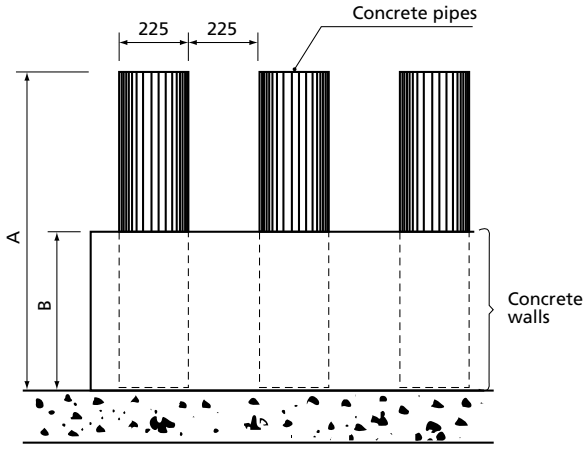


Figure 10.19c **Alternative design**

Figure 10.19 **Tombstone feed fence**

Dimension	Calves	Heifers	Mature cows
A	850–950	1 000–1100	1 100–1 200
B	350	450–500	550
C	50–200	100–300	100–400
D	500–700	650–850	700–900
E	300–550	400–650	450–700
F	150–250	150–450	500
G	130–150	170–200	200

TABLE 10.7
Drinking water requirement for cattle

	Litres/day
Calves	10
Young stock (average)	25 (8–12 per 100 kg body weight)
Heifers	35–45
Beef cows	30–45
Beef cattle	15–30 (30–60 in a hot environment)
Dry dairy cows	40–60
Milking cows	50–100

Water troughs

The size of a water trough depends on whether the herd is taken for watering periodically or is given water on a continuous basis. If water is limited, the length of the trough should be such that all the cows can drink at the same time. A trough space of between 60 cm and 70 cm should be allowed for each cow. For free choice, the trough should be sized for two to three cows at a time. One trough should be provided for every 50 animals. Figures 10.20a and 10.20b show a well-designed trough made of concrete. The length may be increased if necessary.

A float valve installed on the water supply pipe controls the level automatically. A minimum flow rate of 5–8 litres per minute for each cow drinking at any one time is desirable. To prevent contamination of the water trough with manure, the trough should preferably have a 300–400 mm-wide step along the front. The animals will readily step up to drink, but will not back onto the

raised area. An alternative is to make the sides facing the cattle sloping, as shown in Figure 10.20c.

Young stock in a loose housing system require one water trough for every 50–60 animals. A 60 cm height is satisfactory. A minimum flow rate of 4–5 litres per minute for each animal drinking at any one time is desirable.

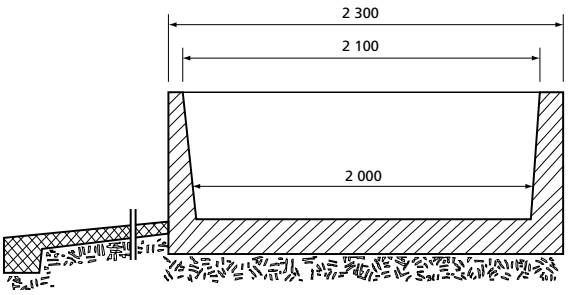


Figure 10.20a **Length section**

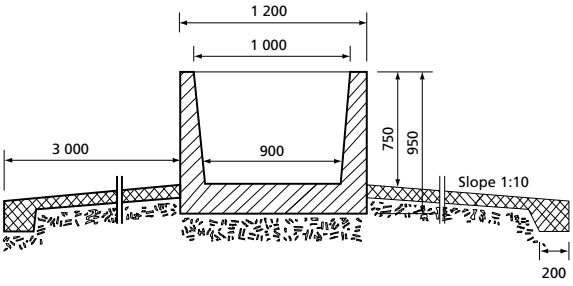


Figure 10.20b **Cross-section (without step)**

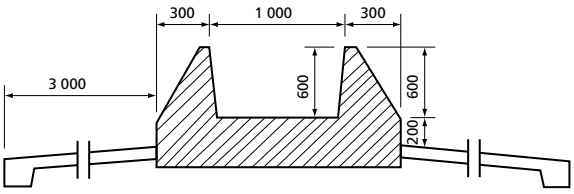


Figure 10.20c **Alternative cross-section**

Figure 10.20 **Concrete water trough**

Automatic drinkers

Automatic drinkers activated by the animals provide a hygienic means of supplying water for cows and young stock (see Figure 10.21). When used in loose housing systems for cows, the bowl should be placed at a height of 100 cm and be protected by a raised area beneath it (1 metre wide and 150–200 mm in height). One bowl should be provided for every 10–15 cows.

A nipple drinker without a bowl provides the most hygienic means of watering for young stock, but most nipples have a limited flow rate and can therefore not be used for calves older than six months.

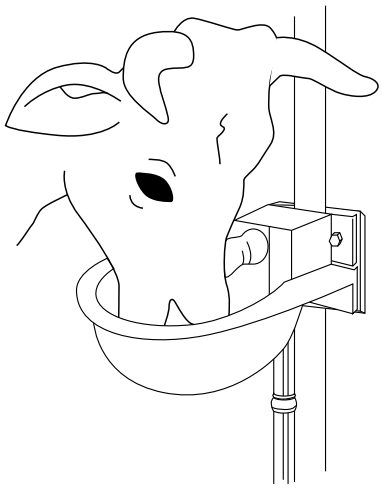


Figure 10.21 **Automatic water drinkers**

Feed handling

The types and quantities of feedstuffs to be handled vary greatly from farm to farm.

Dry hay or forage

If an adequate supply of green forage can be grown throughout the year, then only temporary storage and space for chopping is required. On the other hand, if a prolonged dry season makes it necessary to conserve dry forage, a storage method that will prevent spoilage is essential. A raised slatted floor with a thatched or corrugated steel roof will provide good protection for hay. A simple storage similar to the sunshade shown in Figure 10.4 will be adequate.

If the store is filled gradually, it may help to have some poles in the top of the shed on which to spread hay for final drying before it is packed into the store. Loose hay weighs about 60–70 kg/m^3. Although requirements will vary greatly, a rough guide is 3–5 kilograms of hay or other forage per animal per day of storage.

Silage

Good-quality silage is an excellent feed for cattle. However, it is not practical for the smallholder with only a few cows because it is difficult to make small quantities of silage without excessive spoilage.

Successful silage-making starts with the right crop. The entire maize plant, including the grain, is ideal, as it has enough starch and sugar to ferment well. In contrast, many grasses and legumes do not ferment well unless a preservative, such as molasses, is added as the forage is placed into the silo.

It takes a good silo to make good silage. The walls must be smooth, airtight and, for a horizontal silo, the walls should slope about 1:4 so that the silage packs tighter as it settles. The forage to be made into silage should have a moisture content of about 30–50 percent and must be chopped finely and then packed tightly into the silo. The freshly placed material must be covered and

sealed with a plastic sheet. Failure at any step along the way spells disaster.

The large commercial farmer, with well constructed horizontal or tower silos and the equipment to fill them, has the chance to make excellent feed. However, good management is no less important, regardless of size.

Concentrates and grains

Again, the amount to be stored is highly variable. The method of storing is similar to that for food grains, and suitable storage facilities are discussed in Chapter 16.

Manure handling

Careful waste management is needed to:

- utilize the fertilizing qualities of the manure, urine and other waste;
- maintain good animal health through sanitary facilities;
- avoid pollution of air and water and to provide good hygiene around the farmstead.

The method of disposal depends on the type of waste being handled. Solids can be stacked and spread on fields at the optimum time of year, while liquids must be collected in a tank and may be spread from tank-wagons.

Manure from a livestock production unit may contain not only faeces and urine, but also straw or other litter materials, spillage from feeding, and water. If silage is produced on the farm, the runoff from the silos should be led to the urine collection tank. Depending on the wilt, the amount of effluent can vary from 0 m^3 to 0.1 m^3 or more per tonne of silage, but the normal storage allowance is 0.05 m^3 per tonne.

Manure is handled as a solid when the dry matter content exceeds 25 percent. In this condition, the manure can be stacked to a height of 1.5–2 metres. This condition of the manure is obtained only when urine is drained away immediately and a prescribed amount of litter, such as straw or sawdust, is used. The use of 1–2.5 kilograms of litter per cow per day ensures that the manure can be handled as a solid.

Manure with less than 20 percent solids has the consistency of thick slurry. It must be collected in a tank or pit but is too thick to handle effectively with pumps. It must be diluted with water to less than 15 percent solids before it can be pumped with a conventional centrifugal pump. If diluted in order to use irrigation equipment for spreading liquid manure, the content of solids must be below 4 percent.

The amount of manure and the composition vary depending upon factors such as feeding, milk yield, animal weight, position in the lactation period and the health of the animal. Cattle fed on 'wet' silage or grass produce more urine. Table 10.8 shows the manure production in relation to the weight of the animals.

To estimate the volume of manure and bedding, add the volume of manure from Table 10.8 to half the volume of bedding used. Heavy rain requires the removal of liquid for stacked manure during the storage period. The storage capacity must then be increased by about 50 percent, or a roof should be built over the storage for slurry or liquid manure.

Example

Find suitable dimensions for a slurry manure pit with an access ramp, given the following:

Animals: 5 dairy cows 500 kg
Storage period: 30 days
Maximum slope of access ramp: 15%

Storage capacity *(V)* needed (see Table 10.8);

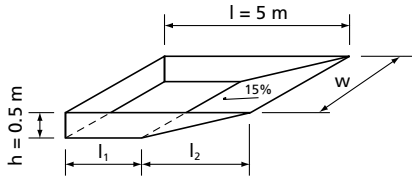
Therefore $V = 5 \times 30 \times 0.055 = 8.25$ m^3

TABLE 10.8
Manure production in cattle

Weight of animal	Faeces	Urine	Total manure storage capacity to allow for*	
(kg)	(kg/day)	(kg/day)	(kg/day)	(m^3/day)
Dairy cattle				
50	2.7	1.2	3.9	0.004
100	5.2	2.3	7.5	0.009
250	14	6	20	0.025
400	23	10	33	0.045
600	35	1 5	50	0.065
Beef cattle				
350	15	6	21	0.025
450	19	8	27	0.035
550	24	10	34	0.045

* These values are for manure only – no bedding is included. Washing water used in the milking parlour may amount to as much as 300 litres/stall/milking. Usually allow for 50 litres/head/day (normal variation can be as much as ±20 percent of the table figures).

Assume the pit will be 0.5 metres deep and 5 metres long (see sketch)



Total width *(W)* will then be:

$$W = \frac{V}{(l_1 + 0.5l_2)h}$$

$$l_2 = \frac{h}{0.15} = \frac{0.5}{0.15} \approx 3.3 \text{ m}$$

$$l_1 = l - l_2 = 5 - 3.3 = 1.7 \text{ m}$$

$$W = \frac{8.25}{0.5(1.7 + 0.5 \times 3.3)} = 4.9 \text{ m}$$

A pit 5 × 5 × 0.5 metres with an access ramp slope of 15 percent is chosen.

Cattle dips

Ticks continue to be one of the most harmful livestock pests in east Africa. As vectors of animal disease, ticks have been a great hindrance to livestock development, especially in areas where breeds of cattle exotic to the environment have been introduced.

At present the only effective method of control for most of these diseases is to control the vector, i.e. the ticks. Dipping or spraying with an acaricide is the most efficient way of reducing the number of ticks.

Siting a dip

The ground where a dip is to be built, and the area around it, should be slightly sloping and as hard as possible, but not so rocky that a hole for the dip cannot be dug. Laterite (murram) soil is ideal. The ground must support the structure of the dip, be well drained and not become muddy in wet weather. It must also be resistant to erosion or gullying of cattle tracks.

Cattle must not be hot or thirsty when they are dipped, so it is important to have a water trough inside the collecting yard fence.

Waste disposal and pollution

All dipping tanks need to be cleaned out from time to time with disposal of the accumulated sediment. It is normal for all the waste dip-wash to be thrown into a 'waste pit' that is dug close to the dip. In addition, dipping tanks may crack with the resulting leakage of acaricide.

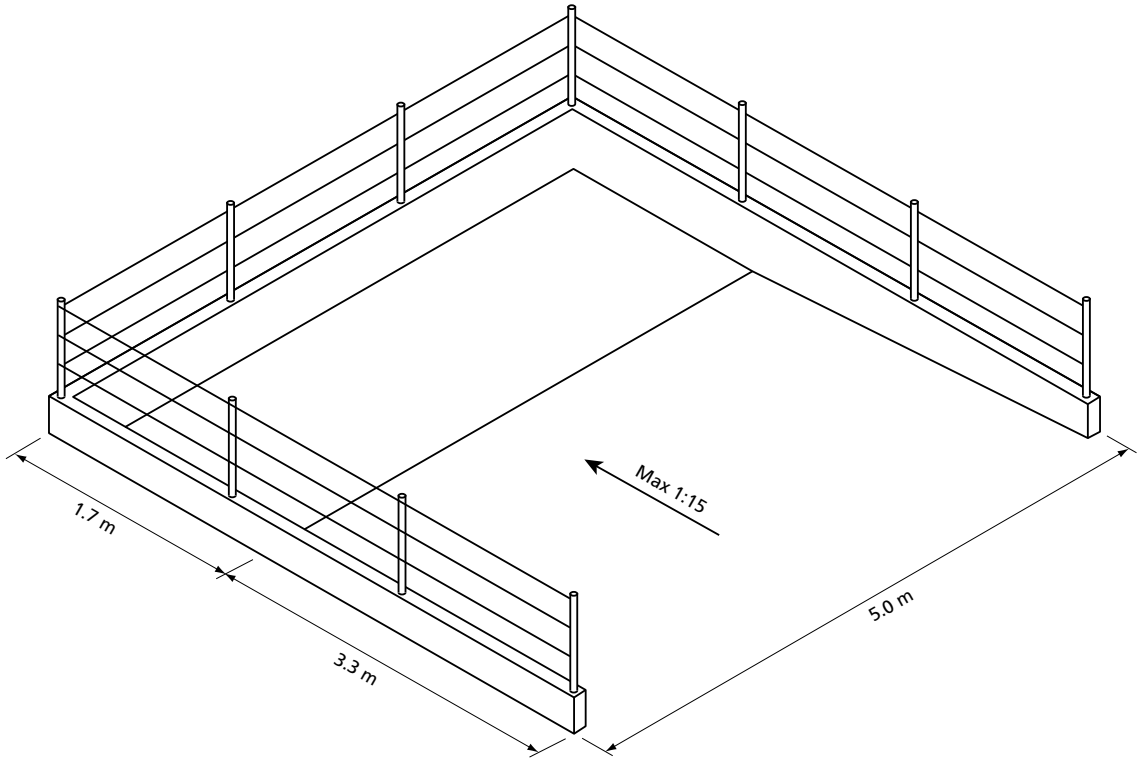


Figure 10.22 **Manure pit with access ramp**

The dip and the waste pit must therefore be sited to ensure that there is no risk of acaricide polluting drinking-water supplies, either by overflowing or by percolating through the ground. The waste pit should be at least 50 metres from any river or stream, 100 metres from a spring or well, and considerably more than that if the subsoil is sandy or porous. Figure 10.23 shows a typical site layout and describes the features in the order that the cattle come to them.

Footbaths

Footbaths are provided to wash mud off the feet of the cattle to help keep the dip clean. At least two are recommended, each 4.5 metres long and 25–30 cm deep but in muddy areas it is desirable to have more. Up to 30 metres total length may sometimes be required (see Figure 10.23). The floors of footbaths should be studded with hard stones set into the concrete to provide grip, and to splay the hoofs apart to loosen any mud between them.

The footbaths should be arranged in a cascade, so that clean water added continuously at the end near the dip overflows from each bath into the one before it, with an overflow outlet to the side near the collecting pen. Floor-level outlet pipes from each bath can be opened for cleaning. If the supply of water is extremely limited, footbath water can be collected in settling tanks and reused later.

Jumping place

A narrow, steep flight of short steps ensures that:

- animals can grip and jump centrally into the dip;
- their heads are lower than their rumps at take-off;
- they jump one at a time;
- dip-wash splashing backwards returns to the dip.

The lip of the jumping place experiences extreme wear and should be reinforced with a length of 10 cm-diameter steel pipe.

Figure 10.24 shows the jumping place 40 cm above the dip-wash level. While such a height is desirable to give maximum immersion, there could be some danger to heavily pregnant cows if the water level should fall a further 40 cm. (The dipping of 1 000 cattle without replenishment would lower the water level to 60 cm below the jumping place.)

Splash walls and ceiling are provided to catch the splash and prevent the loss of any acaricide. The ceiling protects the galvanized roof from corrosion. The walls can be made of wood, but masonry is more durable.

The dipping tank

The dipping tank is designed to a size and shape to fit a jumping cow and allow her to climb out, while economizing as far as possible on the cost of construction and the recurrent cost of acaricide for refilling. A longer tank is needed if an operator standing on the side is to have a good chance of reimmersing the heads of the animals while they are swimming, and increased volume can slightly prolong the time until

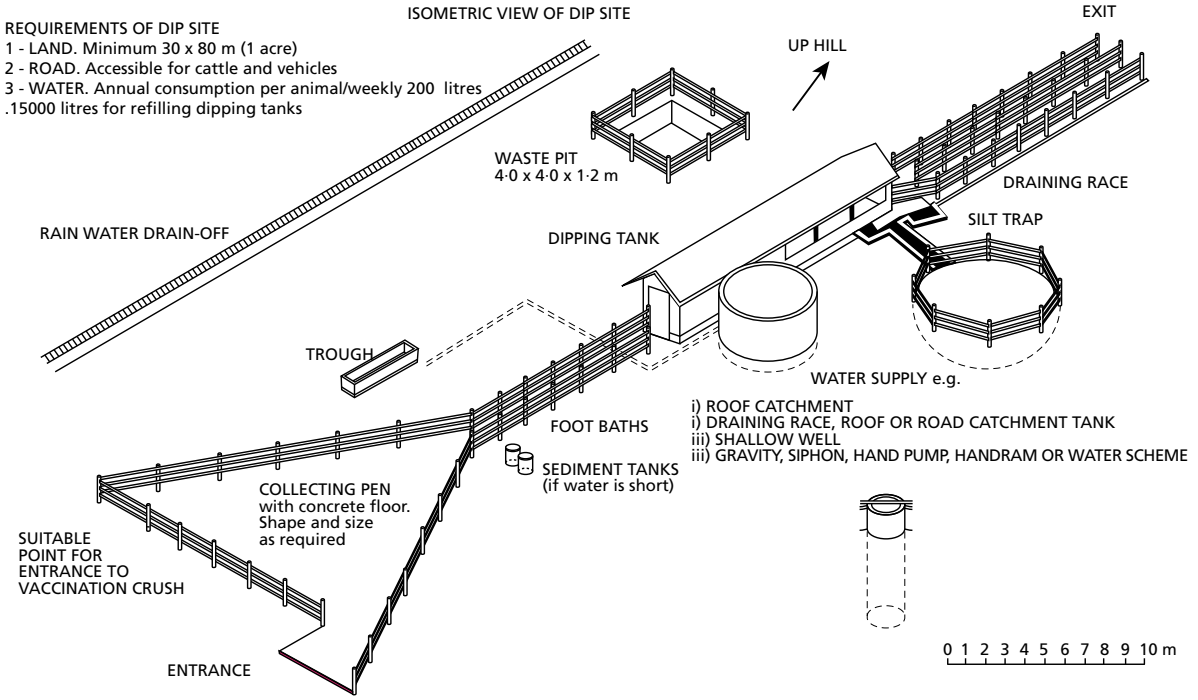


Figure 10.23 **Cattle dip layout**

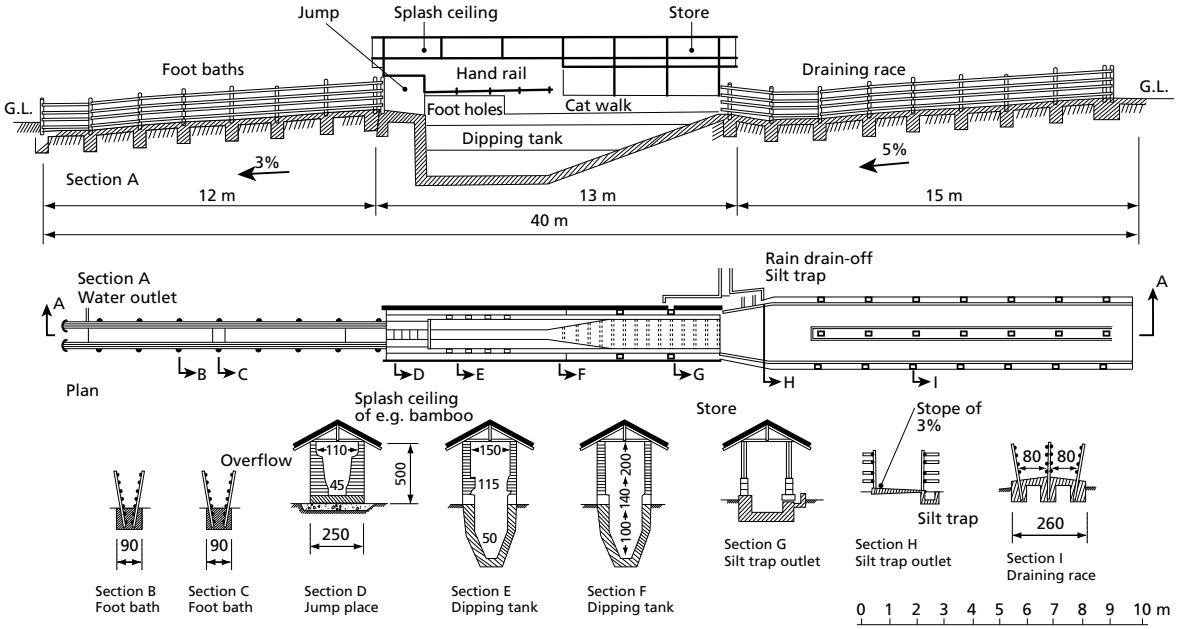


Figure 10.24 **Cattle dip**

the dip must be cleaned out. In areas with cattle of the 'Ankole' type with very long horns the dip-tank needs to be much wider at the top.

Poured reinforced concrete is the best material to use in constructing a dipping tank in any type of soil. While it is expensive if only a single tank is to be built because of the cost of the formwork involved, the forms can be reused. If five tanks are built with one set of forms, the cost per tank is less than the cost of building with other materials, such as concrete blocks or bricks. A reinforced concrete dipping tank is the only type with a good chance of surviving without cracking in unstable ground. In areas prone to earthquakes, a one-piece tank is essential.

Catwalks and handrails are provided to allow a person to walk between the splash walls to rescue an animal in difficulty. In addition to providing shade, a roof over the dipping tank reduces evaporation of the dip-wash, prevents dilution of the dip-wash by rain, and in many cases, collects rainwater for storage in a tank for subsequent use in the dip.

Draining race

The return of surplus dip-wash to the dipping tank depends on a smooth, watertight, sloping floor in the draining race. A double race reduces the length and is slightly cheaper in materials, but a very long single race is preferable where large numbers of cattle are being dipped.

Side-sloping of the standing area towards a channel or gutter increases the backflow rate. The total standing area of the draining race is the factor that limits the number of cattle that can be dipped per hour, and the size shown in the drawings should be taken as the minimum.

A silt trap allows settling of some of the mud and dung from the dip-wash flowing back to the tank from the draining race. The inlet and outlet should be arranged so that there is no direct crossflow. Provision must be made to divert rainwater away from the dip.

Cattle spray race

A spray race site requires the same features as a dip site and these have already been described. The only difference is that the dip tank has been changed for a spray race. The race consists of an approximately 6-metre long and 1-metre wide tunnel with masonry side walls and a concrete floor. A spray-pipe system with a length of 3–3.5 metres in the tunnel with 25–30 nozzles placed in the walls, ceiling and floor, discharges dip liquid at high pressure and exposes the cattle passing through to a dense spray.

The fluid is circulated by a centrifugal pump giving a flow of 800 litres per minute at 1.4 kg/cm^2 pressure. Power for the pump can be supplied by a 6-horsepower to an 8-horsepower stationary engine, a tractor power take-off, or a 5-horsepower electric motor. The discharged fluid collected on the floor of the tunnel and draining race is led to a sump and recirculated.

In addition to being cheaper to install than a dipping tank, the spray race uses less liquid per animal and operates with a smaller quantity of wash, which can be freshly made up each day. Spraying is quicker than dipping and causes less disturbance to the animals. However, spray may not reach all parts of the body efficiently or penetrate long hair. The mechanical equipment used requires power, maintenance and spare parts, and the nozzles tend to become clogged and damaged by horns.

Hand-spraying is an alternative method that can work well if carried out by an experienced person on an animal properly secured in a crush. The cost of the necessary equipment is low, but the consumption of liquid is high as it is not recirculated. The method is time-consuming and therefore only practicable for small herds where there is no communal dip tank or spray race.

PIG HOUSING

Pig farming is relatively unimportant in most regions of Africa, as in most tropical countries except China and South-East Asia. However, pig production is increasing in many tropical countries as processed pork finds an increasing market, and pig production yields a relatively rapid rate of return on the capital employed. Pigs are kept primarily for meat production, but the by-products, such as pigskin, bristles and manure, are also of economic importance. To some extent, pigs compete with humans for food, but they can also utilize by-products and human food waste.

Management improvements

In many tropical countries pigs roam freely as scavengers or are raised in the backyard where they depend on waste for feed. Little attempt is made to obtain maximum productivity. However, a few simple management practices can help to improve the productivity and health of these pigs. They include:

1. Fenced paddocks with shade and water where:
   (a) Pigs are protected from direct sun, which will cause sunburn and sometimes sunstroke, particularly with white-skinned pigs.
   (b) Pigs can be fed supplementary feed secure from neighbouring pigs.
   (c) Some basic measures to control disease and parasites are possible to reduce the often very high mortality rate and to improve the poor reproductive and growth performance and inferior quality of meat found in traditional pig production in the tropics. The paddock can be subdivided into four to six smaller areas to enable pigs to be moved from one enclosure to another at two-week intervals.
   (d) Sows can be bred to selected sires.

2. Simple semicovered pens constructed of rough timber with a thatched roof and concrete floor, as shown in Figure 10.25. An earth floor can be used, but is more difficult to keep clean and sanitary. Several pens can be arranged in a row as required. The main disadvantage with this type of accommodation is the relatively high labour requirement for cleaning.

3. Wallows or sprinklers can be provided to alleviate heat stress. Being unable to sweat sufficiently, pigs have a natural instinct to wallow to increase the evaporative cooling from the skin.

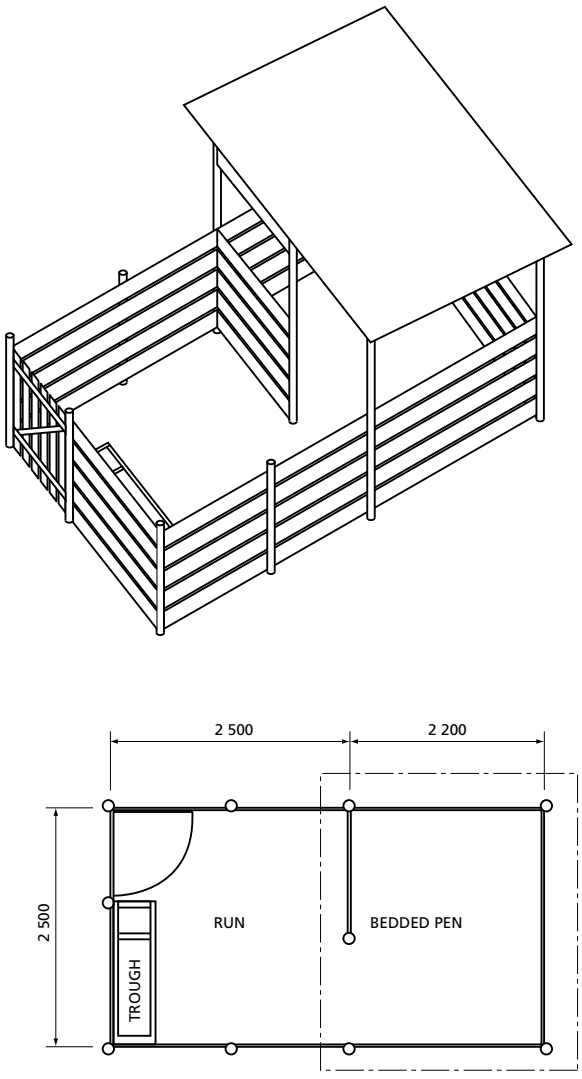


Figure 10.25 **Smallholder's pigsty for one sow with litter, or four to five fattening pigs**

While such improvements have the advantage of low investment in buildings and less need for balanced-feed rations, they should only be regarded as first steps in raising the general level of the present primitive systems.

Raising pigs in confinement is gradually replacing the old methods because of lower production costs, improved feed efficiency and better control of disease and parasites. The confinement system is therefore usually advisable in circumstances where:

- good management is available;
- high quality pigs are introduced;
- farrowing occurs at regular intervals throughout the year;
- land is scarce or not accessible all the year;
- balanced rations are available;
- labour is expensive;
- parasite and disease control is necessary;
- the target is commercial production;
- the herd size is reasonably large.

Some systems keep only part of the herd in confinement. The order of priority for confinement housing for the different classes of animal is usually as follows:

1. Growing/finishing pigs (25–90 kg or more live weight) for higher control of daily gain, better feed conversions and parasite control.
2. Farrowing and lactating sows, to reduce preweaning mortality and for higher quality weaners.
3. Gestating sows, to allow individual feeding and better control of stock.

Management systems in intensive commercial pig production

There is no standard type or system of housing for pigs. Instead, accommodation and equipment are selected to suit the type of management system adopted. However, there are certain similar principles and practices in most systems. These stem from the fact that most pig units will contain pigs of different ages and classes, as shown in Figure 10.26.

Farrowing/suckling pens

In small- and medium-scale intensive pig production units, a combined farrowing, suckling and rearing pen is normally used. The sow is brought to this pen one week before farrowing and stays there, together with her litter, for five to eight weeks, when the piglets are weaned by removing the sow. The sow is often confined in a farrowing crate a few days before, and up to a week after, birth to reduce piglet mortality caused by overlaying or trampling (see Systems I and II in Figure 10.27).

Early weaning after a suckling period of five to six weeks, or even less, can only be recommended where management and housing is of good standard.

The piglets remain in the farrowing pen after weaning and until they are 12–14 weeks of age, or weigh 25–30 kilograms.

Group keeping of farrowing/suckling sows that have given birth within a two- to three-week interval is possible, but is unusual in intensive production. However, there are few acceptance problems, and the litters cross-suckle and mix freely. The pen should have at least 6 square metres of deep litter bedding per sow, with an additional creep area of 1 metre.

In a large-scale unit with a separate farrowing house, sometimes one of the following two alternative systems is used instead of the system described before.

The first alternative (System III in Figure 10.27) is similar to the system already described, but the piglets are moved two weeks after weaning to a weaner pen, where they may remain either until they are 12–14 weeks of age (25–30 kilograms) or until 18–20 weeks of age (45–55 kilograms). Note that the piglets should always remain in the farrowing/suckling pen for a further one to two weeks after the sow has been removed to avoid subjecting them to any new environmental or disease stress while they are being weaned. The weaning pens can contain one litter or 30–40 pigs. The pigs are often fed *ad libitum*.

In the second alternative (System IV in Figure 10.27), the sow is placed in a farrowing crate in a small pen one week prior to birth. Two weeks after farrowing, the sow and the litter are moved to a larger suckling pen. The piglets may remain in this pen until 12–14 weeks of age, or they are transferred to weaner accommodation two weeks after weaning.

Dry sow pens

After weaning, a sow will normally come on heat within five to seven days and thereafter at three-week

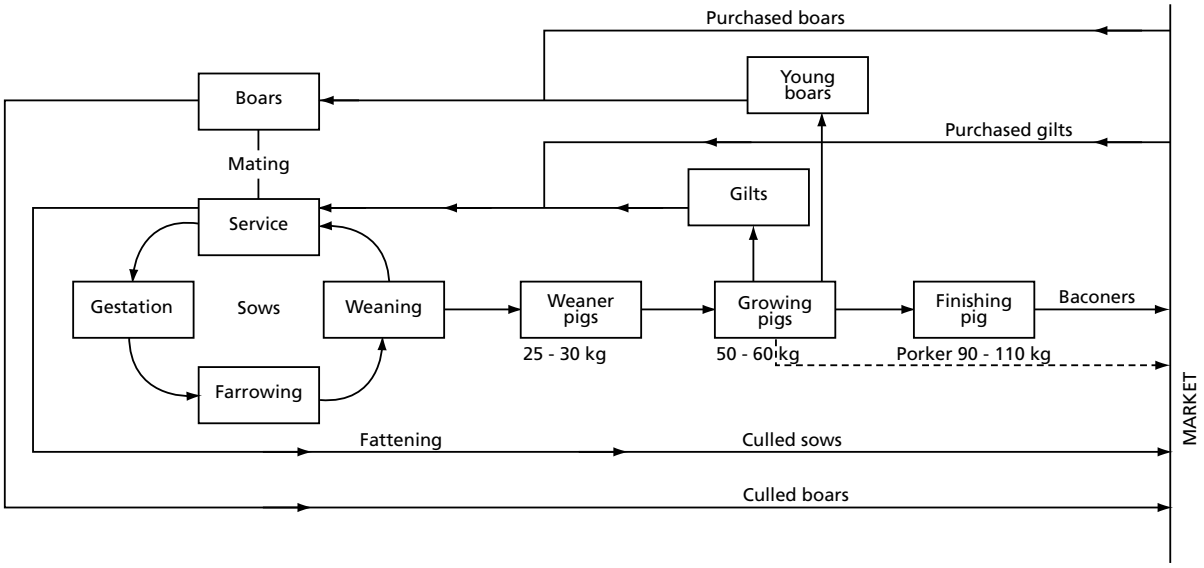


Figure 10.26 **Flowchart of the life cycle of pigs**

intervals until successful mating. The average weaning-to-conception interval can vary between 8 days and 20 days depending on management. If the period until pregnancy has been ascertained, the sow is best kept in a pen or stall in close proximity to the boar pen.

Gestating sows are kept in yards or pens in groups of 10–12 sows that will farrow within a two- to three-week interval. They can also be kept in individual pens confined in stalls or tethered in stalls.

Weaner and fattening pens

The weaners, whether they come from a farrowing pen or a weaner pen, at 12–14 weeks of age will be sufficiently hardened to go to a growing/finishing pen. Finishing can be accomplished either in one stage in a growing/finishing pen from 25 kg to 90 kg (Systems I and IV in Figure 10.27 – or in two stages so that the pigs are kept in a smaller growing pen until they weigh 50–60 kg and are then moved to a larger finishing pen, where they remain until they reach marketable weight (System II in Figure 10.27).

In large-scale production, the pigs are arranged into groups of equal size and sex when moved into the growing/finishing pen. Although finishing pigs are sometimes kept in groups of 30 or more, pigs in a group of 9–12, or even less, show better growth performance in intensive systems. An alternative, where growing and finishing are carried out in the same facility, is to start about 12 pigs in the pen and later, during the finishing period, reduce the number to nine by taking out the biggest or smallest pigs from each pen.

Replacement pens

In intensive systems a sow will, on average, produce three to six litters before it is culled owing to infertility, low productivity or age. Young breeding stock should be separated from the rest of the litter at about three months of age, because they should be less intensively fed than the fattening pigs.

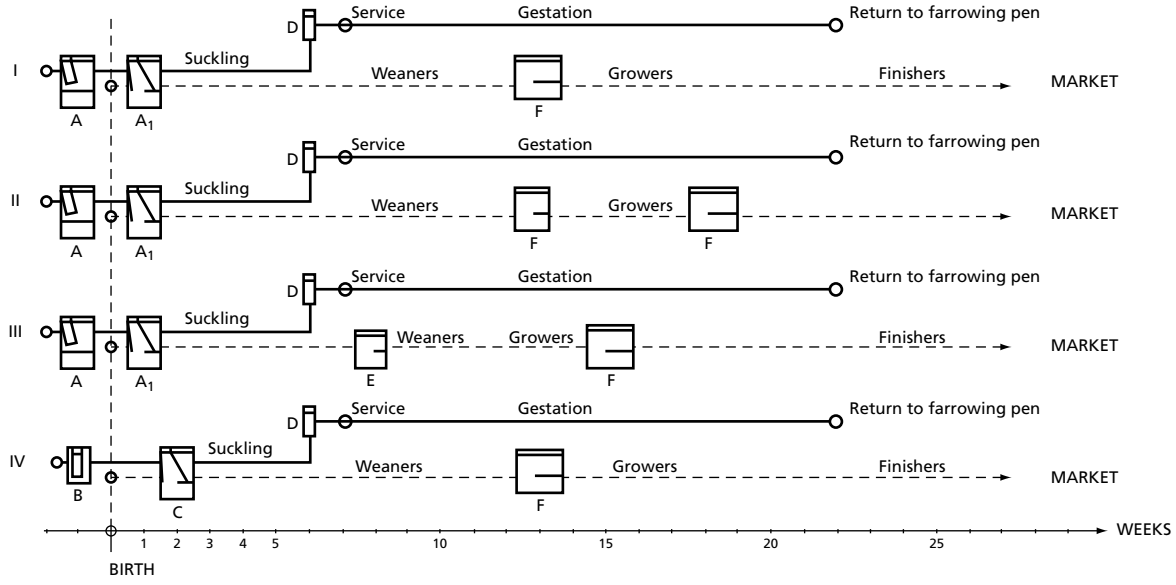
Gilts are first mated when they are seven to nine months of age, or weigh 105–120 kg. After mating, they can either be kept in the same pen up to one week before farrowing, or kept in the gestating sow accommodation, but in a separate group.

Boars in the tropics are usually quiet if run with other boars or with pregnant sows, but may develop vicious habits if shut up alone.

Determining the number of pens and stalls required in a pig unit

One objective of planning a pig unit is to balance the accommodation between the various ages and numbers of pigs. Ideally, each pen should be fully occupied at all times, allowing only for a cleaning and sanitation period of about seven days between successive groups.

In the following example, we determine the number of different pens required in a 14-sow herd where eight-week weaning is practiced.



A - Combined farrowing suckling pen (A_1 - after the crate has been opened or removed);
B - Specialised farrowing pen;
C - Suckling pen;
D - Gestation accommodation;
E - Pen for weaners;
F - Growing/finishing pen

Figure 10.27 **Flowchart of four different pig production management systems**

1. Determine the farrowing interval and number of farrowings per year.

Average weaning-to-conception interval	20 days
Gestation	114 days
Suckling period (7 × 8 weeks)	56 days
Farrowing interval	190 days

Number of farrowings per sow per year: 365 / 190 = 1.9

2. Determine the number of farrowing pens.
The piglets remain in the farrowing pen until 12 weeks of age.

Before farrowing	7 days
Suckling period	56 days
Rearing of weaners	28 days
Cleaning and sanitation of pen	7 days
Occupation per cycle	98 days

Thus one farrowing pen can be used for:
365 / 98 = 3.7 farrowings per year.

A 14-sow herd with an average of 1.9 farrowings per sow per year requires (14×1.9) / 3.7 = 7 farrowing pens.

3. Determine the number of servicing/gestating pens.

Average weaning-to-conception interval	20 days
Gestation period minus 7 days in farrowing pen	107 days
Cleaning and sanitation of pen	7 days
Occupancy per cycle	134 days

Thus one place in the servicing/gestation accommodation can be used for: 365/134 = 2.7 farrowings per year.

With a total of 27 farrowings a year, then 27/2.7 = 10 places would be required.

4. Determine the number of places for replacement stock.

Assuming that the sows have an average of five litters, then 20 percent of all litters will be from gilts.

Rearing of breeding stock (12–35 weeks)	168 days
Gestation period minus 7 days in farrowing pen	107 days
Cleaning and sanitation of pen	7 days
Occupancy per cycle	282 days

About 30 percent more animals are separated than the required number of gilts, therefore the required number of places in a 14-sow herd will be:

(14× 1.9 × 0.2×1.3 ×282) / 365 = 6 places

5. Determine the number of places in the growing/finishing accommodation:

One-stage finishing:	
Fattening of pigs 12–27 weeks of age (25–90 kg)	105 days
Extra period for last pig in the pen to reach marketable weight	21 days
Cleaning and sanitation of pen	7 days
Occupancy per cycle	133 days

Assuming that eight pigs per litter will survive to 12 weeks of age, the number of places required in the finishing accommodation will be:

(14 × 1.9 × 8 × 133) / 365 = 78

That is eight pens with 10 pigs in each, or 10 pens if each litter is to be kept together.

Two-stage growing/finishing unit:
Growing pigs 12–20 weeks of age will occupy a growing pen for 63 days, including 7 days for cleaning. Thus:

(14 × 1.9 × 8 × 63) / 365 = 37 places are required in the unit.

Finishing pigs 20–27 weeks of age will occupy a finishing pen for 70 days, including 14 days for the emptying period and 7 days for cleaning. The emptying period will be shorter if the pigs are sorted for size while being transferred from the growing to the finishing pens. Therefore:

(14 × 1.9 × 8 × 70) / 365 = 41 places are required in the unit.

From the above example it will be appreciated that the number of pens of various kinds required in a pig unit is based on a number of factors. Therefore it is not possible to lay down hard and fast rules about the relative number of pens and stalls. However, a guideline to the requirement of pens in herds with average or good management and performance in tropical conditions is given in Appendix VI.

Space requirement

In intensive pig production systems, all pigs should be raised on concrete floors to ensure a clean and sanitary environment. In semi-intensive systems, a concrete floor is used only in the pens for finishing pigs and perhaps in the farrowing pens, whereas an earth floor or deep-litter bedding is used in other pens and yards. Litter may or may not be used on a concrete floor, but its use is desirable, particularly in farrowing pens.

The cost of a concrete floor is relatively high, resulting in a tendency to reduce the floor area allowed per animal. However, excessively high stocking densities

could retard performance, increase mortality, health and fertility problems, and result in a high frequency of abnormal behaviour, endangering the welfare of the animals. An increase in the stocking density must be accompanied by an increased standard of management and more efficient ventilation and cooling.

In particular, to aid cooling, finishing pigs kept in a warm tropical climate should be allowed more space in their resting area than is normally recommended for pigs in temperate climates. Table 10.9 lists the recommended space allowance per animal at various stocking densities. The figures listed for high stocking density should only be used in the design of pig units in cool areas and where the management level is expected to be above average.

The dimensions of a pen for fattening pigs are largely given by the minimum trough length required per pig at the end of their stay in the pen (see Table 10.10). However, the width of a pen with low stocking density can be larger than the required trough length. This will reduce the depth to 2.0–2.4 metres, and run the risk of having the pigs create manure within the pen.

TABLE 10.9
Dimensions and area of various types of pig pen

	Units	Stocking density		
		Low	Medium	High
A. Farrowing/suckling pen.				
Resting area, if weaner pens are not used	m^2	10.0	7.5	6.0
Resting area, if weaner pens are used	m^2	8.0	6.0	5.0
Manure alley width	m	1.7	1.5	1.3
Farrowing pen (System IV)	m^2	-	4.5	4.0
Farrowing crate, length excluding trough	m	2.0	2.0	2.0
Width depending on size of sow	m	0.65–0.75	0.6–0.7	0.55–0.65
Free space behind the crate	m	0.4	0.35	0.3
Piglet creep (incl. in resting area)	m^2	2.0	1.5	1.0
B. Boar pen				
1. Pen with yard				
Resting area (shaded)	m^2	6	5	4.5
Yard area (paved)	m^2	12	10	08
2. Pen without yard	m^2	9	8	7
C. Gestating sow pens				
1. Loose in groups of 5–10 sows				
Resting area (shaded)	m^2	2.0	1.5	1.1
Yard area (paved)	m^2	3.5	3.0	2.5
Feeding stalls, depth by width	m	2.0 × 0.6	1.8 × 0.55	1.7 × 0.5
2. Individual stalls with access to manure alley, length of stalls excluding trough	m	2.2	2.1	2.0
Width of stalls	m	0.65–0.75	0.60 – 0.70	0.55–0.65
Width of manure alley	m	1.5	1.4	1.3
3. Confined in individual stalls length by width of stalls	m	2.2 × 0.70	2.1 × 0.65	2.0 × 0.60
D. Weaner pen (to 25 kg or 12 weeks)				
Resting area excluding trough	m^2/pig	0.35	0.30	0.25
Manure alley width	m	1.0	1.0	1.0
E. Growing pen (to 40 kg or 17 weeks)				
Resting area excluding trough	m^2/pig	0.5	0.45	0.40
Manure alley width	m	1.1	1.1	1.1
F. Finishing pen, resting area excluding trough				
For porkers (to 60 kg or 21 weeks)	m^2/pig	0.70	0.60	0.50
For baconers (to 90 kg or 27 weeks)	m^2/pig	0.90	0.75	0.60
For heavy hogs (to 120 kg or 33 weeks)	m^2/pig	1.0	0.85	0.70
Manure alley width	m	1.2–1.4	1.2–1.3	1.2

Furthermore, this increases flexibility in the use of the pen and the extra trough space allows additional animals to be accommodated temporarily or when the level of management improves.

Sometimes finishing pens are deliberately overstocked. The reason for this is that all pigs in the pen will not reach marketable weight at the same time and the space left by the pigs sent for slaughter can be utilized by the remainder. Such overstocking should be practiced only in very well managed finishing units.

TABLE 10.10
Minimum trough length and height of partitions in various types of pig pen

		Minimum trough length	Minimum height of pen partitions
		m/pig	m
Sow in farrowing pen		0.7	1.0
Loose dry sows in pens		0.5	1.0
Stall for dry sows		0.5	1.0
Boars		0.6	1.2
Piglets	10 kg	0.14–0.15	0.6
Piglets	15 kg	0.16–0.17	0.7
Pigs	25 kg	0.18–0.20	0.8
Pigs	40 kg	0.22–0.24	0.9
Pigs	60 kg	0.25–0.27	0.9
Pigs	90 kg	0.30–0.32	0.9
Pigs	120 kg	0.35–0.37	1.0

General requirements for pig housing

A good location for a pig unit meets the following requirements: easy access to a good all-weather road; well-drained ground; and sufficient distance from residential areas to avoid creating a nuisance from odour and flies.

An east-west orientation is usually preferable to minimize exposure to the sun. Breezes across the building in summer weather are highly desirable. A prevailing wind during hot weather can sometimes justify a slight deviation from the east-west orientation. Ground cover, such as bushes and grass, reduces the reflected heat considerably, and the building should be located where it can benefit most from surrounding vegetation. A fairly light, well-drained soil is preferable, and usually the highest part of the site should be selected for construction.

Pig houses should be simple, open-sided structures because maximum ventilation is needed. A building for open confinement is therefore essentially a roof carried on poles. The roof supporting poles are placed in the corners of the pens where they will cause least inconvenience. A free-span trussed roof design would be an advantage but is more expensive.

In some circumstances it may be preferable to have solid gable ends and one enclosed side to give protection from wind or low temperatures, at least for part of the year. If such walls are needed, they can often be temporary and be removed during hot weather to allow maximum ventilation. Permanent walls must be provided with large openings to ensure sufficient air circulation in hot weather. If there is not sufficient wind to create a draught in hot weather, ceiling fans can improve the environment considerably.

The main purpose of the building is to provide shade, and therefore the radiant heat from the sun should be reduced as much as possible. In climates where a clear sky predominates, a high building of three metres or more under the eaves gives more efficient shade than a low building. A wide roof overhang is necessary to ensure shade and to protect the animals from rain.

A shaded ventilation opening along the ridge will provide an escape for the hot air accumulating under the roof. If made from a hard material, the roof can be painted white to reduce the intensity of solar radiation. Some materials, such as aluminium, reflect heat well provided that they are not too oxidized.

A layer of thatch (5 cm), attached by wire netting beneath a galvanized steel roof, will improve the microclimate in the pens. A roof of thatch is excellent in hot climates, particularly in non-confined systems, but cannot always be used because of the fire hazard and because it attracts birds and rodents. A pig house with two rows of pens and a central feeding alley would require a ridge height of 5–6 metres if covered with thatch.

The pen partitions and the 1-metre wall surrounding the building, which serves to reduce heat reflected from the surrounding ground, can be made of concrete blocks or burnt clay bricks for durability, or perhaps soil-cement blocks, plastered for ease of cleaning. Regular whitewashing may improve the sanitary conditions in the pens.

Doors have to be tight-fitting and any further openings in the lower part of the wall surrounding the building should be avoided in order to exclude rats. Apart from stealing feed and spreading disease, large rats can kill piglets.

For all types of confinement housing, a properly constructed, easily cleaned concrete floor is required. A 80–100 mm layer of concrete on a consolidated gravel base is sufficient to provide a good floor. A stiff mix of 1:2:4 or 1:3:5 concrete, finished with a wood float, will give a durable non-slip floor. The pen floors should slope 2–3 percent towards the manure alley, and the floor in the manure alley should slope 3–5 percent towards the drains.

Housing for a small-scale pig unit

For units with 2–15 sows, specialized buildings for the various stages of production may not be practical or desirable. For the smallest units of two to six sows, a kind of universal pen can be erected about 2.7 metres wide and 2.8–3.0 metres deep (including feed trough), which can be used for:

1. one sow and her litter; or
2. one litter of weaned piglets; or
3. up to four gestating sows; or
4. growing/finishing pigs up to 90 kg live weight or 1 boar.

This type of pen, shown in Figure 10.28, provides a high degree of flexibility but usually does not allow such efficient use of the building space as the more specialized pens.

When used for farrowing, the pen should be adapted with guard rails 25 cm above floor level and 25 cm from the wall to protect the piglets from being crushed, as shown in Figure 10.28b. However, confinement farrowing is one of the most efficient ways of reducing piglet losses. An arrangement with fixed or removable rails, which divide the pen, as shown in Figure 10.28c, will offer some degree of confinement.

In some climates it may be desirable to give sows with litter access to exercise yards. However, for the relatively short suckling period (six to eight weeks), it is usually considered best to keep the sows confined in pens with their litters.

A creep for the piglets is arranged in one corner of the pen. It is recommended to construct a temporary ceiling (e.g. wire netting covered with straw) 50–60 cm above the floor in the creep area to prevent draughts and to ensure warmer temperatures for the piglets during their first weeks of life. Where electricity is available, heating with an infrared lamp may be used instead. Piglets are fed in the creep area out of reach of the sow.

Figure 10.29 shows a single-row pig unit for two sows and fattening pigs, and Figure 10.30 shows a double-row pig unit for four sows with a central feeding alley. The semicovered manure alleys are arranged along the outside walls, separated from the resting area of the pen. This arrangement allows rainwater to help flush away the waste to the drain channel and on to the manure store, which needs to have extra capacity for this water. However, in the four-sow unit the furrowing pens have fully covered manure alleys for increased protection of the piglets.

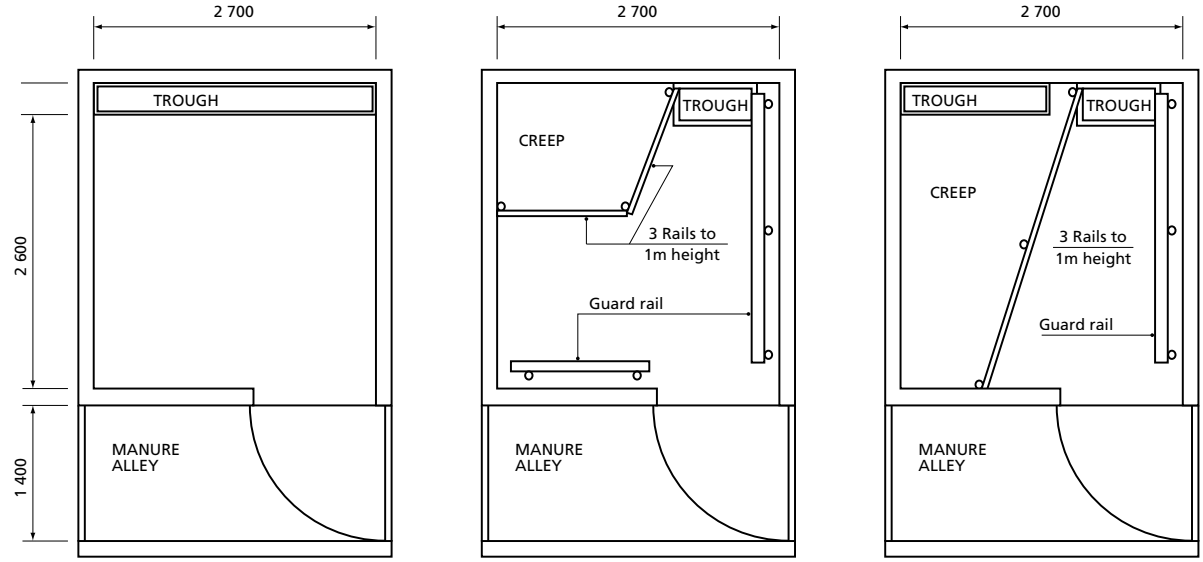
The roof may be equipped with gutters so that rainwater can be drained away separately or collected for use as drinking-water for the pigs.

A single tubular steel or round timber rail 20 cm above the outside rear wall (1 metre high) is desirable to increase security without interfering with ventilation.

Both buildings shown in Figures 10.29 and 10.30 can be extended to accommodate two to four more sows by adding two pens for fattening pigs at one end every time a farrowing pen is added at the other end.

Housing for the medium-scale pig unit

In pig units for more than six sows, it becomes feasible to construct specialized pens for the various production stages, but these can still be accommodated under the same roof. A larger production volume can be accommodated by extending the unit shown in Figure 10.31 up to about 15 sows. Any further increase should then be accomplished by building an additional separate unit of this type with up to 15 sows, as too many animals in one building creates a potential health hazard.

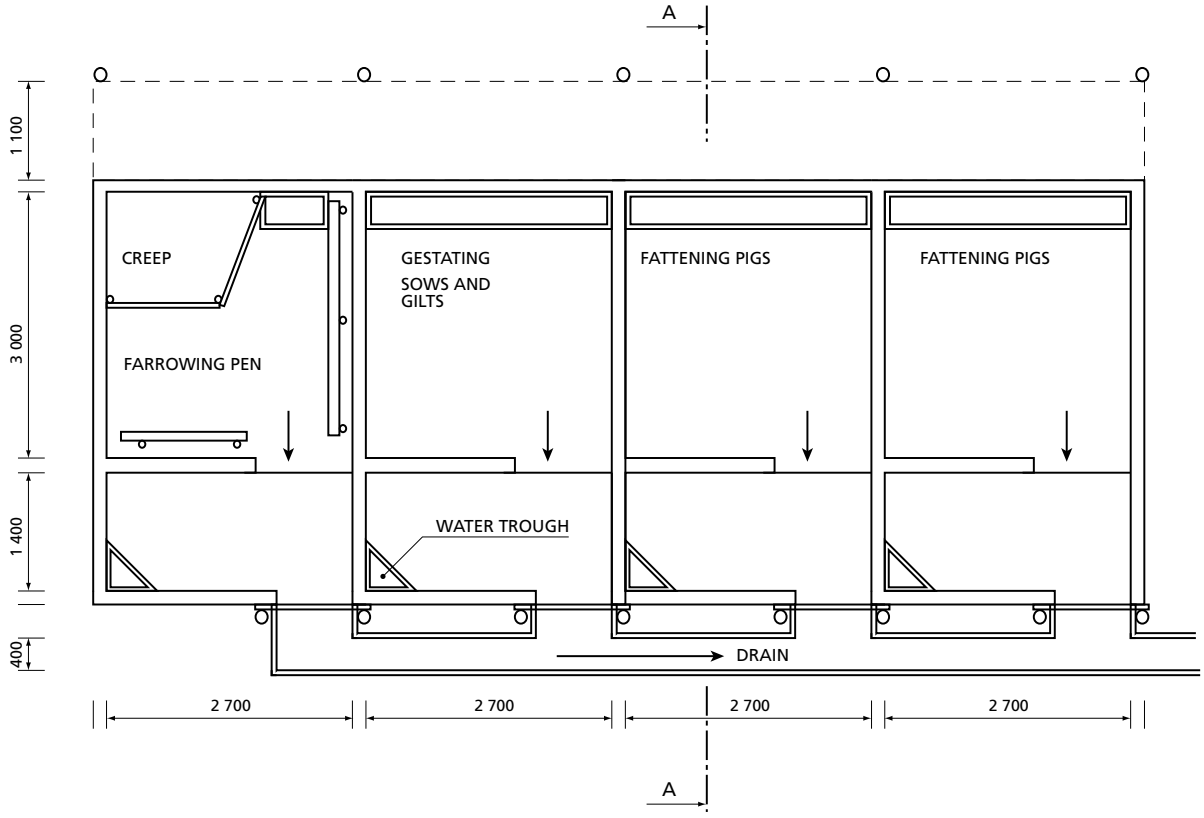


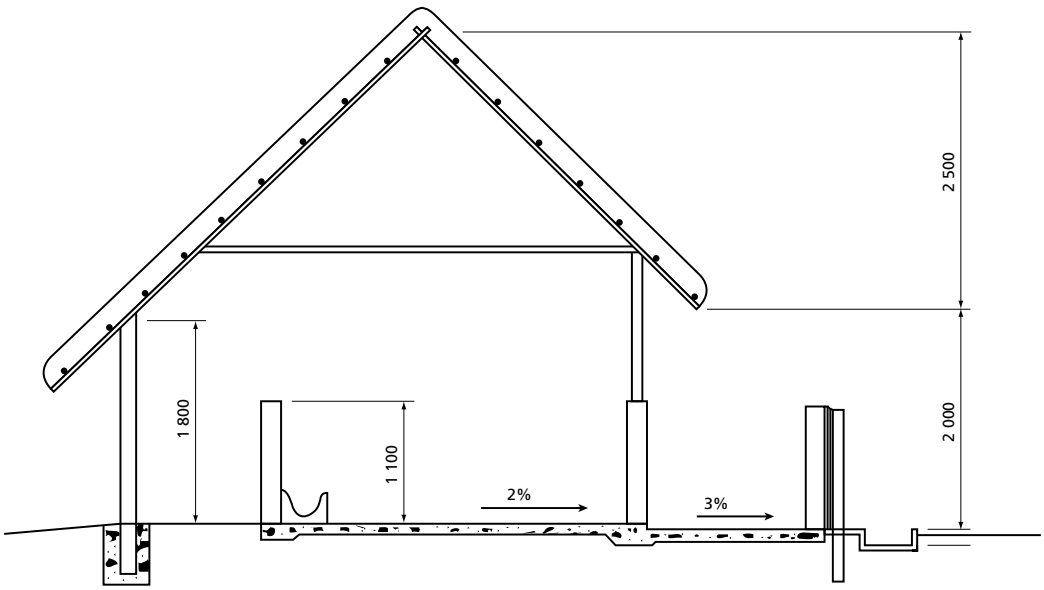
a - Universal pen equipped for fattening pigs.

b - Universal pen equipped for farrowing/suckling (non-confined sow).

c - Universal pen equipped for farrowing/suckling (slightly confined sow).

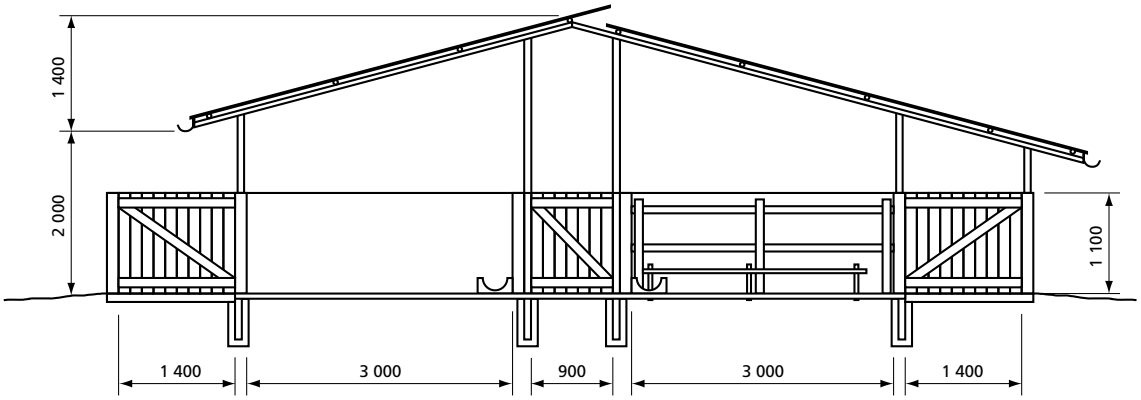
Figure 10.28 **Universal pen**





SECTION A - A

Figure 10.29 **Single-row pig unit for two sows and fatteners**



SECTION A - A

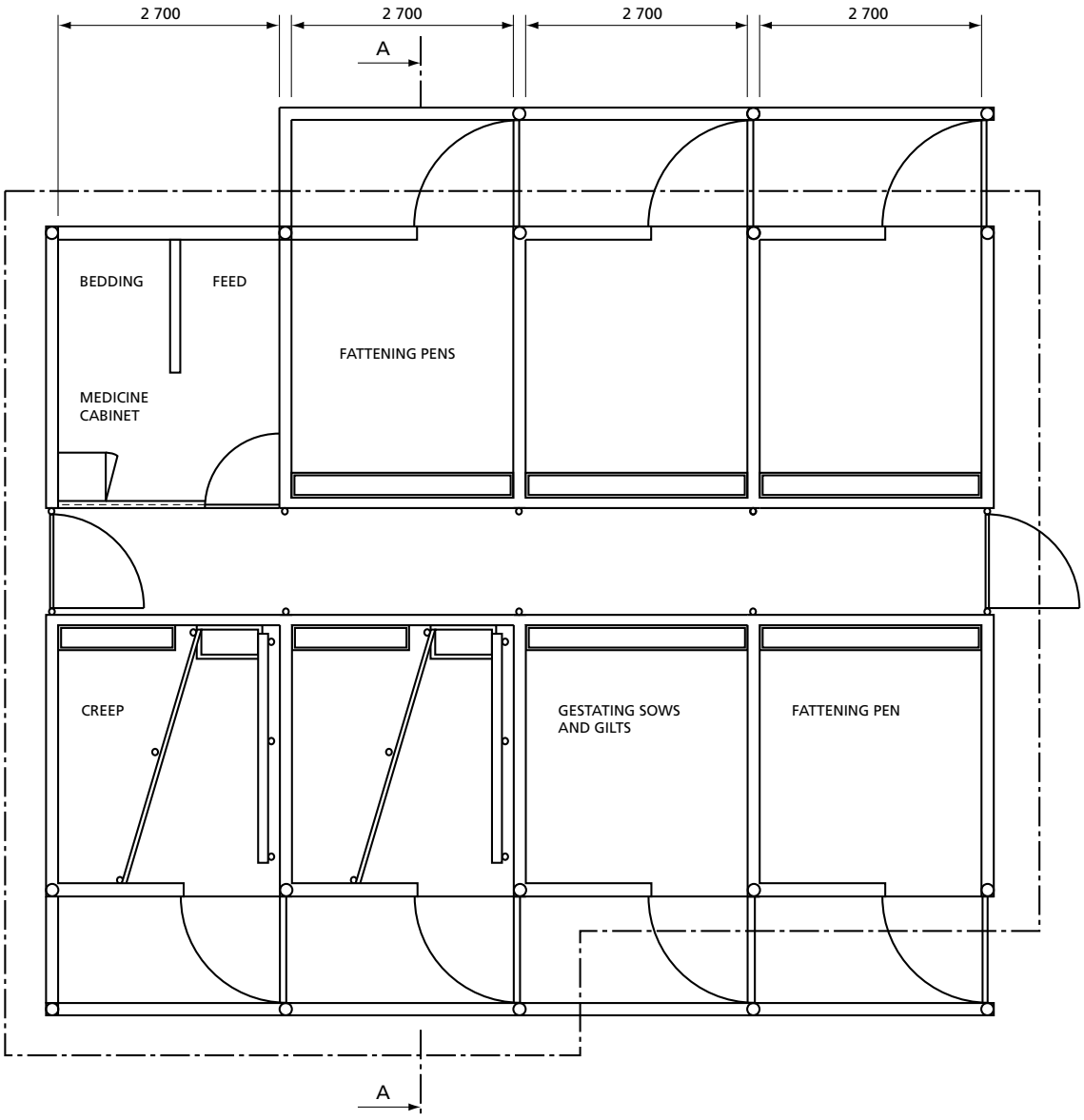


Figure 10.30 **Double-row pig unit for four sows and fatteners**

Housing for the large-scale pig unit

In large scale units, special provisions must be made for efficient health control. This means: not too many animals in one building; animals of approximately the same age housed together; using an 'all-in, all-out' system with thorough cleaning and disinfection of every house between each batch of pigs; placing the buildings 15–20 metres apart and surrounding the entire site with a secure fence.

Specialized pens located in separate houses assigned to the various stages in the production cycle are normally feasible in units of 20–30 sows. Each type of pen can be designed with dimensions for the most efficient use of the building space, as it is not necessary for them to fit in a layout with other types.

Farrowing house

The type of farrowing pen shown in Figure 10.32 offers a relatively high degree of confinement, as the sow is restrained in a farrowing crate during farrowing. Between 5 and 10 days after farrowing, the crate is removed or opened to free the sow, as indicated in the figure. Although a slightly askew arrangement of the farrowing crate will allow for a longer trough for the piglets in the front of the pen, it is more complicated to construct.

A reduction in space requirements can be achieved by putting the sow in a farrowing pen, consisting merely of a farrowing crate with 0.5 metre- and l metre-wide creep areas on either side, one week prior to farrowing. Two weeks after farrowing, the sow and piglets must be transferred to a suckling pen equipped as in the pen shown in Figure 10.52b, but with the dimensions 2.3 metres wide by 2.35 metres deep and with a 1.4-metre wide manure alley.

Housing for growing/finishing pigs

Growing/finishing pens 2.8 metres wide by 1.9–2.2 metres deep and with a 1.2-metre manure alley can accommodate the following number of pigs, according to their weight:

up to 40 kg – 12 pigs
40–90 kg – 9 pigs
over 90 kg – 7 pigs

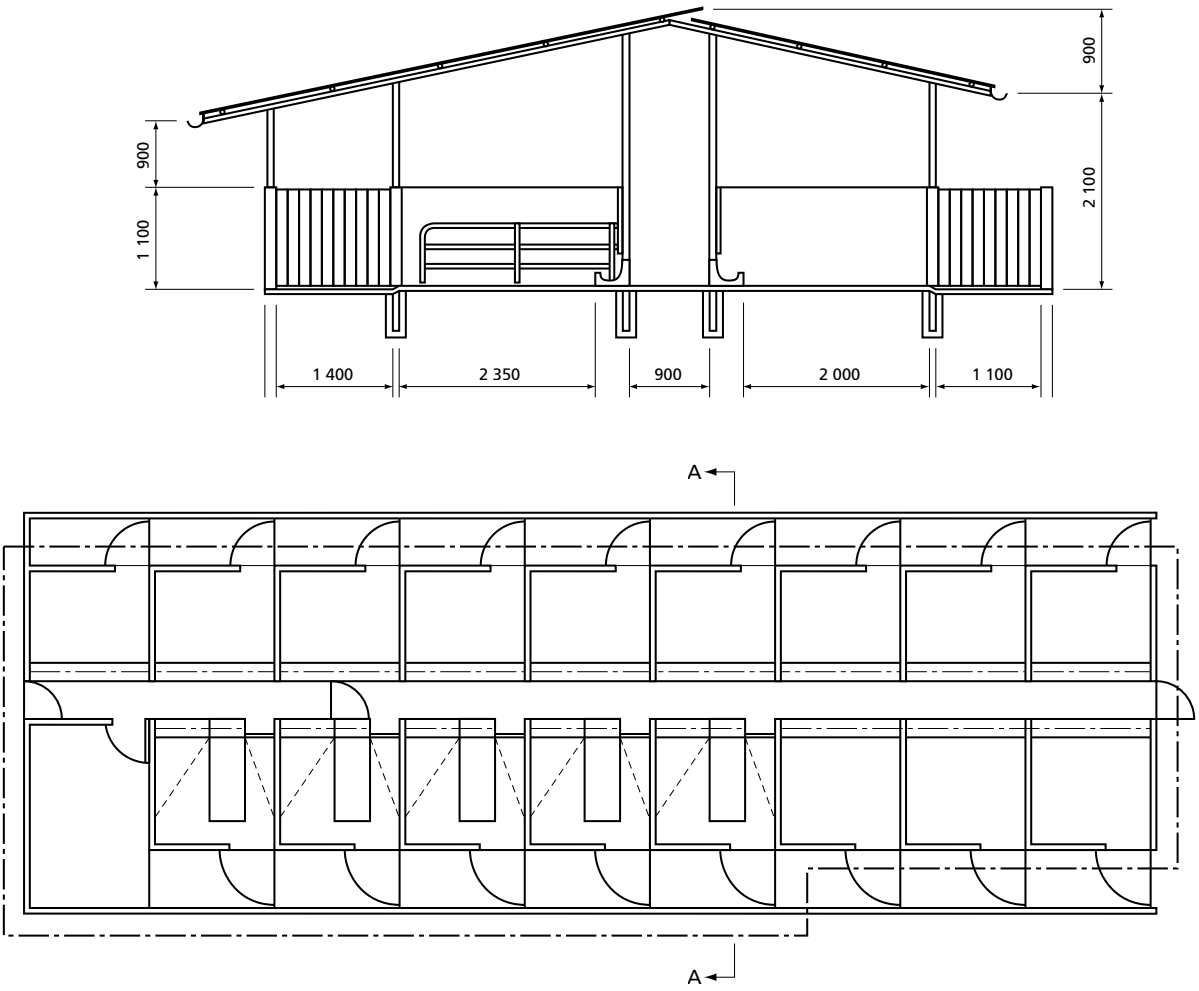


Figure 10.31 **Pig unit for 10 sows and fatteners**

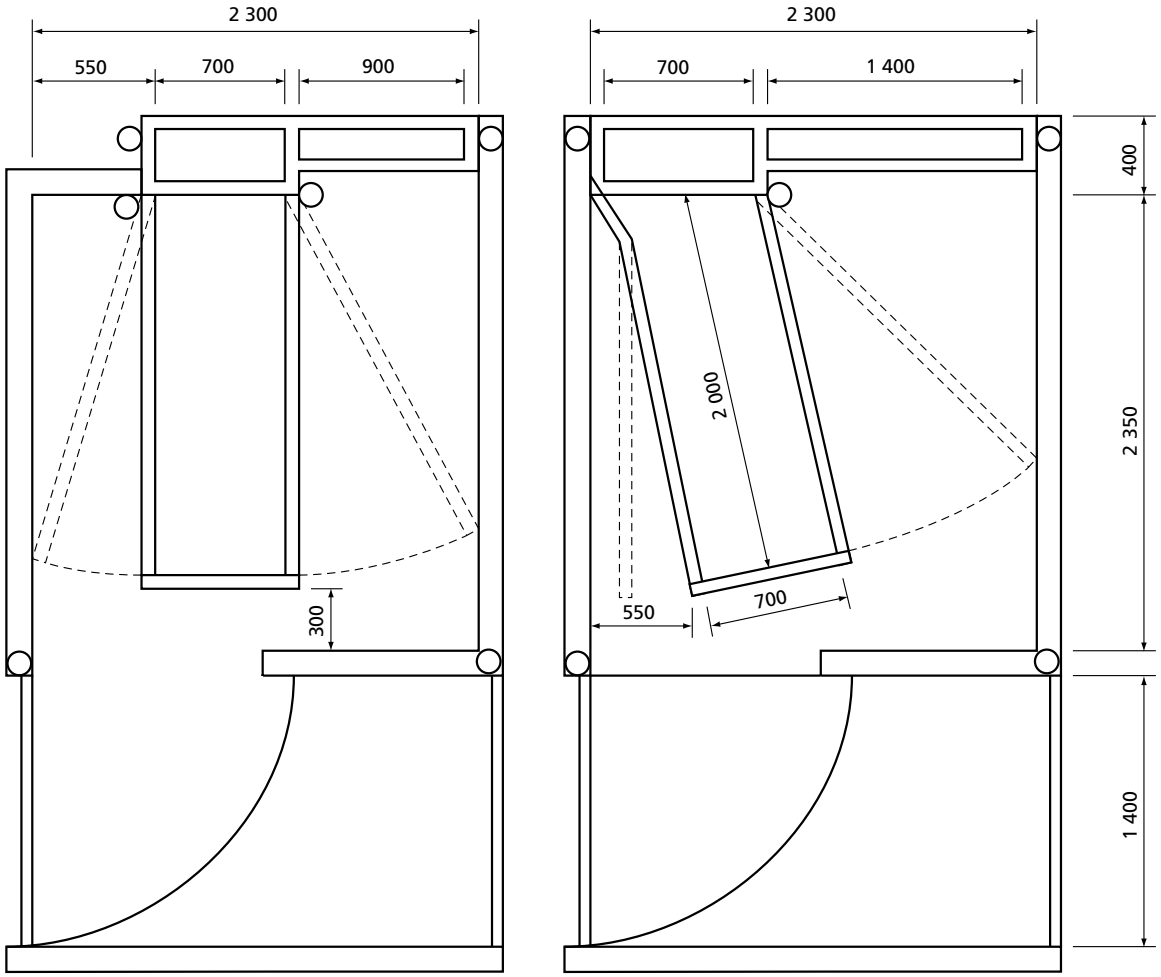


Figure 10.32 **Farrowing pens with crates for confinement of the sow during birth**

Where it is very hot, it is preferable to reduce the number of pigs per pen below the numbers given here. The manure alley must be well drained, preferably by a covered drain, but an open drain will also serve, provided that it is outside the pen to prevent urine from flowing from one pen to another. Bedding in the pens is preferable for the animals' comfort and to reduce stress, as the bedding will provide them with something to do. Controlled feeding is important to ensure the best possible feed conversion.

Housing for gestating sows

Gestating sows are usually the last group in a pig herd to be considered for confinement housing. However, there are obvious advantages in doing so, which could greatly influence production efficiency when sows are confined and controlled during gestation.

As their litters are weaned, sows can be returned to the gestating-sow structure and placed in one of the pens arranged on either side of the boar pens for easy management of sows in heat. After mating and the three-week control period, the sows should be regrouped according to the actual farrowing dates.

The type of accommodation shown in Figure 10.33a will always have four sows per group, as the gates in the manure alley are used to enclose the sows in their stalls while cleaning the pen. The stalls, which are used for both feeding and resting, should be 0.60–0.75 metres wide, depending on the size of the sows.

With the type shown in Figure 10.33b, the numbers in the groups can vary according to the size of the herd and farrowing pattern, but sows in one group should be in approximately the same farrowing period (within about 10–15 days of each other).

The feeding stalls should be 50 cm wide, with a bar that can be lowered after all the sows have entered the stalls. This arrangement will prevent sows from backing out of their assigned stall, and from biting and stealing feed from other sows. When all the sows have finished eating, the bar is lifted and they can leave the feeding stalls.

Behind the feeding stalls there is a manure alley with gates across, which can close the opening of the resting area in order to confine the sow while cleaning out the manure alley. The width of the manure alley can be increased from 1.5 metres to 2.5 metres if desired, so that cleaning can be carried out by a tractor-mounted scraper.

Where exercise yards are considered feasible, they can be arranged behind the building in both types of pen.

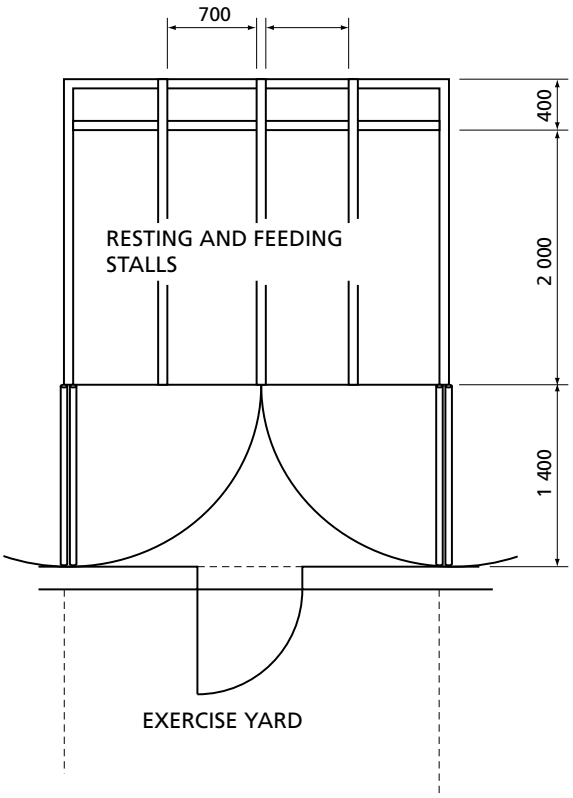


Figure 10.33a **Groups of four sows in resting and feeding stalls with access to a manure alley**

Special arrangements for warm climates

Many of the principles discussed above apply equally to hot and temperate climates and are basic requirements for the housing of pigs. While the open type of confinement system has its limitations, when applied in many warm areas it leads to a major improvement in production.

Complete control of the environment in animal houses is generally far too expensive to be feasible, in particular for non-confined systems. However, provisions for shade, proper roof colour and material, and controlled air movements, which have already been discussed, can be both practical and economic.

A spray or a wallow can considerably reduce heat stress in pigs. A wallow can be anything from a water-filled hole in the earth to a concrete trough. While wallows are effective and need not be expensive, they tend to become unsanitary if not regularly cleaned.

From a hygienic point of view, sprinklers that spray water onto the pigs are preferable, but water consumption can be up to four times greater than with a wallow. Water consumption is about 20 litres per pig per day for 10 hours of continuous spraying, compared with 5 litres per pig per day using a wallow. However, a spray system can be operated intermittently by a timer that can limit use to about 2 litres per pig per day. The spray should be directed onto the pigs and not into the air.

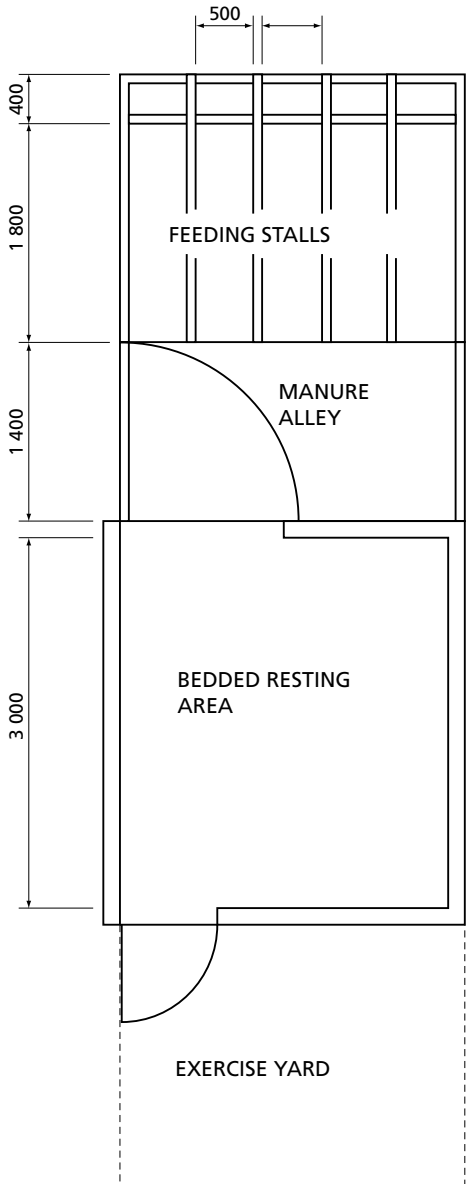
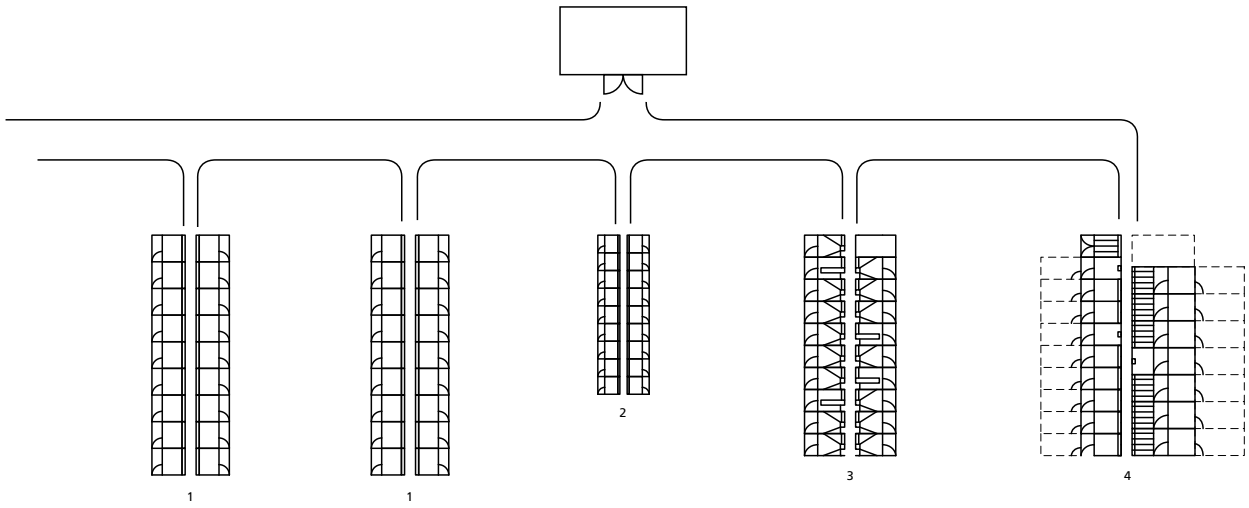


Figure 10.33b **Groups of five sows with access to feeding stalls and a bedded resting area, where they are enclosed during cleaning**

Figure 10.33 **Pens for gestating sows**

The spray system can be effectively used with all categories of pig, except very young piglets. A sprinkler in the manure alley of the farrowing pen, operated from the time the litter is about two weeks old, may help the sow to maintain her feed intake. Hosing pigs once or twice a day is a great deal less effective than a spraying system.



1 - Fattening house
2 - Weaner house
3 - Farrowing house
4 - Breeding house for gilts, gestating sows and boars with exercise yards

Figure 10.34 **Layout of a 50-sow unit**

Feed troughs and feed storage

Efficient pig production requires a reliable supply of water and feed for a balanced diet. A large range of feedstuffs, including by-products and crop surpluses, may be used, provided they are incorporated into a balanced diet. Feed requirements change as pigs grow and depend on the stage of production in sows. Table 10.11 shows the requirement where the feeding is based on a mix of meal feeds, and can be used to estimate the required storage capacity for supply between deliveries.

A wide variety of feeding equipment is available for pig operations. The easiest to clean and sanitize are made from concrete, metal or glazed burnt clay.

TABLE 10.11
Feed and water requirement for pigs

Animal		Feed intake (meal feed) (kg/pig)	Drinking water requirement (litres/day)
Sow in farrowing pen		5–7	22–27
Gestating sow		2–3	12–17
Boar		2.5–3.50	10
Piglet	10 kg	0.60	1.0
Piglet	15 kg	0.75	1.5
Pigs	25 kg	1.10	2.5
Pigs	40 kg	1.70	4.0
Pigs	60 kg	2.30	6.5
Pigs	90 kg	2.90	7.0
Pigs	120 kg	3.10	7.0

Concrete troughs are commonly used and can be prefabricated using a metal mould. The trough is often placed in the front wall of the pen as shown in Figures 10.35d, 10.35e and 10.35f.

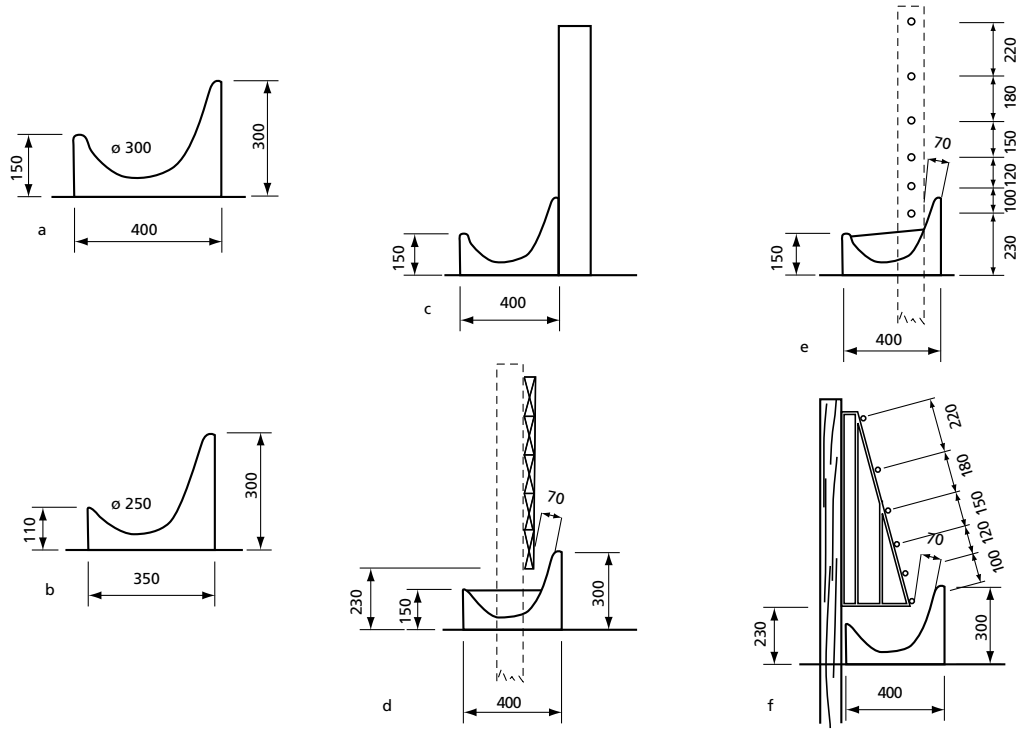
Although such an arrangement involves more difficult construction than having the trough inside the pen it is usually preferred for easier feeding and also preventing the pigs from stepping into the trough. The wall above the trough can be made either solid or open and can be either vertical or sloping inwards to the pen.

An open front improves ventilation in the pen but it is more expensive than a close-boarded wooden front as galvanized steel pipes have to be used for durability. In particular a sow confined in a stall of a farrowing crate will feel more comfortable if it is able to see in front of her. A sloping front will more effectively discourage pigs from stepping into the trough but it is more complicated and expensive to construct.

Two piglet feeders for use in the creep area are shown in Figure 10.36. The same types can be used for growing pigs up to 40–50 kg, but the dimensions will need to be increased. Metal is preferred, although a feeder made of wood can be satisfactory if cleaned regularly and thoroughly.

Watering equipment

The drinking-water requirement is shown in Table 10.11. It is preferable to mix feed meal with 1.5–2.1 litres of water per kilogram of feed. The rest of the water can be given in the trough between feedings or in special drinkers. Clean water must be available to the pigs at all times, including the piglets in a farrowing pen.



a. Feeding trough for pigs over 30kg
b. Feeding trough for piglets up to 30kg
c. Trough outside the pen, vertical close boarded front
d. Trough partly in the pen, vertical close boarded front
e. Trough partly in the pen, vertical open front of pipes
f. Trough outside the pen sloping open front of pipes

Figure 10.35 **Feeding equipment**

Automatic drinkers are the most hygienic and can be used where piped water is available. There are two types: one is placed above the feed trough and sprays into the trough when pushed by the pigs; the other type is operated by the pigs biting around it. This latter type is often placed in the manure alley or in the pen close to the manure alley to prevent the pigs from making the resting area wet.

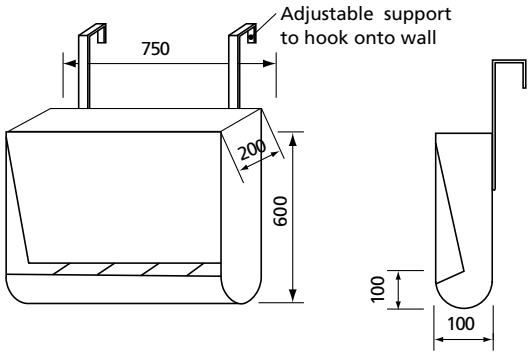


Figure 10.36a **Overall dimensions of a sheet metal feeder**

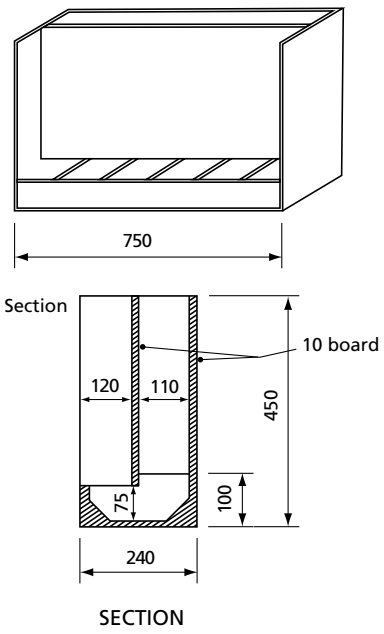


Figure 10.36b **A wood feeder suitable for home construction**

TABLE 10.12
Rates of manure production for pigs

	Wet solid manure (kg/day)	Urine (kg/day)	Total (kg/day)	Storage requirement for slurry m^3 per day of storage
Dry sow and boar	2.0–2.5	4–5	6.0–7.5	0.011 or 0.013 per sow in the herd
Sow with litter	2.5–3.0	8–10	10–13	0.018
Farrowing pigs (45 kg)	0.8–1.0	2.5	3.3–3.5	0.004 or 0.006 per growing/finishing pig
Finishing pigs (45–90 kg)	1.5–2.0	4–5	5.5–8.0	0.008

Manure handling

The pig pens must be cleaned once or twice a day. Provided sufficient bedding is used and the urine is drained away separately to a urine storage tank, the solids may have a consistency that allows stacking on a concrete slab. Where little or no bedding is used or the urine is not separated, a manure storage slab of the type shown in Figure 10.22 can be used. Table 10.12 shows the rates of manure production.

POULTRY HOUSING

Poultry (which includes chickens, turkeys, ducks and geese) offers one of the best sources of animal protein, in the form of both meat and eggs, at a cost most people can afford. Chickens are the most widely raised and are suitable even for the smallholder who keeps a few birds that largely forage for themselves and require minimum protection at night.

At the other extreme, commercial farms may have highly mechanized systems housing thousands of birds supplying eggs and meat to the city market. In between are farm operations in a wide range of sizes, with varying types of housing and management systems proportionate to the level of investment and the supply of skilled labour available.

No single system of housing is best for all circumstances, or even for one situation. Some compromise will invariably be required. Here we discuss the needs of chickens and other classes of poultry and a number of housing systems, along with the principal advantages and disadvantages of each.

General housing requirements for chickens

Proper planning of housing facilities for a flock of laying hens requires knowledge of management and environmental needs during the various stages of the chicken's life. A typical life cycle is illustrated in Figure 10.37.

The laying period may be up to 16 months but, in flocks kept for commercial egg production, the hens are normally culled after a laying period of 11–12 months, or when production has dropped to a point where the number of eggs collected per day is about 65 percent of the number of hens in the flock.

The hens may come into production again after a moulting period of a couple of months, but the production then is not as high and the egg quality is generally not quite as good as in the first laying period. Where prices of poultry meat are reasonable, it is usually more economic to cull all the hens after one year of egg production.

Site selection

The best site is one that is well drained, elevated but fairly level, and has an adequate supply of drinking-water nearby.

Regardless of the type or size of the housing system, the site for construction should be selected to provide adequate ventilation, but be protected from strong winds. An area under cultivation, producing low-growing crops, will be slightly cooler than an area of bare ground. High trees can provide shade while at the same time actually increasing ground-level breezes. Bushes planted at one windward corner and also at the diagonally opposite corner will induce air currents within the building to reduce the effect of the heat from direct solar radiation.

As all buildings used for poultry housing tend to produce odours, they should be located well downwind of nearby dwellings. If there are several poultry buildings in a group, it is desirable to have them separated by 10–15 metres in order to minimize the possibility of spreading disease.

Brooding buildings should be isolated from other poultry buildings by 30 metres or more, and be self-contained in terms of feed supplies and storage of equipment. If the same person cares for both layers

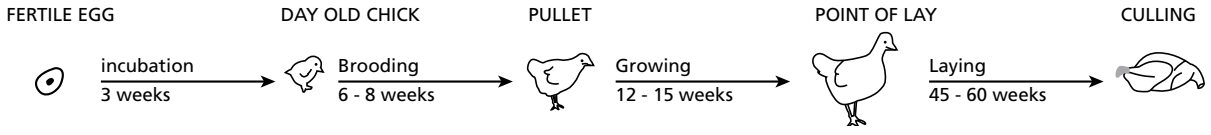


Figure 10.37 **Typical life cycle of a laying hen**

and growing birds, a disinfectant foot bath at the entrance to the brooding area is an added precaution. All buildings should be constructed on well-drained sites where drives and paths between buildings will not become muddy, even during the rainy season.

Environmental requirements

The effects of temperature and humidity on the birds make it apparent that in most areas of east and southeast Africa. the principal environmental concern is to keep the flock as cool as possible. Shade, good ventilation with natural breezes, freedom from roof radiation and the indirect radiation from bare ground are all important. Only in a few high altitude areas does protection from wind and low temperatures become a significant consideration.

Humidity seems important in only two respects. Very low humidity causes objectionably dusty conditions and high humidity, combined with temperatures above 27 °C, seems to interfere with the physiological cooling mechanism and increases the possibility of death. Day-old chicks require a temperature of 33–35 °C. This temperature is maintained for a week and is then gradually lowered to the ambient temperature by the end of five weeks.

In addition to providing a good environment, the housing should offer protection from predators and theft, as well as keeping out rodents and birds. Not only do they carry diseases, they can also consume enough feed to make a significant economic difference.

The effect of light on egg production has been discussed earlier. Additional hours of light can be achieved by installing one 40-watt electric light bulb per 15 square metres of floor space in a position about 2.2 metres above floor level. More important than the hours of light, however, is maintenance of the lighting schedule, because any sudden change in the length of the photo-period is likely to result in a significant drop in production.

Fourteen hours of light throughout the laying period is optimum. A schedule with gradually decreasing hours of light may be used in windowless houses for maturing pullets. This postpones laying but results in larger eggs being produced from the start of laying.

However, in warm climates near the equator, houses are open for natural ventilation and the length of the day is close to 12 hours throughout the year. The result is that pullets start to lay at 14–18 weeks of age and egg size, which is small at first, gradually increases during the first three months. Broiler houses are often lighted 24 hours a day to encourage maximum feed consumption and rate of gain.

Proper design and management of the poultry house can effectively contribute to disease prevention in the flock. In general, it is best if the litter is dry but not too dusty. If no litter is used, the floor and wall surfaces should be designed so that they can be cleaned easily between flocks and stay reasonably clean during use.

Construction details

In most hot climates there will be many more days when a cooling breeze is needed rather than protection from a chilling wind. A wall construction consisting of a solid base, which protects against indirect radiation from the ground, and an open space covered with mesh above it, is therefore preferred for all four walls in most types of chicken house.

A hessian or reed curtain that can be dropped on the windward side will offer extra protection and, if installed on the east and west orientation, it may also protect from direct sunshine. An arrangement where the top end of the hessian is fixed to the wall plate and the bottom end is attached to a gum-pole, around which it can be rolled when not in use, provides for smooth operation. In high altitude areas, offcuts may be used on the gable ends, but 15–20 mm spaces should be left between them to improve ventilation. The width of the building should not exceed 9 metres for efficient cross-ventilation.

The lower wall design, up to 1 metre of solid wall, can be made of any available masonry units. Bag-washing will give a smooth, easily cleaned finish, but adobe blocks will require the extra protection of plastering to prevent the birds from destroying the wall by pecking.

The upper wall design to the total height of the wall, including the solid base, should be about 2 metres. gum-poles treated with wood preservative and set 500 mm deep in concrete provide a practical means for supporting the roof and upper wall structure. Eighteen-millimetre wire mesh is small enough to keep out rodents and birds. A tight-fitting door is essential.

The floor in a poultry house may consist of gravel or well-drained soil, but concrete is desirable because it is easy to clean, durable and considerably more rat proof. A concrete floor should be 80–100 mm thick and be made of a stiff 1:2:4 or 1:3:5 mix, laid on a firm base at least 150 mm above ground level, and given a smooth finish with a steel trowel.

Roof structures with a free span are desirable to avoid any inconvenience from roof-supporting poles inside the building. Corrugated steel sheets are the first choice for roofing material because they are much easier to keep clean than thatch. Insulation under the metal roofing will improve the environment in the house. However, a thatched roof may result in even better conditions and can be used on narrow buildings.

The roof overhang should be 500 mm or more in order to give adequate protection from sun and rain. A ventilation opening along the ridge is usually supplied in layer houses, but not in brooding houses.

Housing systems for layers

The pullets are transferred from the rearing accommodation to the laying accommodation at the age of 17–18 weeks and start laying when they are 20–24 weeks old. At the time of transfer, they should be grouped according to size and stage of maturity.

TABLE 10.13
Recommended minimum floor, feed and water space for chickens

	Floor space stocking density		Feeder space		Water space (birds/m)
	Low (birds/m²)	High (birds/m²)	Trough (birds/m)	Tube (birds/m)	
Chicks and pullets					
1–4 weeks of age	15–20	25–30	40	40	150
5–10 weeks of age	8–11	12–15	15–20	25	75
11–15 weeks of age	5–6	7–8	9–10	12	50
16 + weeks of age	3–4	5–7	7–8	10	40
Breeders	3–4	5–6	6–8	9	15
Layers	6–7	8	10–20		
Semi-intensive					
House-run					
• house	3	4–5			
• run	0.04–0.08	0.10–0.13			
Straw-yard					
• house	3	4–5			
• yard	1.5	2.5			
Fold system	2	2			
Intensive					
Deep-litter floor	3–4	5–7			
Wire floor	7–8	9–10			
Combination floor	5–6	7–8			
Cages, including alleys	8–12	15–25	7–10		

There are five major systems used in housing for layers: semi-intensive; deep litter; slatted or wire floor; a combination of slatted floor and deep litter; and a cage or battery system.

Having considered the factors that affect the comfort, protection, efficiency and production of the birds, it is also important to design a system that is labour-efficient, reasonable in terms of investment and easy to manage. How well each of the systems fills the needs of both the chickens and the people supervising the operation should be the determining factor in the selection of an appropriate system for a specific situation.

Semi-intensive systems

Semi-intensive systems are commonly used by small-scale producers and are characterized by having one or more pens in which the birds can forage on natural vegetation and insects to supplement the feed supplied. It is desirable to provide at least two runs for alternating use to avoid a build-up of disease and parasites. Each run should allow at least 10–15 square metres per hen and be fenced, but a free-range run allowing 40–80 square metres per hen will be required where the hens are expected to obtain a substantial part of their diet from foraging.

A small, simple house, which allows 0.3–0.4 square metres per bird and has a thatched roof, a littered earth floor and slatted or chicken wire walls on at least three sides, will provide protection from inclement weather and from predators at night, as well as providing shade in the daytime. The shelter should be large enough for entry to collect eggs and be equipped with nest boxes, feeders, drinkers and perches. For convenience, the house should be situated so that access to each of the runs can be provided with small outlet doors or 'popholes'.

Figure 10.38 shows another type of shelter for roosting and laying that can be used in combination with daytime foraging by the hens. The legs of this structure have rat guards and ant protection and may be equipped with skids or wheels to make the whole unit easily movable between runs. Feed and water are provided in troughs outside the house.

This system is low in cost, but bird growth and egg production are likely to be lower than with systems offering closer confinement and better feed. Losses may be caused by birds of prey and by failure to find eggs laid in bushy areas. The poultry run requires a considerable amount of fencing.

A fold unit is a house and run combined, part of which is covered with chicken wire and the remainder with solid walls. The unit should allow 0.5 square metres per bird and must be moved each day over an area of grassland. A unit 6 metres by 1.5 metres will take

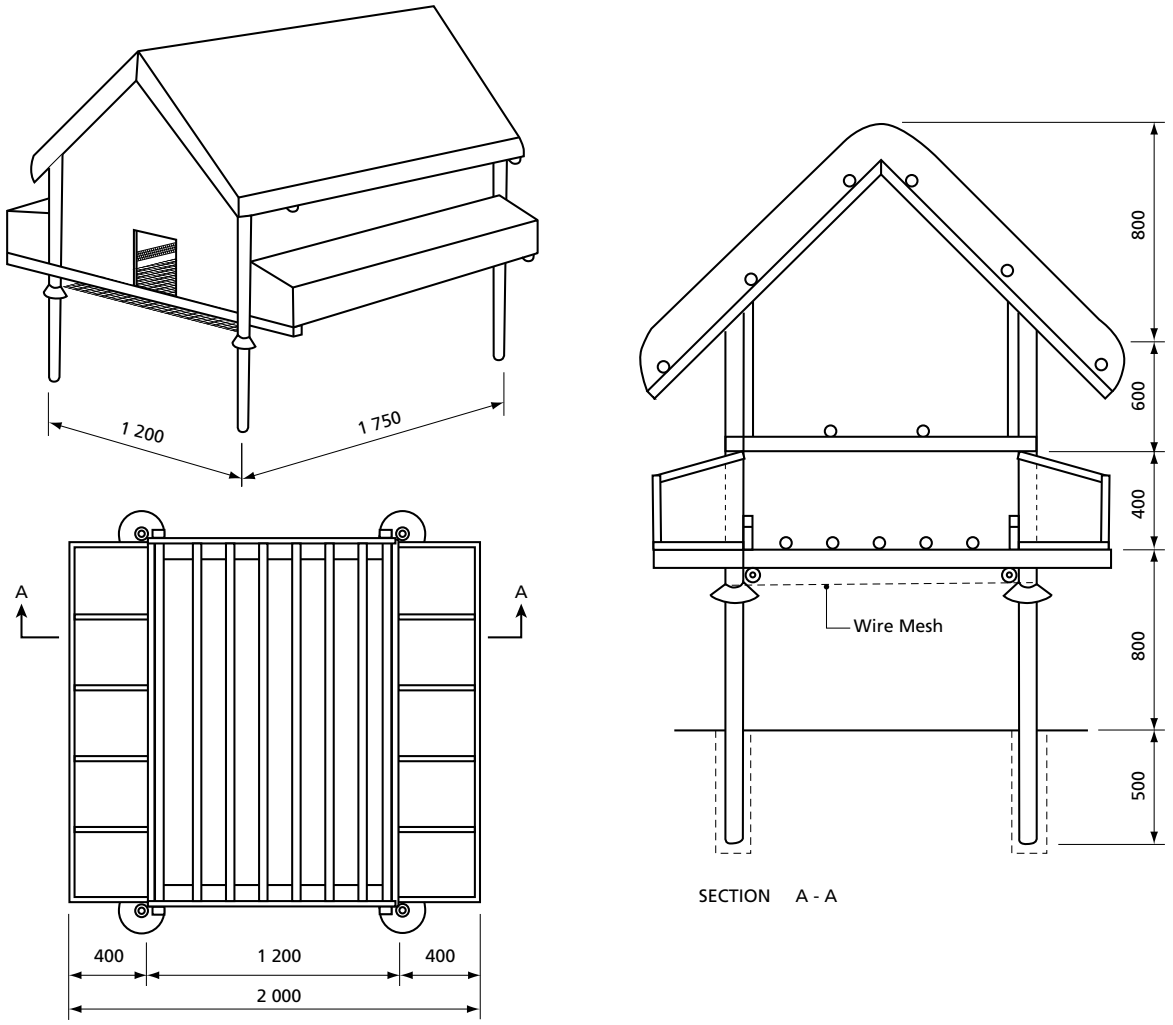


Figure 10.38 **Poultry shelter for 50 layers**

16–18 birds and can normally be handled by one person. For larger flocks, several such units will be used.

Portable units are generally more expensive than permanent houses and may decay quickly because of contact with the ground. The hens have reasonable protection against birds of prey and inclement weather, as well as parasites if the unit is not returned to the same area within 30 days.

In areas where grassland is limited, a yard deeply littered with straw and allowing only 0.4–0.7 metres per bird will provide an outdoor exercise area. This system is similar to the deep-litter system, but requires more space, a considerable amount of litter for the yard, and the fresh green food has to be carried to the birds.

Deep-litter system

Deep-litter houses, as shown in Figure 10.40, confine the birds in a building that offers good protection with a reasonable investment. If well designed, with low masonry walls set on a concrete floor and wire mesh completing the upper part of the walls, the building will keep out rats and birds.

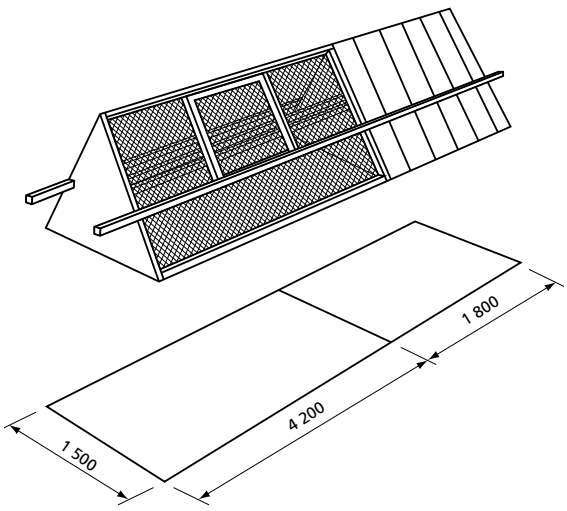


Figure 10.39 **Fold unit for 18 layers**

The principal advantages of this system are easy access for feeding, watering and egg gathering, good protection and reasonable investment. The principal disadvantage is the need for high quality litter. If this is produced by the owner, it is of little significance but, if it must be purchased, it becomes an economic factor. In either case, the litter and manure must be removed periodically.

The deep-litter house can be designed up to 9 metres in width and any length that is needed. A satisfactory density is approximately 4–5 birds per square metre of floor area.

Slatted or wire-floor system

A small house of this type with a slatted floor is shown in Figure 10.41. Alternatively, wire mesh can be used for the floor. It is built on treated wooden piers 0.8–1 metres above the ground. Ventilation and manure removal are both facilitated, no litter is required and bird density can be 6–8 per square metre.

Feeding, watering and egg-gathering are all efficiently handled from the outside. Either a double-pitch thatch roof or a single-pitch corrugated steel roof may be installed, with the eaves about 1.5 metres above the floor. If the latter is used, some insulation under the roof is desirable.

The feed troughs should be equipped with hinged covers, and rat guards should be installed at the top of each pier. The width of this type of building should be limited to about 2 metres to allow easy removal of manure and adequate wall space for feed and nests. The building should be oriented east and west and may be of any length. However, if it is more than 5 metres long, nests will need to be put on the sides, and all remaining wall space on either side used for feeders in order to allow the required 100 mm/bird (see Table 10.13).

If using a slatted floor sufficiently strong for a person to walk on, then a wider building is feasible, as feeders can be placed completely inside where the chickens have access to both sides of the trough. The floor is sectioned for easy removal during cleaning out of manure.

This type of house is said to be cooler than other types, but the building cost is high and management is more complicated.

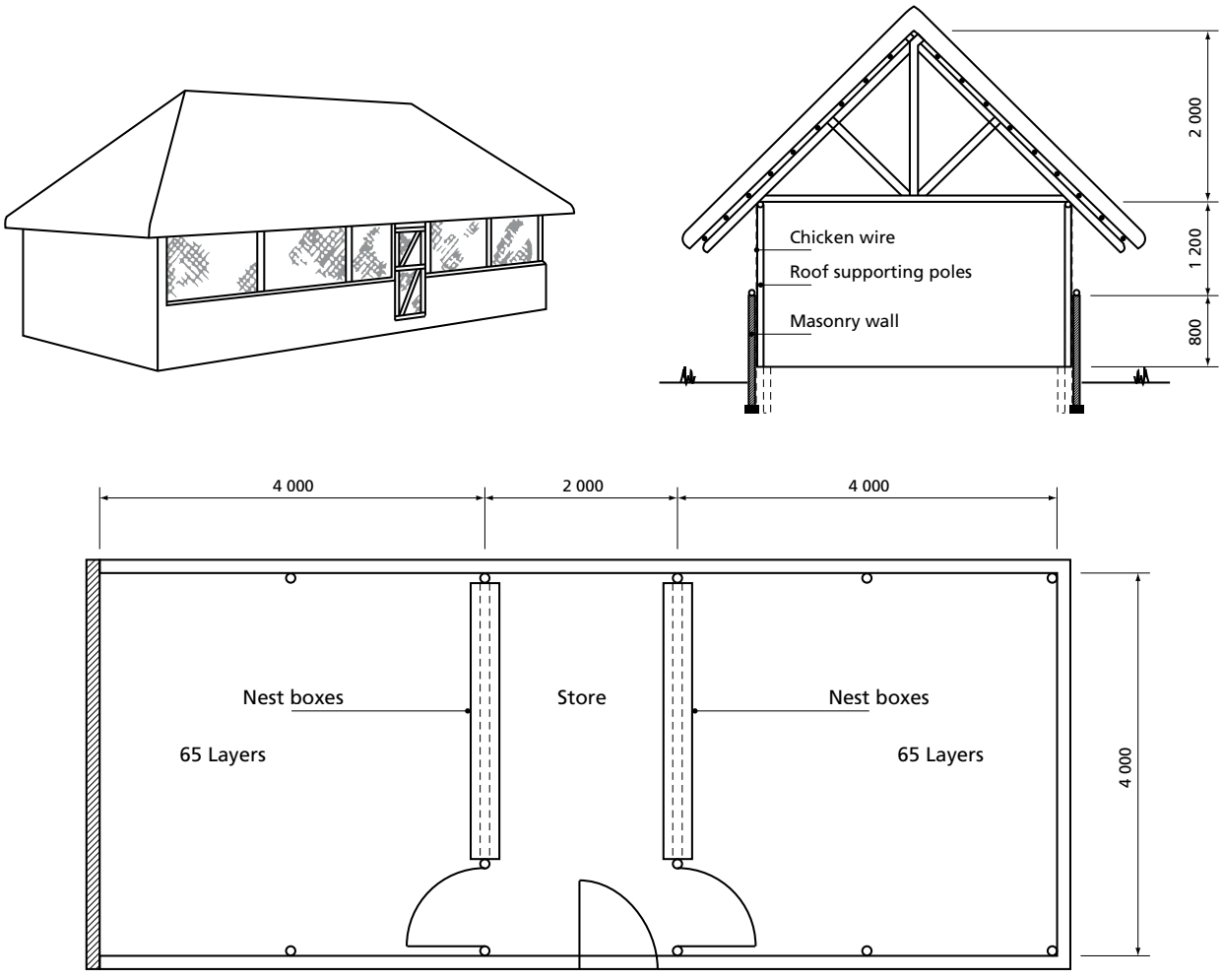


Figure 10.40 **Deep-litter house for 130 layers (or 350 broilers): note the solid wall facing the prevailing wind**

Combination of slatted floor and deep litter

A combination deep-litter/slatted-floor house offers some advantages over a simple deep-litter house, but with some increase in investment. Figure 10.42 shows a house of this type for the small producer.

Approximately half of the floor area is covered with small gum-pole slats or with wire mesh. This area is raised above the concrete floor by 0.5 metres or more to make it possible to clean under the slatted portion from the outside. Waterers and feeders are placed on the slatted area. This type of house is limited in width to 3–4 metres to enable feeders and waterers to be handled from the litter area, and manure beneath the slatted area can be easily removed from the outside without moving the slats or disturbing the birds. Although this system entails added expense for materials and labour to install the slats, the bird density can be increased to 5–7 per square metre, so there is little difference in the cost per bird. This system saves on litter, increases litter life, reduces contact between birds and manure, and allows manure removal without disturbing the hens. Ventilation is improved by the slatted floor. Perhaps the biggest disadvantage is the limited width for convenient operation and the need for some litter.

In medium- to large-scale houses of this type, the slatted floor must be made removable in sections, and at least part of it made strong enough to walk on. However, this results in increased building cost and more complicated management. The house shown in Figure 10.43 has slats over two-thirds of the floor area.

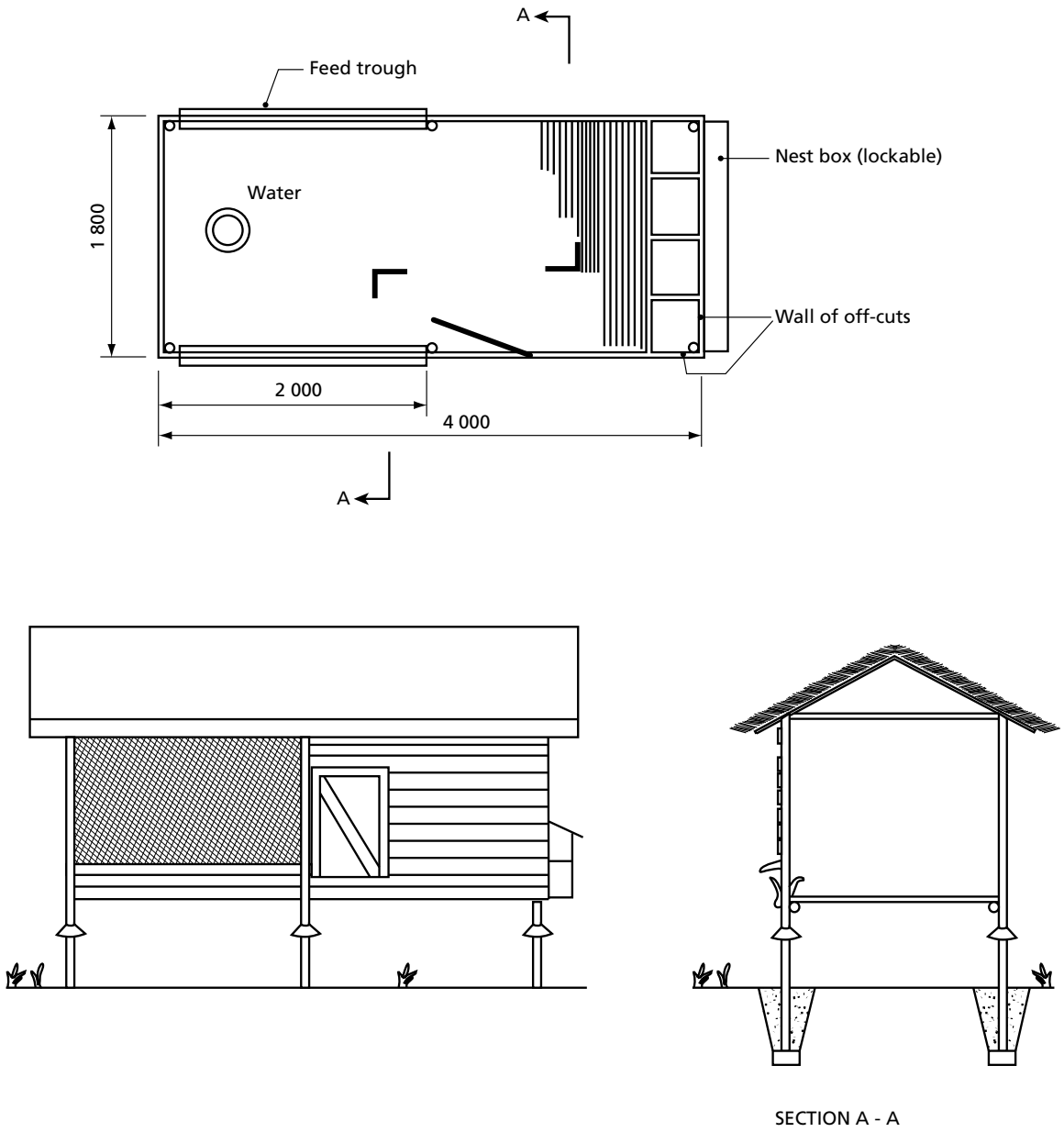


Figure 10.41 **Slatted-floor house for 50 layers**

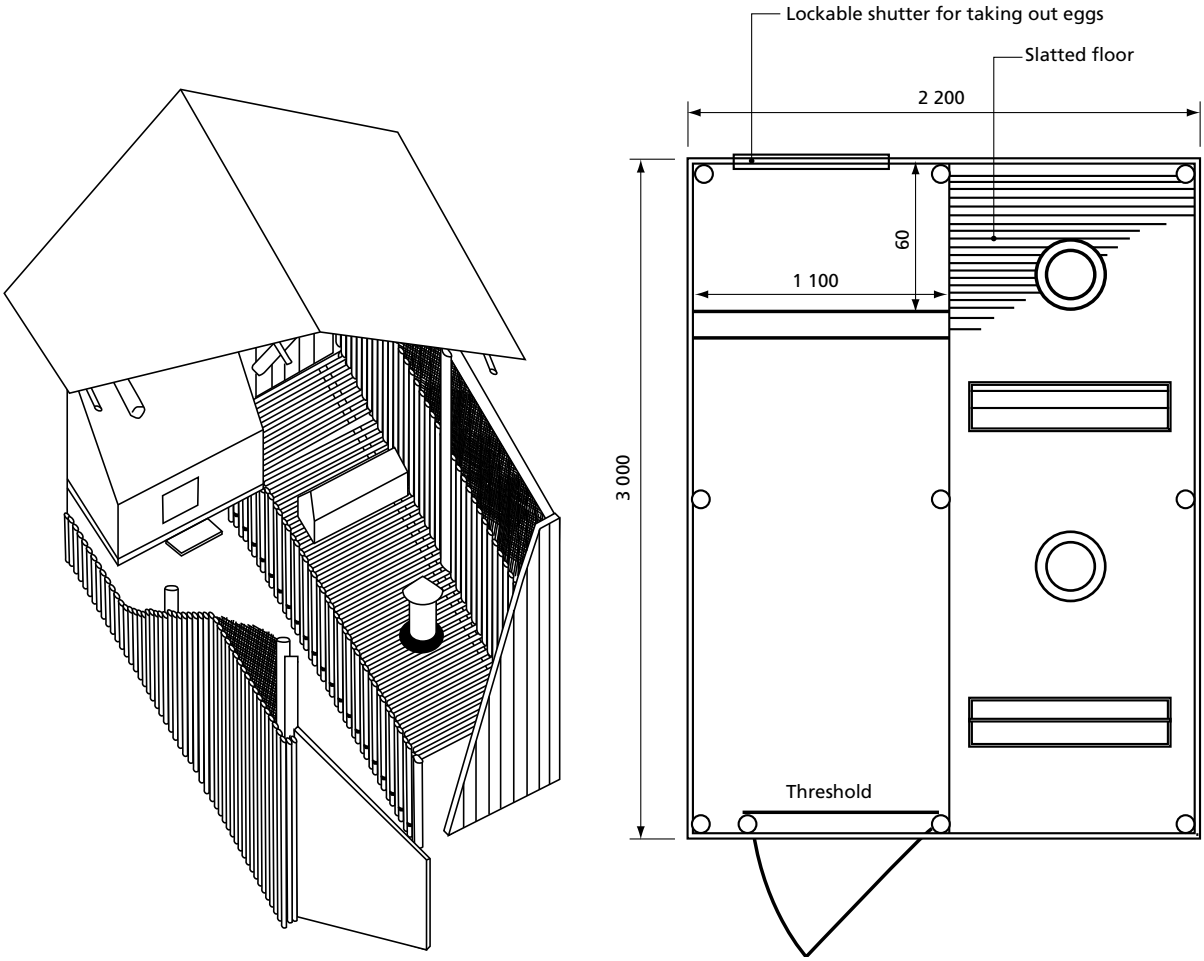


Figure 10.42 **Poultry house for 40 layers, half deep-litter/half slatted-floor**

This is generally considered the maximum for this type of house and allows for a stocking density of up to eight birds per square metre. Automatic tube feeders are placed on the slatted floor. One such feeder, with a bottom diameter of 0.6 metres can serve 60–75 birds, depending on the size of the breed.

The water troughs are suspended from the ceiling. The nest boxes are doubled by arranging them back to back, and have one end resting on the slatted floor and the other suspended from the ceiling. Egg-collection can be facilitated by the use of a trolley, which is supported on a rail just below the ceiling. A tractor shovel can be used for cleaning out between batches if all furnishings and part of the end walls are made removable.

Cage or battery systems

Cage management of layers in very large, well-insulated, windowless buildings has become standard practice in much of Europe and the colder parts of the United States. With complete mechanization of feed, water, egg-collection, manure removal and environmental control, two to three people can care for thousands of birds.

It should be noted that a very large investment is made in order to obtain labour efficiency and ideal environmental conditions. East and southeast Africa currently have relatively low labour costs and a mild climate, which could make a mechanized cage system in an insulated building unnecessary and impractical.

Nevertheless, there are much simpler cage systems that may work very well for commercial growers in this region. These consist of rows of stair-step cages in long, narrow shelters (Figure 10.44). The thatch roof, or insulated metal roof shelter, can be completely open on the sides, with perhaps some hessian curtains in areas where cold winds are experienced. The buildings should be oriented east to west, and be designed to provide shade for the cages near the ends.

A 3.4-metre width can accommodate four cages without overlap and an alley of about 0.9 metres. While a concrete floor makes cleaning easy, smooth, hard soil is less expensive and quite satisfactory. A little loose sand or other litter spread on the soil before the manure collects will make manure removal easier. The building posts should be treated with wood preservative and be sturdy enough to support the cages. Rat guards should be installed on the posts at a height of 0.8–1 metre.

A cast-concrete central alley raised 20 cm is easy to clean and keeps manure from encroaching on the

work area. Feeding and egg-collecting are easily done by hand, while watering may be either by hand or with an automatic system. It is important for the watering trough to be carefully adjusted so that all birds receive water. The simplest method of supplying water automatically, or by hand at one end, is to slope the entire building and row of cages by 10 mm per 3 metres of length.

The trough can then be attached parallel to the cages. Water must run the total length of the trough and it is inevitable that some will be wasted. Consequently a good water supply is essential.

Even though feed is distributed by hand, feed stores should be built convenient to each building to minimize carrying. Eggs can be collected directly on 'flats' stacked on a cart that is pushed down the alley. The cart can be made self-guiding by means of side rollers that follow the edge of the feed troughs or the raised central alley.

Cages that are equipped with pans to catch the manure are not recommended because they restrict

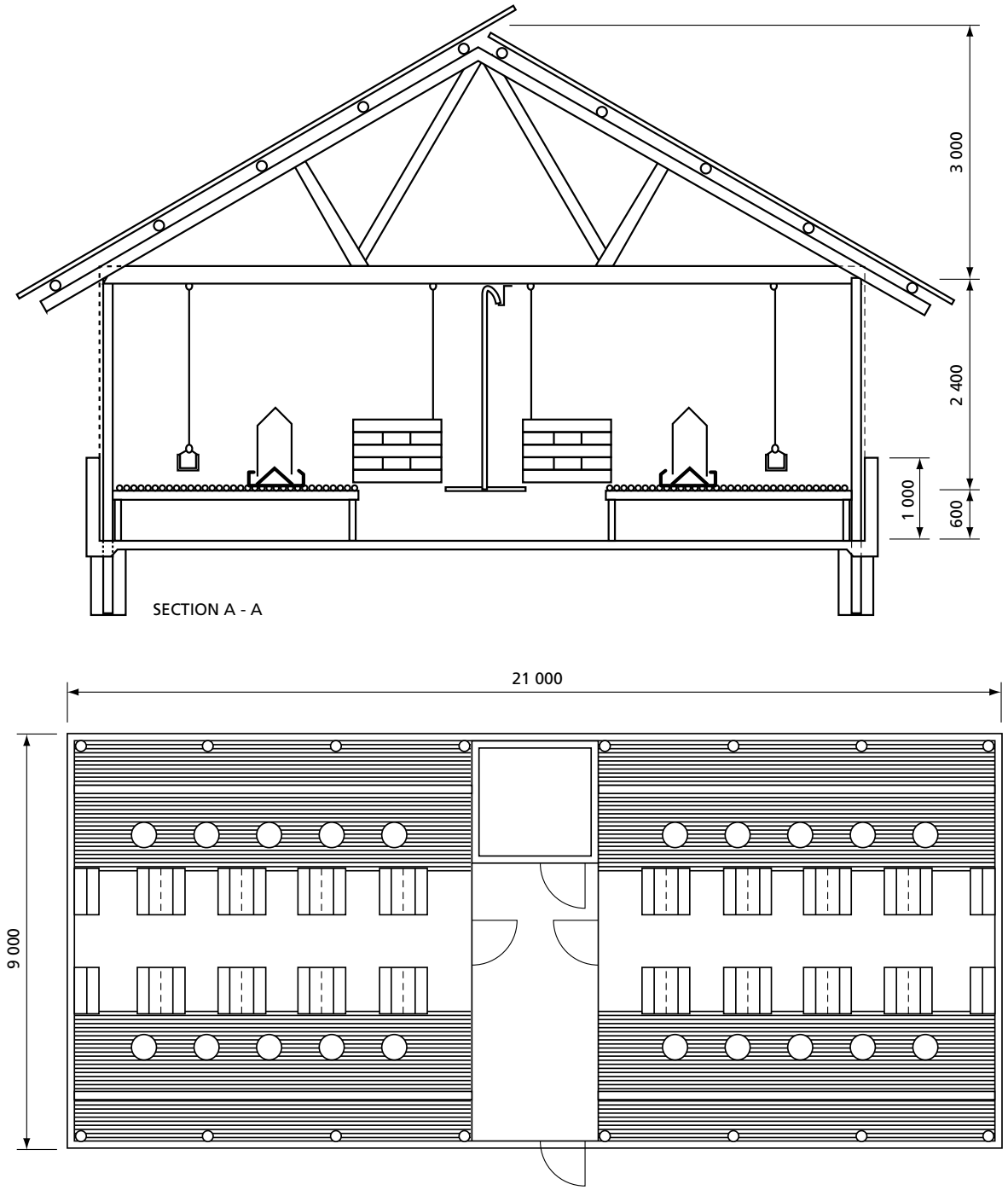


Figure 10.43 **Poultry house with one-third deep litter and two-thirds slatted floor for 1 100–1 200 layers**

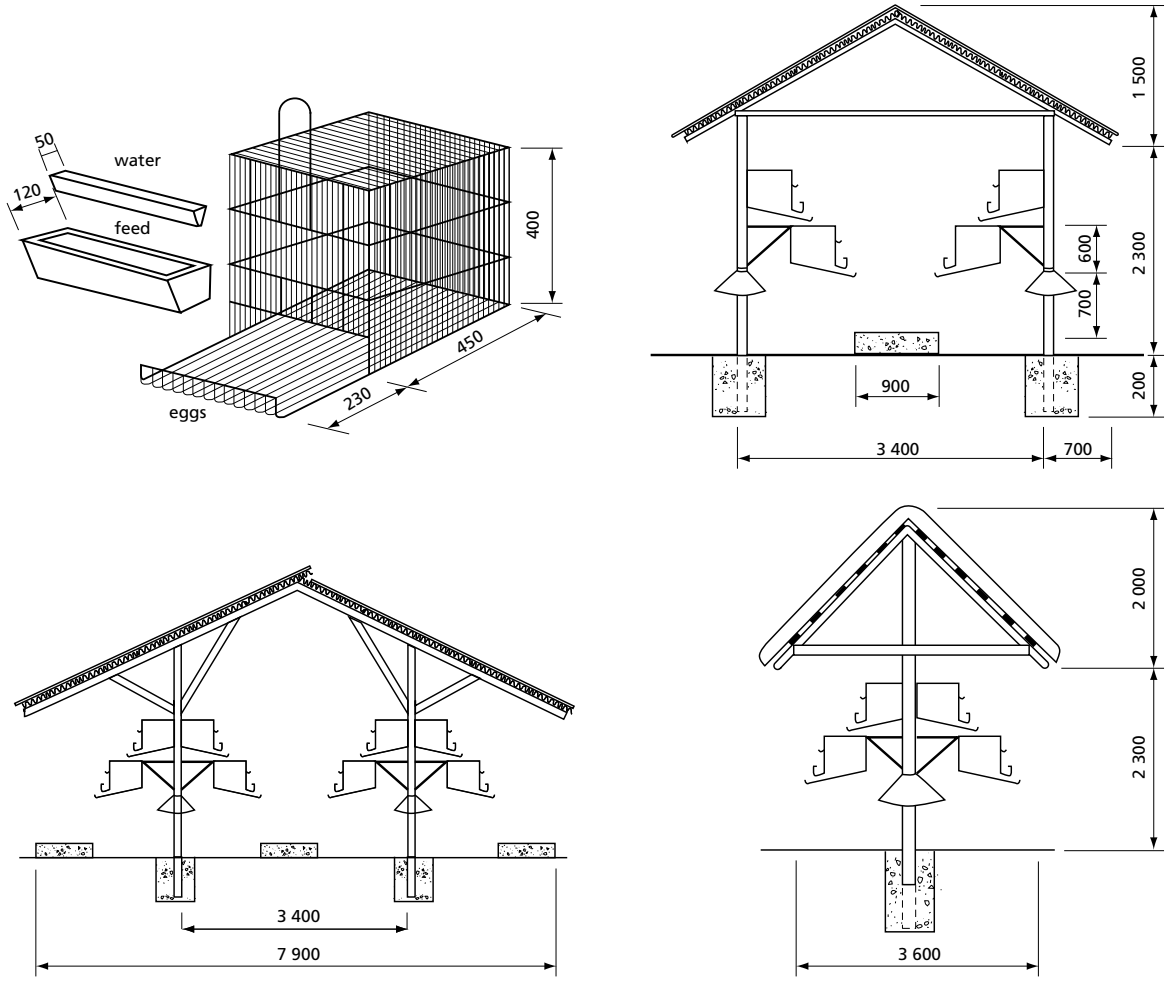


Figure 10.44 **Cage compartment and various arrangements of cage tiers in open-side houses**

TABLE 10.14
Recommended minimum dimensions of cages for laying hens

Layers per cage	Cage area[1] per bird	Width	Depth	Height		Floor slope
				Front	Back	
(number)	(cm^2)	(mm)	(mm)	(mm)	(mm)	(%)
1	1 100–1 300	250	450	500	400	11–15
2	700–900	360	450	500	400	11–15
3	600–750	450	450	500	400	11–15
4	550–650	530	450	500	400	11–15
5	500–600	600	450	500	400	11–15
20	800–900	2 000	850	650	500	15–20

[1] Depending on the size of the breed

ventilation. Previously used cages should be considered only if they are of a suitable design, and have been carefully inspected for condition prior to purchasing.

Summary

The housing systems for layers described should meet the needs of most situations encountered in east and southeast Africa. In the few cases where much colder weather occurs, the buildings described should be built with one or more enclosed walls. However, it must be emphasized that chickens tolerate cold weather better than wet, sticky, foul-smelling litter resulting from inadequate ventilation. If the temperature falls below freezing it is essential for the chickens to have

a continuous supply of free-flowing water (not ice), and eggs must be collected frequently enough to avoid freezing.

Planning for continuous production

Producers who can supply their market with either eggs or meat on a regular and steady basis will undoubtedly find their produce in demand at the best market prices. Planning the poultry housing system has much to do with steady production.

A programme for 1 000 layers is shown in Figure 10.45. A larger or smaller operation can be designed with the same number of buildings, but of a different size.

It is assumed that the brooder house is large enough for brooding only, and that pullets will be transferred to a laying house for growing to laying age. New chicks are started every 13 weeks, brooded for 7–8 weeks, and then transferred to the laying house. After approximately 11 weeks they will start a laying period of 52 weeks, after which they are sold and the house is cleaned and rested for two weeks before the cycle is renewed.

Five laying houses are required. At any one time, four will have layers in full production and the fifth will be either housing growing pullets or empty for cleaning. Each house is on a 65-week cycle: 11 weeks for growers; 52 weeks for layers; 2 weeks for cleaning. The brooder house is on a 13-week cycle: 7–8 weeks for brooding; 5–6 weeks for cleaning and resting. A suggested housing layout is shown in Figure 10.46.

Housing for breeders

Breeders must be housed in one of the floor systems because cocks need to run with the hens. One cock per 5–10 hens is sufficient. Special emphasis is placed on disease control, so often a partially or completely slatted floor design is preferred. Few commercial producers breed their own replacements, but instead buy day-old chicks from a commercial hatchery.

However, most chicks of indigenous breeds are produced by natural incubation in small-scale farms. Although a hen sitting on some 8–10 eggs needs little feed and even less attention, breeding results may be improved by a cool, clean nest at ground level that is enclosed to protect the hen, and later the chicks, from insect pests, vermin and predators, and by a supply of feed and clean water.

Brooders

Naturally hatched chicks are reared and protected by the broody hen and can be left undisturbed, provided that their yard is protected from predators, is of a good sanitary standard and has a supply of feed and water.

Artificially incubated chicks must be started under gas-fired or oil-fired brooders to compensate for the absence of a natural mother, and to keep them warm without crowding together. If electricity is available, a 250-watt infrared lamp is a more reliable and comfortable solution, but it is also more expensive.

A cheap, simple but still efficient brooding arrangement that will serve for about 100 chicks is shown in Figure 10.47. The hover, which prevents the heat from

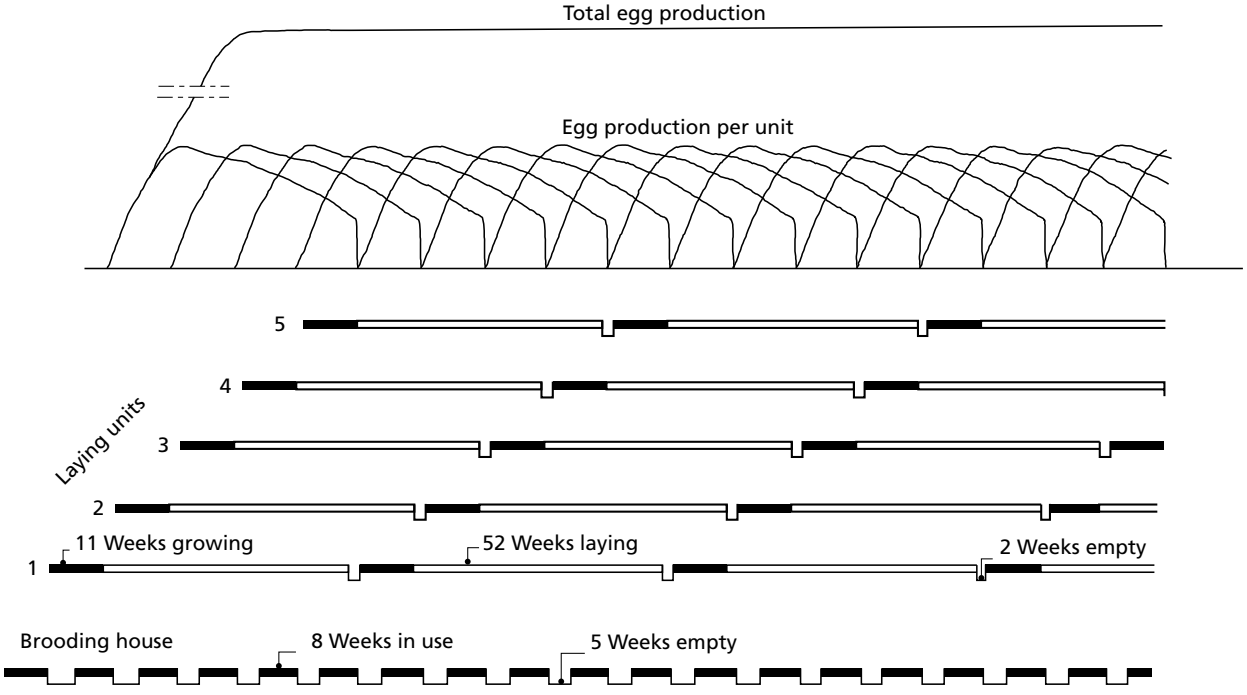


Figure 10.45 **Production flow when starting chicks every three months**

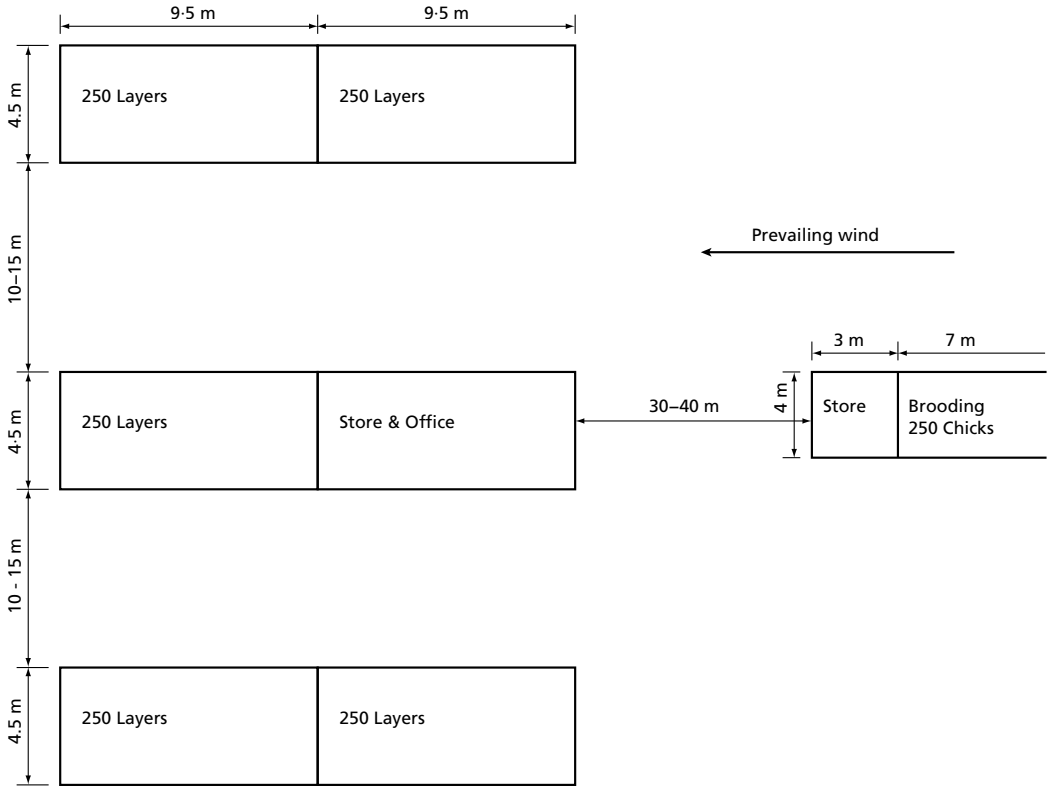


Figure 10.46 **Layout of buildings for 1 000 layers and brooder house for replacements**

escaping and protects the chicks from draughts, is made from a halved oil drum and is equipped underneath with two heaters, e.g. kerosene storm lanterns protected by netting. The hover is suspended by chains from the roof structure, and its height over the floor is adjusted to achieve the required temperature.

A similar but larger brooder for 400–500 chicks has a hover made from two 3-metre long corrugated roofing sheets equipped with six heaters, has a proportionally larger area enclosed by the 60 cm wall, and is supplied with ten water founts and ten feed troughs.

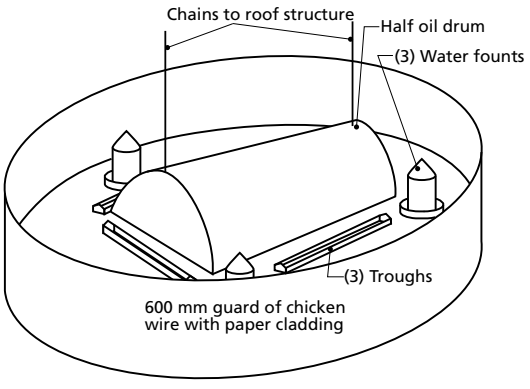


Figure 10.47 **Brooding arrangement for approximately 100 chicks**

Housing for pullets and broilers

In the past, poultry meat has been derived chiefly from culled layers. This is still the main source of poultry meat in most developing countries, although there is an increasing shift towards rearing chickens specifically for meat. Broilers, the common term for meat birds, are fast-growing strains that reach market weight of 1.6 kg in 8–12 weeks. The commercial production of poultry meat is now based primarily on broilers.

In a semi-intensive system, the growing pullets may obtain part of their food by scavenging for forage, seed, etc. A fenced yard allowing 5–8 square metres per bird is preferable to open land. At least part of the yard should have shade cover, and a simple building in which the birds can be enclosed at night will be required. The building should allow 0.2 square metres per bird, have good ventilation and perches for roosting, and offer protection against predators and inclement weather. The birds should be moved at regular intervals to a different yard in order to avoid a build-up of worm infestation.

There is little difference between the system for rearing chicks to become pullet replacements for the laying flock and the system for rearing broilers for market. The same environment and housing are suitable, so they will be considered together.

Brooding and rearing are floor-managed operations. It is common practice to keep broilers or pullets in the same house from the time they are one day old: first

on newspapers or thinly spread litter, and later on deep litter. When broilers are marketed at 8–10 weeks of age, or when pullets are transferred to the laying house at 16–18 weeks of age, the litter is removed so that the house can be thoroughly cleaned and disinfected. The house should therefore be designed and built to allow for easy and efficient cleaning. Pullets and broilers are not grown together owing to the difference in the length of their growing periods and differing schedules for artificial lighting.

Chicks are started in a brooder, which may be of the type discussed in the previous section, and remain there for 6–8 weeks. During this time it is desirable to conserve heat and to prevent draughts and, in this respect, the building design can be an important factor. A method that is widely used in the United States, called 'end-room' brooding, works well and seems adaptable to warm climates as well.

By taking advantage of the fact that chicks up to four weeks old require only one-third to half as much floor space as they will need later on, one end and enough of the adjacent sides are closed in tightly to provide 0.05 square metres of floor space per chick to be brooded. Offcuts, with low thermal capacity, are ideal for enclosing the wall. A hessian curtain forms the fourth (interior) wall to complete the temporary enclosure. The baby chicks can then be confined in the space around the brooder in the enclosed end of the house (see Figure 10.48).

The remaining walls are covered with 18–25 mm wire mesh. At the end of the brooding period, the brooder is raised to the ceiling for storage, the hessian curtain is lifted and the chicks are allowed into the rest of the house, which should provide from 0.08 square metres/bird for broilers, to 0.17 square metres/bird for pullets.

Depending on the maximum temperatures expected, it may be necessary to provide some ventilator openings in the enclosed walls. An adjustable gable-end ventilator is particularly desirable, as the roof will not have a ridge vent for brooding operations. If cool, breezy weather is expected, one or more of the screened sides may be equipped with hessian curtains.

Equipment and stores

In addition to what has already been described, the chicken house will require equipment such as waterers, feeders and a feed store, and perhaps perches for roosting. Houses for floor-managed layers or breeders will require nest boxes. A store for eggs may be required in any laying house. There should be sufficient feeders and waterers for easy access (particularly important for young chicks), long enough for each bird to have its place, and with sufficient holding capacity. Tables 10.13 and 10.15 provide some information relevant to their

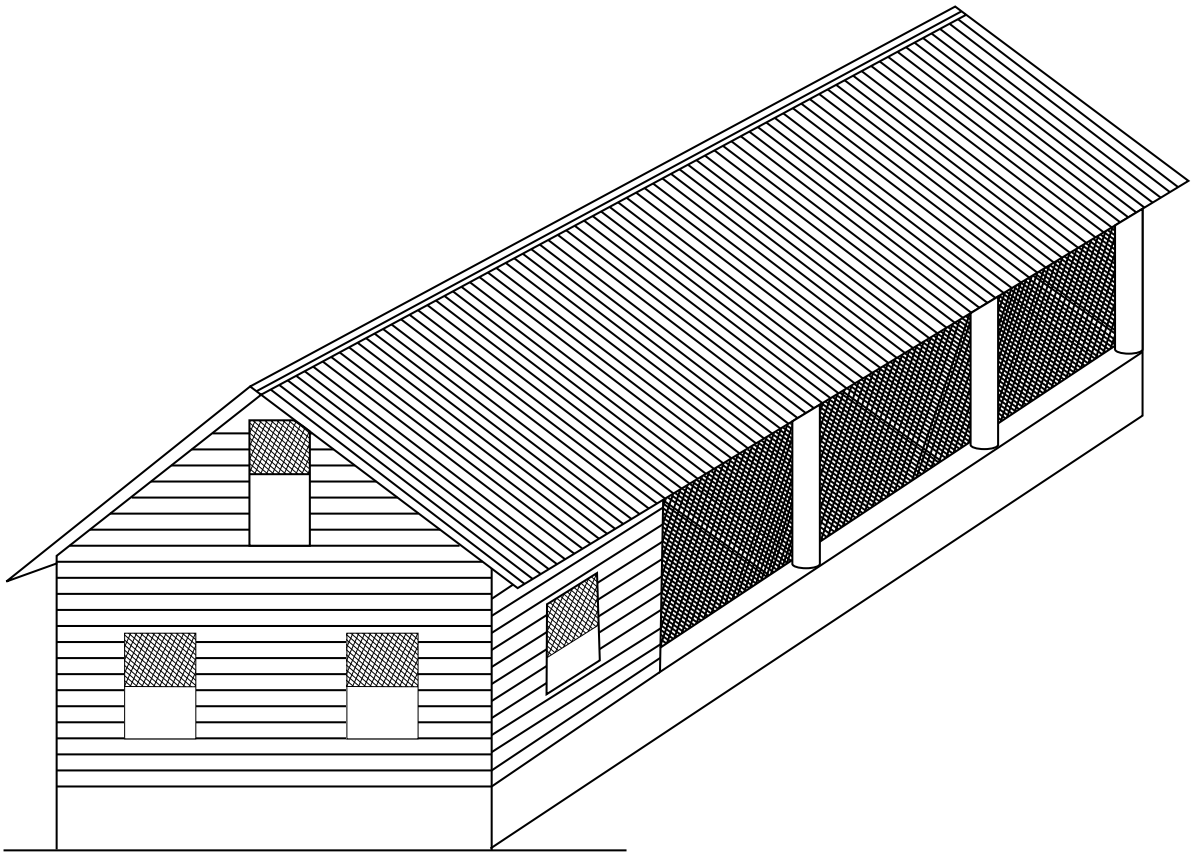


Figure 10.48 **A closed end brooder and growing house**

design. Most chickens in intensive production are fed water and mash on a free-choice basis.

Note: The cumulative feed consumption in pullets from one day to the point of laying at the age of 20–24 weeks is 10–12 kg. The rearing of one broiler from one day old to marketable weight (2 kg live weight) at 9–12 weeks of age requires 4–6 kg feed.

Feeders

Either trough or tube feeders are used for day-old chicks, growing birds and layers, but their size must be selected to suit the birds to be fed. The number of feeders should be such that the distance to the nearest feeder does not exceed 2 metres from any point in the house. A trough should be not too wide, easy to clean and designed to prevent the hens from leaving their droppings in it.

TABLE 10.15
Feed and water requirement for pullets and broilers relative to their age, and for layers relative to their weight and egg production

Chickens	Feed requirements (kg/week per bird)		Water requirement (litres/day per bird)
	Pullets	Broilers	
Rearing birds			
1–4 weeks of age	0.07–0.20	0.10–0.40	0.05–0.15
5–8 weeks of age	0.26–0.36	0.50–0.90	0.16–0.25
9–12 weeks of age	0.40–0.49	1.00–1.10	0.20–0.35
13–20 weeks of age	0.51–0.78	-	0.25–0.40

Egg production: No. of eggs/year				
Layers	100	200	300	
Light breed	0.54	0.65	0.78	0.25–0.35
Medium breed	0.69	0.82	0.94	0.27–0.40
Heavy breed	0.84	0.96	1.10	0.30–0.45

Figure 10.49a shows a good trough design that can be made by the farmer. If used outside in a run, the trough should be sheltered by a roof. Small trough feeders for chicks are used on the floor, but the larger ones are usually mounted on a stand to prevent the chickens from kicking litter into them, and have perches where they can stand while eating (see Figure 10.49b). Tube feeders, as shown in Figure 10.49c, are suspended from the ceiling and are easily adjusted for height (0.3 metres above ground is recommended for mature birds).

Drinkers

An ordinary 10-litre or 15-litre bucket serves very well as a drinker for layers. If it is sunk into the floor or ground so that only about 10 centimetres shows above ground, it may be used for chicks as well. Another arrangement for chicks consists of a shallow bowl supplied with water from an upside-down bottle, as shown in Figure 10.62. Water fountains of the type shown in Figure 10.49d are available in sizes for all ages.

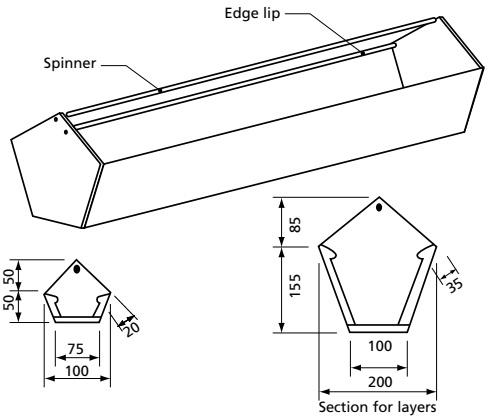


Figure 10.49a **Trough**

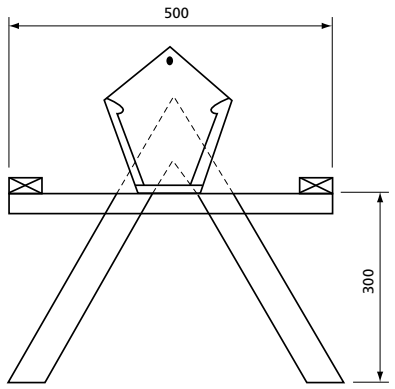


Figure 10.49b **Trough on a stand**

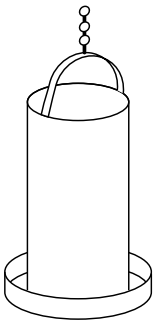


Figure 10.49c **Tube feeder**

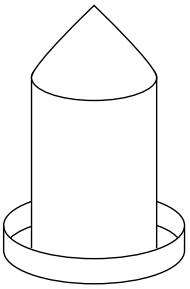


Figure 10.49d **Water fountain**

Figure 10.49 **Feeders and waterer**

Just like feeders, they are used on the floor for small chicks and on stands for older birds. The number of drinkers should be such that all chickens have access to one within a distance of 3 metres.

Automatic drinking nipples may be used for layers in cages. There should be at least one nipple for every two hens. It is desirable for every hen to have access to two nipples, as clogging of a nipple is not always easily detected.

Nest boxes

Layers and breeders, except those managed in cage systems, should have access to nest boxes in which they can lay their eggs. The nests can be used by one or more birds at a time. Single nests commonly have the dimensions 250–300 mm wide, 300–380 mm deep and 300–350 mm high. They have a 100 mm litter-retaining board across the bottom of the opening and a perch 150–200 mm in front of the entrance.

Communal nests should have a space allowance of at least 0.09 square metres per bird. The top of the nest should be steeply sloped to prevent birds from roosting there. One nest should be supplied for every five birds in the flock. Figure 10.50 shows a two-tier nest box arrangement. The bottom row of nests should be 450–600 mm from the floor.

Perches

Chickens have a natural instinct to roost in trees at night. To provide for this, perches are commonly installed in chicken houses from six to eight weeks of age or more, in particular in semi-intensive systems. Perches for young birds should have a diameter of about 35 mm and provide 0.1–0.15 square metres of space per bird, while adult birds need about 50 mm diameter and 0.2–0.3 square metres of space. The perches should be fixed to solid stands 0.6–1 metres above the floor and 0.35–0.4 metres apart, preferably placed lengthwise at the centre of the house. A deck about 200 mm underneath to collect manure is desirable.

Feed stores

Grain stores are discussed in Chapter 16. The feed stores required for a small flock are very similar to those for food grains. For commercial flocks, the type of store depends on how the feed is handled. If it is purchased in bag lots, then a masonry building with an iron roof that is secure against rodents and birds is most suitable. If feed is delivered in bulk, then one or more overhead bins, from which the feed is removed by gravity, will be convenient and safe.

The size of the store required depends entirely on the frequency and size of deliveries, but can be estimated as 0.0035 m^2 floor area per bird in the flock where feed is purchased in bags. If part of the grain is produced on the farm, then some long-term storage of the type shown in Chapter 16 will be required.

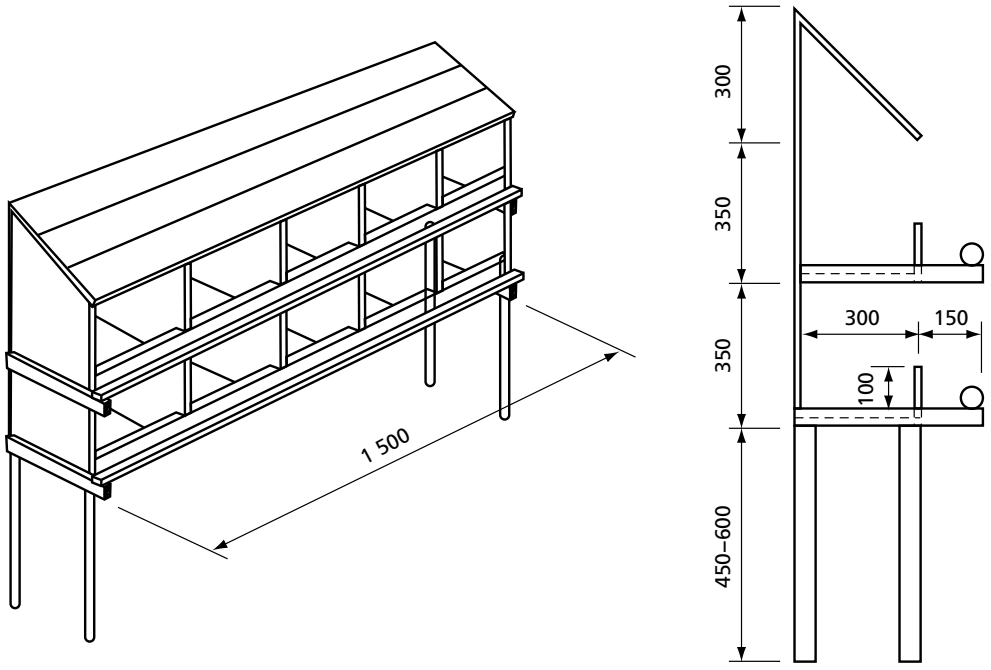


Figure 10.50 **A battery of single laying nests for 50–60 hens**

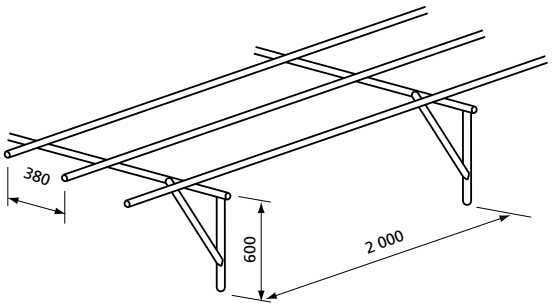


Figure 10.51 **Perches**

Manure handling

A layer is estimated to produce an average of 0.15–0.20 kg manure per day, and a broiler produces 0.08–0.12 kg of manure per day. In deep-litter systems, the litter used may more than double these amounts. Poultry manure is commonly allowed to accumulate in the house under a wire or slatted floor, or as deep litter, for quite extended periods, but alternatively it may be cleaned out regularly and stored in a concrete pond. It is an excellent form of fertilizer. Processed poultry manure has successfully been fed to cattle, sheep and fish as a portion of their total ration.

Egg handling

Eggs are an excellent source of animal protein and are usually less expensive than meat. If properly handled under sanitary conditions, they store well for short periods and reach the consumer in good condition. However, eggs are perishable and possible carriers of salmonella, a serious food poison, so the need for clean conditions and refrigeration cannot be overemphasized. The following list includes several recommended practices and facilities:

1. A clean nest and floor litter will minimize the number of dirty eggs.
2. The egg-handling and storage building should be screened, free of rodents and other vermin.
3. The water supply should be potable and ample.
4. Lavatory and toilet facilities should be available.

Egg-cooling for large commercial laying operations requires approximately 0.25 m^3 of cool store per 1 000 layers per day of storage. For smaller flocks, the store will need to be proportionately larger.

Figure 10.52 shows an *evaporative charcoal cooler* for small farms. A store measuring 100 × 100 cm (for example) is covered by a water tray, from which cloth strips or 'wicks' drip water down into side frames. The frames consist of a 5 cm layer of broken charcoal, sandwiched between 1.25 cm chicken wire mesh. A hinged and latched door is constructed similarly to the sides. The action of water evaporating from the charcoal cools the interior of the box.

Other methods for short-term storage of eggs at the small poultry unit include underground cellars, storage in lime water and storage after dipping in water glass.

For longer periods of storage, a refrigeration system and a well-insulated room is required to maintain a storage temperature of 5–10 °C. To allow storage for six to seven months, a temperature of between -1.5 °C and 0 °C will be required. The refrigeration capacity needed is approximately 200 watts for 5 000 layers, or 300–400 watts for 10 000 layers. Other capacities would be proportionate.

Custom-designed systems with generously sized evaporators should be installed. Room air-conditioners do not provide the desirable humidity for storage. The evaporator is too small and operates at a low temperature, removing too much moisture from the air.

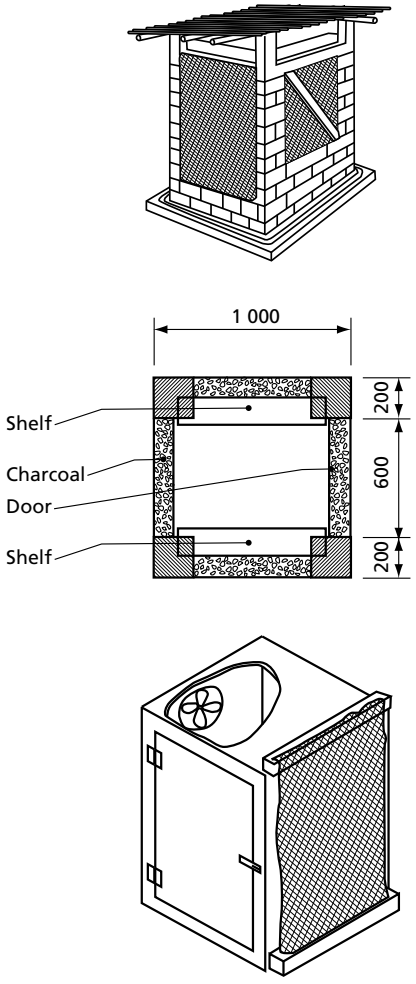


Figure 10.52 **Evaporative cooler for eggs, milk and other foodstuffs. Where electricity is available, a fan-controlled air flow will provide more efficient operation**

Duck housing

Although ducks are kept for both meat and egg production, commercially there is much more demand for meat than for eggs.

On the other hand, egg production does provide a valuable contribution to the family income and diet for the small-scale farmer. Ducks lay more and larger eggs than indigenous chickens. Raising ducks is encouraged in African countries because they are hardy and are easy to raise and manage.

To a large extent they can feed on grass, vegetables and grains produced on the farm. Housing is also quite simple and inexpensive. For these reasons, small-scale farmers would benefit from keeping ducks instead of hens, which are more prone to disease and malnutrition.

Brooding and rearing

Brooding ducks have similar requirements to chickens and the same temperatures are used: 35 °C for the first week, thereafter reduced by 3 °C at weekly intervals until normal air temperature is reached.

Ducklings grow very rapidly, and floor and trough space on deep litter should be provided according to Table 10.16.

TABLE 10.16
Recommended minimum floor and feed space for ducks

	Floor space[1]		Feed trough space
	(m^2/bird)	(birds/m^2)	(birds/m)
1–2 weeks	0.05	20	14
3–4 weeks	0.1	10	11
4–7 weeks	0.2	5	9
7 weeks to market	0.3	3–4	8
Mature birds	0.3–0.4	2.5–3	7–8

[1]Refers to deep litter; on a wire mesh floor the stocking rate can be doubled.

Litter materials include straw, sawdust, shavings and sand. The large quantity of water that ducks drink produces wet manure that causes problems with almost any form of litter. A wire mesh floor is therefore a desirable alternative. The 12.5 mm mesh of 8-gauge wire is suitable.

Fresh air is important and, after a few days, ducklings can be let out in fine weather. They should, however, not be allowed to become wet before feathering is complete on their backs, at about six weeks of age. Ducklings should also be shaded during hot weather to prevent sunstroke.

Housing

Housing for ducks can be very simple (see Figure 10.53). The house should be situated on a well-drained and preferably elevated area.

The *floor* should be raised at least 15 cm above the surrounding ground level to help keep it dry. Ducks tend to be dirty, and plenty of clean litter must be used in floored housing.

Although a concrete floor can be installed for easy cleaning, it is not necessary. If part of the floor is of wire mesh and the ducks have to cross it on their way to the nest boxes, their feet will be cleaned so they do not make the nests and eggs dirty.

Solid walls: Walls 60 cm high are adequate. They may be made from any material, provided that it keeps the ducks in and predators (such as dogs, snakes, rats and wild birds) out. The space between the wall and the roof is covered with wire netting, with a mesh not larger than 25 mm. Total wall height need not exceed 150–200 cm.

A *roof* made of thatch is a fully adequate and inexpensive covering for a duck house. Metal sheets can also be used, but insulation should be installed under the sheets.

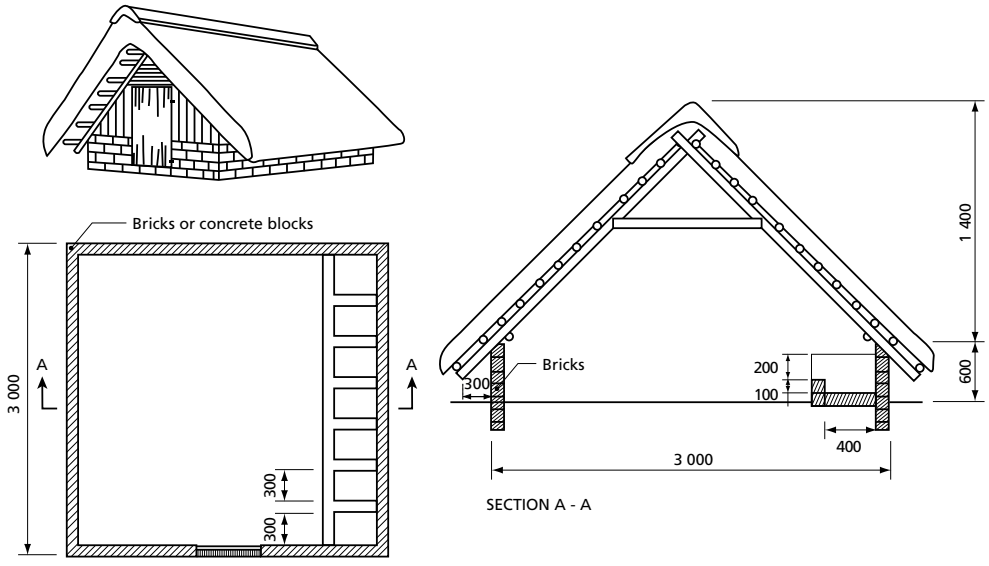


Figure 10.53 **Duck house for 25 ducks**

Nest boxes 30 cm wide, 40 cm deep, and 30 cm high should be provided for every four ducks. The front should be l5 cm high. The nest boxes are placed either on the floor or 30 cm off the floor against a side or rear wall. Although nesting boxes off the floor release more floor space, the ducks may lay their eggs under the boxes.

A *run and fencing* should provide a minimum of 1 square metre per bird, but 2–3 square metres or more will keep the ducks cleaner and give more space for grazing. On open-range pasture the ducks should be allowed 20 square metres per bird.

Feed and water equipment

Duck feeders need to be somewhat wider than chicken feeders to allow for their 'shovelling' eating habits. For the first two weeks, preferably the food should be supplied as crumbs or wet mash. Later the food is best given in the form of pellets. The required trough space is included in Table 10.16. Adult ducks normally consume about 0.2 kg of feed per day, but some ducks in full lay may require up to 0.3 kg per day.

Ducks of all ages drink large quantities of water. Waterers must be designed to allow easy access for the birds and easy cleaning for the farmer.

As ducks like to swim, if possible they should have access to a stream or pond. Contrary to popular belief, there seems to be little benefit in providing for swimming, except that, with water available, the ducks are able to keep themselves cleaner and somewhat higher egg fertility may result.

Geese housing

Geese are foragers and can be allowed to graze on succulent grass as early as three weeks of age. Therefore more encouragement should be given to the development of meat production from geese in east and southeast Africa.

Unless there are a large number of geese, natural hatching will take place. A goose will sit on 10–15 eggs. The sitting goose should be allowed to use her regular nesting place for incubating the eggs.

Rearing goslings is relatively easy if proper care and attention is given. The goose should be confined to a clean coop for the first 10 days while the goslings have access to a small run. Chick mash can be fed for the first three to four weeks, along with succulent grass. After three weeks of age the goslings will graze, but supplementary feed must be given if the grazing is poor.

Geese are selective grazers and will quickly return to newly grown grass after recent grazing. If the geese are herded, a much wider range of grazing is possible.

Housing for geese is very simple, if any is required at all. In tropical areas, geese appear to be quite content left outside at all times of the year. However, there is often a danger of theft and attack by predators, so the geese should be herded into a shelter at night for protection. The shelter can be simple and cheap as long as it serves this purpose.

A wooden framework surrounded by wire mesh is quite adequate. Wooden rails or bamboo can also be used in place of the wire mesh. The same materials can be used for the roof, as a waterproof roof is not necessary. There is no need for a floor, but the ground should be elevated to avoid flooding.

Housing for turkeys

In recent years there has been a steady increase in turkey production. The main demand is still at Christmas and New Year, but the better hotels and restaurants require supplies throughout the year. The demand is only for turkey meat. All the eggs produced are used for incubation by hatcheries.

The production of turkeys should be confined to commercial enterprises. As chickens carry diseases that affect turkeys, the small farmer should not grow the two together.

Brooding and rearing methods for turkey poults are similar to those for chickens, but the brooding temperature is higher. The recommended temperature for the first week is 35–38 °C, after which it can be reduced by 4 °C per week until ambient temperature is reached.

Adequate floor space in the brooder house is important, as the turkey poults grow rapidly. Table 10.17 provides information on space requirements.

At about 10 weeks of age, turkeys are put out on range in a fenced enclosure. In the interest of disease control, it is essential to use clean land that has not carried poultry, turkeys, sheep or pigs for at least two years. Approximately 20 square metres of pasture should be allowed for each bird.

A range shelter with 20 square metres of floor area is suitable for 100 poults up to marketing age. Dry, compact soil is adequate for a floor. The frame should be made of light material, covered with wire mesh, so that the shelter can be moved to clean range each year. The roof, which should be watertight, can be made of thatch or metal sheets. Perches, made from 5 × 5 cm square rails or round rails 5 cm in diameter, should be installed 60 cm from the ground and 60 cm apart, allowing 30–40 cm of length per bird.

The turkey breeder flock can be confined in a deep-litter house similar to the one shown in Figure 10.40 for chickens. Recommended floor, feed and water space for turkeys is given in Table 10.17. Approximately 23 kg of feed is required to produce a 6.4 kg turkey at 24 weeks of age. Adult birds require 0.12–0.3 kg per day depending on the size of the breed.

Early mortality in turkey poults caused by a lack of drinking or feeding is a constant problem and can only be prevented by good management and reliable equipment. Young poults must be coaxed to eat by making sure they have plenty of feeding places and can see the food easily. The same applies to water.

TABLE 10.17
Recommended floor, feed and water space for turkeys

	Brooding 0–6 weeks	Growing 6–12 weeks	Breeding
Floor space	0.1 m^2	0.4–0.6 m^2	0.7–0.9 m^2
Roosting space	-	30–38 cm	30–38 cm
Nests	-	-	60 × 150 cm
		(for 20–25 hens)	
Feeders	4–8 cm	10 cm	12 cm
Water	2 cm	3 cm	4 cm

It is important to keep turkeys from being frightened by people, animals or machines. When alarmed, turkeys have a tendency to stampede, pile up and smother.

SHEEP AND GOAT HOUSING

Sheep and goats are important sources of milk and meat. Both readily adapt to a wide range of climates and available feed supplies. They also have similar housing requirements and will therefore be treated together.

Management systems

Depending primarily on the availability and use of land, three systems of production are practiced:

1. Subsistence, in which a few animals are tethered during the day and put into a protective shelter at night.
2. Extensive, in which the flock/herd grazes over large areas of marginal land unsuitable for agriculture. The flock is usually shut into a yard at night. Both these systems are practiced extensively in East Africa.
3. Intensive, in which the animals are confined to yards and shelters, and feed is brought to the flock. This system offers the greatest protection for the flock from both predators and parasites. Although it may make the best use of limited land resources, this system also increases labour and the capital investment required for facilities.

Housing

Housing in tropical and semitropical regions should be kept to a minimum, except for the more intensive

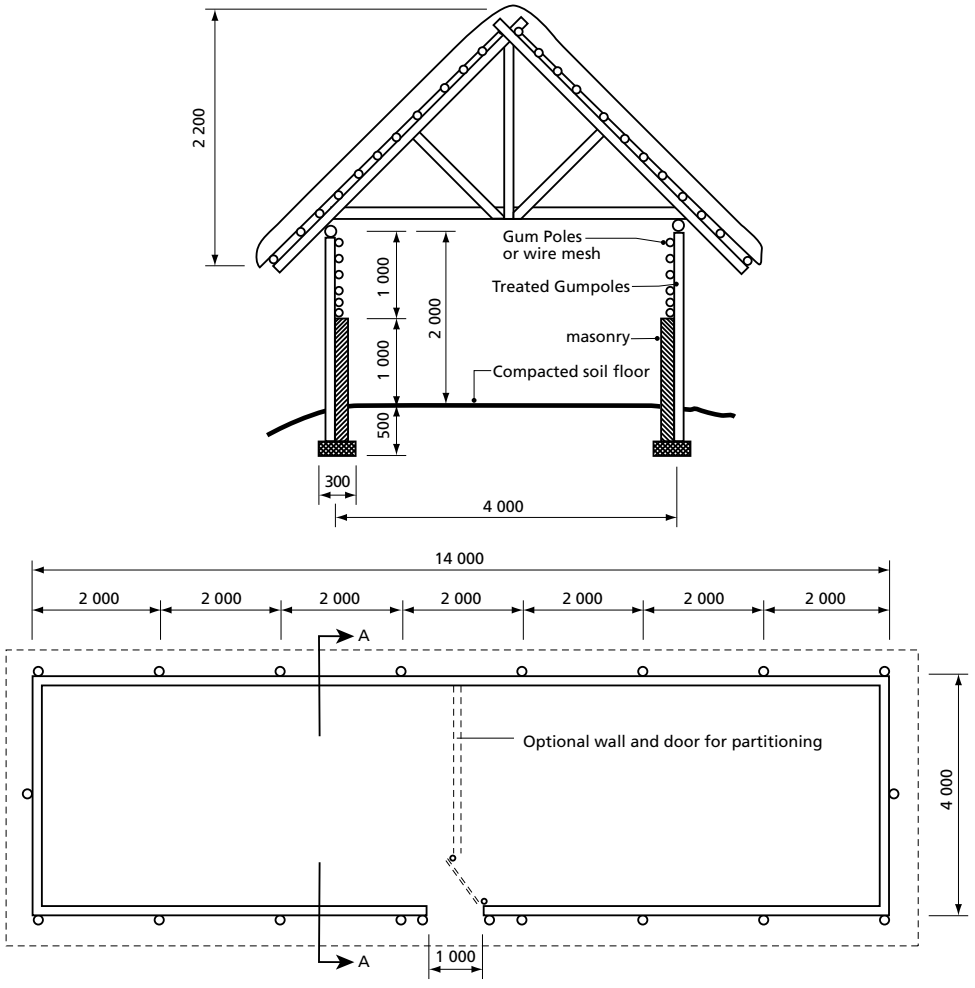


Figure 10.54 **Sheep/goat house for 100 animals. In a warm climate gum-pole rails instead of the masonry walls provide better ventilation**

TABLE 10.18
Recommended floor and trough space for sheep/goats in intensive production relative to live weight

	Weight (kg)	Floor space			Trough space (m/animal)
		Solid floor (m^2/animal)	Slatted floor (m^2/animal)	Open yard (m^2/animal)	
Ewe/doe	35	0.8	0.7	2	0.35
Ewe/doe	50	1.1	0.9	2.5	0.40
Ewe/doe	70	1.4	1.1	3	0.45
Lamb/kid		0.4–0.5	0.3–0.4	-	0.25–0.30
Ram/buck		3.0	2.5	-	0.5

Slats should be 70–100 mm wide, 25–30 mm thick and laid with 25-mm spaces. Individual lambing pens should be 1.5–2.2 m^2, depending on the weight of the ewe and number of lambs expected. A feed trough should be 0.3–0.4 metres deep front to back, and have a 0.5–0.6 metre high front wall facing the feed alley

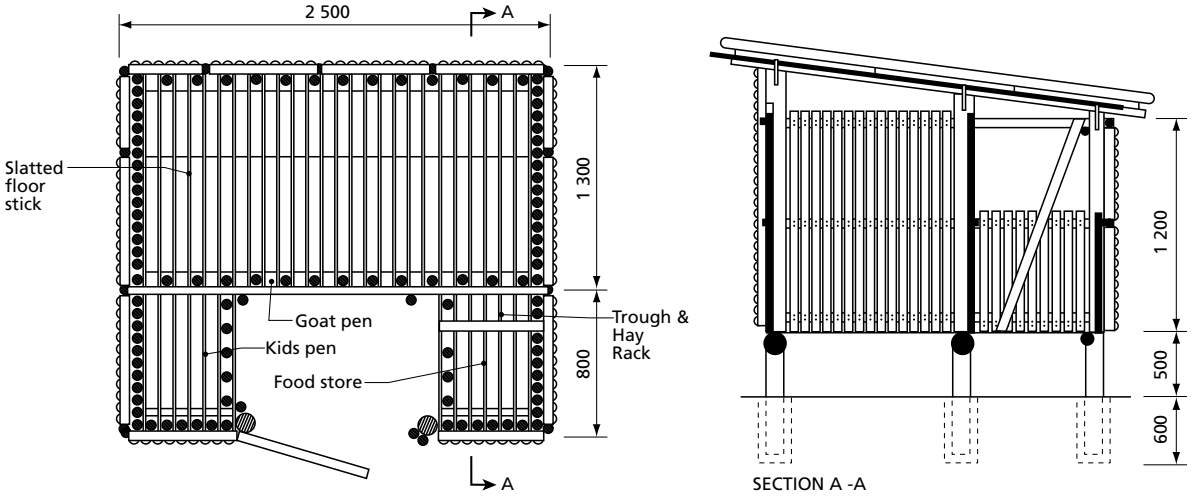


Figure 10.55 **House for two to four sheep/goats in intensive dairy production**

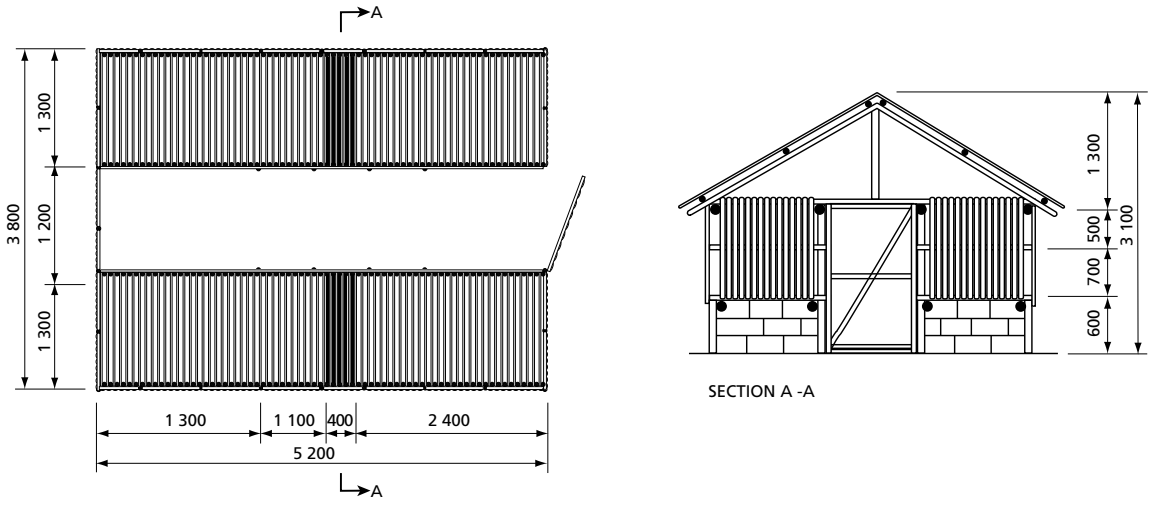


Figure 10.56 **House for 12–18 sheep/goats in intensive dairy production**

systems of production. In the arid tropics, no protection other than natural shade is required. In humid climates, a simple thatched shelter will provide shade and protection from excessive rain. As sheep and goats do not tolerate mud well, yards and shelters should be built only on well-drained ground.

Figure 10.54 shows a sheep/goat house for 100 animals. Unless predators are a serious problem, gum-poles can be substituted for the brick walls. If thatching is difficult to obtain, a lower-pitch roof of galvanized steel is feasible, but some insulation under the roof is desirable.

Where housing facilities are provided, in addition to water, feed troughs and permanent partitions, it will be necessary to provide temporary panels to help divide and handle the flock when necessary, in order to carry out such operations as disease treatment, docking, shearing, milking and lambing.

In temperate climates and at high altitudes, a more substantial structure may be needed. An open-front building facing north provides wind protection and a maximum of sunshine. A rammed-earth floor with a slope of 1:50 towards the open front is recommended. A concrete apron sloped 1:25 and extending from 1.2 metres inside to 2.4 metres outside will help maintain clean conditions in the barn.

In areas of high rainfall it may be desirable to keep the animals off the ground. Stilted houses with a slatted floor raised 1–1.5 metres above the ground, to facilitate cleaning and the collection of dung and urine, are shown in Figures 10.55 and 10.56.

Milking can be facilitated by providing a platform along the feeding fence where the animals can stand while being milked from behind. Such a platform should be 0.8 metres deep and elevated 0.35–0.5 metres above the floor where the milker stands.

Parasite control

A dipping tank and crush are essential in the layout for a large flock, or for a community facility for the use of many smallholders. A typical dipping tank is shown in Figure 10.57. In areas where the bont tick is a

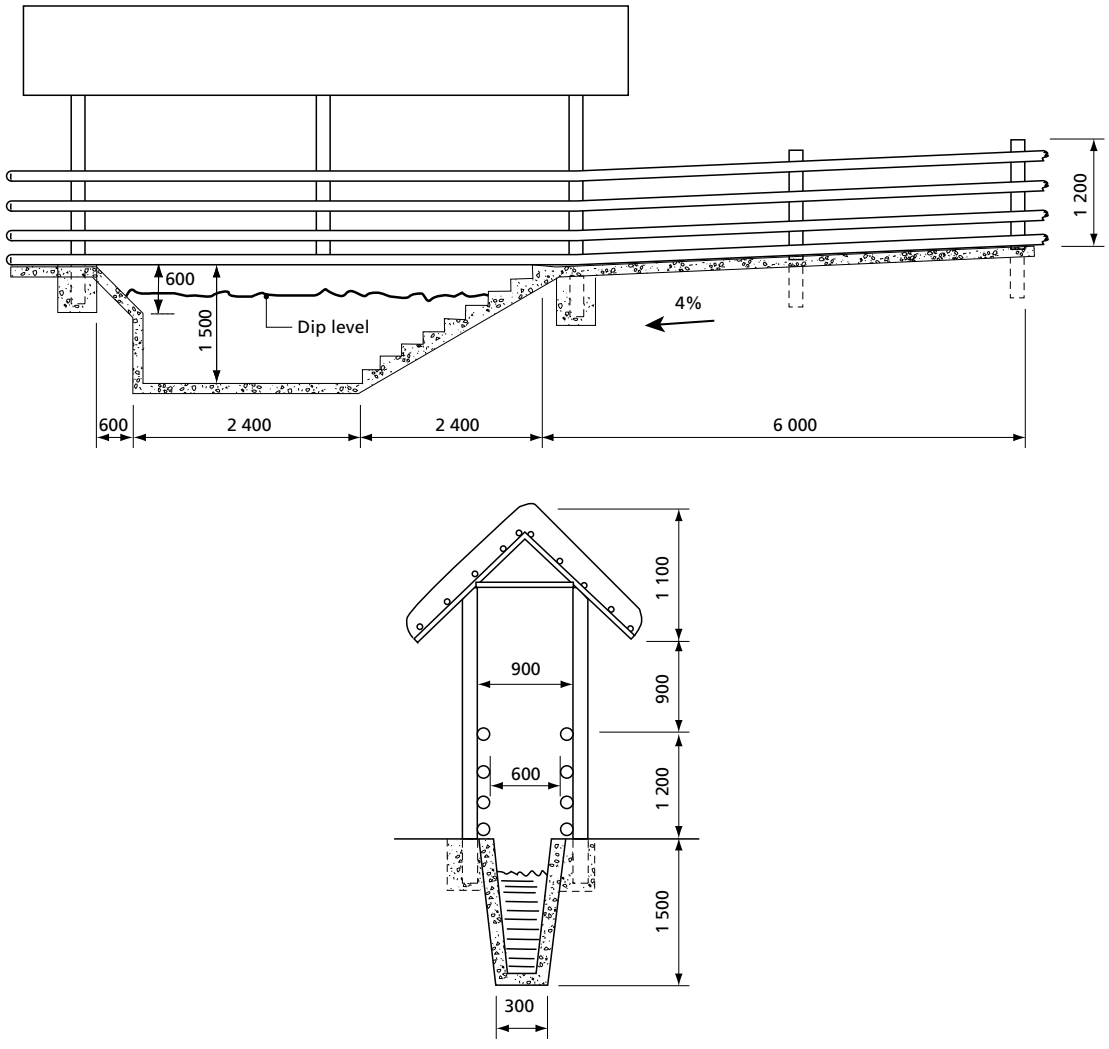


Figure 10.57 **Sheep-dipping tank**

problem, simple walk-through tanks or footbaths may be needed. Figure 10.58 shows plans for a footbath.

RABBIT HOUSING

There are few if any countries where domestic rabbits are not kept for meat and pelts. It is widely recognized that a few rabbits can be kept at low cost to produce a fair quantity of wholesome and tasty meat. However, to raise rabbits successfully one must begin with healthy animals, provide a good hutch, clean and nutritious feed, and take good care of the rabbits.

Management systems

Rabbits, like other domestic animals, may be bred and reared at various intensities. Table 10.19 shows some rabbit production characteristics. Rabbits can be mated at almost any time and, when mating is successful, the doe will kindle 30–32 days later. The doe should be checked for pregnancy 10 days after mating and, if necessary, remated. A shorter interval between kindling and mating will obviously result in a higher number of litters per doe per year.

Commercial producers aim for at least six litters per year, with seven kids weaned per litter, i.e. 42 kids per doe each year. However, with intensive production, the

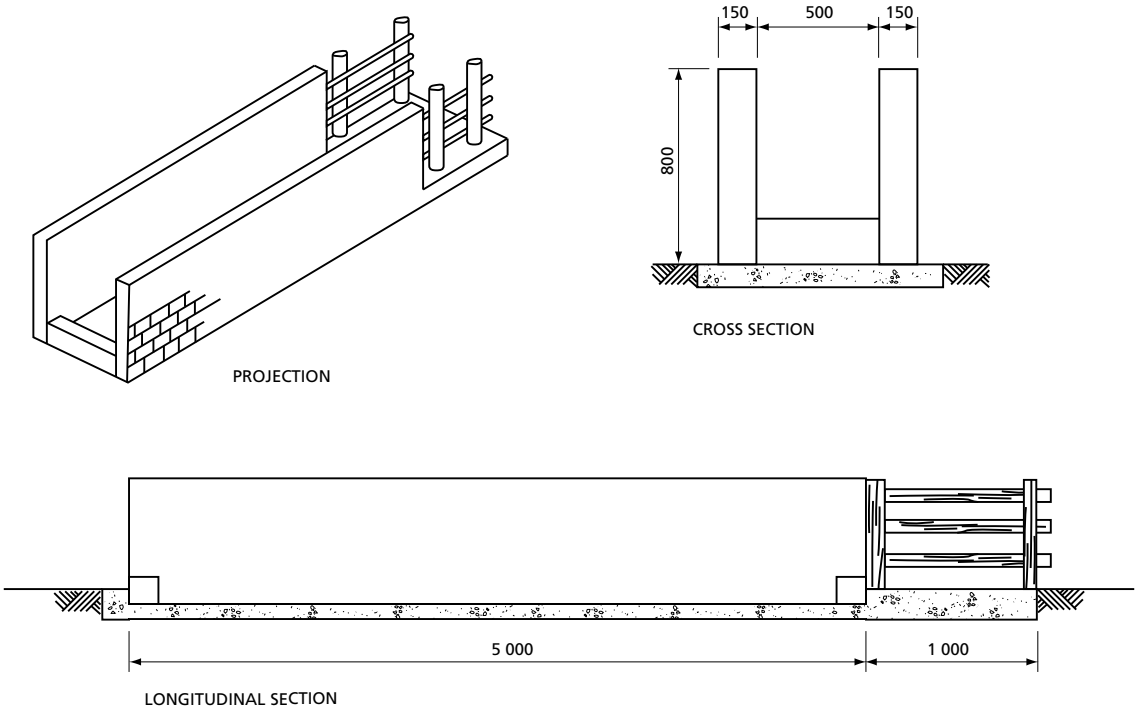


Figure 10.58 **Footbath and drain crush for sheep/goats**

TABLE 10.19
Management practices and production efficiency related to the intensity of rabbit production

	Feed time between kindling and mating		
	Extensive greens (8–10 weeks)	**Semi-intensive greens/ concentrates (4–6 weeks) (or remating 1–2 days after weaning)**	**Intensive concentrates (1–2 weeks)**
Age of young at weaning	8–10 weeks	6–8 weeks	4–5 weeks
Number of litters per doe/year	3–4	5–6	8–10
Number of young weaned per doe/year	10–20	30–40	50–65
Age of young at slaughter	20–30 weeks	12–15 weeks	10–13 weeks
Daily grain during fattening	10–15 g	20–30 g	25–30 g
Production of cold-dressed meat per doe/year	15–25 kg	40–60 kg	75–100 kg

breeding doe may have to be replaced every 1–1.5 years, while, in a semi-intensive system, it may last for three years. Replacement does can be bred for the first time at five months of age.

A balanced diet fed in adequate amounts, good sanitation, disease control, appropriate housing and equipment, and good care are all important factors when aiming at lower mortality and higher daily gain. The mortality in a well-managed rabbit unit should be below 20 percent from birth to slaughter among the young, and below 20 percent annually among the adults, but at present many extensive producers in east and southeast Africa experience mortality of up to three times that.

In semi-intensive systems, a substantial part of the diet for rabbits consists of greens, such as grass, browse, weeds, vegetable waste, roots, tubers and vegetables. This usually necessitates longer breeding intervals and results in lower daily gain than intensive systems where the rabbits are fed with only rabbit pellets or chicken mash. However, because the feeding cost is lower, the farmer may gain an equally large profit.

Hutches

While there are a great many types of hutch, any well-designed hutch should provide certain essential features:

1. Enough space for the size of the rabbit.
2. Fresh air and light, but exclusion of direct rays from the sun.
3. Protection from wind and rain.
4. Sanitary conditions and ease of cleaning.
5. Sound but cheap construction; free from details that could injure the animals.
6. Convenience of handling.
7. A cage for each adult rabbit.

Space requirements

Each adult rabbit must have its own cage or compartment. Domestic rabbits vary in weight from 2–7 kilograms, depending on the breed, so the size of cage may be determined by allowing 1 200–1 500 cm^2 of clear floor space per kilogram of adult weight. This means that a cage for a medium-breed buck should provide a minimum of 80 × 80 cm. However, cages for females should allow extra space for the nest box and the litter, hence 80 cm by 115 cm should be regarded as the minimum for a medium breed doe.

Young rabbits reared for meat can be kept in groups of 20–30 animals until they reach four months of age. The weaned young kept in one group should be about the same age and weight. Such colony pens should allow 900–1 200 cm^2 of floor space per kilo of live weight.

The cages should not be deeper than 70–80 cm for ease of reaching a rabbit at the back of the cage. The floor-to-ceiling height of the cages should be minimum 45–60 cm, and it is desirable to have the floor of the cages 80–100 cm off the ground to handle the rabbits comfortably.

Hutch modules

Any size rabbit unit is conveniently made up from two-doe or four-doe modules. The number of cages required in each of these modules is shown in Table 10.20.

The small-scale producer may only have one such module, covered with its own roof placed directly on the cages, as shown in Figures 10.59 and 5.60, while the medium- to large-scale producer may have several modules placed under a separate roof on posts or in a shed, as shown in Figure 10.61.

Construction details

Proper ventilation of the rabbitry is essential. The walls, roof and door of the hutch can be covered with chicken-wire netting (37 mm mesh), or made from wood or bamboo placed 20 mm apart.

In high altitude areas with lower temperatures, it may be desirable to have a solid wall in the direction facing the prevailing wind. Temporary protection from strong winds, low temperatures and rain can be provided with curtains of hessian, reeds, grass, plastic, etc. The roof of the rabbit unit should be leakproof and can be made of thatch or metal sheets with some insulation underneath.

Ease of management depends to a great extent on the construction of the floor. It may be solid, perforated, or semisolid. Each has its advantages and disadvantages:

TABLE 10.20
Number of hutches required in two- and four-doe modules depending on the intensity of feeding and breeding

	Cage for buck	Cages for does	Cages for fattening weaners	Total number of cages per module
Two-doe modules				
Extensive production	1	2	1	3 (or 4)
Semi-intensive production	1	2	1	4
Intensive production	1	2	2	5
Four-doe modules				
Semi-intensive production	1	4	3	8
Intensive production	1	4	4 (to 5)	9 (or 10)

Note: The cages for fattening weaners allow space for one litter.

A solid floor can be made from wood, plywood or different kinds of board. It allows bedding to be used, eliminates draughts through the floor and causes less trouble from hock sores, but is difficult to clean. The use of a solid floor will permit the hutches to be stacked in two or three tiers, with the bottom row 30 cm off the ground, and this may save some building space. However, a solid floor in the hutch frequently leads to outbreaks of coccidiosis, a disease causing diarrhoea, loss of appetite and often death, because of a build-up of manure in corners of the cage and contamination of feed and water.

A perforated floor is self-cleaning, as manure and urine pass through to the ground, and this assists in disease control but, if not properly constructed, it may injure the animals. It can be made of woven or welded wire of not less than 16 gauge. Suitable mesh sizes are 12 mm for small and medium breeds, and 18 mm for large breeds. Chicken wire can be used, but its thin wires may cause sore hocks, and the urine can corrode the wire to failure within a year. The wire netting is stretched over a wooden frame, trimmed flush with the bottom edge, and stapled every 5 cm. Where it is fastened to posts, the wire edges should be turned down to avoid injury to the rabbits. A self-cleaning floor is usually recommended.

Equipment and store

Drinkers

A doe with litter may require up to 5 litres of water a day if fed only rabbit pellets or chicken mash. Rabbits receiving fresh greens daily will require less water, but all rabbits should have access to clean drinking-water at all times.

An automatic waterer can be made from a large bottle and a small tin can (see Figure 10.62a). Fasten

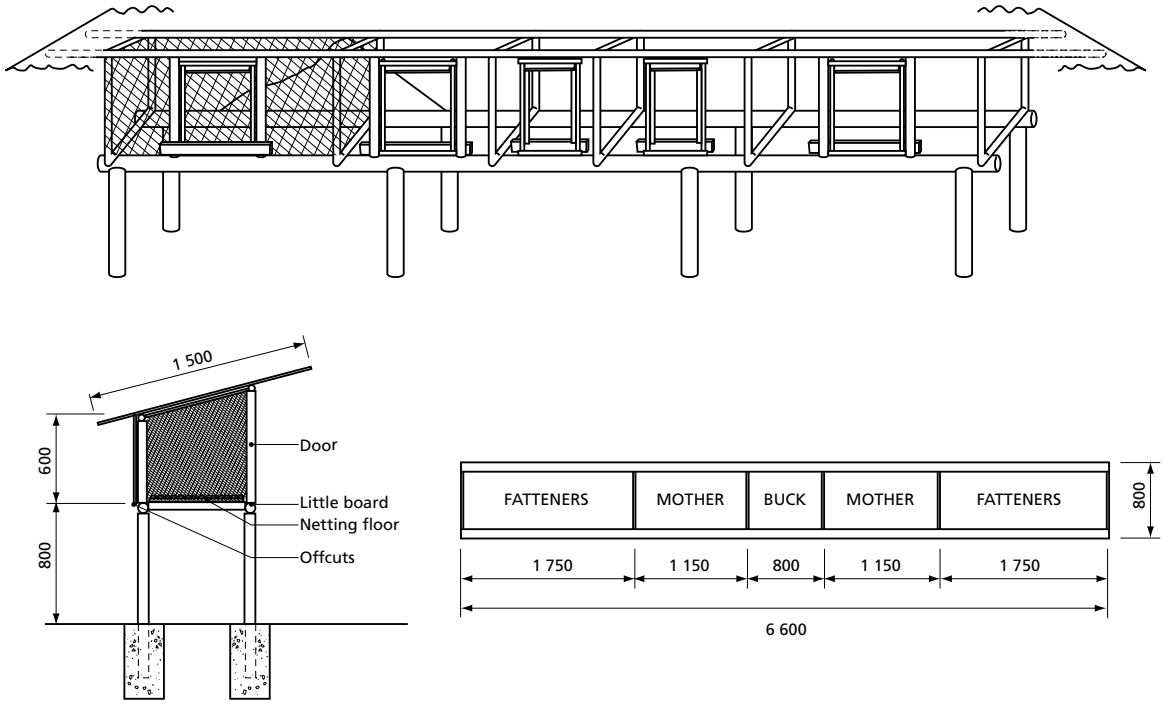


Figure 10.59 **Rabbit unit for two does, one buck and fatteners**

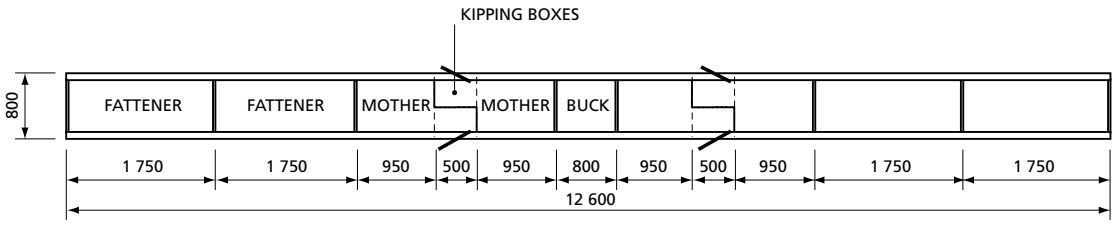


Figure 10.60 **Plan view of rabbit housing module for four does, one buck and fatteners. Kindling boxes are permanently installed with access from each cage for a doe. The kindling boxes have outside doors to facilitate cleaning. The cross-section is similar to the one shown in Figure 10.59.**

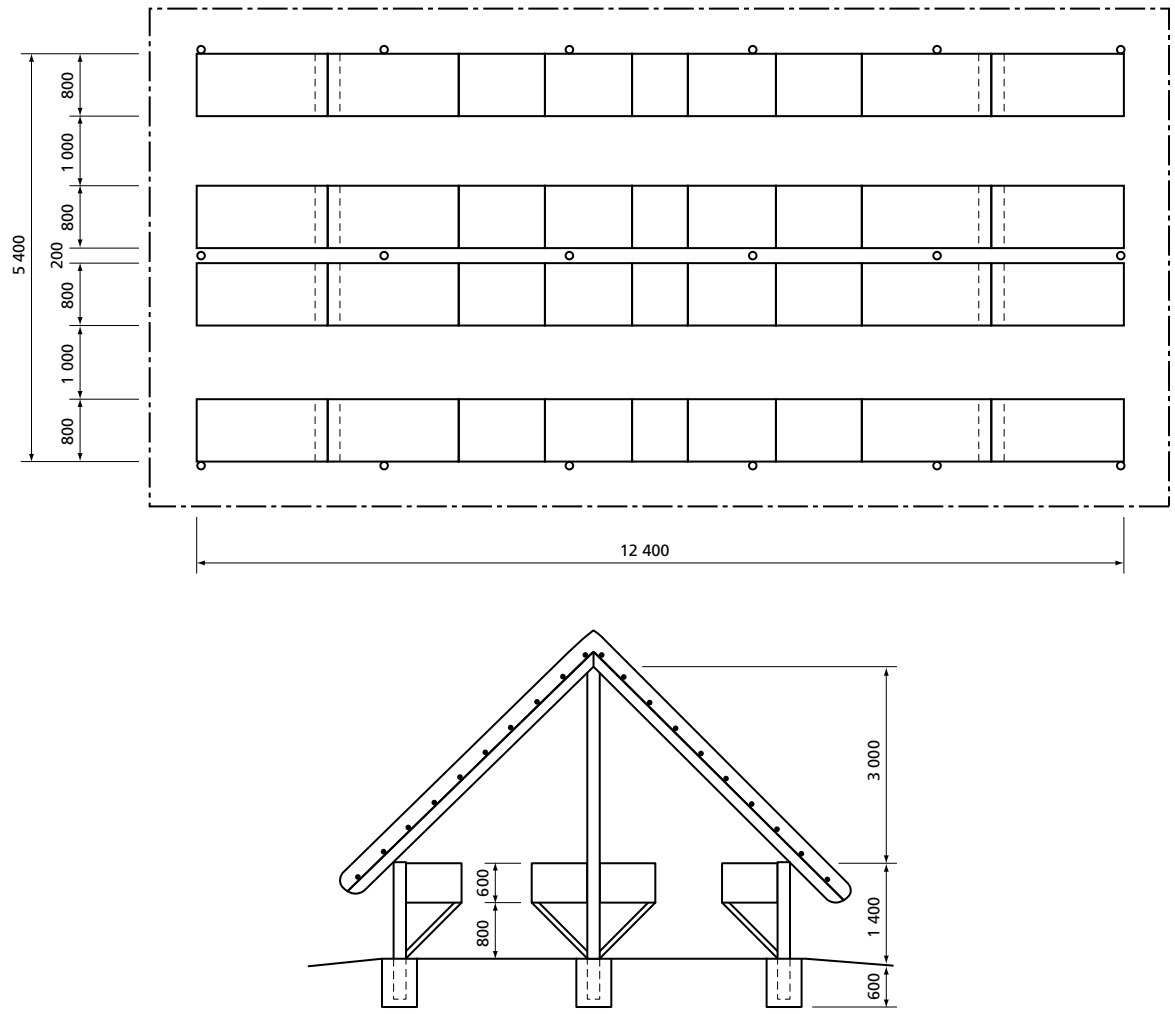


Figure 10.61 **Rabbit house for 16–18 does, 2–4 bucks and approximately 100 fatteners. Note that hay racks have been installed between the cages for fatteners.**

the bottle to the inside of the hutch so that the lip of the bottle is about 1 cm below the rim of the can. Fill the can and the bottle with water and replace the bottle. As the rabbit drinks from the can, the water will be replaced from the bottle.

Alternatively, a nipple drinker made from a bottle, a pierced rubber cork and a piece of 6–8 mm steel pipe can be used, as shown in Figure 10.62b. This allows the bottle to be placed outside the cage for easier refilling, and there is less risk of the water becoming contaminated, as the rabbits drink by licking the nipple.

Feeders

Heavy earthenware pots, measuring about 8 cm deep and 10–15 cm in diameter, make good dishes for feeding grain, pellets and mash because they are not easily tipped over. Tin cans, free of sharp edges, or open sections of bamboo nailed to a small board, can also be used. However, rabbits like to scratch out feed with their feet and, to avoid this, a feed hopper tied to the side of the hutch can be made from an empty 5-litre oil tin, as shown in Figure 10.62c. A flap measuring 6 cm by 12 cm is cut 6 cm from the bottom and strengthened with a piece of timber, and then bent inwards. The top of the tin is removed and the edges bent in against the inside of the tin.

A manger made out of a piece of wire mesh, measuring 40 cm by 40 cm, can be fixed to the door of the cage for feeding greens or hay. This allows the rabbit to pull forage into the cage as it feeds. Greens should not be put on the cage floor as this increases the risk of disease. The remains of greens left on the floor must be removed every day.

Nests

Does like to kindle in a private place. A nest box should be placed in the doe's cage five to seven days before birth. A box for medium-sized breeds should be about 30 cm wide, 40–50 cm long and 20–30 cm high. A lid is sometimes supplied, as some does prefer the nest box to be dark and, in cold weather, the lid will conserve some heat for the babies. Although straw or grass lining of

the box is generally not necessary, it will provide extra protection in cold weather. The box can be made of plywood, hardboard, wooden planks or even bamboo but, whichever is used, it must be easy to clean.

Feed storage

The storage requirement for feed to all categories of animal in a rabbit unit can be determined by multiplying the following figures by the number of does in the unit and the number of days in the storage period:

- In intensive production, each doe unit requires 1.3–1.8 kg of pellets or mash per day.
- In semi-intensive production, each doe unit requires 0.3–0.5 kg of pellets or mash per day.

No storage is required for greens, as they should be fed fresh every day but, if hay is used instead of greens, each doe unit will require 0.1–0.15 kg per day.

SLAUGHTER SLABS AND SLAUGHTERHOUSES

In rural areas of developing countries, the slaughter of animals for meat consumption is often carried out under less than ideal conditions. Where there are no facilities, slaughtering is likely to take place under a convenient tree, where an animal can be hoisted for skinning and evisceration. Meat produced under such conditions lacks veterinary inspection, is often contaminated and must be considered a hazard to human health.

Most countries have a meat control act providing for meat inspection aimed at the control of meat-borne diseases and the protection of consumers from meat of inferior quality or that has not been hygienically slaughtered and handled. The act may state minimum requirements for the design and operation of slaughtering facilities, and must therefore be carefully studied before any construction commences.

While only basic design requirements are discussed here, the throughput and sanitary conditions of a slaughterhouse also depend greatly on equipment, staffing and work organization. Therefore it is advisable to seek the advice of specialists whenever a slaughtering facility is to be planned, especially if the required killing capacity is more than a few animals per day or if other facilities, such as meat processing, are to be included at the same location.

Gantry hoist

In areas where population density is low and relatively few animals are slaughtered, a simple and inexpensive slaughtering facility is desirable. As animals must be hoisted immediately after stunning, to ensure proper bleeding, and then remain in a hanging position during the dressing operation to ensure sanitary conditions, a first step in improving facilities is to build a wooden or steel gantry hoist. While a single gallow should be at least 3.7 metres above floor level, two levels of suspension are desirable: 4.5 metres for bleeding cattle and 3.5 metres for dressing operations. Sheep and goats

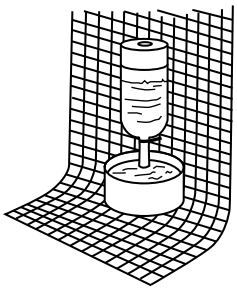


Figure 10.62a **Bottle and tin waterer**

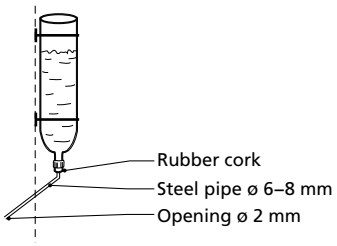


Figure 10.62b **Nipple waterer**

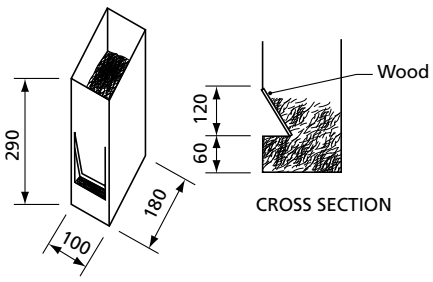


Figure 10.62c **Feed hopper made from a 5-litre tin**

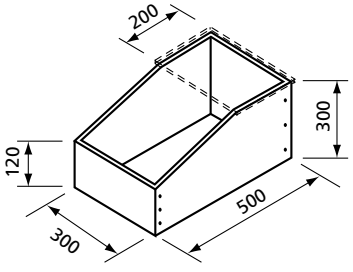


Figure 10.62d **Kindling box**

Figure 10.62 **Home-made feeder, waterer and kindling box**

can be suspended from a rail at a height of 2 metres at the side of the gantry hoist.

Although a mobile gantry hoist that can be transported easily and reassembled is feasible in the first stage towards improved slaughtering, a permanently installed facility will normally be the minimum requirement, as this allows for the construction of a concrete floor and a metal roof. The roof gives protection from sun and rain and allows slaughtering to take place in all weathers.

Whether temporary or permanent, the site should be fenced to prevent access by stray animals and unauthorized persons. Dogs and jackals, in particular, must be prevented from accessing offal and condemned meat. These products may contain the parasite that causes hydatid disease, and infected dogs are a very common vector for transmitting the disease to humans.

Slaughter slabs

After the initial installation of a gantry hoist, concrete slab and metal roof, gradually the facility can be converted into an economical, low-throughput slaughter slab. There should be floor rings to hold animals, skinning cradles for cattle and small stock, rails for hanging the carcasses, and an adequate and convenient water supply.

Satisfactory waste disposal is a requirement from the outset. The slab can be surrounded by a wall 1.5 metres high, and partitions can be installed between clean and dirty operations areas. A lairage should be constructed for both cattle and small animals. Drinking-water should be available for the animals at all times.

Paving the area immediately surrounding the slaughter slab with either concrete or bitumen will improve both sanitary and working conditions. An extended overhead rail allows the carcass to be moved from one operation to the next, until it reaches the dispatch area. Improved sanitation and management are possible using separate bays for cattle and small stock. However, this is a design feature that must be considered at the very outset, when the floor slab is poured.

Slaughterhouses

In areas where a large number of animals are slaughtered, a fully equipped slaughterhouse should be provided, i.e. a large slaughter hall where animals are stunned, bled, slaughtered, flayed and dressed in successive operations. In such a system, live animals enter one end of the building and emerge as dressed carcasses at the other. Capacity can be increased by using more than one bay for each kind of animal. A freezing room is normally included in a slaughterhouse, but only the largest factory abattoirs have facilities for the processing and large-scale storage of meat, and the utilization of inedible by-products.

Pig slaughter

Out of consideration for the Muslim population, pigs should be handled separately in a slaughterhouse

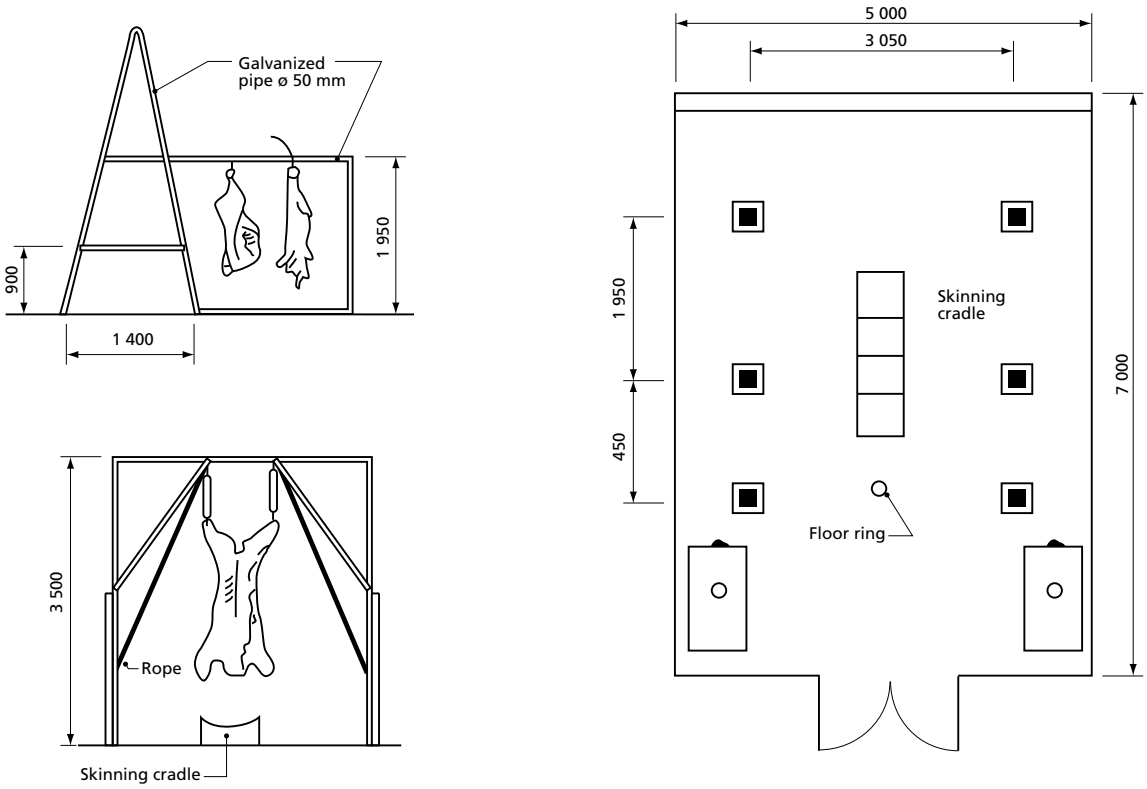


Figure 10.63 **Gantry hoist and layout of fenced area (by courtesy of Dr. I. Mann)**

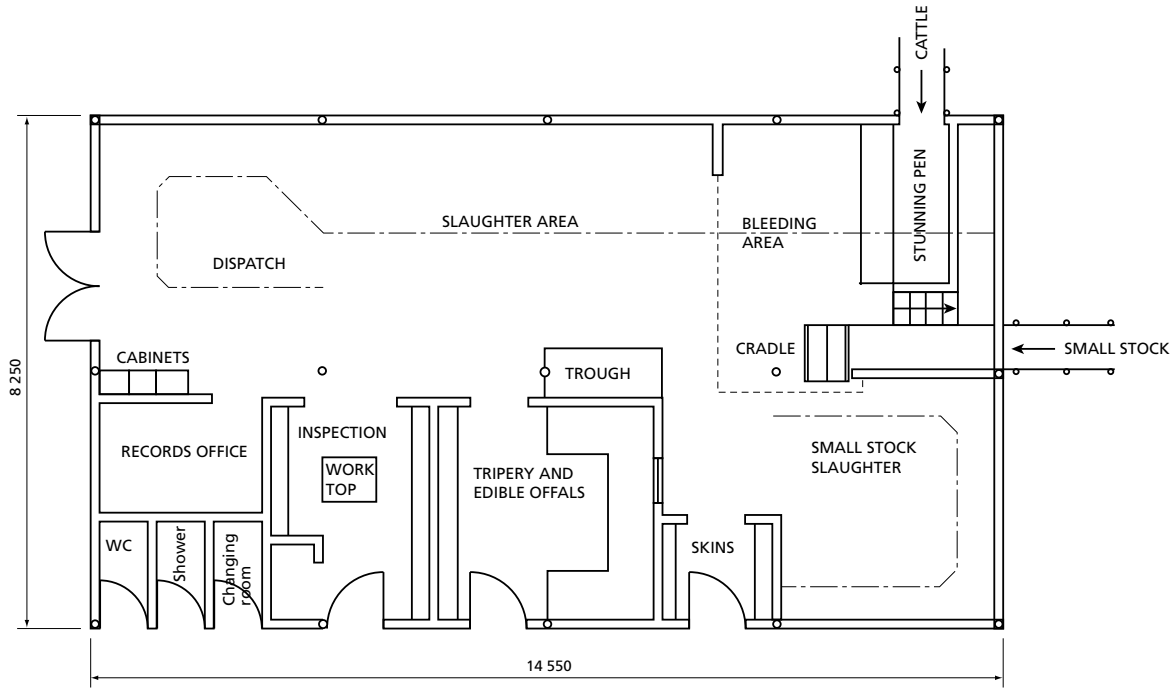


Figure 10.64 **Slaughter of 20 cattle and 40–50 sheep/goats per day (by courtesy of the Ministry of Local Government, Kenya)**

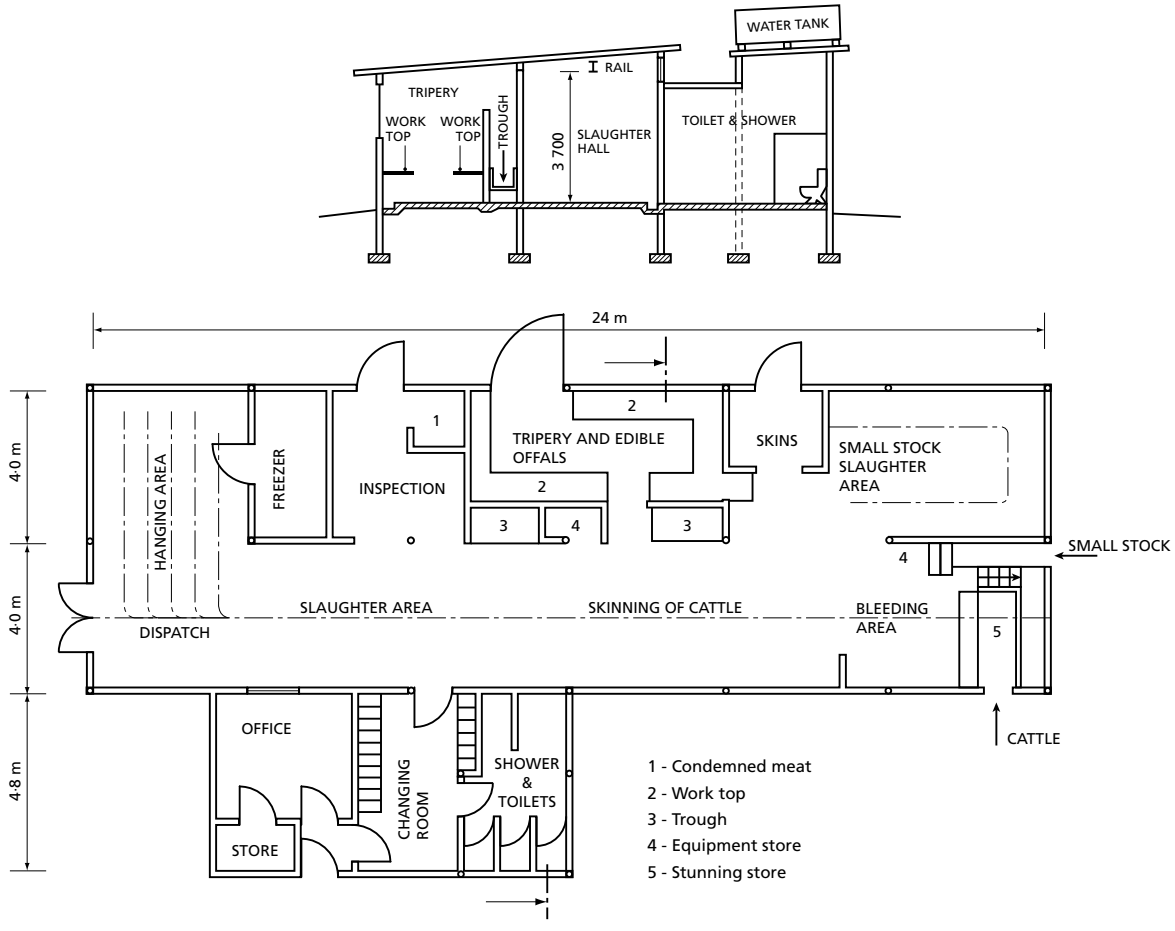


Figure 10.65 **Slaughterhouse for slaughter of 40 cattle and 40–60 sheep/goats per day (by courtesy of the Ministry of Local Government, Kenya)**

designed and used only for that purpose. There are reasons other than religious ones that make it desirable to separate pig slaughtering. The steam from the scalding vats creates adverse conditions for the setting of meat, and the scurf accumulated from scraping pig carcasses is heavily contaminated with meat spoilage organisms. Pig slaughterhouse designs follow the same basic pattern as those for cattle, with provision for the separation of clean and dirty activities. The gallows and rails need to be 3.9 metres above floor level in the bleeding area, and 2.5 metres in the slaughter hall. A water boiler is required to supply the scalding vat with water at a temperature of about 80 °C.

Poultry slaughter

Most poultry for local meat supply in rural areas is slaughtered singly or in small batches as the need arises, and this is often carried out in the kitchen.

It will be feasible to build a slaughterhouse for poultry only in areas where poultry is produced on a medium to large scale to supply meat to an urban area.

General recommendations for design and construction

The site for a slaughter facility should be on ground that is higher than its surroundings, to facilitate drainage. An adequate water supply must be available nearby to allow the slaughtering operations to be carried out under sanitary conditions. An all-weather road ensures timely dispatch of the meat throughout the year. All trees and bushes within 20 metres of the fenced area should be cleared to discourage birds, insects, etc.

In tropical countries, slaughterhouses should be as open to the air as possible, and the building designed in such a way that even a light breeze will produce a ventilating draught. The openings should not be glazed but should be screened, together with grills in the roof ridging, to prevent the entry of insects. The grills allow the warm air to escape and cooler air to be drawn in through the windows.

For sanitary reasons, floors and walls should be easy to clean, impervious to water, and rodent-proof. Concrete floors should be finished smoothly, but not so smooth that they become slippery, and should slope towards the open drains along the walls. Concrete blocks or stone building blocks are preferred for wall construction. All joints should be finished smoothly, and wall and floor junctions will be much easier to keep clean if they are finished with a coving.

The meat must not come into contact with any wooden surfaces or equipment. Steel is prone to rust, and stainless steel is generally very expensive. Hence concrete should be used wherever practicable and, in particular, for such items as troughs for intestines and offal, and for workbenches. If wood is used for doors, a galvanized steel sheet should be fixed to the bottom of the door on the outside for protection against rodents. The layout should be designed to permit expansion without basic alterations to the original structure or suspension of operations (see Figure 10.68).

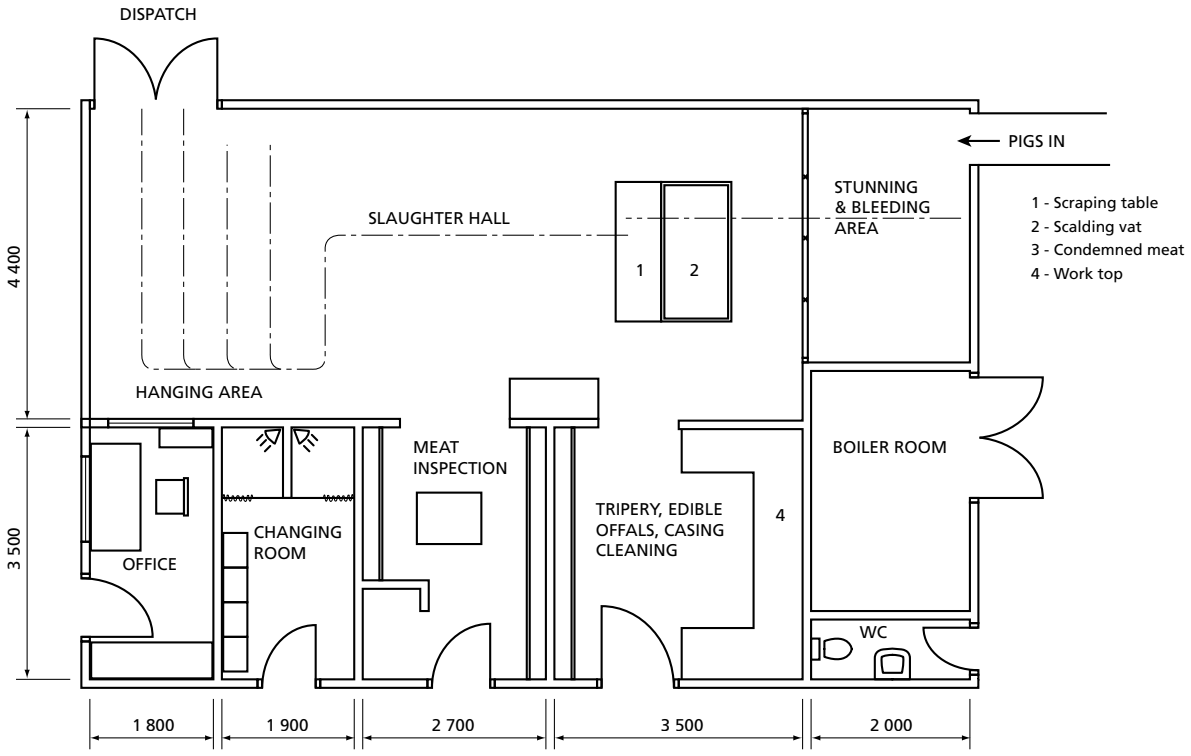


Figure 10.66 **Pig slaughterhouse for 20–30 animals per day**

Lairage

A lairage with a capacity of 1.5 days' kill should adjoin the slaughterhouse. Here the animals are allowed to rest and recover from stress before slaughter, thereby improving the setting quality of the meat. Each pen in the lairage should hold about 15 cattle, allowing at least 2.3 square metres for each animal. At least 0.6 m^2 should be allowed for small animals. While the lairage should be an integral part of the slaughterhouse complex, it should be at least 10 metres distant, and connected by a long, straight cattle race 75 cm wide at the top, narrowing to 45 cm at the bottom, to prevent the cattle from turning around.

The lairage should provide shade and clean drinking-water and a hard, impervious, well-drained floor sloping towards open drains. A separate area, where animals showing signs of sickness or fatigue can be detained for observation and control, is desirable. A holding pasture where the animals are allowed to graze until 24 hours before slaughter should be available. A clean lairage ensures that the animals will enter the slaughtering area as free as possible from contamination.

Water supply

Obtaining an adequate supply of potable water will often be the greatest problem to overcome when constructing a slaughterhouse in a rural area. The following minimum quantities should be available for each animal slaughtered:

1 000 litres for cattle;
100 litres for small animals;
450 litres for pigs.

Although water from wells is best, in many cases it will be necessary to use water from lakes and rivers. Should the quantity of potable water be insufficient, it may be necessary to install a dual water system, with the potable water being used for carcass and edible offal and non-potable water used for watering stock, washing skins, cleaning, etc.

If a water tower is required, the simplest procedure is to purchase a prefabricated steel tank of the correct size. If, on the other hand, an underground tank is installed, it can be made of reinforced concrete. If it is impossible to provide a supply of potable water, it is preferable to use a 'dry' slaughtering method, ensuring that no water comes in contact with the meat. However, the dry-kill method should be used only when a maximum of two animals per day are killed. Water will still be needed for washing floors, walls, etc.

Blood disposal

The large quantities of blood collected from the bleeding area should not be allowed to enter the main drainage system and cause pollution, and must not be mixed with water. Therefore, all the effluent from the stunning and bleeding area should be collected separately and led to an underground tank situated outside the building. The tank should be built with a tight-fitting, removable cover and be constructed in such a way that the liquid can seep through the sides into the surrounding soil. The blood will eventually decompose and it should be necessary to clean the tank only occasionally.

To avoid objectionable odours, the tank should be equipped with a screened ventilation pipe. In tropical areas, the air in the pipe and the upper part of the tank

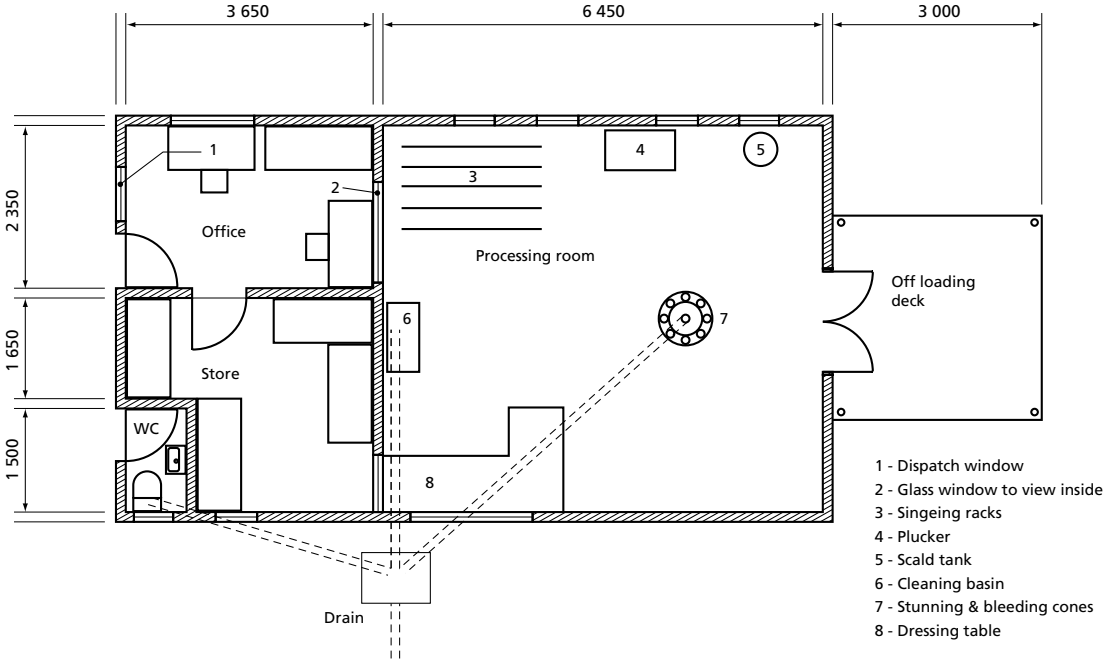


Figure 10.67 **Slaughterhouse for poultry**

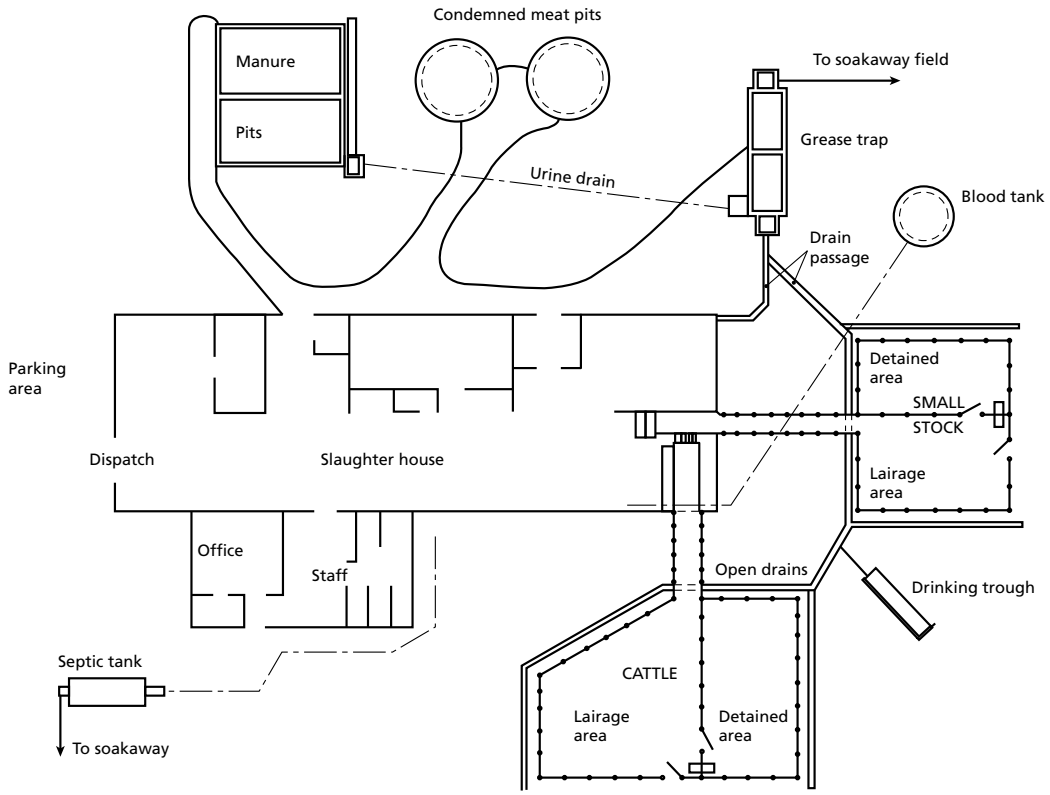


Figure 10.68 **Slaughterhouse with essential facilities**

will be warmed sufficiently during the day to cause circulation and air renewal in the tank.

The blood tank will operate satisfactorily only if the ground water level is below the level of the tank and the surrounding soil is pervious to water.

Removal of manure and condemned meat

The carcass should be dressed out rapidly, and the offal inspected and taken to a separate room where it can be cut up and the stomach and guts opened, cleared of manure and flushed with water. The manure is taken to a manure pit outside the building, whereas the rinsing water is directed into the main drainage system.

Suspect or condemned material is taken to the room set aside for this purpose. At the end of the day, it is disposed of, together with inedible offal, in two concrete pits outside the building. The pits should be equipped with airtight, lockable covers.

Most of the material will slowly decompose and it will not be necessary to empty the pits. Incineration is not recommended, as efficient incinerators are expensive both to buy and to operate, and simple incinerators do not work satisfactorily and burn out quickly.

Drains

As running water is used during slaughtering, and floors are flushed clean, the floors should be sloped so that water and effluent run into open drains placed along the walls. All these drains should be connected by a central drain to a trap for greases and solids. From this trap, the remaining effluent is led either into an evaporation pan, where bacterial action will break down most of the effluent in 20–30 days or, alternatively, into a subsurface seepage field, designed with a series of herringbone-patterned trenches filled with stones.

Soakage pits not less than 6 metres deep and 1.8 metres in diameter and covered with a concrete top are satisfactory for only the smallest units.

Open drains are recommended for the effluent from the slaughterhouse for the following reasons:

(a) It is often difficult to obtain the right type of piping in rural areas, whereas open drains can be cast as the floor is installed.
(b) The quantity of water available is sometimes insufficient to ensure that a system using closed pipes is adequately flushed, and clogged pipes may result.
(c) It is often difficult to obtain sufficient slope to allow the flushing action to take place by gravity, requiring the installation of automatic pumps, which is expensive and impractical for a small slaughter operation.

To prevent rodents from entering, a screen should be fitted to the open drain, where it passes through the slaughterhouse wall, in such a way that it can be easily removed for cleaning.

Cooling, chilling and freezing rooms

As soon as the carcasses have been dressed, they should be removed from the slaughter hall to avoid prolonged exposure to its atmosphere and thereby reduce the development of microflora in, and on, the meat. Most meat in the tropics is distributed, still warm, for consumption on the same day it is slaughtered.

Hence a cooling room will normally not be required. Instead the meat is transferred directly to a dispatch area. This practice implies that the work must start sufficiently early, and the slaughter slab, or slaughterhouse, must have sufficient capacity for slaughtering operations to be finished by about ten o'clock in the morning.

It is desirable to have a freezing room in all but the smallest slaughterhouses. The freezer can be used to sterilize measled meat, because some types of meat parasite are destroyed by the low temperature. It also helps to match the supply of meat more closely to demand. Refrigeration units are expensive and a chill room where meat can be ripened and tenderized can be justified only where there is a demand for meat treated in such a way.

REVIEW QUESTIONS

1. Why is it necessary to consider behaviour patterns of animals when planning and designing animal housing?
2. Which factors influencing animal production should be considered in animal housing?
3. How does climate influence livestock performance?
4. Outline the general requirements for cattle, poultry and rabbit housing.
5. Outline the parameters to consider when determining the number of pens and stalls required in a pig unit.
6. Briefly describe four factors which need to be considered in the design and construction of a slaughter house.

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Chapter 11
Rural buildings

INTRODUCTION

The traditional lifestyle of the rural communities of tropical Africa is undergoing many changes. People are becoming better educated, coming into contact with other cultures and technologies, and gradually losing their knowledge of the traditional crafts and agricultural methods that were practised by their ancestors. This is an encouraging change from the traditional way of life to a more modern way of life with a desire for appropriate dwellings.

Planning the design and construction of a rural dwelling requires decisions with which the rural family must live for a long time, perhaps a lifetime. These decisions are likely to be highly personal because of individual preferences, financial situation, family size, location and other circumstances. There are a number of factors to be considered and questions to be answered before building a home.

This chapter presents information relating to space requirements, together with ideas for planning rural dwellings. It leaves a great deal of opportunity for designs to evolve through the cooperation of the rural family, craftsmen and, perhaps, engineers and architects. The planning will involve careful evaluation of factors such as traditional family culture and social life, climate, government regulations, available materials and the skills of local craftsmen.

The planning process will result in unique designs that may differ greatly from one area to another. However, only a planning process that aims to produce designs that are general in terms of layout, materials, construction and details – within a cultural and environmental context – can contribute to the development of an indigenous building tradition that pursues the native architectural heritage.

SPACE REQUIREMENTS

In planning a rural home, adequate space must be allowed for each of the daily activities. This is not so much related to total space as it is to such things as door widths and heights, corridor widths, adequate space for a bed or a table and chairs and clearance for a door to swing open. It is essential for these dimensions to be checked in every design, as very minimal changes can often make a considerable difference in terms of convenience. Figure 11.1, as well as several figures in the Section 'Functional Requirements for different rooms and spaces', provides a guide to space requirements.

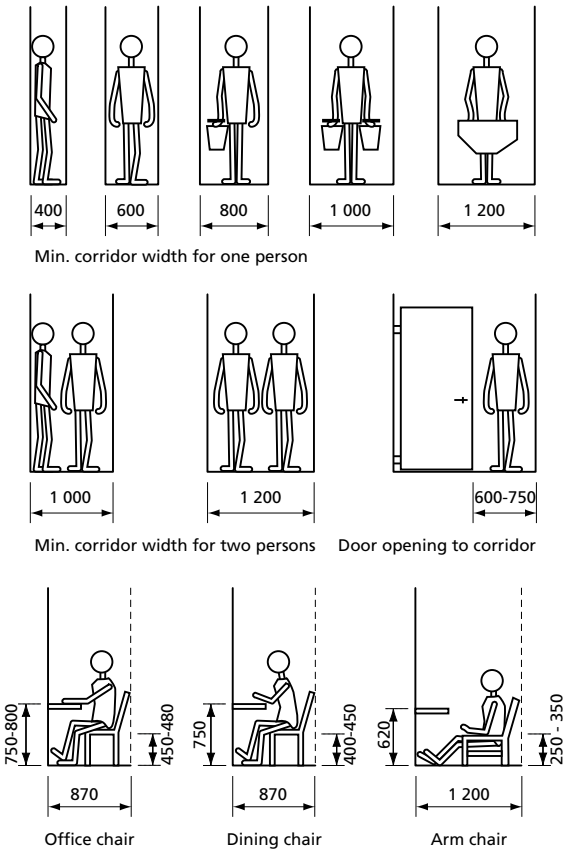


Figure 11.1 **Critical human space requirements**

FAMILY CULTURAL AND SOCIAL REQUIREMENTS

Various tribes and ethnic groups with different cultural and religious backgrounds have developed distinctive customs and social requirements. An analysis of the rural family's daily life, including present requirements and future plans, will help in selecting the important factors for designing an appropriate dwelling house.

A number of questions relevant to rural home design are listed below:

Family size: How many persons will live in the house initially and in the future? What are the family relationships: age, sex, marital status?

Sleeping: Are separate bedrooms and/or houses needed for the husband and wife (wives)? Where do small children sleep: in the parent's room or a separate room nearby? Where do the older children sleep: in

a separate room or a separate house? Are children of different sexes segregated?

Cooking/eating: Does cooking take place inside or outside the house, or in a separate structure? Do cooking and eating take place in the same area? Is there a separation between women and men, children or visitors, during mealtimes? What kinds of water resources are available?

Store: How much food is stored, and where? What types of storage conditions are required? What other items need to be stored – fuel, water, implements?

Resting/conversation: What kind of room is required for resting and conversation: an outside verandah or separate shelter, or an inside kitchen or living room? Are men, women and children separated during these activities?

SPECIAL REQUIREMENTS OF RURAL DWELLINGS

Rural families accustomed to working with nature have different needs in a dwelling from those of families in an urban situation. Although many of the basic requirements are the same for both rural and urban homes, additional factors must be considered when designing a rural dwelling. These include:

- A site that is well drained but suitable for a well and, where necessary, either a latrine or a septic tank and drainage field. A home should never be built on a flood plain.
- How the dwelling relates to other rural buildings to provide a view of the access road and the farmstead.
- The correct orientation of the house to give protection against sun, rain, odour and dust, while providing for ventilation, a view and easy access. An east–west orientation to provide the maximum shade is a general rule. However, it may sometimes be desirable to modify this to take advantage of a prevailing wind for better ventilation or to allow more sun penetration into the house in cool highland areas. See Figure 11.2.
- A design that will enable the house to be built in stages according to the availability of finances.
- Flexibility in the arrangement of rooms to allow for alternative uses and future expansion.
- A kitchen large enough to allow for space-consuming activities, such as cutting meat after slaughter and preparation of homegrown vegetables.
- A separate entrance from the backyard into the kitchen area. A small verandah at the rear of the home where some of the kitchen work can be carried out, and perhaps rural/work clothes can be stored.
- A verandah large enough to allow for activities such as eating, resting and receiving visitors. The verandah, along with windows and ventilation openings, may need to be protected against insects with mosquito netting.
- A separate office for larger farms, while a storage cupboard and the dining table will be sufficient for small farms.
- A place to store dirty farm clothes and shoes, combined with washing facilities if possible.
- A guest room if it is likely to be needed.

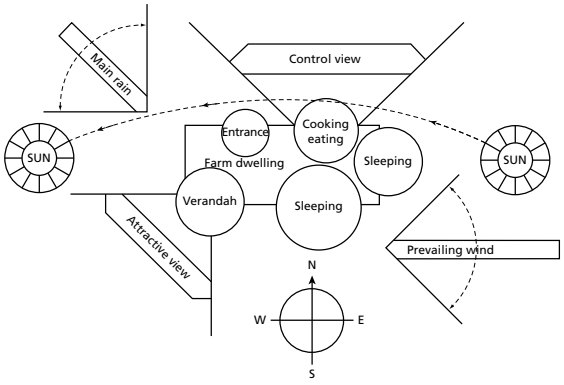


Figure 11.2 **Orientation of a rural dwelling**

CATEGORIES OF RURAL HOUSES

Rural communities may be grouped according to the type of agriculture practised in the area: subsistance, emergent or commercial. The size of the home, the materials used and the method of construction will be influenced by the type of agriculture and the resulting income. The dwelling may range from a self-built structure using local, natural materials and costing little or nothing, to a contractor-built house using mostly commercial building materials and requiring a considerable income to finance. Table 11.1 summarizes various factors relating to housing for the three categories of rural families.

Improvements in layout, design, construction and building materials may allow further development of the rural dwelling; it will also help to extend the lifespan of the dwelling house and make life more comfortable. Table 11.2 summarizes some of the improvements to be expected.

FUNCTION AND COMMUNICATION SCHEMES

Good communications play an important role in the successful management of a farm business. Close supervision and control will help to maximize profits and keep losses to a minimum. Therefore, easy access to ongoing farm activities is imperative. A functionally placed dwelling will serve as a communication centre within the farmstead and will help the farmer to supervise farm operations. Figure 11.3 is a graphic depiction of the dwelling as the centre of farmstead operations.

The human environment and traditional social life have a strong influence on the functional arrangement of rooms within a dwelling. Figure 11.4 attempts to show functional communication between rooms with the essential interconnections.

TABLE 11.1
Summary of factors relating to rural dwelling

	Subsistence farmer		Emergent farmer	Commercial farmer
	Village farmer	Single famer		
Agricultural method used:	Traditional	Traditional	Traditional/modern	Modern
Agricultural products for:	Self-consumption	Self-consumption	Self-consumption/sale	Sale
Income:	Nil - low	Nil - low	Low Medium	Medium High
Dwelling situation:	Village	Plot	Plot/farm	Farm
Design used:	Traditional	Traditional	Traditional/modern	Modern
Building materials used:	Local only	Local only	Mainly local products; few industrial products	Mainly industrial products; few local products
Expected life span of dwelling	5–30 years	5–30 years	30–50 years	50–150 years or more

Traditional house design in east Africa may combine functional and communication requirements in one large multipurpose house with one or several rooms, or in several small one-room single-purpose houses. However, the tradition house designs are rarely used nowadays. This Chapter therefore, concentrates on contemporary plans with varying degrees of privacy and security.

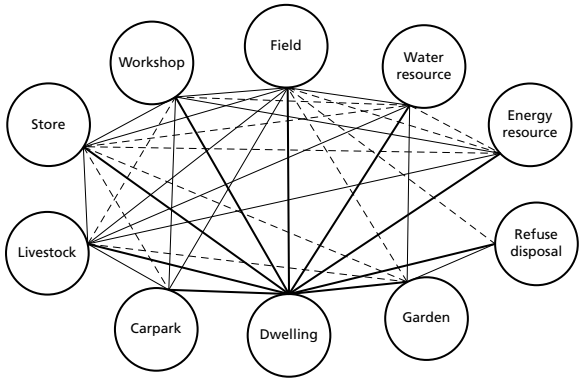


Figure 11.3 **Farmstead functional scheme**

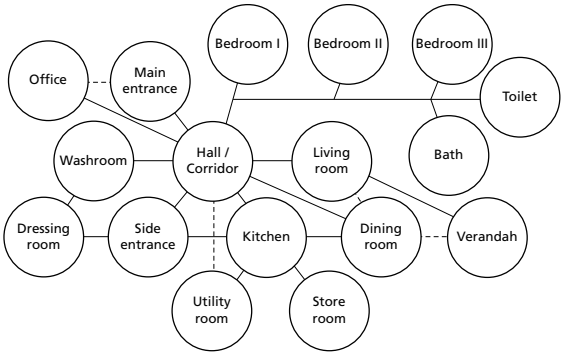


Figure 11.4 **Dwelling house functional scheme**

TABLE 11.2
Summary of improvements in rural buildings

Further improvements	Subsistence farmer	Emergent farmer	Commercial farmer
In layout:	Separation of animal shelters and dwelling	Allowing for further expansion	Functional and flexible farm dwellings
	Nearby water resource	Trees for windbreak and farm use	Future extension
	Trees for wind break		
	facilities like garden, pit latrine etc.	Facilities such as garden and latrine	Carport
In design:	Improvement of traditional design (minimum floor space, minimum room height, etc.)	Design to allow building in stages	Functional design (may consult architect)
In construction:	Proper drainage of surface water	Further training in basic construction	Consult/employ contractor, experienced foreman, etc.
	Raised floor		
	Strong foundation		
	Efficient roof slope		
	Good roof overhang		
In building materials:	Improvement of local building materials, e.g. treatment of wood, surface treatment of walls, etc.	Use of appropriate or improved building materials, e.g. soil-cement, fibre-reinforced roofing, etc.	Use of suitable, well-tested material according to the manufacturer's recommendation

Contemporary designs

Rural areas are rapidly adopting housing influenced by urban culture and industrial building materials. These

designs combine the advantages of privacy, security and improved health conditions without excessive expense for building materials or skilled craftsmen.

Considering the arrangement and communication between rooms, these houses can be divided into four main types, each of which can easily accommodate variations.

External-access type

All rooms have their entrance from outside. Security depends on several expensive outside doors. The lack of internal connection between rooms is often a disadvantage from the functional point of view, but the resulting separation can be advantageous in situations such as an extended family or a change of owner (see Figure 11.5).

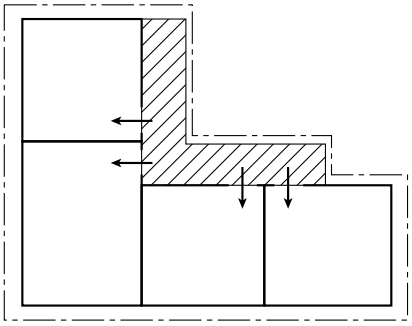


Figure 11.5 **External-access type**

Courtyard type

This type, shown in Figure 11.6, resembles the previous design but the rooms have their entrances from an enclosed yard, which improves the security and privacy of the house.

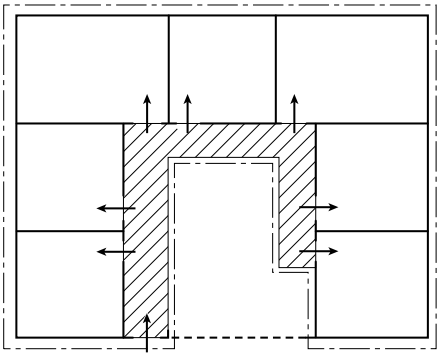


Figure 11.6 **Courtyard type**

Corridor type

All rooms have an entrance from a corridor running through the house, as shown in Figure 11.7. This type provides good security and privacy. However, a long corridor tends to be dark and may be considered as wasted space.

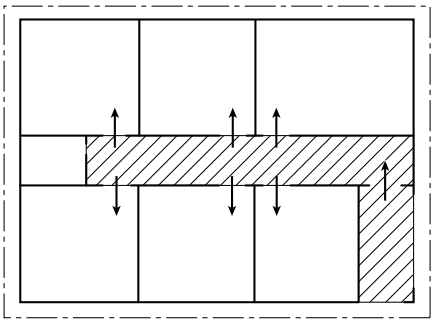


Figure 11.7 **Corridor type**

Central-room type

Instead of a corridor, a central room, such as the meeting or dining room, provides access to the other rooms, as shown in Figure 11.8. While security is very good in this type of house, the central room must be large enough to allow space for both circulation and furnishings for its primary purpose.

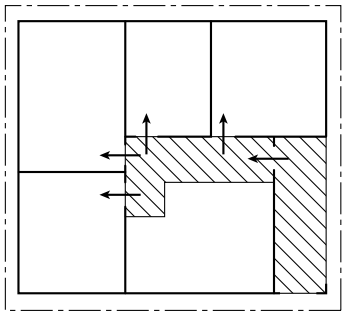


Figure 11.8 **Central-room type**

FUNCTIONAL REQUIREMENTS FOR DIFFERENT ROOMS AND SPACES

Farm families have different needs for rooms and space, depending on their daily activities, way of life and financial resources. The following recommendations range from the basic needs for a subsistence farming family to the high standards required by an affluent commercial farmer. Accordingly, a design should be chosen that best suits the needs of each farm family.

Sleeping

One of the most obvious purposes of a house is to provide shelter for comfortable sleeping. The sleeping rooms need to be clean, well-ventilated, dry and well-lit by day. The minimum floor area for a bedroom should ordinarily be no less than 6 m² with a minimum floor area of 3 m² for each person accommodated (see

Figure 11.9). In hot, humid climates cross-ventilation is essential, while in highland areas it may be difficult to achieve both adequate ventilation and protection against the cold nights. Insect mesh protection for windows and ventilation holes is recommended in mosquito-infested areas.

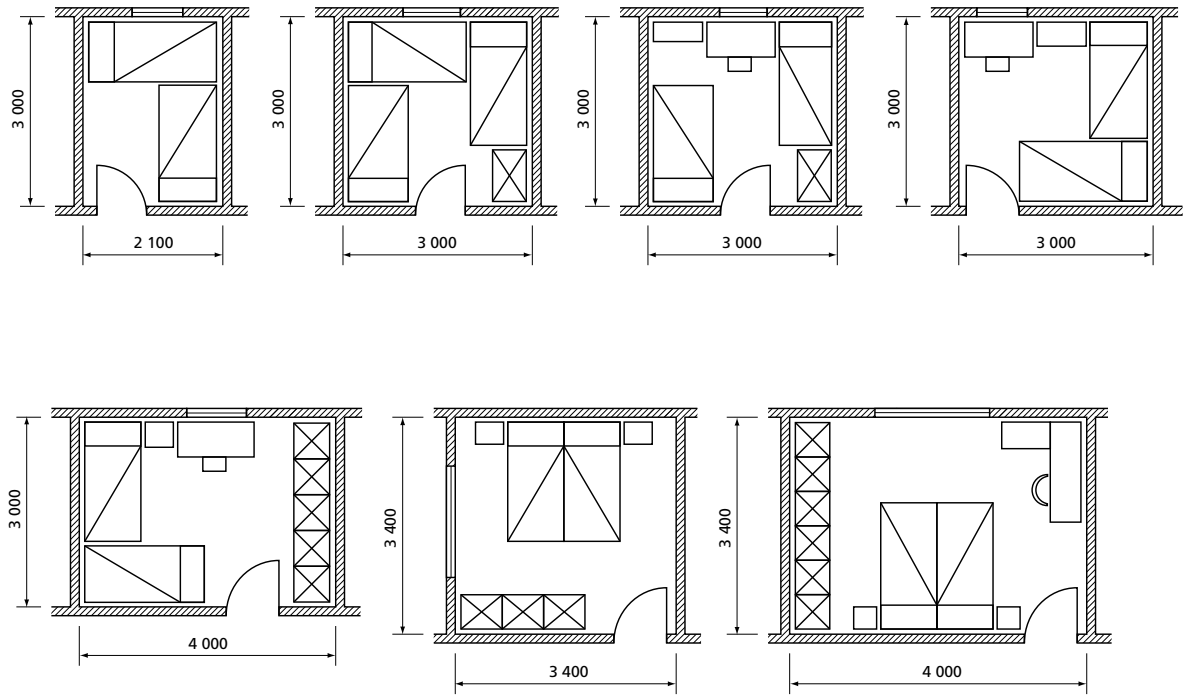


Figure 11.9 **Recommended sleeping spaces**

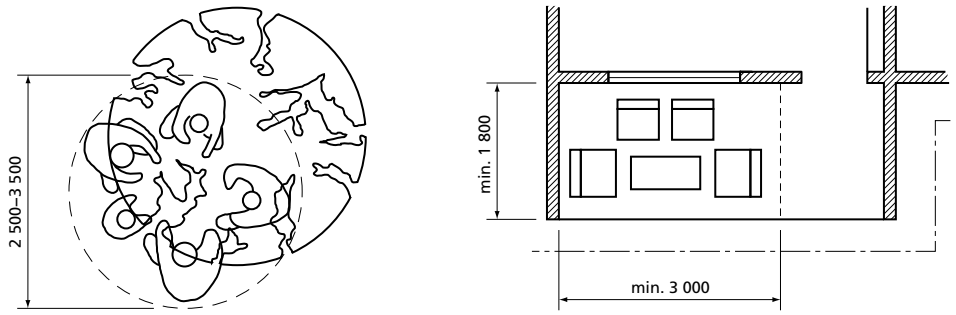


Figure 11.10 **Minimum spaces for outdoor meeting/rest**

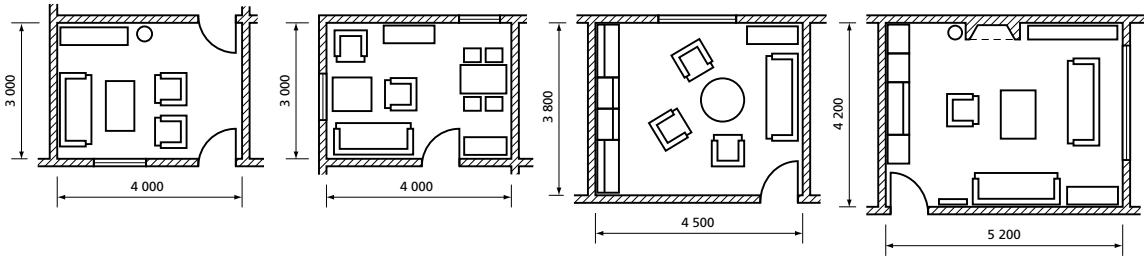


Figure 11.11 **Recommended indoor space for meeting/rest**

Meeting and rest

An important facet of African daily life is a place to meet to talk with family and friends or simply to sit down to rest. To a large extent, this activity takes place outdoors in the shade of a tree, a separate shelter or a verandah. In order to function well, this outdoor space should not be less than the recommendation given in Figure 11.10.

There should also be some indoor space, such as a living room, for similar activities during the evening and in inclement weather. A room with a minimum floor space of 12–15 m², furnished with chairs and tables, will ordinarily be sufficient (see Figure 11.11). Although not an ideal solution, this room can be used for sleeping by children or older boys. If the room is to be more elaborately furnished, an increase in floor space of up to 25–30 m² may be needed. Cupboards, bookshelves, a television, fireplace and other amenities may be included.

Taking meals

Traditionally, meals are eaten either indoors or outdoors, utilizing the same space as for meeting and resting. In some cases, dining is a strictly private matter (out of sight of neighbours) and may even take place in separate groups (men, women, children). In contrast, other families may eat together as a group with no particular desire for privacy. Depending on the culture, in one home it may not be appropriate to have a separate dining room, while in another such a facility will be appreciated. Figure 11.12 gives the recommended space for taking meals indoors.

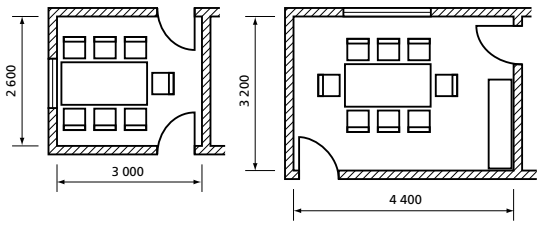


Figure 11.12 **Space for taking meals indoors**

Preparing and cooking food

Once again, cultural and tribal customs may determine whether food is prepared and cooked inside or outside the house. In areas where nights are cold, it may be desirable to cook inside to conserve the warmth, while in warm, humid areas it may be preferable to cook outside the dwelling. In either case, the cooking area should be kept clean and raised above the ground to ensure basic hygiene.

Outdoor cooking facilities in a separate shelter or on a small verandah need to be protected from sun, rain, dust and animals. Food preparation and cooking inside the house require good ventilation, enough openings for lighting and nearby access to the backyard.

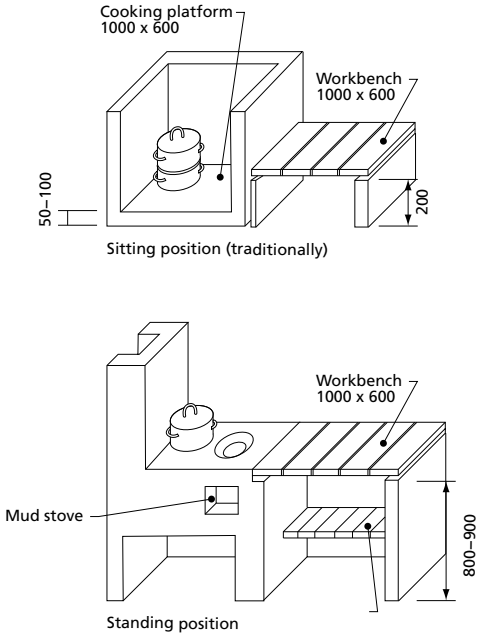


Figure 11.13 **Working levels for food preparation and cooking**

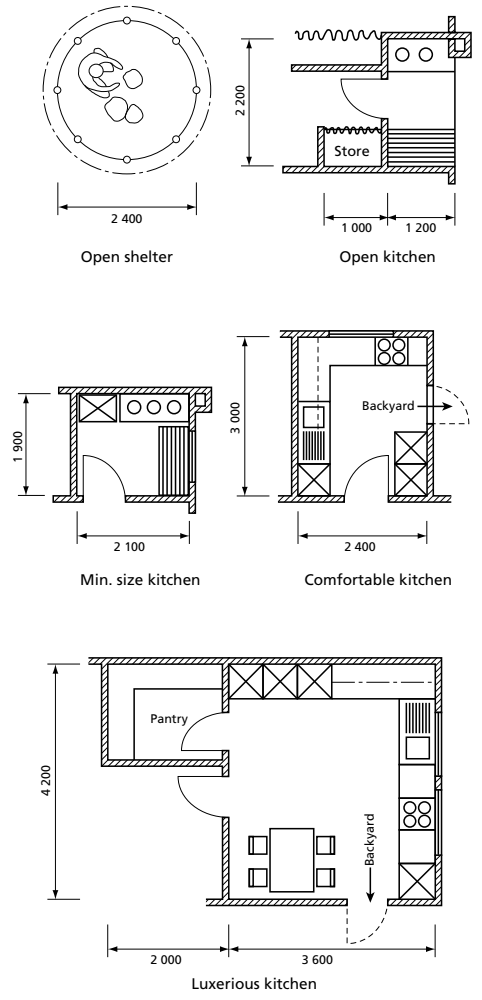
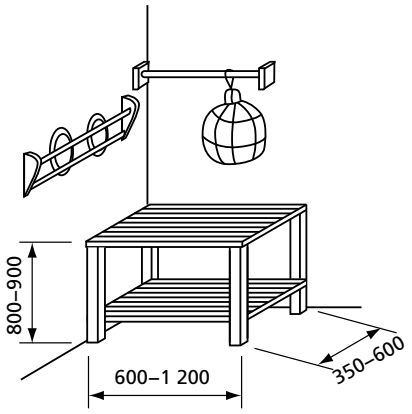
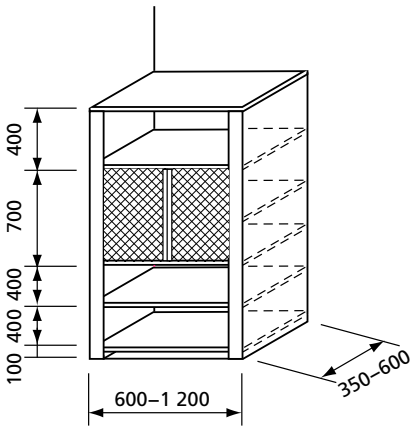


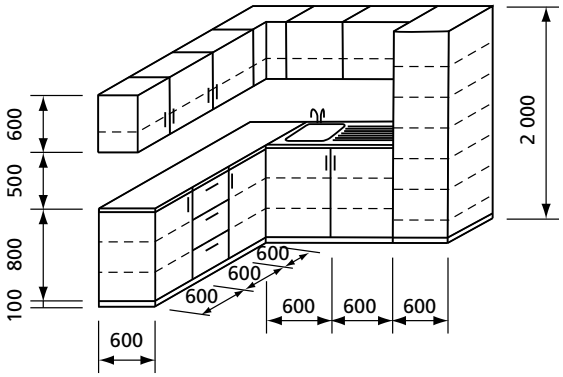
Figure 11.14 **Recommended arrangements for cooking**



Combined workbench, shelves, rack, rail etc.



Cupboard made of bricks and wooden shelves



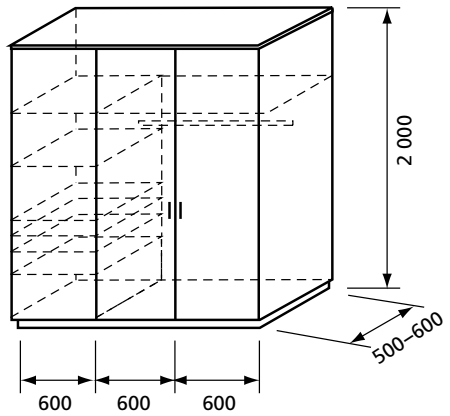
Industr. produced kitchen furnishing

Figure 11.15 **Storage of food and kitchen equipment**

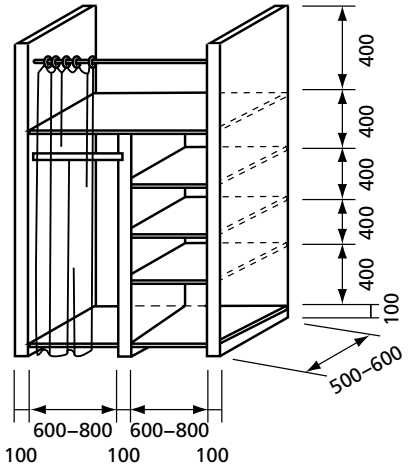
Storage

In a farm dwelling, space is needed to store foodstuffs, kitchen equipment (pots, pans, dishes), clothing and bedding, fuel (fuelwood, charcoal), and perhaps some small farm tools (hoes, spades, machetes). Small items, such as foodstuffs, kitchen equipment and textiles, may be stored in the rooms for cooking, sleeping and meeting. Larger items need a separate store, which may be another room in the house or part of an outbuilding. Kerosene should be stored outside the house.

Kitchen utensils and foodstuffs kept in pots or containers should be raised off the ground for storage. They may be either hung from the roof, or placed on racks or shelves or in kitchen cabinets. A separate store will be needed for larger quantities of grain or produce.



Cupboard made of wood with shelves and drawers



Cupboard made of bricks, wooden shelves, curtains

Figure 11.16 **Storage for clothing and bedding**

Clothing and bedding and small personal belongings should be stored in a clean, dry place, well protected from dust. Boxes and built-in shelves are adequate and inexpensive. Cupboards are more convenient and more dustproof but are somewhat more expensive.

Recommendations for the space required for separate storerooms for foodstuffs and larger items, such as fuel and equipment, are given in Figure 11.17.

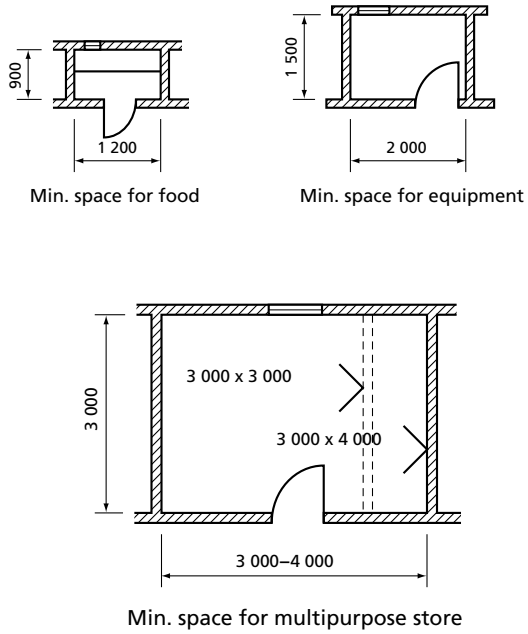


Figure 11.17 **Recommended spaces for separate storerooms**

Washing

Personal washing and the washing of dishes and clothes takes place either inside or outside the dwelling, depending on the availability and source of water (stream, lake, well, piped). If washing takes place inside the house, it is important to deal with the waste water.

Well-drained surfaces and a properly constructed soakaway will avoid muddy areas and breeding places for mosquitoes. Easily cleaned, waterproof materials should be used inside the house. Floors should slope towards a drain leading to a soakaway.

For washing dishes and clothes outside, an easily cleaned, hard surface of at least 3 m² will be necessary. An open shelter and a workbench are recommended improvements. Clothes are usually washed inside the house in the bath or in a separate utility room, while dishes are washed in a kitchen sink or basin.

Personal washing, if not performed in a nearby stream or lake, can be carried out in a simple shelter constructed near the home. A drain and a soakaway are essential. The section on Aqua Privies in Chapter 19 discusses and illustrates a combination bathhouse and lavatory. Personal washing inside the house requires a well-ventilated room finished with waterproof and easily cleaned materials.

If piped water is available, a flush toilet is desirable. A septic tank and drainage field will be necessary with a flush toilet. Figure 11.18 shows space requirements and facility arrangements for various combinations, ranging from a simple washroom to complete bath and toilet facilities.

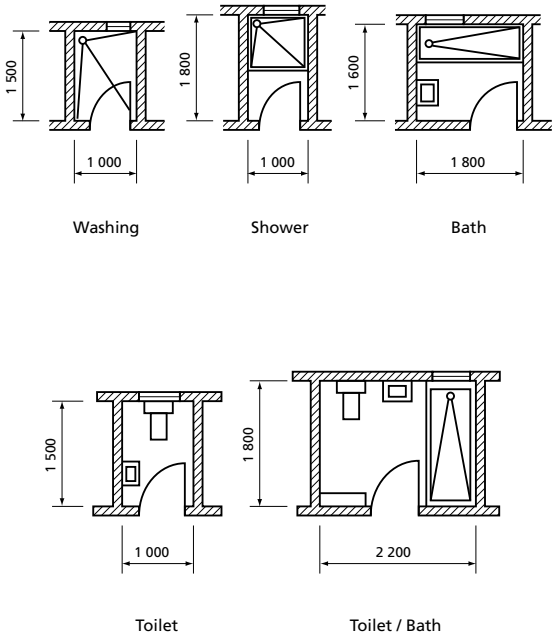


Figure 11.18 **Recommended space for indoor toilet and bathing facilities**

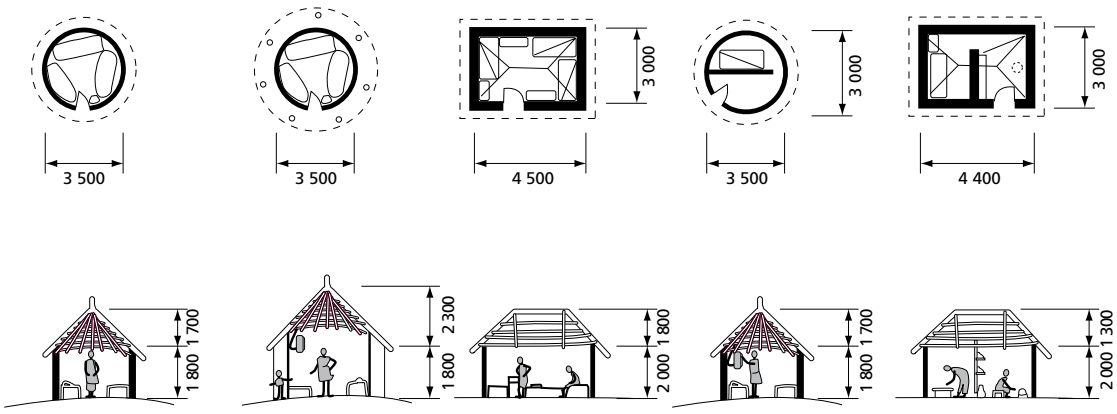


Figure 11.19 **Traditional homes for sleeping, or sleeping and cooking**

Reading and writing

The education level of the rural population is rising steadily, and places to read and write are becoming more necessary for the farm home, especially for children going to school. While the sleeping room may provide the best place in terms of privacy, the meeting room and verandah are possible, but less appropriate, places for intensive studying.

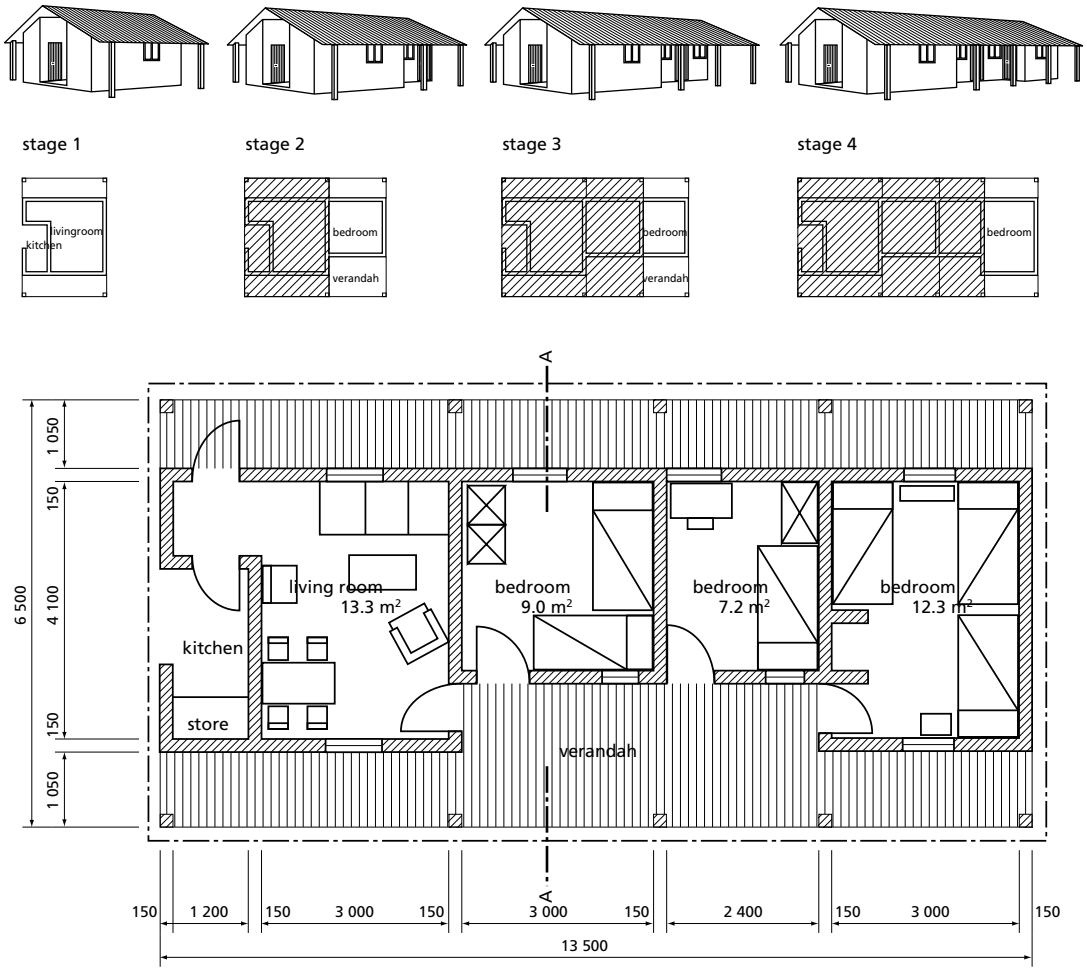
The farmer also needs a place to store documents and records and to attend to the farm business. The dining table, in combination with a cupboard, is sufficient for the small farmer, while on a large farm, a separate office with about 9 m² of floor space may be required. Good natural lighting and artificial lighting are essential wherever reading and writing are carried out.

Entrance

The traditional African house has an entrance protected from wind, rain and sun by a roof overhang, which also provides privacy for the family. In a low-cost farm dwelling the entrance may be combined with the verandah or the main meeting and resting room, and is often used for additional storage space for equipment, farm clothing, bicycles, etc. A larger, more modern farm dwelling should have at least two entrances: one at the front of the house where visitors are received and another near the kitchen or utility room that can be used for coming and going while performing daily tasks around the home and farmstead.

IMPROVEMENT OF EXISTING DWELLINGS

In many cases, improvements can be made to existing homes similar to those shown in Figure 11.19, at little or no cost. For example, separating the animals from the dwelling and installing a well-designed latrine should improve sanitary conditions. Developing a nearby water supply of adequate quantity and good quality will make life easier for the women. A mud stove will



PLAN (stage 1 - 4)

Figure 11.20 **Improved farm dwelling design based on a design by Malawi Government/United Nations Development Programme (UNDP)/United Nations Centre for Human Settlements (UNCHS): Rural Housing Project**

save fuelwood and contribute to the conservation of forest resources. However, the waste heat from a traditional fireplace may be needed for warming the home in cool climates.

Another desirable improvement in many rural homes is additional backfilling with soil to raise the floor level to 10–15 cm above the outside ground level. Unfortunately this will sometimes make ceiling and door heights undesirably low. Cut-off drains will also help to prevent surface water from entering the home. Although a waterproof foundation may be difficult to install in an existing house, it will be helpful in preventing moisture from penetrating the floor and lower walls.

CONTEMPORARY FARM DWELLINGS

For the rural family that chooses to use one of the expandable systems shown in Figures 11.20 and 11.21, a number of local materials are suitable. A foundation of stone, brick masonry or concrete is desirable, on top of which adobe blocks, mud and poles or stabilized soil blocks can be used for the walls. While corrugated steel makes a clean, leakproof and durable roof, where it is available, thatch is less expensive and perfectly satisfactory. Thatch will require a roof slope of approximately 45 degrees and the frame should be built high enough to ensure that the eaves are a minimum of 2 metres above the ground. An overhang in the verandah areas will require support, as shown in the figures.

Where resources allow, the same designs shown in Figures 11.20 and 12.21 may be built with concrete foundations and floors, along with durable masonry walls made of brick, concrete blocks or other available material. The temperature extremes typical of corrugated roofs can be reduced by installing insulated ceilings. The final result will be a secure, easily cleaned and durable home. Although it is considerably more expensive than a dwelling made completely of local materials, this type of construction should be feasible for the emerging farmer who is producing some crops or animals for the commercial market.

Due improved economical situation, especially for commercial farmers, some rural buildings for dwellings are adaptations of modern designs such as that shown in Figure 11.22.

FARM WORKSHOP FACILITIES

A workshop provides a focal point on the farmstead for the repair and maintenance of machinery, implements and structures. It also provides a place where tools can be stored in an orderly manner, a store for supplies and spare parts, and a shelter where work can be carried out during inclement weather. A facility of this type should be available on every farm. However, the size and design of a workshop should be commensurate with the size of the farm and the work to be carried out in the workshop.

The smallholder may be adequately served with a storage cupboard for tools that can be locked for security, and a workbench with a simple home-made vice for holding tools while they are being sharpened or fitted with new handles. From this simple beginning, a more complete facility may gradually evolve as the farm operation grows and more equipment is required. As repair tools and supplies represent a considerable investment, most farmers will want to store them in a secure place.

Many small-scale farmers will not require a separate store for this purpose but, if stored together with hand tools and small implements, the number of items may prompt the farmer to build a storeroom by enclosing part of the workshop with solid walls. Figure 11.23 shows a simple work shelter and store suitable for repair work and the storage of small implements. Note that the doors to the store may be designed with racks and hooks to hold supplies and tools. Fuels and other combustible materials should not be stored with the tools. A simple workbench and vice can also be housed under the shelter.

At the other extreme, a large ranch or commercial farm may need a separate building with extensive equipment for maintaining farm machinery, tractors and vehicles. Farmers may also use their workshop to

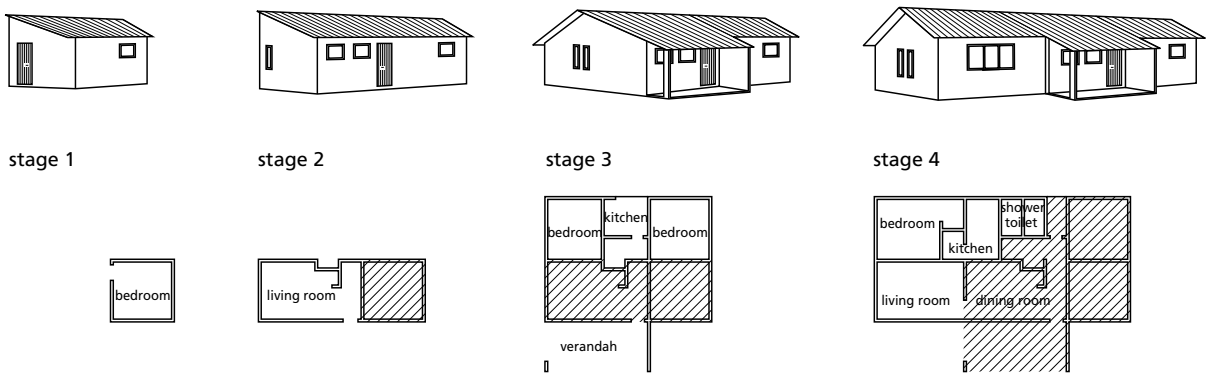


Figure 11.21 **Improved farm dwelling design: Ministry of Agriculture and Water Development, Zambia**

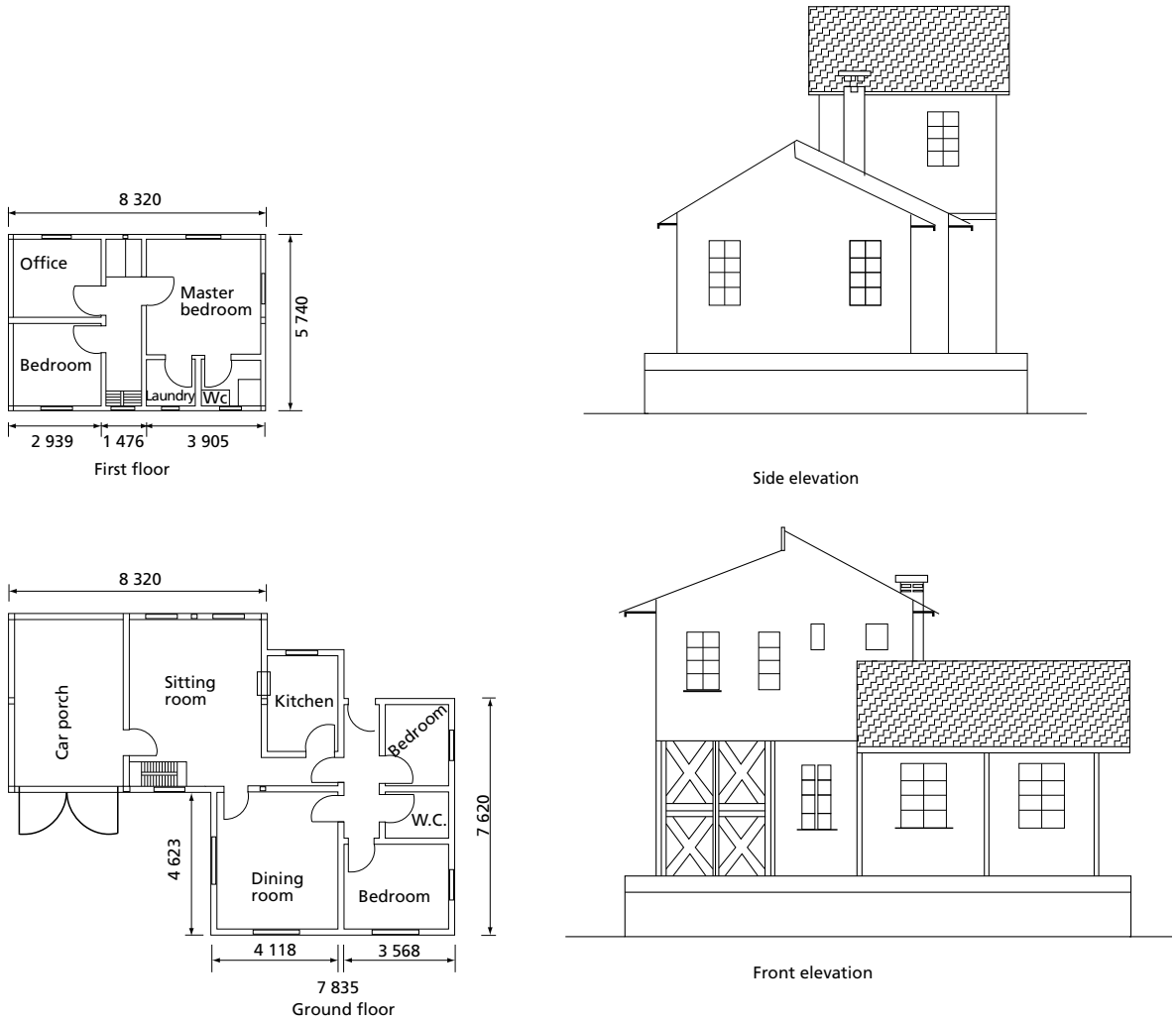


Figure 11.22 **Modern rural building (Courtesy of R. Mathenge)**

carry out routine repairs and preventive maintenance during the off-season, to build or modify some of the equipment used on the farm and to prefabricate building elements to be used in construction projects.

The workshop facilities should be cost-effective. That is, enough savings should be generated from timely maintenance, repairs and construction projects to pay for the cost of the building and the necessary tools and equipment. Although it is difficult to put a monetary value on timeliness, there is no question that it is important to be able to make emergency repairs. Some farm operations (such as planting, spraying and milking) are more sensitive than others to prolonged interruptions, and having facilities to complete repairs on the farm can reduce delays to a minimum.

Other factors, apart from the farm size, which will influence the scale of the workshop facilities, are the number and diversity of machines, the availability of service from dealers, and the interest and mechanical skill exhibited by the farmer and farm labourers. If necessary, a skilled mechanic may be employed. Without qualified personnel to use the workshop it becomes questionable in value and may even contribute to more frequent breakdowns and additional expense resulting from careless work.

The workshop should be located close to the work centre of the farm and convenient to the farm home, on ground that is well drained and sufficiently level to allow easy manoeuvring of equipment. Where electric power is available, proximity to the power source should be considered.

In tropical climates, the workshop may be a simple pole structure with a non-flammable roof. Unless dust is a problem, it may be feasible to leave the sides open to provide good light and ventilation. Heavy-gauge wire netting can be used to make the area more secure without reducing light or ventilation. A pole structure of this sort can be enclosed with offcuts or corrugated steel at a later time but, if this is done, there must be provision for several good-sized windows.

While a simple earth floor is often satisfactory, concrete offers the advantage of an easily cleaned, level surface. To do a clean repair job, a clean work area is essential, and this is particularly important

when lubricated mechanisms are reassembled. The level surface is helpful in some assembly or alignment operations.

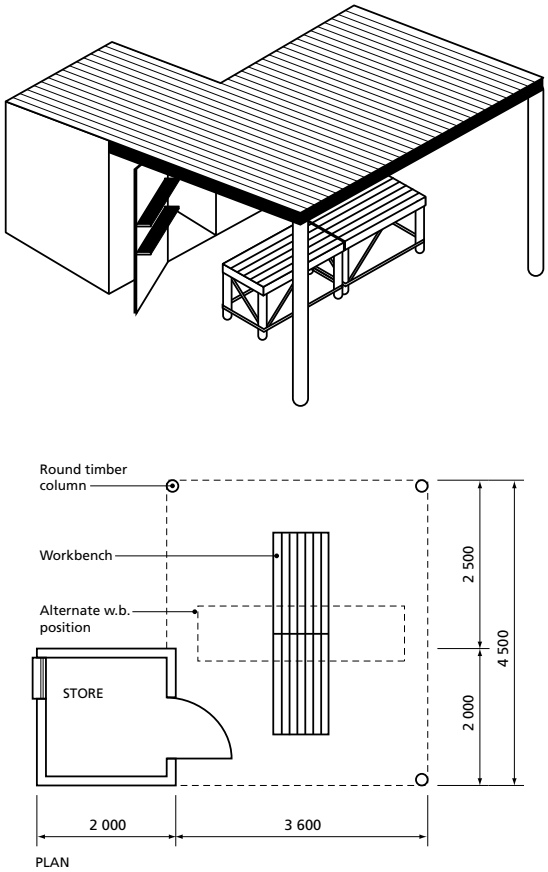


Figure 11.23 **Small farm workshop with a secure storeroom**

The following additional features are important for a safe and efficient workshop:

1. Sufficient room for the largest machine that may need repair, including workspace around it. If the machine is large, truss roof construction may be needed to provide the required space without intermediate supports.
2. An entrance that is both wide enough and high enough for the largest equipment that the workshop has been designed to accommodate. If the building is enclosed with either solid walls or wire netting, a second door is essential for safety in case of fire.
3. Some means of lifting and supporting heavy loads. When the roof span is 3 metres or less, a timber beam is often adequate. For larger spans or very heavy loads, a truss will be required. Alternatively, a portable hoist can be used.
4. Electric lighting and electrical sockets for power tools.
5. A water supply for both convenience and safety.
6. One or more fire extinguishers of a type suitable for fuel fires. Two or three buckets of dry sand are a possible substitute or supplement for a fire extinguisher.
7. Storage cabinets for tools, supplies and spare parts. Sturdy doors can be locked for security, as well as providing space to hang tools and display small supplies for easy access.
8. A heavy workbench attached to the wall or otherwise firmly supported. It should be 1 metre high, up to 800 mm deep and at least 3 metres long, and equipped with a large vice. There must be sufficient clear space around it to manoeuvre work pieces and, if attached to a solid wall, ample window openings above it to provide light.

Equipment needed in the workshop will depend on the type and extent of work to be done. Generally this means the tools required to perform day-to-day maintenance on machines and to carry out general repair work and small construction jobs on farm buildings and equipment.

However, any workshop, regardless of size, will need some simple woodworking tools, some means of sharpening field tools, and wrenches (spanners) of various types and sizes. If the workshop equipment includes a welder, in the interest of safety it should be located away from the woodworking area and preferably near the main door where it can be used conveniently inside or outside the building.

Flammable materials, such as sawdust, shavings and oily rags, must never be allowed to accumulate in the workshop as they represent a fire hazard, and fuels should be stored in a separate area. Generally speaking, good order and cleanliness in the workshop makes for efficient work, convenience and safety.

MACHINERY AND IMPLEMENT STORAGE

On many small-scale farms in Africa, all cultivation and transport operations on the farm are performed manually. The few small hand tools and implements used for such farming can normally be stored in any multipurpose store at the farmstead. The store needs to be secure to protect the equipment from theft and vandalism, and dry to avoid deterioration of the metal and wooden parts.

The tools will last longer if they are cleaned and working surfaces are greased prior to storage. The tools may be hung on rails or hooks on the wall, or from the ceiling, for order and convenience and to protect them from dampness penetrating an earth floor in the store.

Implements such as ploughs, harrows and cultivators suffer little rust damage when left outdoors. If they are properly cleaned prior to storage, and metal surfaces, particularly all threaded parts used for adjustments, are greased, then a little rust is not likely to harm performance enough to justify the cost of a storage structure. A fenced compound can offer adequate protection against

theft during storage. Although implements containing wooden parts are more susceptible to decay, these parts can usually be replaced at low cost.

Tractors and other complex machines will function better when needed if they have been stored under cover and given a complete off-season check-up. An adequate storage structure for these machines is likely to be economically justifiable.

For most purposes, a narrow open-sided shed with a well drained, raised earth or gravel floor will be adequate for machinery storage. The sides of the building can be partly or wholly enclosed with netting or solid walls when security conditions make this necessary. The building must be high enough to accommodate the tallest machine. A smooth, level floor makes it easier to attach and detach tractor-mounted equipment or to move other machines.

The space required can be determined by obtaining the dimensions of all the machines and implements to be stored. Then, using graph paper, the outline of the machines can be sketched onto a plan view, allowing additional space for manoeuvring. Any roof-supporting posts inside the building or in the open sides must be marked on the drawing because they will restrict the way the floor space can be utilized. In many cases machines cannot be moved easily, so it is desirable to arrange the stored machines in such a way as to make shifting them unnecessary.

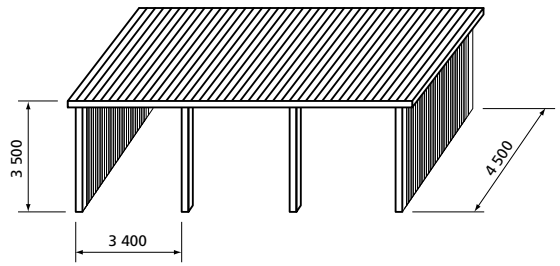


Figure 11.24 **Narrow open-sided implement shed**

Fire-resistant construction is desirable where tractors, cars and other powered machines are stored. A pole structure with an earth floor, sheet metal walls, timber trusses and metal, asbestos–cement or sisal–cement roofing will provide adequate fire resistance.

Machinery stores and farm workshops are constructed in much the same way and are usually placed close together for convenience. In fact, they may be housed in one building with a workshop section at one end and machinery and implement storage in the rest of the building.

FUEL AND CHEMICAL STORAGE

Many materials that are used on farms fall into the category of 'hazardous materials' because they are either highly flammable or poisonous. The type and quantities of these materials requiring storage will vary from one farm or one cooperative store to the next, and only a few basic requirements for safe storage will be considered here. Other materials frequently used on farms, such as fertilizers and cement, also have special storage requirements, mainly because they are hygroscopic, i.e. they tend to absorb moisture from the atmosphere.

Storage of hazardous products

Hazardous materials stored on farms normally include the following:

1. *Highly flammable materials* such as engine fuels and oils (petrol, diesel, kerosene and lubricating oils).
2. *Gases* such as butane, propane and acetylene. Oxygen promotes the combustion of other materials and must be handled carefully.
3. *Paints* containing flammable solvents, cellulose thinner or alcohol.
4. *Poisonous materials* such as herbicides, insecticides, rat poison, sheep dip and cattle dip.
5. *Acids and alkalis* such as detergents, cleaning liquids, lye and quicklime (CaO).
6. *Medicines* such as veterinary drugs and supplies. Some drugs may require refrigeration.
7. Wood *preservatives* and corrosion-inhibiting paints.

Hazardous materials should always be stored in a separate location containing only these materials. Larger quantities of flammable and poisonous materials should be stored in separate rooms. Ideally, each type of material should be given its own storage space, with its own shelf in a cupboard or a storage room, or its own room in a cooperative or merchant store.

Quantities of flammable products greater than about 3 litres of cellulose thinner, 10 litres of petrol, 20 litres of kerosene or 50 litres of diesel fuel should be stored in a separate building at least 15 metres from any other building. For this purpose, a pole building with steel netting walls offers shade and security.

Any store for hazardous products must be well-ventilated to prevent the accumulation of explosive or toxic fumes. Ventilation openings should be provided at both low and high levels, or alternatively the door can be covered with netting. The store, including the ventilation openings, should be vermin-proof to prevent rodents from breaking open packages. It must be possible to lock the store to prevent the theft of expensive materials and to keep unauthorized persons, in particular children, from accidentally coming into contact with the hazardous materials.

Some chemicals are harmful to the skin. Washing facilities should therefore be available nearby for immediate use. Stores for hazardous materials should never have a drain in the floor, as no spillage or washdown water containing the materials must be allowed to enter any watercourse or drinking water

source. It is frequently recommended to construct the floor and lower part of the walls, including the door sill, with concrete to form a reservoir to hold any accidental spills. This type of store must be clearly marked with an appropriate warning notice.

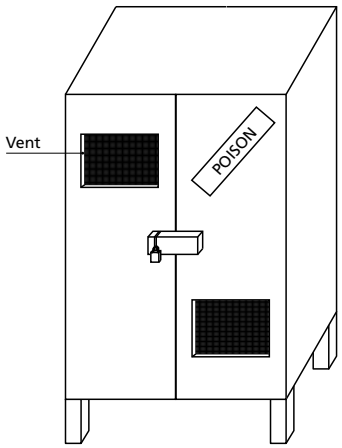


Figure 11.25 **Cabinet for the storage of chemicals**

Storage of fertilizers and other non-hazardous materials

Some fertilizers are hygroscopic and easily absorb moisture from humid air or from the ground. This causes them to become lumpy and to deteriorate. Cement, although not very hygroscopic, will deteriorate if exposed to damp conditions. Other materials may be adversely affected by prolonged exposure to high storage temperatures and therefore must be shaded. Fertilizers and cement are normally sold in plastic lined bags offering some degree of protection. They should be handled and stored in such a way as to avoid the bags being punctured or otherwise damaged.

In addition, the storage conditions should be as dry as possible. Bags should be placed on a raised platform in the store. This allows ventilation and prevents ground moisture from penetrating from below. The pile should be protected from rain by a roof or some other type of watertight cover. Fertilizer can be very corrosive to metals and should not be stored close to machinery or tools.

REVIEW QUESTIONS

1. Why do you need to calculate space requirements in a rural dwelling?
2. Which factors would you consider in the design of rural houses?
3. Briefly describe the functional requirements for different rooms and spaces of a rural house.
4. Outline features that are important for a safe and efficient workshop in a rural setting.
5. Briefly describe the types of hazardous products that are usually stored on farms.

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Chapter 12
Fundamentals of heating and cooling

HEAT TERMINOLOGY

Heat is a form of energy. The molecules of a body are in constant motion and possess kinetic energy, referred to as heat.

Temperature is the intensity of heat, i.e. the velocity of the molecules. Under the Système Internationale (SI) system, it is measured in degrees celsius (centigrade) or kelvin (absolute).

Ambient temperature is the temperature of the medium surrounding a body, e.g. the air temperature within a building.

Quantity of heat is measured in joules (J). One calorie of heat will raise 1 gram of water 1 kelvin. This equals 4.187 joules.

Sensible heat is the heat that causes a temperature change when there is a heat transfer, e.g. heat moving through the walls of a home causing a temperature rise.

Latent heat is the heat that causes a change in state but no change in temperature, such as heat that is absorbed when ice changes to water, or when boiling water changes to vapour. However, water will evaporate to vapour over a wide range of temperatures. When air moves across the surface of water, some of the air's sensible heat is converted to latent heat, causing the air temperature to drop. The latent heat of vaporization changes with temperature:

°C	kJ/kg
0	2 500
30	2 430
100	2 256

Thermal capacity is the ability of a material to absorb and hold heat. It is measured in J/(kg.K). The thermal capacity of water is 4 187 J/(kg.K) or 4.187 J/(g.K).

Specific heat is the dimensionless ratio between the thermal capacity of a material and that of water. However the actual thermal capacity measured in J/(kg.K) is often listed as specific heat.

Total heat content. Bodies with great mass can store large quantities of heat, even at low temperatures. For instance, thick masonry walls are slow to warm up during the hot daytime and slow to cool down during a cool night. A match has a high temperature and little heat content. A large tank of water may have a low temperature but still possess a large content of heat.

HEAT TRANSFER

Basic to any discussion of insulation and ventilation is an understanding of the way heat is transferred. Heat is transferred whenever there is a temperature difference, by conduction, convection, radiation or a combination of these methods.

Conduction

In conduction, heat energy is passed from molecule to molecule in a material. For heat to be conducted, it is essential to have physical contact between particles and a temperature difference. Thermal conductivity is a measure of how easily heat is passed from particle to particle. The rate of heat flow depends on the temperature difference and the thermal conductivity of the material. The rate of heat conduction through a substance is given by Fourier's equation:

$$q = -kA\left(\frac{\Delta T}{\Delta L}\right)$$

where:
q = heat conduction rate (W)
k = thermal conductivity of material ($W/m^2.°C$)
A = cross-sectional area normal to the direction of heat flow (m^2)
ΔT = temperature gradient (°C)
ΔL = thickness of the material conducting heat (m).

Convection

Heat is transferred by convection when a heated liquid or gas (often air) actually moves from one place to another, carrying its heat with it. The rate of heat flow depends on the temperature of the moving fluid and the rate of flow. Convection transfer can occur in any liquid or gas. The rate of heat transfer by convection is:

$$q_c = h\,A(T_s - T_\infty)$$

where:
q_c = convective heat transfer rate (W)
h = heat transfer coefficient ($W/m^2.°C$)
A = surface area (m^2)
T_s = surface temperature (°C)
T_∞ = free stream fluid temperature (°C).

Radiation

Heat energy can be transferred in the form of electromagnetic waves. These waves emanate from a hot body and can travel freely only through completely transparent media. Heat cannot move by radiation through opaque materials, but instead is partially absorbed by and reflected from their surfaces. The atmosphere, glass and translucent materials pass a substantial amount of radiant energy, at the same time absorbing some and reflecting some. Although all surfaces radiate energy, there will always be a net transfer from the warmer to the cooler of two surfaces facing each other, which is calculated as:

$$q_r = F_e F_a A \sigma (T_1^4 - T_2^4)$$

where:

q_r = radiative heat transfer rate (W)

F_e = radiation factor allowing for part of the radiation being re-radiated to the body it came from (dimensionless)

F_a = a geometric factor allowing for size, slope, and orientation of the two bodies (dimensionless)

A = surface area of the smaller of the two bodies (m^2)

σ = Stefan–Boltzmann constant (5.67×10^{-8} $W/(m^2.K^4)$)

T = absolute temperatures of the radiating bodies (K).

THERMAL RESISTANCE OF BUILDING COMPONENTS

The calculation of temperatures within buildings, or of heating and cooling loads, requires knowledge of the thermal conductivity, specific heat capacity and density

TABLE 12.1
Thermal properties of building and insulating material

		Conductivity (C)		Thermal resistance		
Material (thickness used)	**Density kg/m³**	**Per metre W/(m.K)**	**As used W/(m².K)**	**Per metre (m.K)/W**	**As used (m².K)/W**	**Specific heat J/(kg.K)**
Air surface - still	1.2		9.09		0.11	1 012
0.5 m/s	1.2		12.50		0.08	1 012
3.0 m/s	1.2		25.00		0.04	1 012
Air space, wall, Dull surface	1.2		6.25		0.16	1 012
One shiny surface (See Table 10.2 for ceiling spaces)	1.2		1.64		0.61	1 012
Asbestos-cement board (6 mm)	945	0.19	33.33	5.26	0.03	840
Bark fibre	48	0.045		22.22		1 700
Bitumen floor	960	0.16		6.25		1 470
Brick, adobe (300 mm)			4.17		0.24	300
Common (110 mm)	1 760	0.65	5.88	1.53	0.17	920
Concrete, solid, dense	2 400	1.45		0.69		880
solid coarse	2 000	0.91		1.10		800
hollow block 100 mm	1 450		7.69		0.13	880
200 mm	1 375		5.00		0.20	880
Sand and sawdust	1 600	0.65		1.54		300
Coconut husk fibre	48	0.53		1.89		
Gypsum plaster (15 mm)	1 220	0.37	2.44	2.70	0.041	1 090
Gypsum board (15 mm)	1 220		12.50		0.08	1 090
Mortar, cement (15 mm)	2 000	1.12	76.92	0.89	0.013	795
Plywood, 5 mm	530		12.50		0.08	
Polystyrene (-38 °C)	16	0.039	0.78	26.64	1.28	340
(-18 °C)	16	0.030	0.60	33.33	1.67	340
Polyurethane (50 mm)	24	0.025	0.50	40.00	2.00	450
Rockwool or glass-wool (50 mm)	32-48	0.033	0.66	33.30	1.52	900
Soil (14% moisture)	1 200	0.37		2.70		1 170
Straw (50 mm)	75-200	0.042	0.81	23.81	1.24	1 050
Shavings	190	0.06		16.67		
Tile, clay roof (19 mm)	1920	0.84	43.48	1.90	0.023	920
Timber, Pine radiata (25 mm)	506	0.10	4.00	10.00	0.25	2 090
Water	1 000	0.60		1.67		4 190

of the construction materials. The thermal resistances of air films adjacent to surfaces, and of air spaces, are also required and, as the latter are dependent on the emittances of surfaces, data on these parameters are also needed.

Table 12.1 contains a list of materials with their thermal properties. The thermal resistance, which is the quotient of thickness and thermal conductivity, has been given and, where appropriate, for the material thicknesses most commonly used. As in most cases there is a linear relationship between thickness and thermal resistance, other values are readily calculated.

This may not be the case for granular materials when the grain size becomes comparable with the thickness and therefore caution should be shown when assigning resistance values to such materials.

Insulating materials

The choice of an insulating material will depend on the application, availability and cost. Loose granular materials work best when installed above a ceiling or poured into existing wall cavities. Batting or blanket materials are easiest to install as walls are constructed. Rigid insulating boards may be placed under concrete floors or cemented to masonry walls.

Reflective surfaces, such as aluminium foil or paint, are most effective when exposed and not in contact with other materials. They are also more effective in preventing the downward flow of heat and in relatively high-temperature applications.

Local natural materials, such as straw, shavings or coffee hulls, while not as resistant to heat flow as commercial insulation, may be the material of choice because of their availability and low cost. A greater thickness will be required when using natural materials, but they may not be as fire- and vermin-resistant.

Selecting insulation

The following factors should be considered when selecting insulation material:

- R-value: the higher the R-value, the better the insulation.
- Fire resistance: some materials may require a fire-resistant liner to prevent rapid flame spread.
- Cost: preparation, installation, protection and purchase price all increase the cost.
- Part of the building to be insulated: roofs and walls have limitations on insulation thickness, while ceilings require thicker insulation material.
- Ease of installation: some materials are time-consuming and labour-intensive to install.
- Exposure to animals: consider whether the animals will come into contact with the insulation – if so, a protective covering may be necessary.

Surface resistances

The values of surface resistances are influenced by several factors, the most important of which is the rate of air movement over the surface. Values for 3 metres per second and 0.5 metres per second of air movement and for still air are shown in Table 12.1.

Thermal resistance of pitched roof spaces

The calculation of *U* values for a roof-ceiling combination requires knowledge of the resistance of the airspace between the ceiling and the roofing material. Table 12.2 gives resistance values for four design combinations.

TABLE 12.2
Thermal resistance of pitched roof spaces

		Resistance (m^2.K/W)	
	Direction of heat flow	High-emittance surfaces*	Low-emittance surfaces**
Ventilated roof space	Up	nil	0.34
	Down	0.46	1.36
Non-ventilated roof space	Up	0.18	0.56
	Down	0.28	1.09

***Dull, dark surfaces **Shiny, light surfaces**

Overall heat transfer coefficients

The overall heat transfer coefficient or thermal conductance, *U*, is the rate of heat transfer through a unit area of a building element (wall, ceiling, window, etc.). When the building element is made of two or more different materials, the *U* value is calculated as the reciprocal of the sum of the resistances of the individual components of the elements, as expressed in the equation:

$$R = \frac{1}{k} \text{ (for conduction) or } R = \frac{1}{h} \text{ (for convection)}$$

$$R_T = R_{si} + R_1 + R_2 + \ldots + R_{so}$$

$$U = \frac{1}{R_T}$$

where:

R = thermal resistance of each homogenous material making up the building element
K = thermal conductivity of the material
R_T = resistance to heat flow through a composite element
R_{si}, R_{so} = thermal resistance of the inside and outside air surfaces of the building element
U = overall coefficient of heat transmission (air to air).

Using values from Tables 12.1 and 12.2, overall heat transfer coefficients (U) have been calculated for a number of composite wall and roof constructions. Although estimates were necessary for some materials, the U values are realistic. Table 12.3 shows several of the construction units.

TABLE 12.3
Overall heat transfer coefficients, U

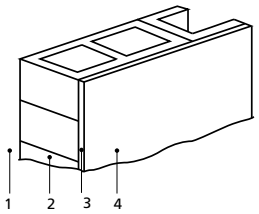
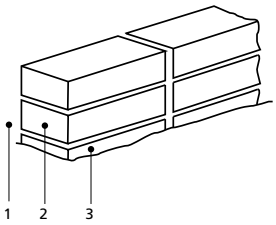
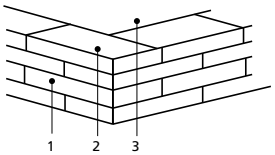
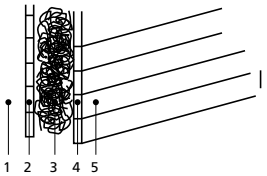
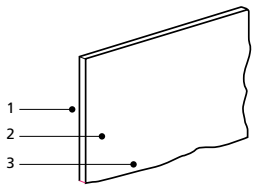
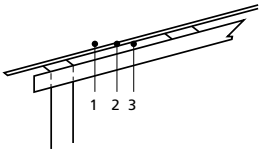
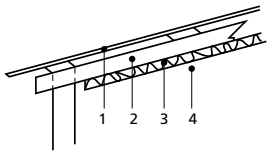
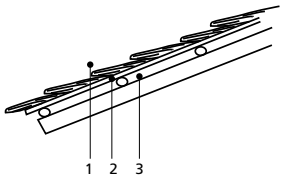
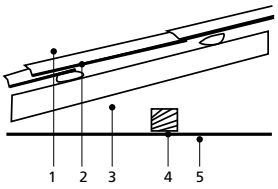
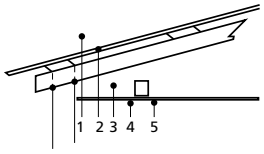
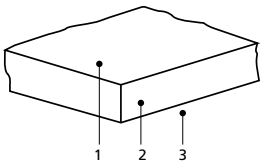
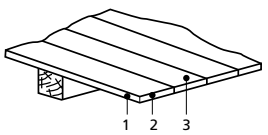
	Construction		Resistance, R (m^2.K)/W	Thermal capacity (kJ/m^2.K)	
Concrete block (190 mm) Indoor plaster	1. Outdoor air film		0.04	0	
	2. 190 mm hollow concrete block		0.19	164	
	3. 20 mm cement:sand (1:4) plaster		0.037	25	
	4. Indoor air film		0.12	0	
	Total resistance, R_T		0.387	189	
	U = 1 / 0.387 = 2.6 W/ (m^2.K)				
	Without plaster				
	R_T = 0.387 – 0.037		0.350		
	U = 1 / 0.350 = 2.9 W/ (m^2.K)				
Adobe	1. Outdoor air film		0.04	0	
	2. 300 mm adobe block		0.240	300	
	3. Indoor air film		0.12	0	
	Total resistance, R_T		0.40	300	
	U = 1 / 0.400 = 2.5 W/ (m^2.K)				
Common brick	1. Outdoor air film		0.04	0	
	2. 200 mm brick		0.34	372	
	3. Indoor air film		0.11	0	
	Total resistance, R_T		0.49	372	
	U = 1 / 0.49 = 2.04 W/ (m^2.K)				
Wood-fill–wood	1. Outdoor air film		0.04	0	
	2. Timber (25 mm)		0.25	21	
	3. Shavings (50 mm)		0.83	0	
	4. Timber (25 mm)		0.25	21	
	5. Indoor air film		0.11	0	
	Total resistance, R_T		1.48	42	
	U = 1 / 1.48 = 0.68 W/ (m^2.K)				
Single glazing	1. Outdoor air film		0.04	0	
	2. 6 mm float glass		0.006	13	
	3. Indoor air film		0.12	0	
	Total resistance, R_T		0.166	13	
	U = 1 / 0.166 = 6.0 W/ (m^2.K)				
Sheet metal roof, no ceiling	1. Outdoor air film	0.04	0.04	0	
	2. Metal roof	0.11	0.11	0	
	3. Indoor air film	0.11	0.11	0	
	Total resistance, R_T	0.26	0.26	0	
	U = 1 / 0.26 = 3.85 W/(m^2.K) heat flow down				
	U = 1 / 0.26 = 3.85 W/(m^2.K) heat flow up				

TABLE 12.3 (continued)
Overall heat transfer coefficients, U

	Construction	Resistance, R (m^2.K)/W		Thermal capacity (kJ/m^2.K)	
Sheet, metal roof and insulation plastic and chicken wire	1. Outdoor air	0.04		0	
	2. Metal roof	0.11		0	
	3. *Air space (200 mm)	1.36		0	
	4. Coffee hulls (50)	0.83		10	
	5. Indoor air	0.11		0	
metal roof 0.11	Total resistance (R_T)	2.45		10	
	*Low-emittance, shiny metal				
	U = 1 / 2.45 = 0.41 $W/$ (m^2.K) heat flow down				
Thatch + plastic sheet (150 mm)	1. Outdoor air	0.04		0	
	2. Thatch (150 mm)	3.72		16	
	3. Indoor air	0.11		0	
	Total resistance, R_T	3.87		16	
	U = 1 / 3.87 = 0.26 $W/$ (m^2.K)				
Tiled roof, gypsum board	1. Outdoor air film	0.04	0.04	0	
	2. 19 mm tiles, clay roofing	0.023	0.023	34	
	3. Roof space (ventilated)	–	0.46	0	
	4. 13 mm gypsum board	0.077	0.077	12	
	5. Indoor air film	0.11	0.11	0	
	Total resistance, R_T	0.250	0.710	46	
	U = 1 / 0.250 = 4.0 $W/$ (m^2.K) heat flow up				
	U = 1 / 0.710 = 1.4 $W/$ (m^2.K) heat flow down				
Sheet metal roof, ceiling	1. Outdoor air film	0.04	0.04	0	
	2. Metal roof	0.11	0.11	0	
	3. Roof space (vent, low- emittance)	0.34	1.36	0	
	4. Gypsum board	0.08	0.08	3	
	5. Indoor air film	0.11	0.11	0	
	Total resistance, R_T	0.68	1.70	3	
	U = 1 / 0.68 = 1.47 $W/$ (m^2.K) heat flow up				
	U = 1 / 1.70 = 0.59 $W/$ (m^2.K) heat flow down				
Concrete slab on soil	1. Outdoor air film	0.11		0	
	2. 100 mm concrete (2 400 kg/m^3)	0.069		210	
	Total resistance, R_T	0.179		210	
	U = 1 / 0.179 = 5.59 $W/$ (m^2.K)				
	With 2 mm vinyl tiles				
	R_T = 0.179 + 0.003 = 0.182				
	U = 1 / 0.182 = 5.49 $W/$ (m^2.K)				
Timber	1. Outdoor air film (upper)	0.11		0	
	2. 19 mm T & G flooring (hardwood)	0.120		19	
	3. Indoor air film (lower)	0.11		0	
	Total resistance, R_T	0.340		19	
	U = 1 / 0.340 = 2.94 $W/$ (m^2.K)				

The effect on U values and overall heat transfer of timber and metal frames in walls is in the order of 5 percent and may usually be ignored. However, local effects may be observed. The more rapid heat loss through the framing of a heavily insulated wall may lower the wall temperature adjacent to the framing locations to the point where it causes condensation.

RATE OF OVERALL HEAT LOSS OR GAIN FROM A BUILDING

Once the U values have been calculated for each element of the building (walls, ceiling, windows, doors, etc.), the area of each element is determined and design temperatures for inside and outside are chosen. It follows that, for each building element:

$$Q = A \times U \times \Delta T$$

where:
Q = total heat transfer rate through an element (W)
A = area of the building element (m^2)
U = coefficient of heat transfer for the element ($W/m^2.K$)
ΔT = temperature differential across the element (K).

For the building as a whole, the total heat exchange rate will equal the sum of the Q values. Total heat transfer in joules for a given period may be found by multiplying kilowatts by 3.6 Megajoules times the number of hours. Figure 12.1 provides some rough approximations of maximum and minimum temperatures for design purposes. Temperature data for the immediate area in which the building will be constructed will provide the most accurate results.

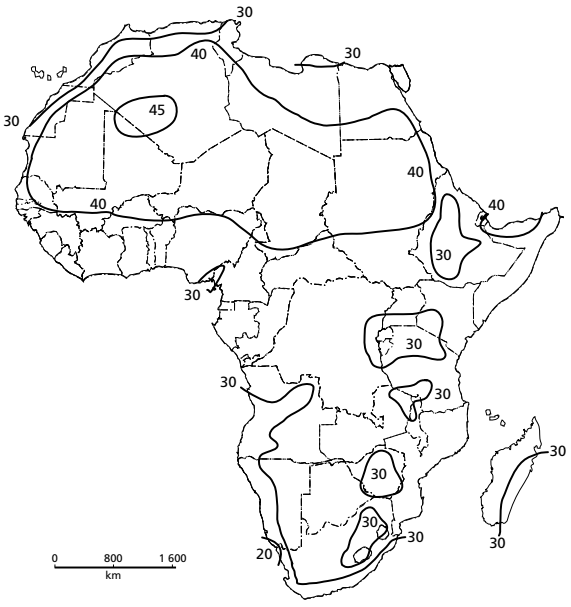


Figure 12.1a **Highest mean monthly maximum temperature (°C)**

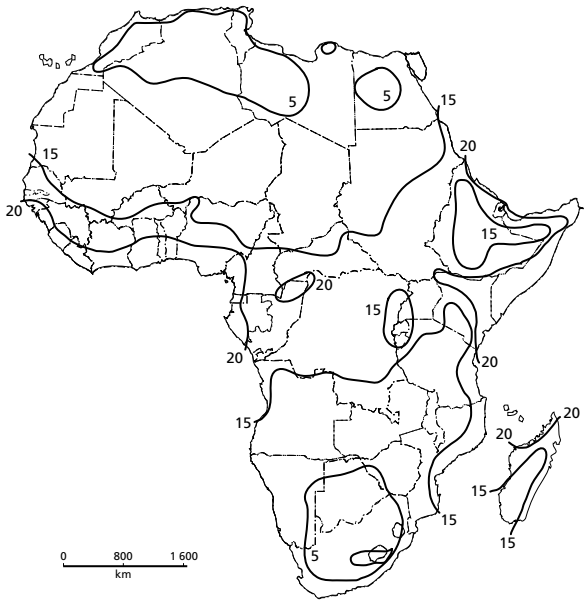


Figure 12.1b **Lowest mean monthly minimum temperature (°C)**

Solar load

In the countries of east and southeast Africa, the effect of solar radiation can be significant during some seasons and at certain times of the day. The orientation, design, and materials used will all influence the amount of solar heat gain to which a building is subjected.

A method of determining the degree and extent of solar gain has been developed, which is called sol-air. This concept provides a solar increment in the southern hemisphere, to be added to the design air temperature used for horizontal roofs and northerly facing walls. These increments range from 10 °C to 30 °C.

However, they apply for only a few hours per day and decrease in significance if the building is designed to offset the effects of solar radiation. The following two examples illustrate how this can be accomplished.

In an area of high diurnal-nocturnal temperature difference, the roof and walls of a building should be constructed of materials with a great deal of mass (adobe bricks or rammed earth). The resulting high thermal capacity will limit both daytime temperature rise and the night-time temperature drop, reducing the high solar radiation effect to a minimum.

In the case of a refrigerated store, it would be desirable to use a roof design that provides attic ventilation and is covered with a light-coloured reflective surface, which, in combination, will minimize the effect of solar radiation on the store.

Example of heat loss from buildings

Take two homes in Botswana. One is constructed with adobe block walls and a thatch roof, while the other is made of hollow core concrete blocks with a sheet metal

roof. Each house measures 5 metres square, 2 metres high at the eaves, 3 metres at the ridge, has 1 m² of window and 1.5 m² of timber door. Find the heat lost from each house when the temperature is 0 °C outside and 15 °C inside.

From Table 12.3, the *U* value for a sheet metal roof is 3.85 *W*/(m².K); for a thatch roof, 0.26 *W*/(m².K); for an adobe wall, 2.5 *W*/(m².K); for a concrete block wall, 2.9 *W*/(m².K), and for single glass, 6 *W*/(m².K).

The calculated *U* value for a 25 mm timber door is 2.4 *W*/(m².K).

$Q = A \times U \times \Delta T$

Thatched roof

Roof 5.4 × 5 =	27.0 m²	27.0 × 15 × 0.26 = 105 W
Walls 5 × 2 × 4 =	40.0 m²	
Gable ends	+ 5.0 m²	
Door and window	- 2.5 m²	
Total wall	42.5 m²	

Wall	42.5 × 15 × 2.5 = 1 594 W
Door	1.5 × 15 × 2.4 = 54 W
Window	1.0 × 15 × 6.0 = 90 W
Total heat loss	1 843 W

Metal Roof

Roof	27 × 15 × 3.85 = 1 559 W
Wall	42.5 × 15 × 2.9 = 1 849 W
Door	1.5 × 15 × 2.4 = 54 W
Window	1.0 × 15 × 6.0 = 90 W
Total heat loss	3 552 W

It is obvious that much more heat must be supplied to the metal roof house. A ceiling with 50 mm of rockwool or glasswool would provide a substantial saving.

	R
Air layer	0.04
Metal	0.11
Air space (non-ventilated, dull)	0.18
Rockwool	1.52
Hardboard	0.08
Air layer	0.11
R_T	2.04

$$U = \frac{1}{R_T} = \frac{1}{2.04} = 0.49\,W/(m^2.°K)$$

Heat losses

Roof	27 × 15 × 0.49 = 198 W
Wall	= 1 849 W
Door	= 54 W
Window	= 90 W
Total heat loss	2 191 W

Saving 3 552 - 2 191 = 1 361 W

While the 'modern' house is almost as heat efficient as the traditional style house and should be more hygienic and durable, the traditional house can be constructed entirely from locally available materials and by local craftsmen and will therefore require a minimum of cash expenditure.

PSYCHROMETRY

The earth's atmosphere is a mixture of gases and water vapour. An understanding of the physical and thermodynamic properties of air–water-vapour mixtures (psychrometrics) is fundamental to the design of environmental control systems for plants, crops, animals or humans.

Properties of moist air

Pressure, volume, density and thermal properties are related by the use of the laws for a 'perfect gas'. For a mixture of dry air and water vapour, this law can be used with only negligible error at the range of temperatures and pressures used for environmental control.

$$P = \frac{MRT}{V}$$

where:
P = absolute pressure (*Pa*)
M = mass (kg)
R = gas constant (J/(kg.°C))
T = temperature (K)
V = volume (m³).

Dalton's Law: Each component in a mixture of gases exerts its own partial pressure, for a mixture of air *(a)* and water vapour *(w)*.

$$P = P_a + P_w = \frac{M_a R_a T_a}{V_a} + \frac{M_w R_w T_w}{V_w}$$

Assuming a uniform mixture:

$$P = \frac{T}{V}(M_a R_a + M_w R_w)$$

When the volume and temperature of the mixture are equal, the following is true:

$$\frac{P_w}{P_a} = \frac{M_w R_w}{M_a R_a}$$

Thus, if the total pressure and water-vapour weight is known, the partial pressures may be calculated.

Specific humidity (H) is the weight of water vapour in kilograms per kilogram of dry air. It is sometimes

called absolute humidity or humidity ratio. The base of 1 kilogram of dry air is constant for any change of condition, making calculations easier.

$$H = \frac{M_w}{M_a} = \frac{P_w V}{R_w T} = \frac{P_a V}{R_a T} = \frac{P_w R_a}{P_a R_w} = \frac{P_w R_a}{(P - P_w) R_w}$$

Relative humidity (RH) is the ratio of the actual water-vapour pressure (P_w) to the vapour pressure of saturated air at the same temperature (P_{wsat}).

$$RH\% = 100 \frac{P_w}{P_{wsat}}$$

The vapour pressure at saturation (P_{wsat}) is given in steam tables for different dry-bulb temperatures.

Specific volume is the volume of *dry* air per mass of dry air.

Humid volume is the volume of an air-moisture mixture per mass of dry air. In ventilation calculations, the volume is in cubic metres of mixture (air + water vapour) per kilogram of dry air. The base of 1 kilogram of dry air is used because the kilogram of dry air entering and leaving the system in a given time will be constant once a steady state flow is established. Humid volume increases as the temperature or water-vapour content increases. The humid volume of air–water-vapour mixtures is given in standard thermodynamic tables, or may be read from a psychrometric chart.

Temperatures: Air–water-vapour mixtures can be described by the dry-bulb temperature, and either the wet-bulb or dew point temperatures:

- dry-bulb temperature is measured with a common thermometer, thermocouple or thermistor
- wet-bulb temperature is the temperature at which water, by evaporating into moist air, can bring the air to saturation adiabatically in a steady-state condition
- dew point temperature is the temperature at which moisture starts to condense from air cooled at constant pressure and specific humidity.

Enthalpy (h) is the heat-energy content of an air–water-vapour mixture. The energy is a combination of both sensible heat (indicated by dry-bulb temperature) and latent heat of vaporization (energy content of the water vapour). Enthalpy scales appear on psychrometric charts expressed as kJ/kg of dry air.

Enthalpy can be calculated from the equation:

$$h = S \times t_{db} + H \times h_w$$

where:
S = specific heat of dry air (1 004 kJ/(kg.K))
t_{db} = dry-bulb temperature
H = specific humidity
h_w = enthalpy of water vapour (kJ/kg water vapour).

Thus:

$$h = 1.004 \times t_{db} + H(2454 + 1858 \times t_{db}) \text{ kJ/kg}$$

where:
2 454 = latent heat of vaporization (kJ/kg)
1 858 = specific heat of water vapour (kJ/(kg.K)).

Psychrometric chart

A psychrometric chart (Figure 12.2 and Appendix V:4-6) is a graphical representation of the thermodynamic properties of moist air. It is useful for solving engineering design problems. Charts for agricultural applications are usually corrected to standard atmospheric pressure of 101.325 kPa. However, charts for other elevations are available. The following properties are shown on a psychrometric chart:

- dry-bulb temperature
- wet-bulb temperature
- dewpoint temperature
- moisture content or specific humidity
- enthalpy
- relative humidity
- specific volume
- humid ratio

The intersection of any two property lines establishes a given state, and all other properties can be read from that point. The changes that take place between any two points are of particular use. The vertical lines show dry-bulb temperatures; the curved lines show relative humidity; the slant lines show wet-bulb temperatures and enthalpy; the horizontal lines show dewpoint temperatures and specific humidity; and the steep slant lines show specific and humid volume.

The wet- and dry-bulb temperature for a building area may be read from a psychrometer and then used to establish a point of intersection on the chart. Psychrometers consist of two thermometers mounted close together, one of which has a wick on the bulb that has been moistened with a few drops of distilled water. Air movement is necessary. A sling psychrometer, which is actually swung in the air, is the simplest and least expensive type of psychrometer. However, for locations with restricted space, a motorized psychrometer must be used. The air movement in a ventilation duct is adequate to provide accurate readings from stationary temperature sensors.

Air–water-vapour mixture processes

Conditioning of air–water-vapour mixtures involves heating, cooling, humidifying or dehumidifying, or a combination of these factors.

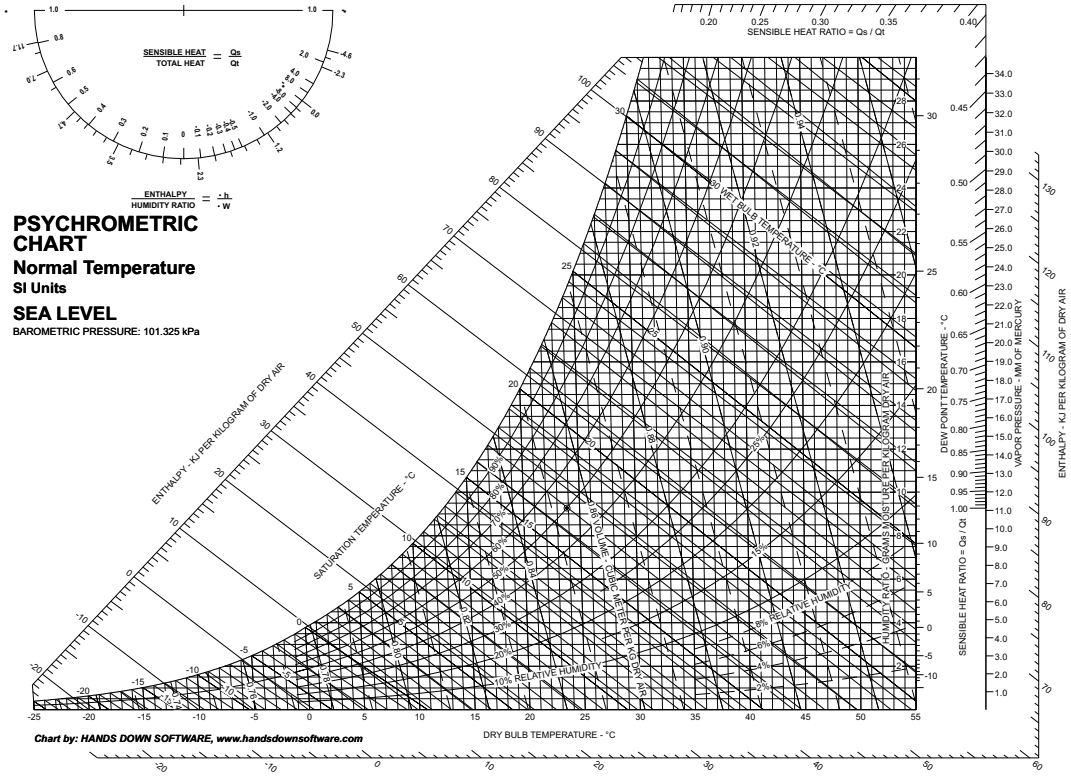


Figure 12.2 **Psychrometric chart**

Sensible heating or cooling of moist air

When moist air is heated or cooled without a gain or loss of moisture, the process is called sensible heating or sensible cooling, respectively. Figure 12.3 is a sketch showing these two processes as horizontal lines on a psychrometric chart. In both, the humidity ratio remains constant, as does as the dewpoint temperature. Changes in the dry-bulb and wet-bulb temperatures are evident. Line 1 to 2 is sensible heating, and line 2 to 1 is sensible cooling.

Applications of sensible heating include heated-air grain drying and winter heating of room air in cool-climate homes. An example of sensible cooling is the air passing over a cooling coil with a surface temperature above the dewpoint of the air. The final temperature must not be below the initial dewpoint temperature or water vapour will condense and the process will remove latent heat.

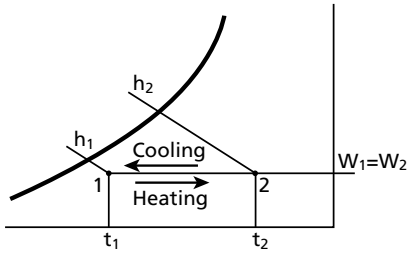


Figure 12.3 **Graphical representation of the heating and cooling process**

The steady flow and material balance equations that apply to the sensible heating process are as follows:

$$\dot{m}_{a1} h_1 + \dot{q}_{1\text{-}2} = \dot{m}_{a2} h_2$$

$$\dot{m}_{a1} = \dot{m}_{a2}$$

$$\dot{m}_{a1} W_1 = \dot{m}_{a2} W_2$$

where:
$\dot{m}_a$ = air flow rate (m^3/s)
$\dot{q}_{1\text{-}2}$ = sensible heat added between state 1 and state 2 (W)
W = humidity ratio (kg water/kg dry air)
h = enthalpy of moist air (kJ/kg dry air).

Therefore, for sensible heating,

$$\dot{q}_{1\text{-}2} = \dot{m}_a (h_2 - h_1)$$

Cooling and dehumidifying process

Cooling and dehumidifying is the lowering of both the dry-bulb temperature and the specific humidity. The process path depends on the type of equipment used. In summer, when air-conditioning air passes over a cold, finned evaporator coil of a refrigeration unit, the process of cooling and dehumidifying is represented by a straight line 1 to 2 on the psychrometric chart (Figure 12.4).

As air passes over the cooling coils of an evaporator, the moisture is condensed from the air (W_1 to W_2)

at a variable temperature from the initial dewpoint temperature *(A)* to the final saturation temperature (t_2). Latent heat will be lost in this process (h_1 to h_3). The air is also cooled from t_1 to t_2, giving up sensible heat (h_3 to h_2). Unless it is reheated or initially saturated, the final relative humidity of the moist air is always higher than at the start. Relative humidity 2 will be at 100 percent (saturation) as the air leaves the evaporator. The reverse of this process (from 2 to 1) represents the heating and humidifying process.

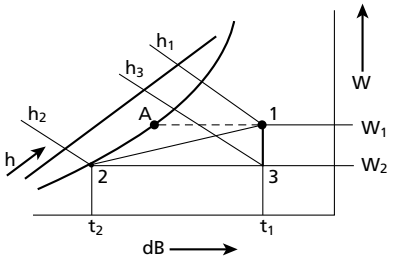


Figure 12.4 **Graphical representation of the cooling and dehumidifying process**

Evaporative cooling

Evaporative cooling is an adiabatic saturation process (where no sensible heat is gained or lost) and follows an upward trend along a constant wet-bulb temperature line on the chart (Figure 12.5). Air to be cooled is brought into contact with water at a temperature equal to the wet-bulb temperature of the air. The sensible heat of the initial air evaporates the water, lowering the dry-bulb temperature of the air. Sensible heat is converted to latent heat in the added vapour, so the process is adiabatic.

Evaporative cooling is effective in hot, dry climates where wet-bulb depression (the difference between dry-bulb and wet-bulb temperatures) is large, and where the disadvantage of increased humidity is more than offset by a relatively large temperature drop. Evaporating moisture from *a* to *b* cools the air from *c* to *d*. As 1 and 2 are on the same enthalpy line, the process is adiabatic (no change in heat) and the relative humidity rises from 1 to 2.

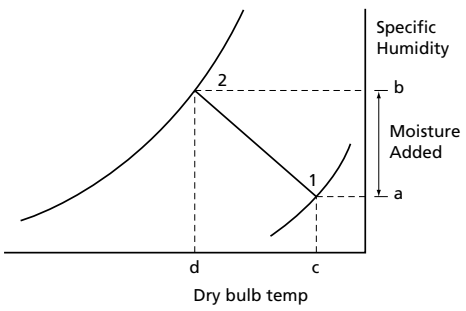


Figure 12.5 **Evaporative cooling process**

Adiabatic mixing of two air streams

A frequently encountered process in air-conditioning is the mixing of two or more streams of air with different psychrometric properties. Figure 12.6 represents a schematic drawing of the two flow streams mixing, and the pyschrometric chart for the process.

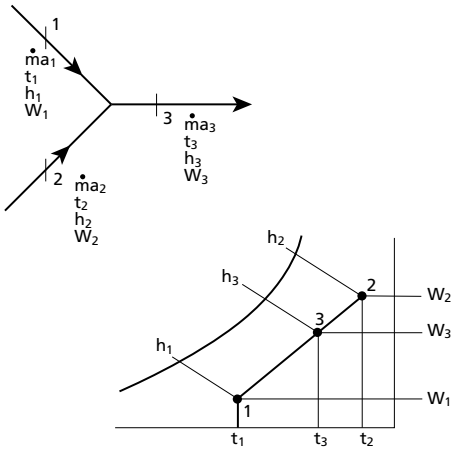


Figure 12.6 **Schematic and psychrometric chart for the mixing process**

Some useful relationships in this process are given below:

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{h_2 - h_3}{h_3 - h_1} = \frac{W_2 - W_3}{W_3 - W_1}$$

$$t_3 = \frac{\dot{m}_{a1} \times t_1 + \dot{m}_{a2} \times t_2}{\dot{m}_{a1} + \dot{m}_{a2}}$$

$$W_3 = \frac{\dot{m}_{a1} \times W_1 + \dot{m}_{a2} \times W_2}{\dot{m}_{a1} + \dot{m}_{a2}}$$

$$h_3 = \frac{\dot{m}_{a1} \times h_1 + \dot{m}_{a2} \times h_2}{\dot{m}_{a1} + \dot{m}_{a2}}$$

The solution of a mixed-air problem in psychrometrics normally makes use of one of these equations, after which the remaining mixed-air properties are determined by graphical means.

Example: mixing problem

Eight cubic metres per minute of air at 2 °C dry-bulb (dB) temperature and 100 percent relative humidity (RH) are mixed with 16 m^3/min of air at 29 °C dB temperature and 50 percent RH. Assuming sea-level conditions, what will be the dry-bulb temperature, humidity ratio and enthalpy of the mixture?

Solution

Step 1. Determine the psychrometric properties of the two air streams from the psychrometric chart

Condition 1	Condition 2
8 m³/min at 2 °C dB, 100% RH	16 m³/min at 29 °C dB, 50% RH
Specific volume	*Specific volume*
υ_1 = 0.7842 m³/kg	υ_2 = 0.8722 m³/kg
Humidity ratio	*Humidity ratio*
W_1 = 0.00436 kg/kg	W_2 = 0.01255 kg/kg
Enthalpy	*Enthalpy*
h_1 = 12.97 kJ/kg	h_2 = 61.20 kJ/kg

Step 2: Determine the mass of the two air streams in kg/minute

$$\dot{m}_{a1} = \frac{air\ flow_1}{\upsilon_1} = \frac{8}{0.7842} = 10.20\ kg/\min$$

$$\dot{m}_{a2} = \frac{air\ flow_2}{\upsilon_2} = \frac{16}{0.8722} = 18.34\ kg/\min$$

Step 3: Determine the psychrometric properties of the mixed air. On the psychrometric chart, draw a straight line joining state 1 and state 2. Calculate the dry-bulb temperature of the mixture.

$$t_3 = \frac{\dot{m}_{a1} \times t_1 + \dot{m}_{a2} \times t_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{10.20 \times 2 + 18.34 \times 29}{10.20 + 18.34} = \frac{552.26}{28.54} = 19.4\ °C$$

where t_3 = 19.4 °C intersecting the mixture line between states 1 and 2 determines the mixed-air condition, state 3. From the chart at state 3, find t_{wb3} = 15.5 °C, W_3 = 0.00944 kg/kg, h_3 = 43.5 kJ/kg, dewpoint t_{dp} = 13.2 °C.

The process and solution are illustrated in Figure 12.7.

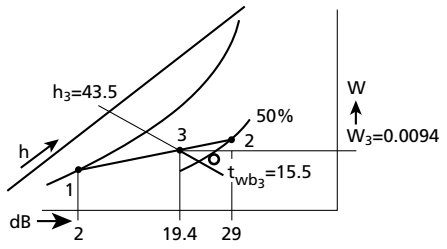


Figure 12.7 **Illustrative solution for the mixing problem**

MOISTURE TRANSMISSION

As stated in Dalton's law, water vapour in the air exerts a separate pressure that is proportional to the amount of moisture present. This partial pressure is independent of the partial pressures exerted by other components of the air.

As warm air can hold more moisture than cool air, it is typical for the vapour pressure to be higher on the warm side of a wall. Wherever a pressure difference exists, there is a tendency for moisture to permeate through the wall until the pressure equalizes. If, when permeating a wall, a dewpoint temperature is encountered, condensation will occur and free moisture will reduce the effectiveness of insulation, or cause deterioration in wood or metal.

In cold climates, building-walls should be designed with vapour barriers on the warm side of the wall in order to reduce moisture permeation. In all climates, but especially in warm, humid areas, it is essential to install a good vapour barrier on the warm side of a refrigerated storage wall.

To understand air-moisture movement and to make the calculations in a vapour transmission problem, it is necessary to understand the following terms.

Vapour pressure is the partial pressure in the atmosphere caused by the presence of vaporized moisture. It is measured in mm Hg or Pa.

Permeability is the property of a material that allows the migration of water vapour. It is measured for 1 metre of thickness, and the units are g/(24 hr.m³.Pa).

Permeance is the term used for the transfer of water vapour for the thickness of the material used. The unit of measurement is g/(24 hr.m³.Pa).

The permeability of a material may be determined by subjecting it to 100 percent relative humidity on one side and 50 percent on the other (wet-cup method), or to 0 percent relative humidity on one side and 50 percent on the other (dry-cup method). Of the two, the wet-cup value is usually a little higher, but either value may be used for moisture-transfer calculations.

Moisture transmission may be calculated as follows:

$$W = M \times A \times T \times A_P$$

where:
W = total moisture (g)
M = permeance (g/(24 hr.m².Pa))
A = area unit (m²)
T = time unit (24 hr)
A_P = pressure difference (Pa).

As with heat transfer, only resistance may be added. Therefore, if a wall has more than one vapour-resisting layer, the following equation is used:

$$\frac{1}{M_T} = \frac{1}{M_1} + \frac{1}{M_2} + \ \ldots\ + \frac{1}{M_n}$$

where:
M_T = the overall permeance of the wall;
M_1 = permeance of a layer, etc.

Table 12.4 lists the permeability of several materials used in building construction.

TABLE 12.4
Moisture permeability of materials

Material	Permeability /m thickness g/(24hr.m³.Pa) × 10^{-3}	Permeance thickness as used g/(24hr.m².Pa) × 10^{-3}
Air	15.3	
Exterior plywood (6 mm)		3.45
Pine timber	0.053–0.68	
Concrete	0.38	
Asphalt roofing		0.23
Aluminium paint		1.5–2.48
Latex paint		27.23
Polystyrene:		
Extruded	0. 15	
Bead	0.26–0.75	
Polyurethane	0.53–0.23	
Polyethylene (0.1 mm)		0.4
Polyethylene (0.2 mm)		0.2

VAPOUR BARRIERS

Any enclosed wall that has a significant temperature difference or humidity difference between the two sides for a substantial part of the day should have a vapour barrier installed on, or near, the warm or humid side. In cold climates, this applies to the walls in any enclosed building that is heated, or where the humidity is high. In warm climates, it applies primarily to air-conditioned or refrigerated buildings.

Probably the most effective vapour barrier that is also reasonable in cost is polyethylene sheet. The vapour barrier should be as continuous as possible. This can be achieved by using large sheets with well overlapped and sealed joints and as few nail-holes as possible.

Condensation on surfaces and within walls

If the insulation in the wall of a refrigerated store is inadequate, or if it has defective spots, the outside of the wall may cool enough to bring it below the dewpoint temperature. The result will be condensation on the outer wall surface. Remedies for this condition are:

- better insulation
- reduction of outside humidity
- increased air movement across the wall

Materials such as stone, concrete and brick are not affected by condensation.

Condensation within the wall is more serious and results from either the absence of a vapour barrier or a defective barrier. In this situation, moisture moves into the wall from the warm side until it reaches an inner wall layer that is below the dewpoint temperature. The resulting condensation soon reduces the effectiveness of the insulation and causes permanent damage. Remedies for this situation are:

- a better vapour seal on the warm side
- a more permeable layer on the cold side
- a reduction in humidity on the warm side through ventilation or other means

HEATING AND COOLING LOADS

The cooling load

The cooling load is the rate at which heat is removed from the conditioned space to attain the desired temperature and relative humidity. Heat-gain analysis on the building should be carried out in order to calculate the cooling load. The cooling-loads are normally calculated when sizing heating, ventilation and air-conditioning (HVAC) systems and their components. The types of heat gain into a building are illustrated in Figure 12.8.

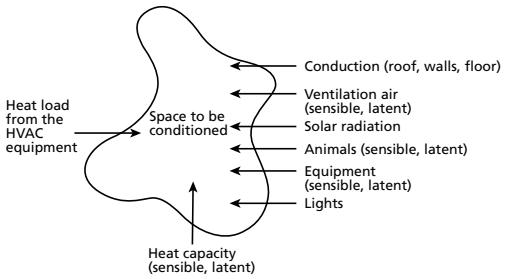


Figure 12.8 **The types of heat gain into a building**

The heating load

Heat loss calculations are made to determine a building heating load. The heat losses are essentially of two kinds:

- the heat transmitted through walls, ceiling, floor, or other surfaces
- the heat required to warm outdoor air entering the space

The types of heat loss from a building are illustrated in Figure 12.9.

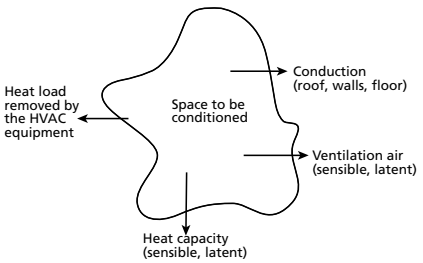


Figure 12.9 **The principal types of heat loss from a building**

Methods of estimating cooling and heating loads

The handbooks of the American Society of Heating and Refrigeration Engineers (ASHRAE) and the standards of the American Society of Agricultural & Biological Engineers (ASABE) provide detailed procedures for calculating the cooling and heating loads for human and animal occupation, respectively. They use the quantities illustrated in Figures 12.8 and 12.9, in addition to other information as necessary. Some of the procedures are quite complex and require the use of a computer.

OVERVIEW OF HEATING, VENTILATION AND AIR-CONDITIONING SYSTEMS AND EQUIPMENT

The purpose of an HVAC system is to provide a suitable environment for people, animals and plants by controlling temperature, humidity, air contaminants and air circulation. HVAC systems are categorized into heating, air-conditioning, ventilation and air-handling and electrical systems.

Heating systems

Some heating systems produce heat from the combustion of fossil fuels, such as oil and coal, while others use electricity or solar power. The heat produced is distributed through ducts and pipes by fans and pumps. The equipment used in heating systems includes furnaces, boilers, heat pumps and heat exchangers.

Furnaces: Furnaces use forced convection to remove heat produced within a furnace's firebox, and are classified according to airflow type. The upflow furnace (Figure 12.10) has a blower located below the firebox heat exchanger, while the downflow furnace is the reverse, with air flowing downward. Natural gas, liquefied propane gas (LPG) and fuel oil can be used as energy sources for furnaces.

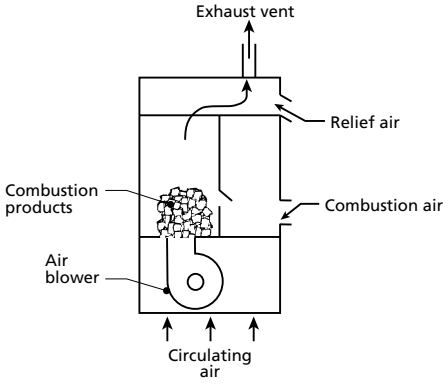


Figure 12.10 **Schematic of a forced-convection furnace**

Boilers: A boiler is usually made from copper, steel or cast iron, and transfers the heat from a combustion chamber (or electric resistance coil) to water, in either the liquid phase or the vapour phase, or both. Boilers are classified both by the fuel used (gas, fuel oil, wood, coal or electricity) and by the operating pressure (low or high pressure).

Electric heat pumps: A heat pump is a unit that (i) extracts heat from the environment, (ii) raises the air temperature to the desired level, and (iii) delivers the air to the required space.

Heat exchangers: A heat exchanger is a used to transfer heat from one medium to another, whether in direct contact or separate.

Air-conditioning systems

An air-conditioner is a unit that can provide both cooling and dehumidification in order to attain the desired conditions inside a building. Occupants within a building produce excess heat and moisture, which must be dissipated. The capacities of air-conditioning systems are often expressed in either tons or kilowatts (kW) of cooling. The ton is a unit of measure related to the ability of an ice plant to freeze one short ton (907 kg) of ice in 24 hours, and its value is 3.51 kW). Some examples of air-conditioning systems include chillers, cooling towers and evaporative cooling systems.

Chiller: The most common types of chiller are reciprocating, screw, centrifugal and absorption chillers. These are often used in large commercial buildings.

Cooling tower: In a cooling tower, water is recirculated and evaporatively cooled through direct contact heat transfer with the ambient air. This cooled water can then be used to absorb and reject the thermal energy from the condenser of the chiller.

Evaporative cooler: This system is effective under hot and dry conditions. It uses the adiabatic evaporation of water in air. Air is drawn through the wetted pads or sprays and its sensible heat energy helps to evaporate some water, which reduces the dry-bulb temperature of the air. Most greenhouses use evaporative coolers for cooling in the summer period.

Ventilation and air-handling systems

Air-handling systems transfer the heated or cooled air between the main heating or cooling units and the building space. Examples of air-handling systems include cooling coils, fans, ducts and diffusers.

Coils: Coils are essentially heat exchangers designed to transfer heat to or from an air stream, and are used to provide air heating, preheating, reheating, cooling and dehumidification.

Fans: Fans move air through ducts and system equipment to provide heating, cooling and ventilation to the building zones. A fan utilizes a power-driven, rotating impeller that creates a pressure differential causing air flow. Fans are discussed in more detail in Chapter 13.

Ducts: Ducts are conduits used to carry air from air-handling units to or from the ventilated spaces. They can be used to supply, return or exhaust the air to or from the conditioned space.

Diffusers: These are usually installed at the end of the duct systems (at the point where ducts enter or exit a conditioned space) and are designed to induce air circulation, which ensures air mixing.

Electrical systems

An electrical system includes all the electrically operated equipment found inside the building or at the building site, such as lighting fixtures, appliances, motors and transformers.

Electrical motors: Motors convert electrical energy into mechanical energy and are commonly used to drive machines that, in turn, perform various functions, such as moving air (supply and exhaust fans), moving liquids (pumps), moving objects (conveyors), compressing gases (air compressors or refrigerators) and producing materials (production equipment).

Lighting systems: Lighting fixtures produce the required lighting for the occupants, as well as excess heat that must be removed by the cooling equipment.

Transformers: A transformer is a device that can change the voltage of an alternating current for different applications. A typical transformer consists of two windings: primary (connected to the power source) and secondary (connected to the load).

REVIEW QUESTIONS

1. One wall of an un-insulated house has a thickness of 0.30 metres and a surface area of 11 m^2. The wall is constructed from bricks with thermal conductivity of 0.55 *W*/mK. The outside temperature is -2 °C while the house temperature is kept at 25 °C. The convection heat transfer coefficient is estimated to be 21 and 7 *W*/m^2 K for outside and inside conditions respectively. Calculate the rate of heat transfer through the wall, as well as the surface temperature on either side of the wall.
2. The air in the storage room has a dry-bulb temperature of 15 °C and 30 percent relative humidity. Determine the remaining air properties, assuming sea-level conditions.
3. A stream of 500 m^3/min outdoor air at 10 °C dry-bulb temperature and 5 °C wet-bulb temperature is adiabatically mixed with 1 500 m^3/min of recirculated air at 28 °C dry-bulb temperature and 50 percent relative humidity. Find the dry-bulb temperature and wet-bulb temperature of the resulting mixture. Illustrate your solution in a psychrometric chart.
4. Illustrate a heating and humidification process and derive expressions for determining (a) the rate of water evaporation and (b) the rate of heat transfer.
5. How much heat is required to heat 300 m^3/min of moist air at 10 °C dry-bulb and 5 °C wet-bulb temperature to a final temperature of 30 °C dry-bulb, with no change in the humidity ratio?

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Chapter 13
Ventilation

INTRODUCTION

The quality of the environment in agricultural buildings is governed by such factors as temperature, light, moisture, air quality and movement, dust, odours and disease agents. The environment affects animal comfort and health – and ultimately production. It also influences the quality and longevity of stored products. From an engineering standpoint, the environment can be closely controlled. However, economic factors often limit the extent to which control can be justified.

The particular region of the country and the associated climatic zone will influence the manner in which environmental requirements are met. A humid area may require homes with open construction to provide continual ventilation for comfort, whereas an arid region may need buildings of great thermal capacity to protect against daytime heat and night-time chill.

As a general rule, tropical climates are found within the tropics. However, the influence of the climate on structures makes the techniques used applicable to many regions outside the tropics, e.g. the Middle East.

The following brief discussion of Africa's climatic zones is general and such zones can be found worldwide in the tropics. It illustrates the wide variety of situations with which engineers are faced when designing environmentally suitable buildings for people, animals and products.

CLIMATIC ZONES

There are several climatic zones on the African continent, with widely varying characteristics.

1. Low-latitude, wet equatorial: high rainfall and humid, with a mean temperature close to 27 °C throughout the year. (Congo Basin).
2. Monsoon and trade wind littoral: climate dominated by trade winds. Maximum rain in high-sun season; minimum rain following low-sun season. Intense showers in eastern coastal zone. Warm throughout the year. (Central and western Africa and east coast).
3. Wet–dry tropical: typified by very wet high-sun season and a very dry low-sun season, (West and southern Africa).
4. Dry tropical: characterized by extreme heat in the high-sun season and cool in low-sun periods. Gradually changes from arid to semi-arid and into wet–dry tropical zone. (Sahara, South Africa).
5. Dry subtropical: a north–south extension of the dry tropical zone. Greater annual temperature range. (North and south Africa).
6. Altitude-modified wet–dry tropical: increases in altitude generally result in an increase in precipitation and a reduction in mean temperatures. Precipitation is seasonal and varies from 500 to 1 500 mm, depending on local conditions. (Inland east and southeast Africa).

Climate can also vary greatly over relatively small areas, in particular where the country is hilly.

For design purposes, local climatic data from a nearby meteorological station should be obtained if possible.

VENTILATION PROCESS

Ventilation is one of several methods used to control the environment in farm buildings where it fulfils two main functions: controlling the temperature and controlling the moisture within a building. Ventilation may also be necessary to maintain adequate levels of oxygen and to remove generated gases, dust, odours and pathogens.

There is a considerable range of ventilation requirements that depend on the local climatic conditions and the specific enterprise being served. This is illustrated by the following examples:

1. A cattle shelter in a tropical climate requires little more than shade from a roof with the structure located to obtain maximum breeze.
2. A cattle shelter in a cold climate (seasonal frost) may be open on the sunny side and provided with ventilation openings at the ridge and along the rear eaves. The temperature will be cold but condensation will be controlled.
3. A poultry house (with cages) in a cold climate, if heavily insulated, can be kept comfortably warm while mechanical ventilation removes excess moisture and odours.
4. Potatoes that are stored in either a mild or a cold climate may be cooled by ventilation alone. Continual air movement is required to maintain a uniform environment. The amount of insulation used will be dictated by the lowest temperature expected.

A great deal of research has been carried out to determine the ideal environmental conditions for

various classes of livestock, types of plant and animal products. Within economic constraints, the better these ideal conditions can be maintained, the more successful the enterprise will be. Meat animals will gain weight faster and more efficiently, dairy cattle will produce more milk, and stored produce will maintain better quality and suffer fewer losses.

Determination of ventilation rates

The objective of designing a ventilation system is to determine the ventilation rate to maintain an acceptable temperature, as well as acceptable moisture and contaminant levels, inside a building. To determine the ventilation rates, heat and moisture balance calculations have to be performed on a building envelope. Chapter 10 [Table 10.2] presents the heat and moisture production rates of some selected animals. The sensible heat balance is used to determine the maximum ventilation rate for summer conditions, while the moisture balance is used to determine the minimum ventilation rate for winter conditions. The following examples illustrate these methods.

Heat balance for determination of maximum ventilation rate

Figure 13.1 below illustrates sensible heat balance in an animal house.

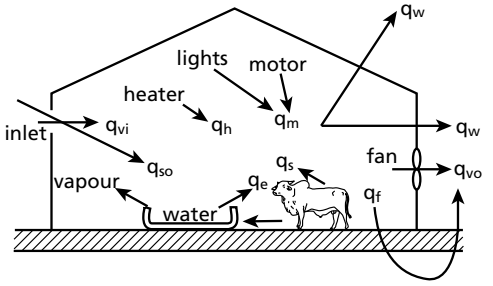


Figure 13.1 **Sensible heat balance in a typical animal house**

The steady-state heat balance in Figure 13.1 requires heat gains to equal heat losses. These are illustrated below. The heat gains are:

- sensible heat from animals (q_s)
- sensible heat from motors and lights (q_m)
- sensible heat from the sun (q_{so})
- sensible heat from heaters (q_h)
- sensible heat from the ventilation system (q_{vi})

The heat losses are:

- sensible heat loss through the ventilation system (q_{vo})
- sensible heat loss through the building shell (q_w)
- sensible heat loss through the floor (q_f)
- sensible heat loss used to evaporate moisture (q_e)

The sensible heat loss used to evaporate moisture (q_e) is normally included in the q_s term and thus not expressed explicitly.

The overall steady-state equation is:

$$q_s + q_m + q_{so} + q_h = \left(\sum_c (AU)_c + FP + C_p \cdot \rho \cdot V \right) (t_i - t_o)$$

where:

U = overall unit area thermal conductance of component (W/m^2K). Table 12.1 shows U values for some selected structural components

A = area of structural component (m^2)

c = path of heat transfer, which may be a wall or roof component

P = building perimeter (m)

F = an experimentally determined perimeter heat loss factor (W/mK). The values of F for an un-insulated and unheated slab floor on grade range between 1.4 and 1.6 W/mK, depending on how low the ambient temperature is

C_p = specific heat of moist air (J/kgK)

ρ = air density (kg/m^3)

V = the volumetric airflow rate (m^3/s)

t_i and t_o = indoor and outdoor temperatures (°C).

The above equation is used to determine: (i) the required ventilation rate to maintain a given inside temperature for a given heater capacity; (ii) the minimum outside temperature (balance temperature) to maintain the desired inside temperature without using supplemental heat (q_h = 0) at a given ventilation rate; and (iii) the size of heater required to maintain the desired inside temperature for a given ventilation rate and outside (design) temperature.

Example

Determine the ventilation rate for a laying-hen house with 30 000 hens having an average body mass of 1.40 kg. The inside temperature is to be maintained at 18 °C, with relative humidity of 60 percent. Assumptions: no supplemental heating; no solar heat; no heat from motors; the ΣAU and FP factors are 1 001 and 272 W/°C, respectively. The outside temperature is 0 °C.

Solution

Using the above equation, the unknowns are q_s and ρ.

Find q_s:

From Table 10.2, the sensible heat production per bird is 3.9 W/kg.

Therefore,

q_s = 3.9 W/kg × 1.40 kg/bird × 30 000 birds/house = 163 800 W/house.

From the psychrometric chart, with a dry-bulb temperature of 18 °C and 60 percent relative humidity, the specific volume is 0.826 m³/kg. The density is the inverse of specific volume, so the density is 1.21 kg/m³.

Hence, $V = \dfrac{163800 - (1001 + 272)(18 - 0)}{1006 \cdot 1.21 \cdot (18 - 0)}$

= 6.4 m³/s-house

Moisture balance for determination of minimum ventilation rate

Figure 13.2 below illustrates moisture balance in an animal house.

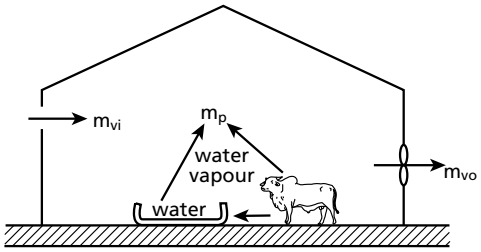


Figure 13.2 **Moisture balance in a typical animal house**

The steady-state moisture balance in Figure 13.2 requires that:

$m_{vo} = m_{vi} + m_p$

where:
m_{vo} = the rate at which moisture is carried out of the airspace by ventilation air (kg/s)
m_{vi} = the rate at which moisture is carried into the airspace by ventilation air (kg/s)
m_p = the rate at which moisture is produced within the airspace (kg/s).

After a few steps, the above equation can be rewritten as:

$$m_a = \rho \cdot \dot{V} = \left(\frac{m_p}{W_i - W_o} \right)$$

where:
m_a = mass flow rate of moisture (kg/s)
ρ = density (kg/m³)
$\dot{V}$ = volumetric flow rate (m³/s)
m_p = moisture production of the animals (kg/s)
W_i and W_o = humidity ratio of inside and outside air conditions (kgw/kg da).

Example
A total of 70 dairy cows at 500 kg body mass are housed in a mechanically ventilated building. What must be the ventilation rate in order to maintain 70 percent relative humidity at 20 °C if the outside temperature is 5 °C, with 90 percent relative humidity?

Solution
From the psychrometric chart, at 5 °C and 90 percent relative humidity, W_o = 0.0049 kgw/kg da. At 20 °C and 70 percent relative humidity, W_i = 0.0102 kgw/kg da.

From Table 10.2, the moisture production data are shown at 12 °C (445 g/h-animal) and 25 °C (910 g/h-animal). Since we need the moisture to be produced at 20 °C, we interpolate to obtain the moisture production. This yields 731 g/h-animal.

The moisture content may also be expressed as:

$$\frac{731\ g\ water}{h\text{-}cow} \cdot \frac{1\ h}{3600\ s} \cdot \frac{1\ kg}{1000\ g} = 0.000203\ kg\ water/s\text{-}cow$$

Therefore:

Total moisture produced = 0.000203 *kg water/s-cow* × 70 *cows/house* = 0.014214 *kg water/s-house*

Then:

$$M_a = \frac{0.014214\ kgw/s \cdot house}{(0.0102 - 0.0049)\ kgw/kg\ da} = 2.68\ kg\ da/s\text{-}house$$

For inlet conditions, ρ_i = 1.27 kg/m³

Hence, $V_i = \dfrac{M_a}{\rho_i} = \dfrac{2.68}{1.27} = 2.11$ m³/s

For outlet conditions, ρ_o = 1.20 kg/m³

Hence, $V_i = \dfrac{M_a}{\rho_i} = \dfrac{2.68}{1.20} = 2.23$ m³/s

Figure 13.3 shows an example of a ventilation curve for both temperature and moisture control. In summer, the main objective of ventilation is temperature control, while in winter the main objective is moisture control.

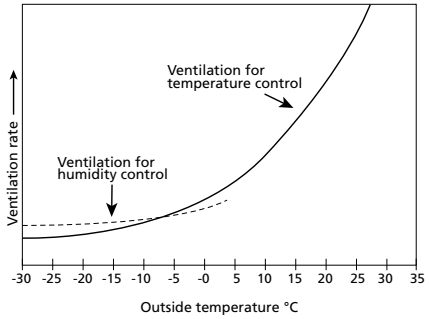


Figure 13.3 **A sample ventilation curve for both temperature and moisture control**

Natural ventilation

Thermal convection or stack effect

Natural ventilation is provided from two sources: thermal convection and wind. Air that is hotter than the surrounding air is less dense and experiences an upthrust caused by thermal buoyancy.

Whenever a building contains livestock, the production of sensible metabolic energy is always available to warm the air entering from the outside. Similarly, air may be heated in a greenhouse by incoming radiation. Provided there are two apertures with a height differential, convection currents will force the heated, less dense air out of the upper aperture to be replaced by an equal volume of cooler, denser air from outside. This is referred to as the 'stack effect'.

Natural ventilation caused by the stack effect can provide the minimum ventilation requirement under winter conditions. While this system may be less expensive than a mechanical system, it will also be less positive in its ventilation action and more difficult to control.

A building that is open on one side may be ventilated naturally by leaving the ridge open for an outlet and a slot along the rear for an inlet. An enclosed building may be more positively ventilated with stack outlets and correctly sized inlets.

Determination of air inlet and outlet sizes

To determine the inlet and outlet areas required to provide a given ventilation rate by thermal convection, the following equation, based on stack effect theory, can be used:

$$\frac{1}{A_i^2} = \frac{1}{A_o^2} = \frac{2g \cdot h \cdot H_p}{T_i(\rho \cdot S \cdot V + W)V^2}$$

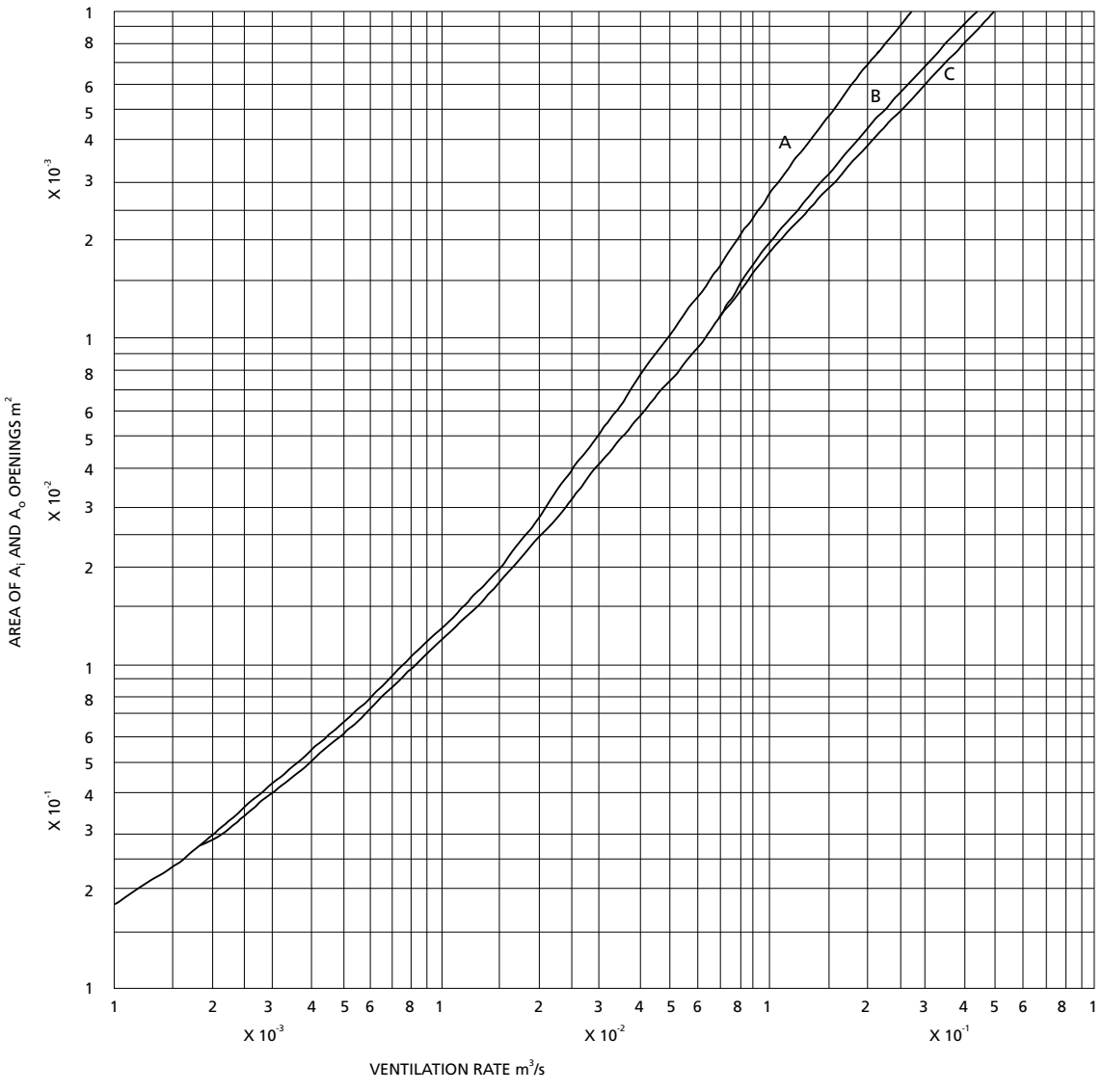


Figure 13.4a **Natural ventilation stack design (dryer)**

where:
A_i = inlet (m²)
A_o = outlet area (m²)
g = acceleration due to gravity (9.76 m/s²)
h = height difference, inlet to outlet (m)
H_p = heat supplied to building (W)
T_i = absolute temperature in building (K, K = (°C + 273))
ρ = density of air in building (kg/m³), 1.175 at 25 °C
S = specific heat of air (1 005 J/kg °C)
V = ventilation rate (m³/s)
W = heat loss through building shell (W/°C).

The values in Figure 13.4a and Figure 13.4b were developed using this equation. The values in (a) are for a solar-flue dryer, while those in (b) fit the conditions in a building more closely.

Natural ventilating systems may be non-adjustable, manually adjustable, or automatically controlled. As natural systems are likely to be chosen for economy reasons where conditions are not severe, manual adjustment should be the method of choice in most cases.

Wind ventilation

As the wind flows around a building, gusts and lulls create regions where the static pressure is above or below the atmospheric pressure in the free air stream. In general, these pressures are positive on the windward side, resulting in an inflow of air, and negative on the leeward side, resulting in an outflow of air. Pressures are generally negative over low-pitched roofs. Figure 13.5 shows natural ventilation in a gable-roof building primarily as a result of wind blowing over the ridge.

Factors to consider in the design of a naturally ventilated structure

The following factors should be considered in the design of a naturally ventilated structure:

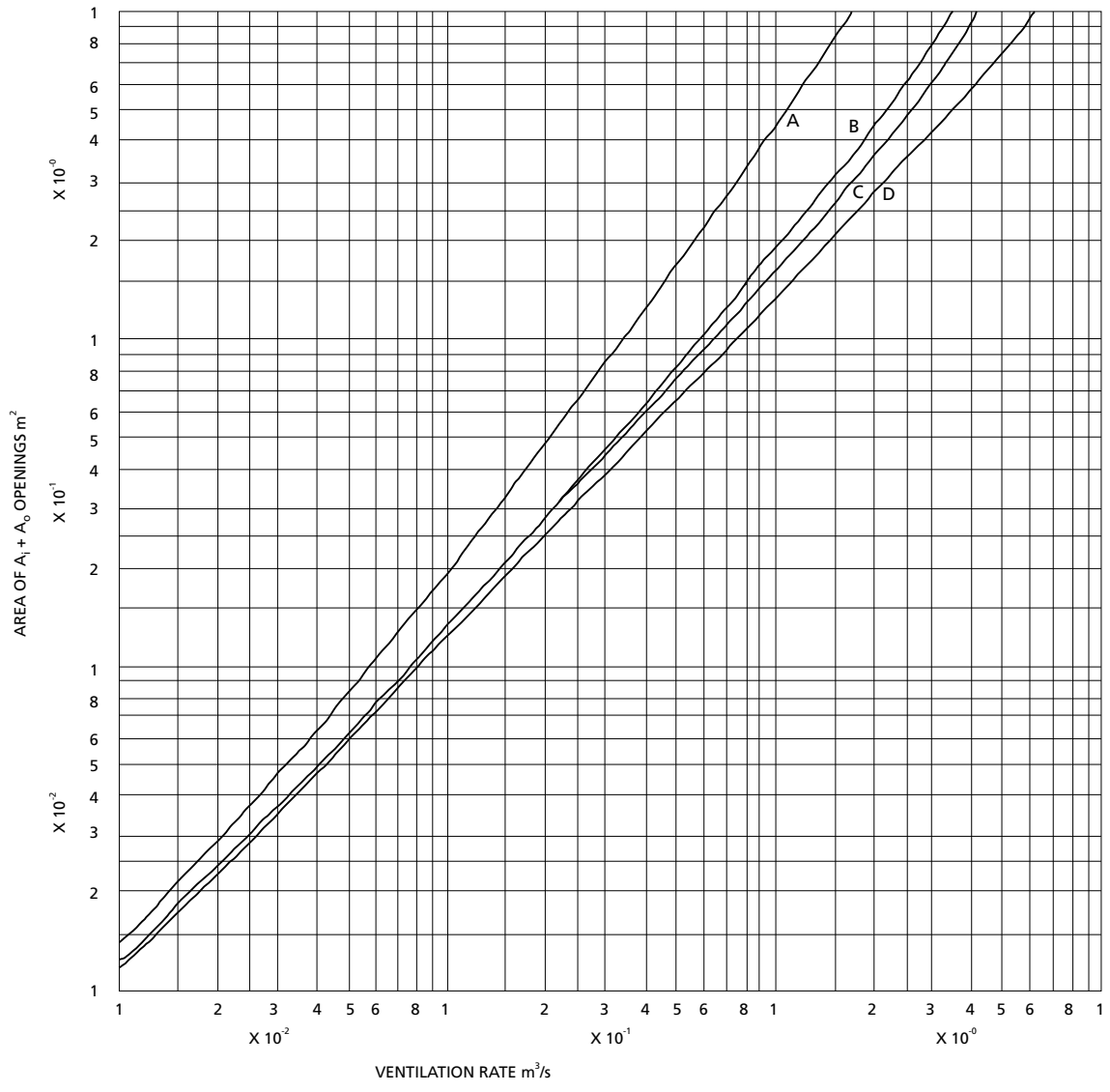


Figure 13.4b **Natural ventilation stack design (barn)**

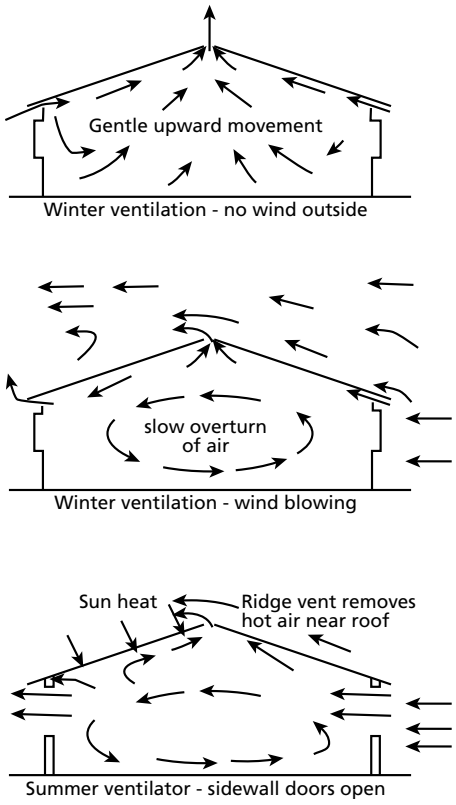


Figure 13.5 **Natural wind ventilation over a gable-roof building**

Location of the structure: The structure should be located so that the ridge of the building is perpendicular to the prevailing summer winds. When structures are set side by side, the following equation may be useful in determining the separation distance:

$$DSD = 0.4 \times H \times \sqrt{L}$$

where:
DSD = separation distance (metres)
H = total height of the obstruction (metres)
L = the length of the obstruction (metres).

Insulation: The walls and ceilings should be insulated in order to reduce excessive heat transmission into and out of the building.

Ceiling slope: The ceiling slope depends on the configuration of the building. If no ceiling is used, the lower side of the roof should slope between 1:3 and 1:2 to allow air to move up toward the ridge at an adequate rate.

Ventilation openings: The size of the ventilation openings is critical to ensure proper ventilation rates.

Ways of controlling natural ventilation

Natural ventilation is difficult to control. However, manipulation of the following parts of the structure may help.

Building width: The wider buildings become, the more difficult it becomes to distribute fresh air to all parts of the building. The widest buildings may be found in areas with higher average wind speeds and may not exceed about 14 metres. Wider buildings will require mechanical ventilation assistance.

Sidewall openings: Openings along the length of the building provide a means for fresh air to enter. Moveable curtains are used for controlling the opening size to accommodate various wind speeds and outside temperatures. Insulated curtains reduce conductive heat loss and the infiltration of cold air during winter periods.

Ridge openings: The purpose of the ridge-vent system (Figure 13.6) is to generate fresh-air ventilation during cold winter periods, thereby removing stale, moist air from the building. When the wind flows perpendicular to the ridge, it produces suction at the ridge which, when combined with thermal buoyancy, provides the force to extract air from the building. Upstands (Figure 13.7) of 15–30 cm above the ridge increase suction at the ridge and thus increase the ventilation rate. A baffle control can then be used to decrease ventilation if the need arises.

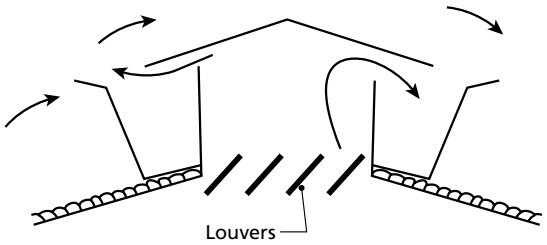


Figure 13.6 **The ridge-vent system with adjustable louvers**

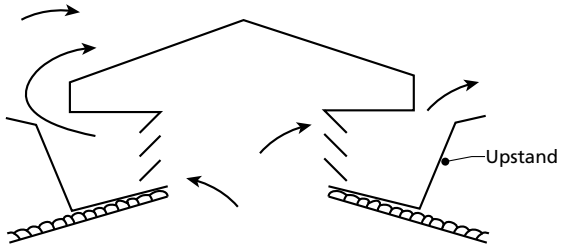


Figure 13.7 **Ridge ventilator with upstands to prevent rain and increase suction**

MECHANICAL VENTILATION

Compared with natural ventilation, mechanical ventilation using fans is more positive in its action, less affected by wind, and more easily controlled.

Initial installation usually costs more and there is the added cost of operation. However, in many cases the advantages of mechanical ventilation outweigh the added expense.

Exhaust versus pressure systems

There are two main types of mechanical ventilating system: pressure and exhaust. In a pressure system, the fan blows air through inlet openings into the building, creating a positive indoor pressure that pushes air out of the building through the outlet openings. In exhaust ventilation, the fan expels air from the building, creating a lower-than-atmospheric pressure inside the building. It is the pressure difference between outside and inside that causes the ventilation air to flow in through the inlets. For good control of the airflow, it is important for the building to be tightly sealed.

The exhaust ventilation system is popular because it is easier to control the distribution of the incoming air, and is generally less expensive, as well as being less complex than a pressure system. However, there are situations when the pressure system (one that forces air into the building) performs better. These include:

- very dusty conditions that tend to load up the fans
- buildings with excessively loose construction (many cracks)
- when continuous recirculation is required.

Under some circumstances, pressure systems may cause humid air to be forced into building walls and ceilings. This can result in condensation and damage to wood and other materials.

A mechanical ventilation system comprises three main components: fans, air-distribution system and controls to regulate the fans.

Fans and blowers

A fan is a mechanical device that uses energy inputs to move air, and can be described as the 'heart' of a mechanical ventilation system.

The two general types of fan are axial-flow and centrifugal. Axial-flow fans are normally divided into propeller and tube-axial types. They move air parallel to the shaft and are the most widely used types. Centrifugal (radial flow) fans (blowers) discharge air at right angles to the shaft and often operate at substantial pressures.

Propeller fans are the least expensive and the easiest to install. A propeller fan may have two to six (or more) blades. In general, the more blades a fan has, the greater the pressure the fan will develop. The best propeller fans have a close-fitting, curved inlet shroud or inlet ring, which improves the efficiency of the fan. Propeller fans are best suited to moving large volumes of air at pressures in the range of 30–50 Pa (3–5 mm of water), and they are the most commonly used in conventional farm building ventilation (Figure 13.8).

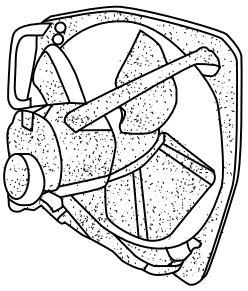


Figure 13.8 **A propeller fan**

The *tube-axial fan* is a more refined version of the propeller fan (Figure 13.9). It has aerofoil-shaped fan blades on an impeller with a large hub, all mounted in a close-fitting tube. Tube-axial fans are capable of operating against higher static pressures than ordinary propeller fans and are made for ducted installations with high resistance to airflow. If it is necessary for a tube-axial fan to operate under very considerable pressure, it may be designed with two impellers in tandem, described as a multistage model.

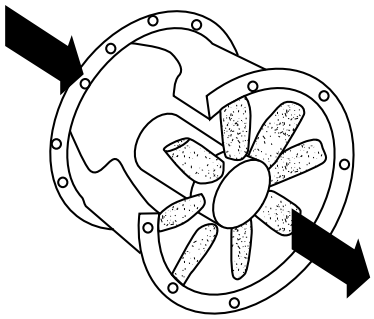


Figure 13.9 **Tube-axial fan**

Centrifugal (radial flow) fans are used for ducted installations or where air must be moved through a product such as grain or potatoes. The blades on the blower may be radial, for example straight from the shaft, curved forward in the direction of rotation, or curved backward opposite to the direction of rotation. The latter can achieve the highest performance efficiencies under high pressure and are most suitable for agricultural applications.

The most important attribute of the backward-curve blower is its non-overloading characteristic. Both the radial and forward-curved types require their greatest power input when airflow is cut off. An air blockage is therefore likely to overload the motor and cause damage (Figure 13.10).

All but the smallest fans should be powered by a capacitor-start motor that is enclosed to provide dust and moisture protection. It should be equipped with an overload protector and bearings with a long

lubrication life. The fan should be enclosed with a wire safety guard. Shutters and hoods are necessary in cold climates but should not be needed in mild climates.

The type of fan selected is largely related to operating pressure. It is important to choose a fan with high performance efficiency in the required range of operating pressures in order to avoid unnecessarily high energy consumption.

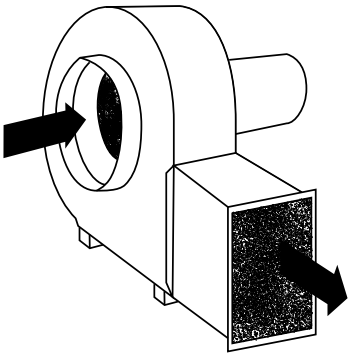


Figure 13.10 **Centrifugal blower**

Static pressure

When an exhaust fan is installed in the wall of a closed building, lower air pressure will develop inside, or if the fan blows air into the building, a slight pressure increase will occur. Manometers or draught gauges are two simple but dependable devices that can be used to measure these small pressure differences (Figure 13.11). They are usually calibrated to read in millimetres of water. That is, if the two columns of water in a glass U-tube are equal, and then a plastic tube is connected from one side of the U-tube to a building with an operating fan, the columns will become unbalanced. The difference is the millimetres of static pressure.

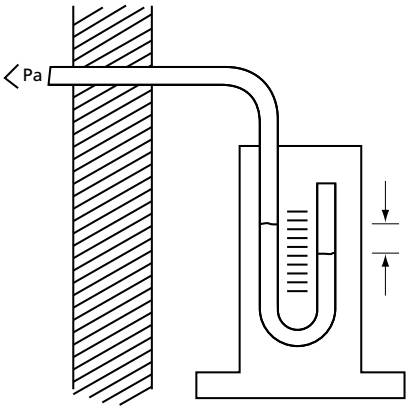


Figure 13.11a **Manometer, which measures static pressure. < Pa = less than the atmospheric pressure**

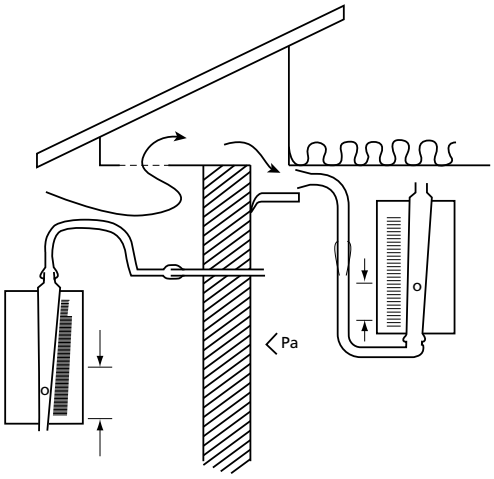


Figure 13.11b **Float-type gauge, which measures static pressure or air velocity**

TABLE 13.1
Illustrative fan performance table

Fan diameter (cm)	Fan speed (rpm)	Motor size (hp)	Airflow in cubic meters per minute (m^3/min) at the indicated static pressure (inches of water)			
			0	1/10	1/8	1/4
20	1 650	1/50	11	9	8	-
25	3 416	1/6	35	34	34	32
30	1 600	1/12	33	30	29	23
36	1 752	1/3	73	67	65	56
41	1 725	1/3	71	67	66	60
46	1 648	1/3	126	115	112	94
53	1 725	3/4	138	134	133	126
61	1 071	1/3	184	159	152	103
76	855	1	284	272	268	242
91	460	1/2	300	255	220	81
107	490	1	438	401	392	-
122	495	1	540	487	469	-

Fan performance and selection

Fan performance is expressed as the volume of air moved in cubic metres per second (m^3/s), or pressure or resistance to airflow in Pa or millimetres of water static pressure (mm WG). Fan performance tables and/or curves are available from the manufacturers. These tables illustrate the maximum or cut-off pressure, efficiency and sound levels at different rotation velocities (rpm) and blade-angle settings, as well as the power requirements for various operating conditions. An illustration of fan performance data is given in Table 13.1.

Fan efficiency and efficiency ratios

Fan efficiency is measured as the amount of air moved by the fan motor per unit of electrical energy input. Factors that influence the energy efficiency of a fan are motor efficiency, speed, blade design, blade-to-housing clearance and fan housing design.

Fan laws

When fan blades are mounted directly onto the motor shaft, it is assumed that the manufacturer has correctly matched the combination. However, some fans are belt-driven, allowing for a motor with a different speed, or pulleys of different sizes, to be substituted while the fan is in operation. Knowledge of the following basic fan laws can reduce problems:

- The delivery volume of a fan varies directly with its speed.
- The cut-off pressure of a fan varies directly as the square of its speed.
- The power requirement of a fan varies directly as the cube of its speed.

For example, assume a fan is belt-driven by a 300 W output and 1 725 rpm motor. If that motor is replaced by a 300W/3 400 rpm motor without changing pulleys, the following would occur: the volume discharged would be doubled, the cut-off pressure would be quadrupled and the horsepower requirement would be increased eightfold. The result would be such a badly overloaded motor that it would burn out unless the overload protector stopped the motor before any damage was done.

The mild climate of east and southeast Africa greatly simplifies the housing requirements for most animals and some plant products. However, it seems worthwhile to discuss several ventilation factors that apply primarily to cooler climates.

VENTILATION SYSTEM DESIGN: COOL CLIMATES

Fan location: Assuming an enclosed building, one to three fans can be located at ceiling level midpoint on the protected side (opposite the prevailing wind) of the building. A greater number of fans may be distributed along the protected side. The high level on the wall is desirable for summer heat removal and has little effect on the efficiency of moisture removal in cold weather. Efficiency, in this case, means the amount of moisture removed per unit of heat used or lost. If outlet ducts are required, they should be insulated to an R of 0.5 to prevent condensation.

Air distribution

In addition to the ventilation rate, it is necessary to consider the distribution of incoming air throughout the building. This is particularly important in both livestock-production buildings and product stores.

When considering fresh-air distribution, two distinct temperature situations are involved. In areas with winter frost, the outside air is cooler than the air inside the buildings, and fresh air must be delivered away from the stock to avoid cold draughts. However, in summer the animals may be subject to heat stress and may suffer considerably unless cooling air currents are directed to remove excess heat from their vicinity. A good air-distribution system also ensures that the animals receive an adequate supply of oxygen and that noxious gases are removed.

Air inlets

Ventilation is accomplished in an exhaust-type mechanical system by reducing the pressure within the building to below outside pressure, causing fresh air to enter wherever openings exist. The principal factors affecting the airflow pattern in a building are the speed and direction of the incoming fresh air. The size, location and configuration of the air inlets are therefore important factors when designing the distribution system.

The flow of air that streams through openings has been closely investigated and the results are summarized by the following statements:

- The speed at which the air stream travels is directly affected by its initial speed through the inlet.
- The distance the air stream travels is proportional to the initial speed at the inlet.
- The higher the initial speed of air entering the building, the greater the mixing of incoming air with the existing air.
- The higher the speed of cool air entering the building, the less it will sink.

It can be deduced from these findings that, in winter, openings should be small enough to provide sufficiently high velocities to avoid cold air falling directly onto the stock, to provide good air mixing, and to maintain the required airflow pattern at the low winter ventilation rate.

Velocities of around 3.5 to 5 m/s usually satisfy these requirements. However, at these velocities it is important to consider the effect of internal partitions, structural members and other obstructions to the flow, and it is also important for the building to be relatively airtight.

When air flows through an opening of any shape, the cross-section area of the issuing jet is reduced to

60–80 percent of the total free area of the opening. A reasonable design value is 70 percent. This phenomenon, the *vena contracta* effect, increases the velocity of air emerging from the opening. The total area of air inlet must be proportional to total fan capacity. According to a common rule of thumb, the size of air inlets should be 0.4 m² of area for each m³/s of fan capacity (Table 13.2).

TABLE 13.2
Ventilation inlet data (vena contracta = 0.7)

Static pressure (mm H_2O)	Velocity (m/s)	Inlet area (m² per m³/s)
5	2.9	0.493
10	4.1	0.348
15	5.0	0.286
20	5.8	0.246
25	6.5	0.219
32	7.3	0.196

The pressure drop across the inlet affects fan performance and therefore should be no higher than necessary. A draught gauge may be used to check the pressure difference across the inlet (between the inside and outside of the building at the inlet). A pressure difference of 10–20 Pa indicates a velocity of 4–6 m/s. Inlet openings, regardless of type, must be adjustable so that the correct air velocity can be maintained throughout the year.

Compared with inlets, the fan outlets have a minor role to play in the distribution of fresh air in a livestock building. The effect of an outlet is to cause a general slow drift of air towards the outlet position. This drift is easily overcome by convection, animal movements or the pattern of air movement established by the inlets. Only near the fan (within approximately 1 metre) can a positive air movement be detected. This applies to outlets in both exhaust and pressurized systems of ventilation. However, it is recommended that no inlet be placed closer than 3 metres to a fan.

Wind has a major effect on ventilation systems because it causes pressure gradients around buildings and directly impinges on components of the system. The pressure gradients will cause problems of uneven air entry, with more air entering on the windward side than on the leeward side of the building. Wind blowing against a fan reduces output and hoods do little to alleviate the problem. Wind blowing across a ridge chimney outlet may cause overventilation.

Wind effects can be reduced by the following actions:

- Orient the building for minimum wind exposure.
- Provide wind breaks.
- Operate the system at relatively high pressure.
- Use attic inlets or openings at the outer edge of wide soffits, as shown in Figure 13.12.

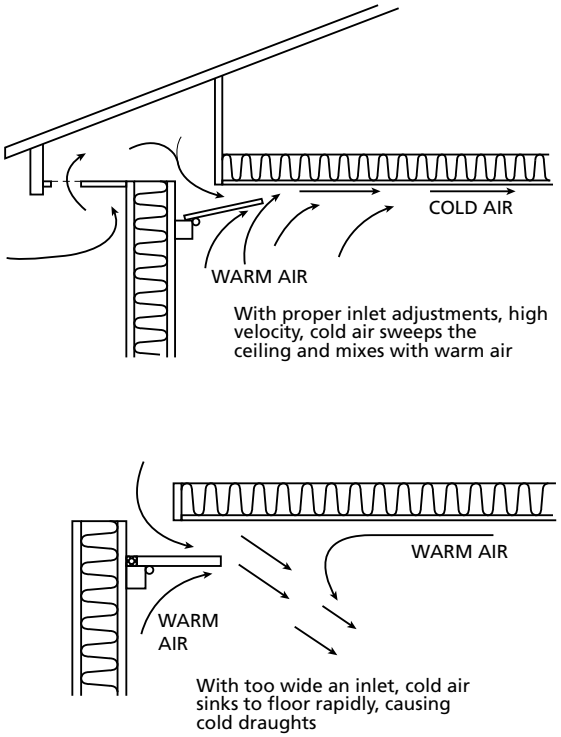


Figure 13.12 **Air inlets: winter adjustment**

In situations where air must be distributed but wall or ceiling inlets are not feasible, polythene tubes punched with holes along their length work well. Usually two rows of holes are spaced at 600–750 mm intervals along the tube. The total area of the hole should be equal to approximately 1.5 times the cross-section area of the tube. Ducts should be sized to provide 4–6 m/s velocity. They may be used either to distribute air in a pressure system or as an inlet for an exhaust system. Sizing is the same in either case.

Ventilation controls

Simple on–off thermostats have given dependable and satisfactory control of many ventilation systems. If the building is small and served by one fan, then a two-speed motor with a thermostat provided with two set temperatures will work well. When several fans are required, one or more may be operated continuously to provide the necessary minimum ventilation rate.

Others may be controlled by a thermostat set at the minimum design temperature. These will cycle on and off in cold weather. The remaining fans may be controlled with a thermostat set at the maximum design temperature. These will only operate in warm weather when it is necessary to remove excessive heat.

Filled or bimetallic thermostats, placed at a height of 2 metres near the centre of the building, work well as controllers. Electronic controllers, using multiple thermistors to sense temperatures in several locations, combined with variable speed motors and automatically-adjusting inlets are available. Although

they undoubtedly do a more precise job of controlling the building environment, their additional cost is difficult to justify. Humidistats have not proved very satisfactory as controllers for mechanized ventilation systems.

Ventilation design example

Although calculating the heat and moisture balance for a building in cold weather (below 0 °C) is not a typical problem for tropical climates, a sample will show how the psychrometric chart is used, as well as the possible difficulties encountered in cold climates.

Assume a farm has sixty 600-kg cows housed in a 10 m by 40 m by 3 m barn, with 20 m² of windows and 12 m² of doors. *R* values are: window 0.17, door 1.0, ceiling 2.6 and wall 2.1. The temperature and relative humidity are - 10 °C and 90 percent outside and + 12 °C and 75 percent inside. The total heat and latent moisture production from the animals is found in Table 10.2 and is 1 130 W and 0.485 kg/hr per cow.

From Appendix V:6, the 1 500 metre psychrometric chart, - 10 °C and 90 percent equals - 6 kJ/kg enthalpy and 0.0016 kg/kg specific humidity. Also + 12 °C and 75 percent equals 31 kJ enthalpy and 0.0078 kg/kg specific humidity. From the chart, the humid volume at 12 °C and 75 percent equals 0.98 m³/kg the value at which the fans are exhausting air. 1 kJ = 1/3.6W.

Procedure

Heat production	60 × 1 130	= 67 800 W
Respired moisture production	60 × 0.485	= 29.1 kg/hr
Heat loss through:		
Ceiling	400 × 1 / 2.6 × 22	= 3 385 W
Wall	(300-32) × 1 / 2.1 × 22	= 2 808 W
Windows	20 × 1 / 0.17 × 22	= 2 588 W
Doors	12 × 1 / 1.0 × 22	= 264 W
Total heat loss		9 045 W

Heat available for ventilation 67 800 – 9 045 = 58 755 W
Minimum airflow to remove moisture
29.1 / (0.0078-0.0016) = 4 694 kg/hr

Fan capacity at minimum flow
4 694 × 0.980 / 3600 = 1.28m³/s
Heat removed by airflow
4 694 × (31.5-(-6) / 3.6) = 48 896 W

As the heat available for ventilation is greater than the heat actually removed by the minimum ventilation rate, the inside temperature will tend to rise or the relative humidity will fall, but a cycling of additional fan capacity will maintain the desired temperature.

It should be pointed out that, although the values for moisture production in Table 10.2 include normal evaporation from feed, manure and urine, the real evaporation may well be higher or lower, depending primarily on how large a surface area of wet floor is exposed from which evaporation can take place. Greater evaporation would reduce the moisture to be removed with the manure.

If the heat removed by the ventilation is greater than that available for ventilation, the inside temperature will fall as a result unless the insulation of the building is improved and/or supplemental heating is installed. It should be noted that a lower minimum ventilation rate aimed at maintaining the temperature may cause the inside air to become saturated and result in condensation on cold surfaces such as windows.

Calculations using outside summer temperatures, e.g. 21 °C, would show the need for additional fan capacity to remove heat and maintain an acceptable temperature difference between inside and outside, e.g. 4 °C.

Maximum ventilation rate is the product of sensible heat production divided by temperature difference (inside–outside) and isobaric specific heat capacity.

The sensible heat production, according to Table 10.2, is 465 W per animal at 25 °C (inside temperature) and the maximum ventilation rate is therefore:

(60 × 465) / (4 × 0.35) = 19 950 m³/hr or 5.54m³/s.

Between the cold- and warm-weather rates, thermostats trigger a cycling of fan operation to maintain temperatures within the desired range.

COOLING

During high-temperature periods, ventilation alone may be insufficient to maintain satisfactory temperatures in animal buildings. The following cooling system can be used effectively in totally enclosed buildings. Other cooling techniques, such as spray cooling, are discussed in later sections.

Evaporative cooling

The evaporative cooler operates on the simple principle of a fan drawing hot air into the building from outside through a wet pad. The hot air is cooled by evaporating water, which changes sensible heat in the air into latent heat in the vaporized moisture, thereby lowering the temperature.

Air temperature reductions of as much as 11 °C can be achieved in buildings during hot periods with low humidity. Although in humid weather the cooling effect is considerably reduced, in many areas the system may be suitable for the greater part of the hot season.

Commercial evaporative coolers are available in sizes varying in capacity from 1 to 95 m³/s. Since they are sold complete with built-in fans, it is essential to select suitable units with correct ducting, diffuser and register sizes to allow balanced air distribution in the building. Ample exhaust vents should be provided around the perimeter of the building to allow the free outlet of air. A thermostat is advisable to control the units.

Where humidity control is required, a humidistat can be added to the control circuit. Some designs incorporate

a heat exchanger. In these designs, the air that has been cooled while passing through the wet pads is used to cool other air, which actually enters the building. Although this results in less humid air being used for ventilation, the extra step causes a loss in efficiency.

An alternative to the packaged evaporative cooler can be assembled using a pad and fan system. Pads made of 50 mm thick compressed 'wood wool' or other suitable material are installed, usually in the long wall of the building, and exhaust fans are positioned in the opposite wall. Incoming air is cooled as it passes through the wet pads and then, after passing through the building, it is exhausted by fans (Figure 13.13).

For effective operation, the air velocity through the pad area should be limited to about 0.8 metres per second. This is accomplished with 1–1.5 m² of pad area per m³ and second of airflow. The cooled air leaves the pad at a relative humidity of 85–90 percent, but is quickly moderated by the ambient air.

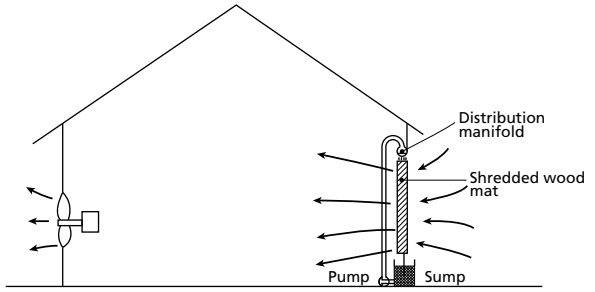


Figure 13.13 **Evaporative cooler**

Water is spread evenly over the pads from a manifold supplied from a sump with a float-controlled water level. Water should recirculate through the pads at the rate of approximately 160 ml/s for each m³/s airflow. The actual water consumption, i.e. the evaporation of water into the passing air, varies with the changing conditions of temperature and humidity. However, as a guide, it is approximately 20 percent of the water recirculation rate. Evaporative cooling is discussed further in Chapter 14.

Evaporative coolers, which rely on wind pressure to force air through the wet pads, are less effective as the airflow is likely to be either too low or too high most of the time. While naturally ventilated evaporative coolers require larger pad areas, the fact that no fan or power is required to drive a fan recommends these designs for small-scale applications in rural areas. They can usually be constructed using local materials and operated and maintained by the farmer at low cost.

The value of evaporative cooling systems depends on the application and on the typical wet-bulb temperatures of the region. In areas of high humidity, they work well for greenhouses and potato stores, but are unsatisfactory for poultry and other animals that depend on respiration for body cooling at high temperatures. Evaporative cooling is much more practical in dry regions, where the air can be cooled significantly while the humidity is still low enough to have little effect on animal comfort.

Refrigeration

The use of ventilation alone or evaporative coolers may be insufficient to meet the temperature requirements for storing some products. If the product has sufficient value to justify mechanical refrigeration, then nearly ideal conditions can be provided.

Principles of refrigeration

Most fluids occur as either a liquid or a vapour, depending on pressure and temperature. The higher the pressure and the lower the temperature, the more likely it is that the liquid phase will occur. Whenever there is a change of phase there will be a concurrent latent heat exchange. This means that when a liquid changes to a vapour, heat is absorbed; when a vapour changes to a liquid, heat is given off. There are several materials that happen to change state at pressures and temperatures that make them useful in mechanical refrigeration systems.

Refrigeration systems

A refrigeration system comprises four main parts:

- a compressor
- a condenser
- an expansion valve or other restriction in the refrigerant line
- an evaporator

The components are connected together in a complete circuit in the order listed. In addition, there may be a receiver (small tank) between the condenser and the expansion valve (see Figure 13.14).

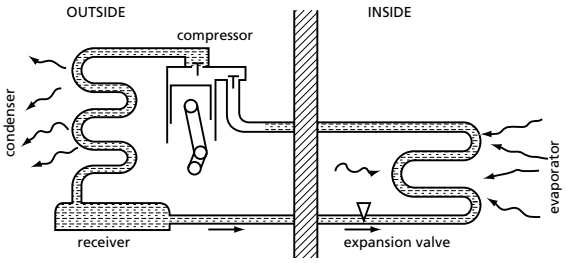


Figure 13.14 **Refrigeration system**

When the system is charged with a refrigerant, operating the compressor reduces the pressure in the evaporator and causes the refrigerant to boil, evaporate and absorb heat. This causes a drop in temperature. At the same time, the compressor is pumping the evaporated vapour into the condenser at high pressure. This causes the refrigerant to condense back to a liquid

while giving up heat. The temperature in the condenser will rise. The receiver serves as a reservoir for liquid refrigerant.

Obviously the evaporator is installed in the room to be refrigerated, while the condenser is located where ambient air can readily absorb the heat produced. The expansion valve is the temperature control mechanism for the system. If it is adjusted to further restrict the refrigerant flow, both the pressure and boiling temperature in the evaporator will drop and, within the limit of the system's capacity, the room temperature may be maintained at a lower level.

The pressure on the condenser side is determined largely by ambient conditions. If the air temperature is relatively low, the condenser discharges its heat easily at normal pressures. However, in very hot weather, or if the airflow through the condenser becomes restricted by dust or other debris, the temperature and pressure may rise to levels dangerous to the system, unless a high-pressure safety switch has been installed.

Refrigerants

A number of fluorocarbon refrigerants are used for various temperature applications, especially in small refrigeration systems; however, fluorocarbon refrigerants are ozone layer depleting and are to be completely phased out by the year 2030 according to the Montreal Protocol on substances that deplete the ozone layer. For example, manufacture of the formerly popular R12 has stopped in developed countries. Therefore, owners of functional R12 systems that may need refrigerant replacement are encouraged to use alternatives such as R134a or decommission the systems. Another popular fluorocarbon, R22, is also undergoing replacement. Detailed information about these refrigerants can be found in an up-to-date handbooks on refrigeration and air conditioning or directly from the manufacturers.

The popular inorganic refrigerant for industrial systems is the ammonia (R717). R717 is toxic, has a strong pungent odour, burns in certain concentrations in air, is prone to leaking and is piped with steel pipes. However, ammonia is cheaper and more efficient because it has a much higher evaporation heat, requiring smaller component parts throughout. Consequently, in spite of the disadvantages, ammonia systems are often chosen for large stores because of the economies.

Evaporators

Fabricating a refrigeration system requires the specialized equipment and knowledge of a contractor. However, it is a distinct advantage for the customer to know how the evaporator size and corresponding operating temperature relate to the conditions required in the cold store.

A given storage room and product quantity will impose a particular load (watts) on the refrigeration system. That load can be met by operating a relatively small evaporator at a very low temperature (heat moves to its limited surface rapidly), or by operating a larger evaporator at a more moderate temperature (heat moves more slowly but to a much greater surface area). Air passing through an evaporator will, in nearly all cases, be cooled sufficiently to reach saturation (100 percent RH).

The psychrometric chart shows that the moisture-holding capacity (specific humidity) of air at two slightly different temperatures will be nearly the same, while air at widely differing temperatures will have quite different specific humidities.

For example, assume a store temperature of 10 °C and an evaporator temperature of 8 °C. The absolute humidity of saturated air at 8 °C is 0.0066 kg/kg. That will allow a relative humidity at 10 °C of 89 percent, which is desirable for a potato store. In contrast, onions store best at 0 °C and 75 percent RH, so a smaller evaporator operating at - 5 °C and 0.0025 kg/kg at saturation would provide the desired 75 percent RH.

Unfortunately, refrigeration contractors may not understand, or care about, this relationship and therefore present a bid for a system based on too small an evaporator, which would need to be operated at too low a temperature. While this would have a lower purchase cost, it would fail to provide the proper conditions. Finally it should be pointed out that, in air conditioners for homes, one of the objectives is to reduce humidity. Consequently small evaporators operated at low temperatures are perfectly satisfactory.

REVIEW QUESTIONS

1. Determine the ventilation rate for a W-36 laying hen house with 100 000 birds with an average body mass of 1.40 kg. The inside temperature is to be maintained at 21 °C with relative humidity of 50 percent. Assumptions: no supplemental heating; no solar heat; no heat from motors; the ΣAU and FP factors are 1 350 and 200 W/°C, respectively. The outside temperature is 8 °C.
2. Describe how natural ventilation works.
3. A total of 250 growing–finishing pigs at 60 kg body mass are housed in a mechanically ventilated building. Determine the ventilation rate to maintain 60 percent relative humidity at 20 °C if the outside temperature is 15 °C with 80 percent relative humidity.
4. Discuss the ventilation curves for both moisture and temperature control.
5. Using similar relevant data, as shown in the previous example of the ventilation design, design a ventilation system for 120 000 W-36 laying hens housed in a barn measuring 70 metres long by 30 metres wide and 2.7 metres high at sea level. The house does not have windows.

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Chapter 14
Greenhouses

INTRODUCTION

A greenhouse is a structure using natural light within which optimum conditions may be achieved for the propagation and growing of horticultural crops, for plant research, or for isolating plants from diseases or insects. In the 1970s, in the tropical areas of Africa, applications were limited because there were only a few situations in which a greenhouse could be justified owing to the optimum growing conditions required for a high-value crop or a research project. However, as from the 1980s, with the establishment of an export-oriented horticulture industry (Kenya's horticulture industry is one of its largest foreign-exchange earners), greenhouses are now found in most countries of Africa.

The cost of various greenhouse designs varies greatly and a careful assessment is required to match the requirements for a given enterprise to the cost of the greenhouse. For example, a greenhouse used for all-year flower production can justify the cost of glass, while a greenhouse used for a month or two for starting vegetable plants can only justify a polythene covering.

Location of the greenhouse

The following factors should be considered when deciding where to locate a greenhouse.

Topography: The land should be nearly level, with the ideal gradient being 1 in 100 to 1 in 200. This facilitates moving carts of plants around the complex. The land should also be well-drained and located in an open area with no shade from trees or buildings.

Soils: Good soil is essential, with the ideal soil being deep, medium-textured loam. Soils that are less than ideal would be worth improving. Very heavy soils are not usually satisfactory.

Windbreaks: Nearby buildings and hedges act as windbreaks to slow winds before they hit the greenhouse, which could lead to roofs being blown off and other damage. However, any windbreak should be far enough away from the greenhouse to prevent shading. Normal air movement is also essential for natural ventilation systems and to prevent locally stagnant conditions.

Water supply and quality: A good, clean water supply is of paramount importance. A full crop system may require up to 8 400 m^3 per hectare (840 litres/m^2) in a single year, and the source of water must be able to supply all that will be required. Before using any water, have it tested for excessive amounts of sodium or iron and a pH imbalance, which should be corrected before using the water for plant irrigation. Pond water should be chlorinated at the time of use to kill algae and root-rot organisms.

Electricity: Electricity will be required if ventilation is to be mechanized and if stationary machinery is to be used in the greenhouse.

Roadways: Roadways are essential for the delivery of supplies and to collect harvested plants and/or produce. Retail operations should have an entrance for customers separate from the one used by service providers and there should be adequate parking space.

Labour force: The business of cultivating crops under greenhouses is labour-intensive. Mechanization of some of the operations, such as automated irrigation equipment, computer-controlled heating and cooling systems, automated seeders and potting machines, can reduce labour requirements. Although the initial capital outlay can be considerable, these devices enable owners to raise productivity with fewer but better-trained permanent employees.

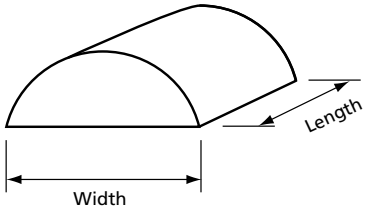


Figure 14.1a **The Quonset design with the arch extending to the ground**

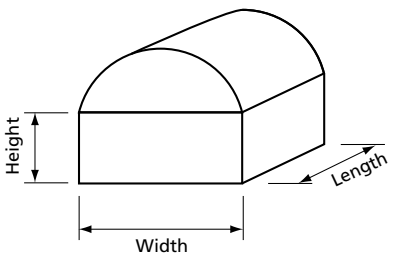


Figure 14.1b **The Quonset design with the arch set on vertical walls**

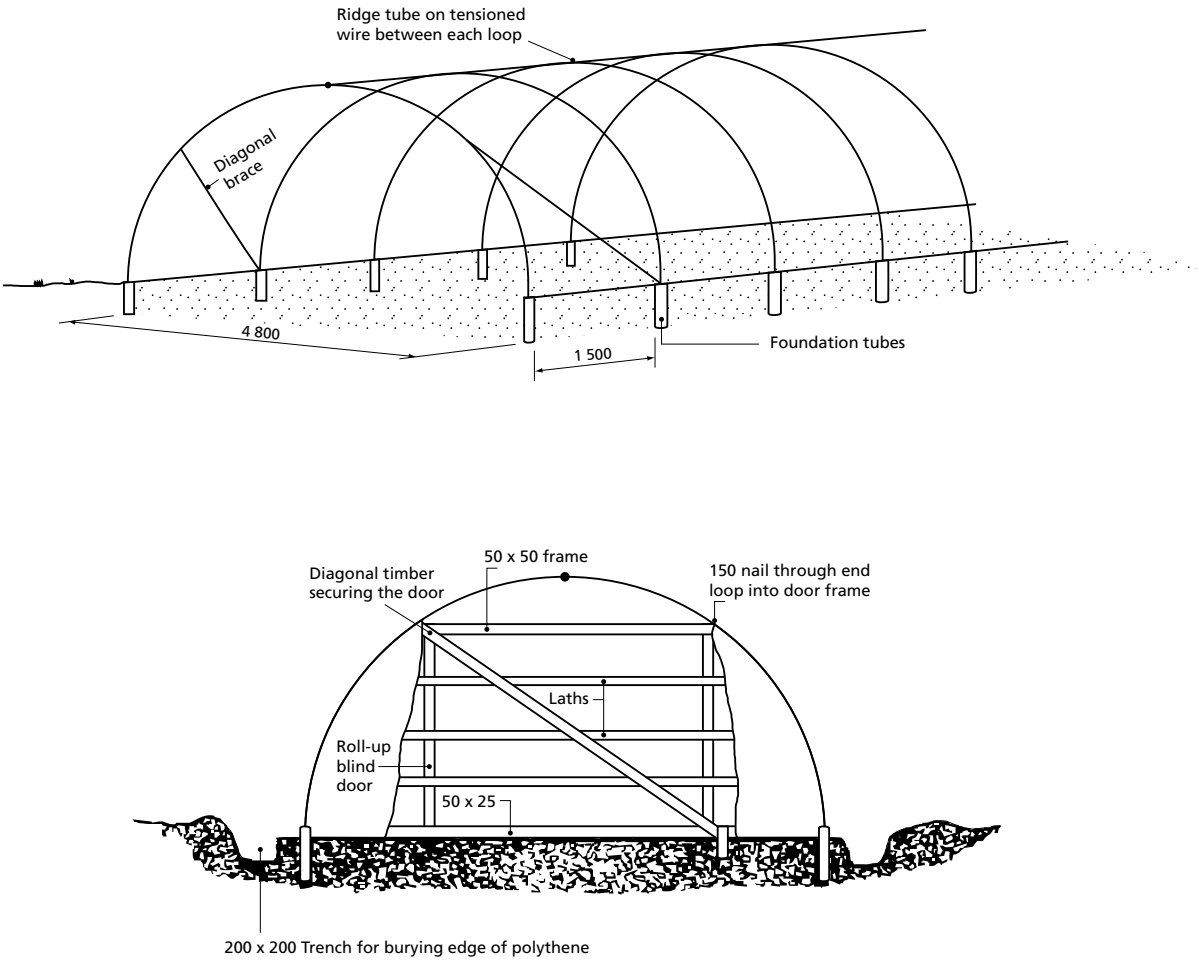


Figure 14.1c **A Quonset greenhouse frame construction**

Types of greenhouse

There is a wide variety of greenhouse designs. However, most of these are derived from two basic designs: the *Quonset* and the *A-frame*. The Quonset is based on an arched roof that permits stresses on the structure to be efficiently transferred to the ground. Quonset greenhouses are normally available in two basic designs.

In the first, the arch extends to the ground with no sidewalls (Figure 14.1a). In the second, the arch essentially forms the roof and gable sections of the greenhouse and is set on straight vertical walls (see Figure 14.1b). Figure 14.1c shows some construction details of the Quonset type of greenhouse structure.

Usually, but not always, the A-frame has a series of supporting trusses that form the roof and gables. The strength of this structure comes primarily from the trusses set on vertical walls. The weight of the structure and other stresses are borne by the trusses and transferred to the vertical walls, which in turn transmit the stresses to the ground.

A-frame greenhouses may have even spans or uneven spans. In the former, both roof sections are of equal length, whereas in the latter they are of unequal length (or missing entirely). These two basic designs may be single, stand-alone structures (Figure 14.2a), or combined side-to-side to form ridge-and-furrow or gutter-connected structures (Figure 14.2b). In this case, the interior walls are usually absent.

Most commercial greenhouses now utilize some variation of the gutter-connected design. This is primarily because the gutter-connected design allows for a larger unobstructed interior than would be possible with stand-alone greenhouses. This improves the ability to automate common tasks such as irrigation and increases space usage efficiency. Also, by eliminating interior walls (which would be exterior exposed walls in free-standing structures), the construction and heating costs are reduced.

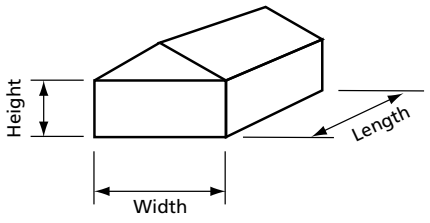


Figure 14.2a **The stand-alone A-frame structure**

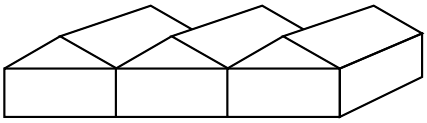


Figure 14.2b **The gutter-connected A-frame structure**

There are several potential drawbacks with gutter-connected facilities. As the entire production area is a single space, the ability to maintain different environmental conditions (as is possible using numerous individual structures) is lost. In addition, as the size of the gutter-connected span increases, uniformity and control of light, temperature, airflow and humidity may be reduced.

One way to minimize these drawbacks is to have drop-walls or curtains made of polyethylene film that can be raised or lowered between sections. This allows sections within the structure to be partially isolated so that different temperatures or relative humidity levels can be maintained – if only to a limited degree.

Greenhouse design parameters

Increasingly in recent years, most greenhouses are designed by engineering firms or are constructed from packages developed by engineering firms. The design and all the materials may be provided by the design firm. In many cases, the design firm will also build the structure. However, it is useful to understand the basic design considerations.

Light: It is important for crops being grown in a greenhouse to receive the optimum amount of light, not only when the skies are clear (direct light), but also when they are cloudy (diffuse light). The shape and construction of the greenhouse should be such that it allows the best possible entry of light. The size and cross-section of all the load-bearing members have a pronounced effect on light transmission.

The gutters of multispan roofs produce considerable shade, and similarly, in widespan greenhouses, the heavier roof trusses tend to cause more shading. Thus, open trusses with narrow-section members are desirable. Light colours and reflective surfaces improve light transmission. In spite of a good design for natural light, artificial lighting may be needed for the production of photoperiod-sensitive plants.

Design loads: The greenhouse should be able to withstand both the dead load and the live load. The dead load includes the weight of the structure, framing, glazing, permanent equipment, heating and cooling units and vents. The live load includes the weight of people working on the roof, hanging plants and wind loads.

The foundation: The foundation must support the structure and transfer loads to the ground. In some cases, the structure may be set on an intact concrete foundation or slab. Supports may be bolted onto the foundation. In other cases, whether or not a concrete foundation is present, the structure may be supported by vertical beams placed on concrete footings.

Orientation: Within the latitudes found in the tropics it is desirable to orient the ridges of greenhouses north–south to reduce the overall shading by the framing members. This is true for all types of frame, including multi-span greenhouses.

Size: While multi-span blocks of 3.2 metres each are the least expensive to build, wider spans allow somewhat better light transmission. Furthermore, the general management in wider greenhouses (movement of machines, optimum cropping layouts, etc.) may justify the extra cost. As a general rule, the cost is lowest when the length is four to five times the span width. This is particularly true with wide-span greenhouses.

Height: The height of a greenhouse should be sufficient for the operation of machinery and the comfort of the workers. An increase in height improves natural ventilation during still conditions and makes it easier to obtain the desired plant climate. However, with very high roofs, maintenance becomes more difficult. Gutter heights of 2.8–3.0 metres are recommended for multi-span greenhouses to allow machines to move freely. In single-span greenhouses, eave height should be at least 2 metres to provide unrestricted work space.

Structural materials

These can be grouped into floors, frames and coverings.

Floors: Floors may be constructed of porous concrete, Portland cement, gravel or compacted clay covered with a strong polypropylene fabric. Porous concrete is usually strong enough to bear most loads encountered in greenhouse situations, and allows for drainage through the surface. Portland cement is more expensive and does not allow drainage through the surface. However, Portland cement might be desirable in traffic areas where heavy loads occur.

Concrete floors should have a slight gradient to promote drainage and prevent puddling of water. Gravel is inexpensive and allows drainage, but can allow the growth of weeds and may not accommodate all types of equipment. Although polypropylene fabric may be a low-cost alternative, the floor can become uneven over time and can cause puddling and algae growth.

Frames: Greenhouse frames range from simple to complex, depending on the imagination of the designer and the engineering requirements**.** Greenhouses are generally built of steel, aluminium or wood and are glazed with good-quality glass, clear polythene sheet, or fibreglass-reinforced polyester panels.

Steel must be galvanized after fabrication, as any welding or drilling breaks the galvanized layer. Steel is cheaper than aluminium and is ideal for the main roof frame.

Aluminium is very resistant to corrosion and is easily formed into complex sections. While it is expensive, it is most suitable for glazing bars. As it cannot be welded economically, bolted construction is used.

Wood is less suitable for the lightweight construction and high moisture conditions found in greenhouses, so only top-grade timber of the most decay-resistant species, which has been treated with a water-based wood preservative, should be used. The recommended wood preservatives for greenhouses are chromate copper arsenate (CCA), ammoniacal copper arsenate (ACA) copper naphthanate and zinc naphthanate.

Coverings: The type of frame and cover must be matched correctly. Greenhouse coverings include the following:

Glass: Glass is expensive, but it is the most durable covering and transmits the most light (90 percent). However, the gradual build-up of dirt and algae, along with surface etching, eventually causes a reduction in light transmission. The minimum width of glass ordinarily used is 610 mm. Also common is the 730 mm width. Both of these are 4 mm thick and weigh 2.8 kg/m². An aluminium frame with a glass covering provides a maintenance-free, weathertight structure that minimizes heat costs and retains humidity.

Tempered glass is frequently used because it is two to three times stronger than regular glass. The disadvantages of glass are that it is easily broken, is initially expensive to build and requires much better frame construction than fibreglass or plastic. A good foundation is required, the frames must be strong and they must fit together well to support heavy, rigid glass.

Fibreglass: Fibreglass is lightweight, strong, and practically hail-proof. A good grade of fibreglass should be used because poor grades discolour and reduce light penetration. Use only clear, transparent, or translucent grades for greenhouse construction. Tedlar-coated fibreglass lasts 15–20 years. The resin covering the glass fibres will eventually wear off, allowing dirt to be retained by exposed fibres.

A new coat of resin is needed after 10–15 years. Light penetration is initially as good as glass but can deteriorate considerably over time if poor grades of fibreglass are used. Fibreglass-reinforced polyester panels are more impact-resistant than glass and more durable than polythene sheet. Light transmission is about 85 percent but declines significantly unless the surface is cleaned and resurfaced with acrylic sealer every 4–5 years. Fibreglass is intermediate in cost between glass and polythene.

Double-wall plastic: Rigid double-layer plastic sheets of acrylic or polycarbonate are available to give long-life, heat-saving covers. These covers have two layers of rigid plastic separated by webs. The double-layer material retains more heat, so energy savings of 30 percent are common.

Acrylic sheet is a long-life, non-yellowing material; although polycarbonate normally yellows faster, it is usually protected by an ultraviolet-inhibitor coating on the exposed surface. Both can be used on curved surfaces; the polycarbonate material can be curved more. As a general rule, each layer reduces light by about 10 percent. About 80 percent of the light filters through double-layer plastic, compared with 90 percent for glass.

Film plastic: Film-plastic coverings are available in several quality grades and several different materials. In general they are replaced more frequently than other covers. Structural costs are very low because the frame can be lighter and plastic film is inexpensive. Light transmission of these film-plastic coverings is comparable to glass. The films are made of polyethylene (PE), polyvinyl chloride (PVC), copolymers, and other materials. Commercial greenhouse-grade PE has ultraviolet inhibitors in it to protect against ultraviolet rays; it lasts 12–18 months. Copolymers last for 2–3 years.

New additives can be used to manufacture film plastics that block and reflect radiated heat back into the greenhouse, as does glass, which helps to reduce heating costs. PVC or vinyl film costs two to five times more than PE but lasts as long as five years. As it attracts dust from the air, it must be washed occasionally.

Ventilation

In tropical regions, ventilation is likely to be the most important environmental control feature of the greenhouse. The air inside the building is exchanged for outside air to lower temperature, to reduce humidity, and to maintain a supply of carbon dioxide for photosynthesis. This is accomplished by natural means, with vents and doors, or by mechanical means, using fans.

The ventilation rate is usually expressed as cubic metres per second of airflow per square metre of floor area. To obtain a reasonable heat rise of less than 4 °C in a glass-clad greenhouse, the airflow rate in the tropics should be 0.04–0.05 m³/s and per m² of floor area.

Polythene-clad greenhouses do not become as hot because of the transparency of the plastic to long-wave radiation that is transmitted back out of the greenhouse. The ventilation rate for a polythene-clad greenhouse can therefore be reduced to 0.03–0.04 m³/s and m². This further reduces the cost of a polythene-covered greenhouse.

Adequate natural ventilation is often provided by large doors at each end, even though this may amount to only 3–7 percent of the floor area. These large doors not only aid ventilation but also allow easy access to the greenhouse.

Installing circulating fans in the greenhouse is a good investment. In cold regions, during the winter when the greenhouse is heated, air circulation must be maintained so that temperatures remain uniform throughout the inside of the structure. Without air-mixing fans, the warm air rises to the top and cool air settles around the plants on the floor.

Small fans with a cubic-metre-per-minute (m³/min) air-moving capacity equal to one-quarter of the air volume of the greenhouse are sufficient. For small greenhouses (less than 18 metres long), the fans should be located in diagonally opposite corners, but away from the ends and sides. The goal is to develop a circular (oval) pattern of

air movement. In addition, the fans should be operated continuously during the winter and turned off during the summer when the greenhouse will need to be ventilated.

Cooling

As a result of the long hot season in the tropics, the greenhouse must be cooled to achieve the desired conditions. Glazing materials allow shorter-wavelength radiation (i.e. visible light) to pass through, but long-wavelength radiation such as infrared (heat) is trapped inside the greenhouse. The temperature inside a greenhouse may be up to 20–30 °C higher than the ambient temperature outside (hence the greenhouse effect). Owing to the greenhouse effect, greenhouses require both summer and winter cooling systems.

Summer cooling systems

Passive systems

Venting: High summer temperatures mean that there is a constant need to remove heat from the greenhouse. This may be accomplished by replacing existing air in the greenhouse with cooler air from outside the structure. If outside temperatures are low enough, and if temperatures in the greenhouses are not excessive, warm air may be passively exhausted through roof vents.

The upward and outward movement of warm air pulls in cool air from side- or end-vents. This system is most effective in the winter, spring and autumn. It is limited in its effectiveness for summer cooling, as the incoming solar load and the outside air temperature may exceed the capabilities of this system.

Shading: Shading is another method of passive cooling used to reduce the amount of light transmitted into the greenhouse, thereby reducing the solar load. In glass houses, shading may be achieved simply by applying water-based whitewash to the inside of the roof to cut down light transmission. When the weather conditions are steady and reliable, whitewash is cheap and effective and easily washed off when it is no longer needed. Whitewash seems particularly appropriate for shading in tropical areas.

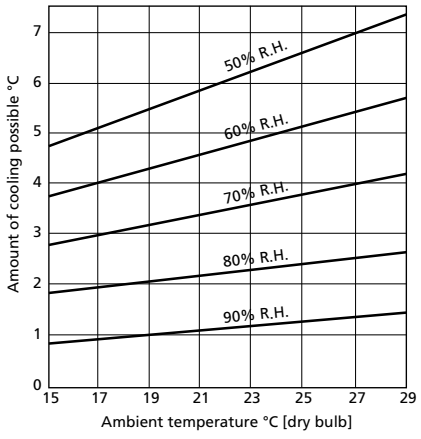


Figure 14.3 **Limits of evaporative cooling**

Active systems

Fan-and-pad system: This is the most common type of active cooling system used in commercial greenhouses. The system uses the principle of the latent heat of evaporation, i.e. as liquid water evaporates it absorbs energy from the environment (surrounding air), which results in a lowering of the temperature of the surrounding air. This process is called evaporative cooling. The evaporative cooler works best when the humidity of the outside air is low. Figure 14.3 shows the temperature reductions that are possible with evaporative cooling. The evaporative cooler capacity should be sized at 1.0–1.5 times the volume of the greenhouse.

In a fan-and-pad system, pads made from cellulose (or another material) are placed in one wall of the greenhouse and fans are placed in the opposite wall. The fans expel air from the greenhouse, which creates a pressure drop inside and causes air to enter through the pads at the opposite end of the greenhouse. All vents, except for the pad opening, must be closed when the fan and pad system is in operation. Figure 14.4 shows the fan-and-pad cooling system, and Figure 14.5 shows a schematic of the evaporative cooling pad.

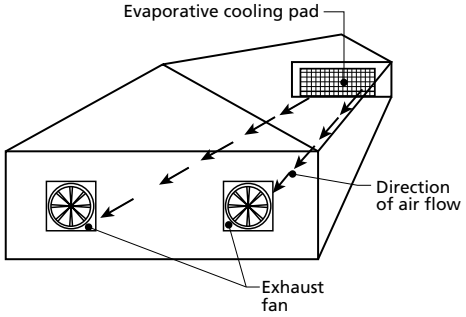


Figure 14.4 **The fan-and-pad cooling system**

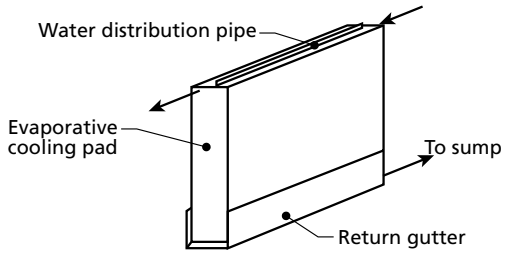


Figure 14.5 **The evaporative cooling pad**

During operation, the water is pumped to the pad from a tank or sump that serves as a reservoir. The water is first supplied to a feed-line that runs the length of the pads. Holes in the top of the feed-line allow water to be forced out of the line. The water is forced

upward, strikes a cover plate and trickles down to the pads. A cover material may be placed over the pad to ensure more even wetting of the pad.

The water trickles down through the pad, is collected in a catch basin and is recycled back to the reservoir. Water evaporates as it passes through the pads, with the result that it must be continuously resupplied to the reservoir. This is accomplished by having a water supply line to the reservoir that is controlled by a float-valve. The reservoir should have sufficient water-holding capacity to fill all pipes and saturate the pads. The water supply system should operate so that the entire pad is kept wet.

Pads need to be properly maintained, particularly as salt build-up and algae growth are the greatest threat to pad longevity. As water evaporates, salts accumulate on the pads. These deposits physically block air movement through the pads and prevent uniform wetting. If the water supply is high in salts, blended water should be used.

Algae can also accumulate on the pads, and several types of biocide can be added to the water to prevent their growth. Sodium hypochlorite (bleach) may be added at a rate of 1 percent by volume, which provides a 3–5 parts per million chloride(Cl^-) solution. However, the bleach will tend to raise the pH of the water, and this can damage pads by softening the glue holding together the pad layers. Calcium hypochlorite, or pool bleach, is a preferred biocide for use with fan-and-pad cooling systems.

If the efficiency of the evaporative cooling system is known, the temperature of air exiting a cooling pad can be calculated using the following equation.

$$T_{cool} = T_{out} - (\%\ \text{efficiency}) \times (T_{out} - T_{wb})$$

where:
T_{cool} = temperature of air exiting the cooling pad (°C)
T_{out} = temperature of the outside air (°C)
T_{wb} = wet-bulb temperature of the outside air (°C)

A well-designed, properly installed and operated evaporative cooling system may have an efficiency of up to 85 percent.

Fog-cooling systems: These systems use evaporative cooling, just as in the fan-and-pad system. However, with fog-cooling systems, very small droplets of water (approximately 0.1 cm in diameter) are forced into the air. Owing to the small size of the droplets, they remain suspended in the air (and thus do not wet the plant material).

The droplets evaporate while suspended in the air, thereby cooling the air through evaporation. The water-saturated air is slowly removed from the greenhouse through roof vents or low-volume fans mounted in the greenhouse walls. Fog-cooling systems require some specialized equipment and are most useful for cooling structures used for propagation and seed germination.

Winter cooling systems

In some regions, high light levels or fluctuating temperatures may necessitate cooling even during cold days. In addition, during some seasons heating may be required at night and in the early morning, while some cooling may be required during the day when solar loads are high. Passive venting, as discussed, is one method that may be used for this type of cooling. However, if the solar load is too high, an active cooling system may be required to increase the rate at which warm inside air is replaced with cool air from outside the greenhouse.

In such a situation, the top vent may be closed and fans in the greenhouse walls activated. Louvered vents in the opposite walls open to allow air to move into the greenhouse. The fans may be multispeed fans so that just enough air is exhausted from the greenhouse (and replaced with outside air) to maintain the desired temperature. If temperatures continue to increase, the fan speed can be increased.

Another method used for cold-season cooling utilizes fans placed in the gable of the greenhouse, combined with a polyethylene tube extending the length of the greenhouse in the gable. The inlet vent is louvered and opens only when the fans turn on. There is an additional set of louvered vents at the opposite end of the greenhouse that allows warm greenhouse air to escape, while cooler outside air is forced into the structure. The cool air is forced through the polyethylene tube to ensure more even distribution of the cool air.

Calculating greenhouse cooling requirements

To determine the specifications for a cooling system, the volume of the greenhouse must be calculated. Some rules of thumb and assumptions are often used and a flow-rate per minute (air exchange) requirement is determined.

As an example, cooling specifications are outlined below for a Quonset greenhouse that is 10 metres wide and 24 metres long.

The volume of the structure is determined as: $0.5\times (\pi r^2 L)$

$= 0.5\times [(3.14)(5^2)(24)]$

$= 942\ m^3$

An air exchange of 1–1.5 times per minute is required. The higher value of 1.5 would be used if the greenhouse were to be used during the hot (summer) months when very high solar loads and temperatures are experienced. In this example, one exchange per minute is used, so that 942 m^3/min is required.

Fans should be spaced not more than 7.6 metres apart. This structure therefore requires two fans spaced along the 10-metre wall. The structure will require two fans with a capacity of (942 m^3/min/2) = 471 m^3/min. From Table 13.1, two 1-horsepower fans measuring 122 cm in diameter, operating at 1/10 inch of water static pressure are selected, providing a total of 974 m^3/min.

A particular brand of pads may be selected. In this example, we assume that 10.2-cm (4-inch) cellulose pads are selected and included to create a fan-and-pad cooling system. From the pad specifications of the manufacturers, assume that 1 square metre of this type of pad will accommodate 75 m^3/min. Therefore, 974 m^3/min/75 = 13 m^2 of pad wall is required. The pad wall should extend the entire length of the wall. Therefore the pad should be 10 m wide and 13 m^2/10 m = 1.3 m tall.

The pump capacity must take into account the water flow volume required by the system (pipes and pads), as well as water loss through evaporation from the pads.

To accommodate the system, assume that 6 litres are required per metre length per minute. Therefore, 10 metres × 6 litres/metre/minute = 60 litres per minute to accommodate the system.

To compensate for evaporation, 0.2 litres are required per 28 m^3/min of airflow. Therefore, (974 m^3/min/28 m^3/min) × 0.2 = 7.0 litres are required to compensate for evaporation.

The total pump capacity is 60 litres per minute + 7.0 litres per minute = 67 litres per minute.

To determine the sump capacity, assume 60 litres/m^2 of pad area. The sump capacity is 13 m^2 of pad × 30 litres/m^2 of pad = 390 litres.

HEATING

For some climates, there is at least one period during the year when the ambient temperatures outside are too low for crop production. During such periods, it is essential to provide heat energy to maintain optimal temperatures within the greenhouse. During heating, the heating system employed should be able to replace heat at the rate it is lost from the greenhouse.

The heat is lost by conduction (through the glazing, metal purlins, doors and fans), infiltration and ex-filtration (loss through cracks between or around glass panels, doors and fans by mass airflow) and radiation (energy loss from the emission of radiant energy from a warm body [greenhouse] to a cold object [outside objects], with little warming of the air). A heat balance should be calculated to quantify the amount of supplementary heating required to maintain the desired indoor conditions.

Greenhouses may utilize central heating systems or localized heating units. Central heating systems generate heat (usually using a large boiler) in one location, and distribute the heat generated to many locations. Localized heating systems (such as convection heaters and radiant heaters) are located in the greenhouse, or greenhouse section, that they are responsible for heating.

For large operations, a central-heating system may be more efficient than a localized one. However, the cost of installation and maintenance of a centralized heating system can be high and may not be justifiable for smaller operations. The size of the boiler unit, the fuel source, size of the operation and maintenance costs must therefore all be considered when deciding whether to use a centralized or localized heating system.

Methods of heat conservation

The methods of heat conservation should focus on:

- *Greenhouse design*: minimizing the exposed surface area can reduce heat loss. This is accomplished primarily through the use of gutter-connected designs
- *Glazing selection*: heat loss can be reduced by selecting glazing with low thermal conductance values
- *Wall insulation*: heat loss may also be reduced by including insulated curtains walls along the lower level (1–1.2 metres) of the greenhouse walls
- *Thermal screens*: polyester, cloth, or polyethylene screens that can be pulled closed at night reduce heat loss through the roof panels of the greenhouse
- *Windbreaks*: windbreaks reduce the effect of wind on heat loss. However, windbreaks (i.e. high walls or trees) can also reduce light entering the greenhouse if placed too close to the structure
- *Air leaks*: broken panels, loose panels, poorly sealed doors, and other openings in the greenhouse structure, increase the mass air flow (infiltration and exfiltration) and increase heat loss.

AIR QUALITY IN GREENHOUSES

The air quality in greenhouses can influence many aspects of plant growth and crop quality. The degree of control over air quality is at least partially dependent upon the type of greenhouse structure being used and the technology available. There are three basic aspects of the greenhouse atmosphere that should be considered: carbon dioxide, humidity and pollutants.

Carbon dioxide and light: Carbon dioxide (CO_2) and light are essential for plant growth. As the sun rises in the morning to provide light, the plants begin to produce food energy (photosynthesis) and oxygen. In open-field conditions, the process proceeds without any concern for the availability of CO_2. The CO_2 availability in atmospheric air was estimated at 300 ppm in 2002, which was sufficient to meet the photosynthetic requirement of field crops.

In closed-field conditions, such as in greenhouses, the enclosed air may have a CO_2 concentration of 1 000 ppm from respired CO_2 that remains trapped overnight. As the sunlight becomes available, the photosynthesis process begins and CO_2 in the greenhouse is depleted, falling below 300 ppm well before noon. Additional CO_2 from other sources would then be needed.

The amount of CO_2 required for enrichment is the amount of CO_2 used by plants minus the amount of CO_2 lost through infiltration. The amount used by plants varies with the microclimatic parameters, type of crop and level of nutrition. For calculation purposes,

the general range varies from 0.6–1.2 litres per hour per m^2 of floor area. The loss of CO_2 is greater in glass than in plastic film greenhouses as a result of differences in infiltration rates. The infiltration loss can be determined using the expression given below:

$$I_L = V_g \times N \times 10^{-6} \times (D_L - 300)$$

where:
I_L = infiltration loss (m^3/h)
V_g = volume of greenhouse (m^3)
N = number of air changes per hour
D_L = designed CO_2 level (ppm).

The CO_2 in the greenhouse is replenished through ventilation. As CO_2 and light complement each other, electric lighting combined with the injection of CO_2 is used to increase yields of vegetable and flowering crops. Bottled CO_2, dry ice and combustion of sulphur-free fuels can be used as CO_2 sources. Commercial greenhouses use such methods.

Relative humidity: High humidity promotes the development of certain diseases (e.g. black spot and powdery mildew), as well as various physiological abnormalities (e.g. leaf-edge burn in poinsettia and blossom-end rot of tomatoes) in some greenhouse crops. In addition, high humidity can increase condensation on the inside of the glazing, reducing light levels and causing water to drip onto plants.

During the summer, vents are usually open and the ambient relative humidity outdoors is the humidity at which the greenhouse will be maintained (although the relative humidity in the greenhouse may still be higher than that outside because of evaporation–transpiration). However, during cool months when vents are closed and heating is required, very high relative humidities can occur. To control this, growers will periodically increase greenhouse temperatures to saturate the air with water vapour and then vent the warm saturated air out of the greenhouse.

Pollutants and toxic substances: Carbon monoxide is dangerous to humans. It is generated by malfunctioning heaters and other machinery with internal combustion engines. Unit heaters without internal heat exchangers should be avoided, as they emit exhaust and carbon monoxide directly into the structure they are intended to heat. Malfunctioning heaters may also generate ethylene, which is damaging to plants. Numerous chemicals, including herbicides, paints and cleaning materials, may release potentially damaging volatile chemicals and caution should be exercised when using them in or around greenhouses.

Equipment maintenance

Proper maintenance of all equipment used in the greenhouse is critical. Maintenance should include appropriate cleaning and checking of the air intake, exhaust system, fuel lines and fans. The burner system and the heat exchanger should be checked periodically. Calibration of the thermostat, as well as checks of the structural integrity, and any other maintenance items prescribed by the manufacturer on all pieces of equipment used, should be undertaken periodically.

REVIEW QUESTIONS

1. Discuss the factors that must be considered when designing a greenhouse.
2. Calculate how far apart the fans should be spaced in a greenhouse given a fan capacity of 700 m^3/min, ventilation rate of 4.0 m^3/min/m^2 and a distance between the fan and outlet of 45 metres.
3. Outline the procedure for determining the size of an evaporative cooling pad and the capacity of the cooling water tank in a greenhouse.
4. Describe the evaporative cooling phenomenon.
5. Identify a greenhouse near you and perform an energy analysis on it to determine whether it requires heating or cooling.

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Chapter 15
Handling semi-perishable and perishable crops

SEMI-PERISHABLE CROPS

Food crops fall into two broad categories: perishable crops and non-perishable crops. This normally refers to the rate at which a crop deteriorates after harvest and thus the length of time it can be stored. While some crops fall clearly into one or other category, others are less easy to categorize. For example, cereal grains can be stored for over a year and are considered to be non-perishable, whereas tomatoes are perishable crops and, when picked fresh, will deteriorate in a few days. However, tubers, such as potatoes, may be successfully stored for periods extending to several months.

Although there are methods for preserving many of the perishable crops, such as canning and freeze-drying, these are normally industrialized processes and are not found on farms. However, it is possible to apply farm-scale methods of preservation to cereals and pulses, as well as the less perishable crops such as potatoes. To do this successfully, it is necessary to know the ways in which a crop can deteriorate, and hence the methods for controlling this process.

Crops may need conditioning at harvest time to make them storable, and they may also require periodic inspection and care during the storage period. The viability of seed must be maintained and susceptibility to damage by fungal and insect pests must be minimized.

In contrast to grain, crops such as potatoes, yams, carrots and onions are more perishable and require carefully managed storage conditions to maintain top quality. While market value is seldom great enough to justify the expense of ideal levels of temperature and humidity control, first the desired conditions will be discussed and then various methods of achieving levels as close to ideal as is economically justifiable will be described.

Properties

The properties of the many horticultural crops are far more varied than those of grains and pulses. This in turn results in highly varied storage characteristics. For example, yams and potatoes can be stored adequately for several months, while cassava, if not processed, can be kept for only a few days without deterioration.

The initial moisture content after harvest is much higher in these mature crops than in grains. With grains, a loss of moisture is desirable for storage and does not affect the subsequent use of the crop. This is not the case with fruits and vegetables. Loss of moisture may cause the crop to become unmarketable. Yet, with high moisture content, storage of these crops is more difficult because there is a greater likelihood of insect and fungal damage.

Whereas lowering the moisture content of grain inhibits sprouting without affecting viability, the high-moisture vegetable crops, which cannot be allowed to dry out, are more prone to sprouting. However, there is generally a period of dormancy following harvest that can be used to good advantage.

Perishable and semi-perishable crops are living organisms and, as such, continue to respire. Consequently, any storage will need ventilation to remove the heat and moisture of respiration and to prevent condensation on cool surfaces.

Fruits and vegetables are nearly always susceptible to physical damage such as bruising, cutting and cracking. Much of this results from dropping the fruits or tubers onto hard surfaces or onto other fruits and tubers while they are being loaded into containers or bins. In many cases, 200–300 mm is the maximum safe drop.

Further losses can occur if the heat of respiration is allowed to cause a temperature rise. For example, 'black heart' in potatoes is a serious problem resulting from high temperatures under storage conditions. In contrast, low temperatures approaching freezing produce a characteristic sweetening in potatoes.

Losses can also be caused by disease. This tends to be worse if the crop has been damaged, allowing the organisms that cause disease to enter through surface cuts and cracks. Removal of soils adhering to the crop and careful loading before storage can help to reduce this problem.

Storage requirements for potatoes and other horticultural crops

Potatoes are the most commonly stored root crop, for which the greatest amount of research has been conducted into ideal storage requirements. However, very similar facilities and operating conditions are suitable for several other crops with varying perishability characteristics. Although the following sections deal primarily with potatoes, much of the information, including the storage facilities described, also applies to other semiperishable crops.

As mentioned, some bruising and cutting of the tubers is likely to occur during harvesting. These fresh wounds provide an ideal entry point for disease and rot

organisms. The infection can be minimized by storing the potatoes for the first 1–2 weeks at a temperature of 13–20 °C and a relative humidity of 90–95 percent. During this curing period the skin toughens, making the tubers much less subject to further injury or disease.

Potatoes are naturally dormant for about 2 months. However, it is often necessary to store them for longer periods of time by extending the dormancy period and by keeping shrinkage to a minimum. Temperature and humidity are important factors in this respect. Suitable temperatures for long-term storage are related to the eventual use of the potatoes.

For seed stock, temperatures of 3–5 °C will delay sprouting for up to 8 months. For ware potatoes, 4–8 °C will allow 4–8 months of storage without serious sprouting, while lower temperatures increase the risk of sweetening, that is, the conversion of starch to sugar. Finally, for processing potatoes, a minimum temperature of 7–10 °C is required in order to prevent discoloration and to keep sweetening to an absolute minimum. In stores with higher temperatures, it is possible to control sprouting in ware and processing potatoes for up to 6–8 months by using a sprout-suppressant chemical.

The *relative humidity* (RH) of the air in the store is of great importance. Low RH will lead to shrinkage and weight loss, while excessively high RH will cause condensation on the surfaces. This is undesirable because free water on the potatoes greatly increases the possibility of rot and the spread of disease. A potato tuber comprises roughly 80 percent water and, strictly speaking, air is in equilibrium with the tuber at a relative humidity of 98 percent. However, in practice the relative humidity is kept between 90 percent and 96 percent, to avoid condensation.

Potatoes exposed to direct or indirect sunlight will turn green and develop a bitter taste, which is poisonous and makes the tubers unsuitable for human consumption. Stores should therefore have no windows and ventilation openings should have light traps.

Potatoes that have been held at low temperatures tend to be brittle and subject to considerable damage when being handled. If the store has been maintained at low temperatures throughout the storage period, it is best to warm the store to about 10 °C for a few days prior to removing the potatoes.

Storage without buildings

Delayed harvest

The simplest form of storage for some crops is to leave them in the ground and harvest them only as required. There is a risk of pest and rodent damage, but any deterioration that may take place after harvest may exceed field losses; hence delayed harvest is a reasonable choice. This is particularly useful for cassava, where field deterioration is normally substantially less than post-harvest losses even for short-term storage. On the other hand, some crops deteriorate substantially in quality if left in the ground beyond a certain stage. For example, carrots tend to become tough and woody.

Clamp

In areas that have low mean soil temperatures, a simple ground clamp (Figure 15.1) may be suitable, especially for potatoes. The potatoes are piled on the ground in a long row and covered with 150–200 mm of straw or coarse grass. Chicken wire is laid all around the base to protect against rodents, and then soil is dug out around the pile and placed on the straw. This store is not likely to be satisfactory for more than a month or two unless the soil temperature is near 10 °C and air temperatures at night are 10 °C or lower. To control soil pests, the ground can be treated with an insecticide before the clamp is made.

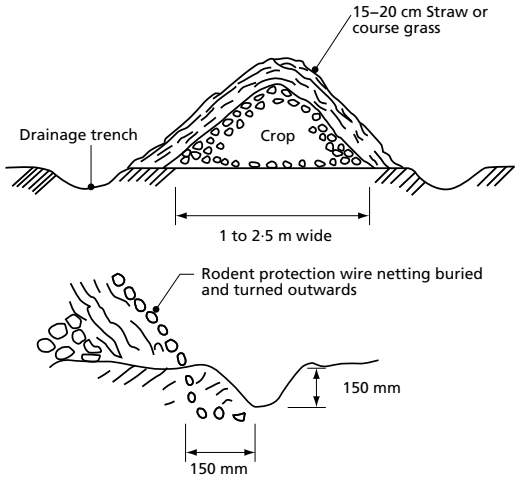


Figure 15.1 **Simple root-crop clamp**

Covered clamp

Another simple solution for short-term storage is the covered clamp (see Figure 15.2) consisting of a raised platform on which the potatoes are heaped and then covered with 10 cm of grass or straw. Air is free to circulate through both produce and straw. A thatch roof overhead provides shade to help reduce daytime temperatures. Protection from rodents will be required.

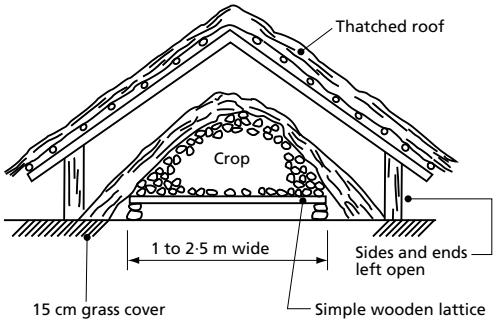


Figure 15.2 **Covered clamp raised from the ground**

Storage in multipurpose buildings

Slatted boxes or bins

Square boxes of slatted construction, each holding about 1 m³ of potatoes, provide a good option for both small- and large-scale stores. The boxes can be larger, but not deeper, than 1 metre. If they are located in a well-insulated building, fluctuations in daytime temperatures will be reduced. The boxes should be raised about 250–300 mm above the floor to enable air to circulate freely. With little insulation and only natural ventilation, this method is best suited to cooler areas, but only for relatively short storage periods of 3–4 months.

Smaller boxes can be handled manually, while larger boxes of 1 m³ or more cannot be moved manually when filled (see Figure 15.3).

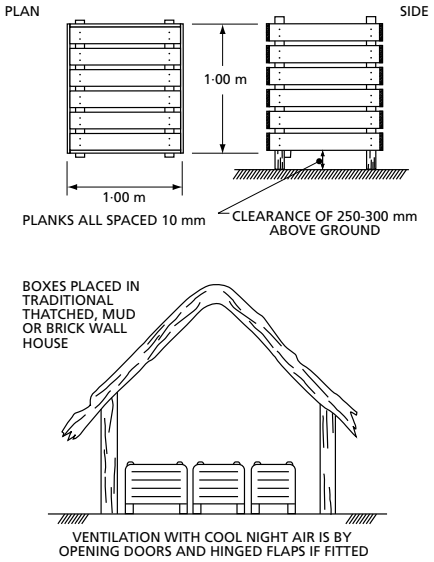


Figure 15.3 **Box store for root crops**

Clamp on floor

Using a building similar to that shown in Figure 15.3, a clamp offers an alternative to boxes. To allow adequate ventilation with cool night air, a duct under the crop is included, as shown in Figure 15.4.

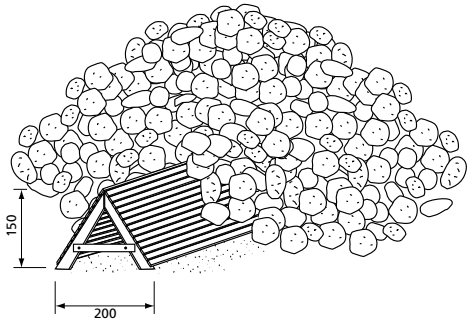


Figure 15.4 **Duct under produce heap**

Naturally ventilated stores

Figure 15.5 shows an example of how to build a potato store suitable for small-scale production. The store, which holds about 1 500 kg, is naturally ventilated and measures 150 × 160 cm square. The walls are 150 cm high and a slatted floor is placed 90 cm off the ground to keep rodents away.

The store shown in Figure 15.5 is made of offcuts, but other materials may be just as good. For insulation, the walls have a 20 cm-thick layer of straw, which will be compressed to about 10 cm when the store is loaded. The floor should be covered with about 5 cm of straw before loading, and 20 cm of straw should be spread evenly on the top to protect the potatoes from sunlight and drying.

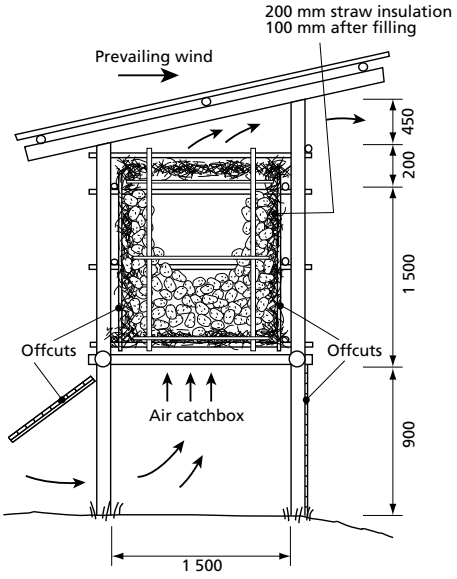


Figure 15.5 **A naturally ventilated store**

The method of operating the store is dependent on the average temperature of the location. If the average temperature is above 20 °C, it is necessary to extend the walls on three sides down to the ground, like an apron. The fourth side will have a flap that is kept open only at night in order to take advantage of the cooler air for ventilation.

At higher altitudes with mean temperatures below 20 °C, it is possible to operate this potato store with continuous ventilation, and the apron and the flap can be left out. In this case, the store legs should be fitted with rat guards. There should be just enough ventilation to remove the heat caused by respiration, without causing an excessive loss of moisture.

Larger stores

Buildings for storing large quantities of potatoes or other root crops in bulk must be of substantial construction to resist the force of the crop against

the walls. In addition, the walls and ceiling must be well insulated, regardless of whether outside air or refrigeration is used for cooling.

The wall sills must be securely anchored and the studs firmly fastened to the sill in order to withstand the considerable lateral force of the potatoes. It is desirable for the concrete floor to be tied to the foundation with reinforcing bars. Tie beams should connect the top of the sidewalls on opposite sides of the building to resist the load, with braces at frequent intervals to withstand uneven loading.

Insulation and vapour barriers

Regardless of the climate of the area in which they are built, large air-cooled or refrigerated stores should be well insulated. In the uplands (e.g. in southern Africa), some insulation will prevent freezing of the potatoes in midwinter. In contrast, in hot regions where mechanical refrigeration may be necessary, substantial insulation will help to reduce the operating cost. An *R* value of 4–5 in the ceiling and 3–3.75 in the walls should be adequate to prevent condensation in a cold climate and to ensure economical operation in warm areas. These large stores are expensive buildings and it is important to install high-quality commercial insulation.

Vapour barriers are essential to prevent the accumulation of moisture in the insulation. Moisture migrates from the warm side to the cold side of a wall or ceiling, requiring a vapour barrier to be installed on the warm side. In a refrigerated store in a warm area, the proper place to install a polythene vapour barrier is on the outside of the wall and ceiling, where the temperature is highest.

However, air-cooled stores are much more difficult to design, as the outside temperature may be higher at the start of the storage season, and the inside temperature may be higher later on. A very careful assessment must be made when deciding whether or not to use a vapour barrier and, if so, on which side to install the vapour barrier. Alternatively, non-permeable rigid insulation can be installed to resist moisture penetration from either side.

Ventilation system

There are many different types of air distribution system incorporated into large stores, not only for potatoes, but for several other fruits and vegetables. They range from simple natural ventilation to manually controlled fans and inlets, and finally to complex automatically controlled dampers and variable-speed fans. The choice of system is determined not only by environmental needs, but also by economic factors.

A ventilation system of medium complexity, as shown in Figure 15.6, can be installed in a store

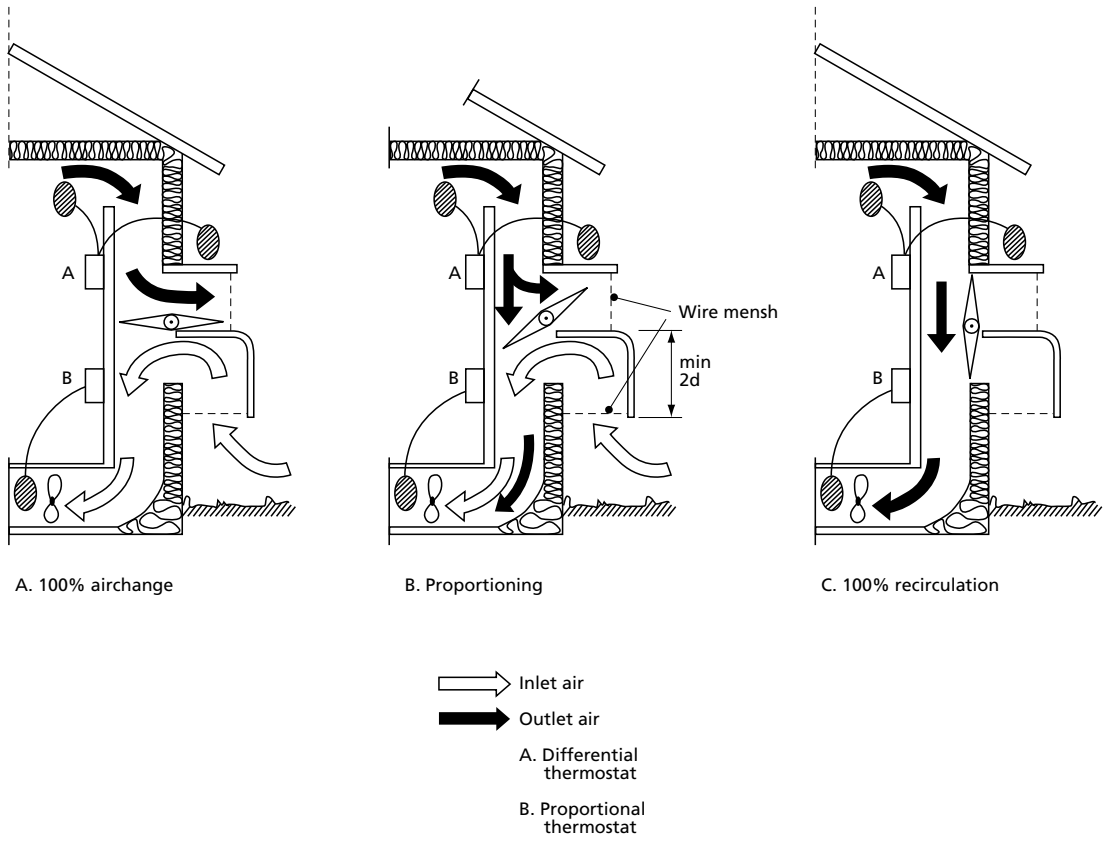


Figure 15.6 **Ventilation system**

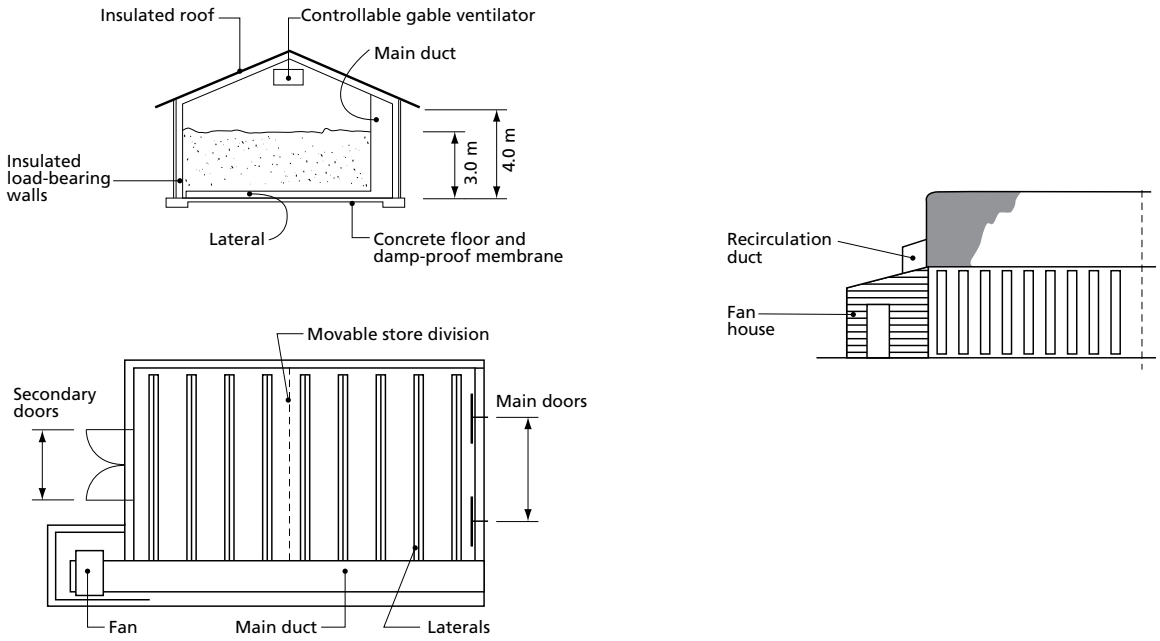


Figure 15.7 **Large bulk store**

similar to that shown in Figure 15.7. The ventilation system allows a complete exchange of air, as well as complete recirculation, or various combinations of both. Although automatic controls will provide more accurate regulation of the system, manual control is possible because conditions change slowly in a large store. To control the relative humidity in the store and the temperature of the incoming air, a humidifier can be installed in the ventilation system.

Air distribution

Air from the proportioning system is forced into a main distribution duct, and from there into lateral ducts cast into the concrete floor. The laterals may be covered with removable 50 by 100 mm wood slats, allowing an elevator to be set up in the duct for unloading the bin.

The spacing of the lateral ducts is limited to 80 percent of the height of the heap, i.e. 0.8 H between centres, and dimensioned to limit air velocity to no more than 5 m/s. The ducts should be tapered or stepped, in order to maintain a fairly uniform velocity as air is fed off to one bin after another. As the potatoes cover about 75 percent of the open area, the wood slats should be spaced to give four times the area needed for the correct velocity.

Evaporator size

As described earlier, the size of an evaporator influences the temperature at which it can operate, and the difference between the temperature of the evaporator and that of the store greatly affects the relative humidity of the store.

It is satisfactory to choose an evaporator size that will require roughly a 6 °C temperature difference during the loading period. When the field heat has dissipated and the heat load is much smaller, the difference can then be reduced to less than 2 °C and an adequate humidity level will be maintained. Unit-blower evaporators are most commonly chosen for the storage of produce.

Any cool store should have an adjacent room for grading, packing and shipping the produce. It should be well lit and adequate in size to store empty containers and packed produce for immediate shipment.

As mentioned earlier, prior to handling potatoes that have spent a period in cold storage, they need to be warmed to at least 10 °C. If they have been stored in bulk in the store, they must be warmed where they lie. If they have been stored in pallet boxes, they may be warmed in the packing room, which can be maintained at a comfortable temperature for the workers. If the cool store is used for other produce, it may be desirable to have some refrigeration in the packing room so that grading and packaging of perishable produce can be completed under cool conditions.

Later in this chapter the storage requirements for a number of fruits and vegetables are discussed. In many cases, the temperature and humidity requirements are similar to those for potatoes and many of the points covered in relation to potatoes apply equally to other produce, with a few exceptions. If produce is held in storage for a short time, the air-distribution system is probably not necessary and unit-blower evaporators will be adequate. Note also that several fruits and vegetables are not compatible for simultaneous storage, even though they may require similar storage conditions.

Grading and handling facilities

Grading of crops for sale is more likely to be required where large volumes are handled. The principle

requirements of a structure for this purpose are to protect the crop during handling and to allow grading to be carried out in any weather. Both the stored produce and the workers require protection from sun, rain, wind and dust. In some cases, a pole-building without walls will be adequate. In other situations, an enclosed room with lighting, ventilation, and perhaps either heating or cooling, will be required.

Seed potato stores

Seed potatoes must be kept from one season to the next. Clearly it is important to maintain the tubers in good disease-free condition and to keep them as viable as possible. Seed potatoes may be held satisfactorily in a refrigerated store at 4–5 °C for up to 8 months, but that is not always possible. A lower-cost alternative is to keep seed potatoes in naturally ventilated stores at ambient temperature where sprouting is allowed under the influence of diffuse sunlight.

This technique is well proven and seed held over the long term has been found to be nearly as viable as that held in refrigerated stores for a similar length of time. This method of using the ambient temperature together with diffuse sunlight, which allows chits (short, sturdy sprouts) to form, can be used for seed potatoes as soon as the dormancy period has come to an end. However, once the chits have developed it is important to control aphids by the routine application of a systemic insecticide, failing which viral diseases are likely to be introduced.

Potato chitting trays

Regardless of how seed potatoes are stored, it is desirable for the tubers to chit (sprout) before planting, and this is done by deliberately exposing them to either artificial light or diffused natural light. The light must reach all of the potatoes, and consequently shallow trays with slatted bottoms are required for both good light distribution and adequate air circulation. A good design is shown in Figure 15.8. For good light penetration, the alleyways between stacks of trays should be at least 1 metre wide, and lines of trays should be placed in the store to give the best lighting from the sides and top (if lighting panels are fitted in the roof). Space under the bottom trays is essential for air circulation.

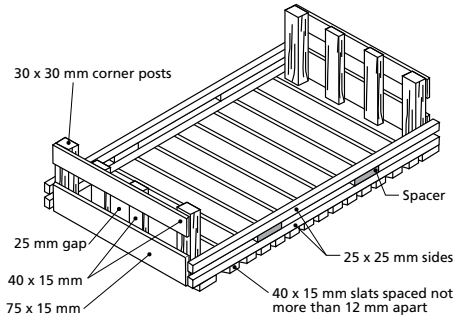


Figure 15.8 **Potato chitting tray (approx. 350 × 500 mm)**

Small seed potato chitting stores

For the small landholder who requires a limited quantity of chitted potatoes, a rack similar to that shown in Figure 15.9, built under the eaves of the family home, is a simple and inexpensive solution.

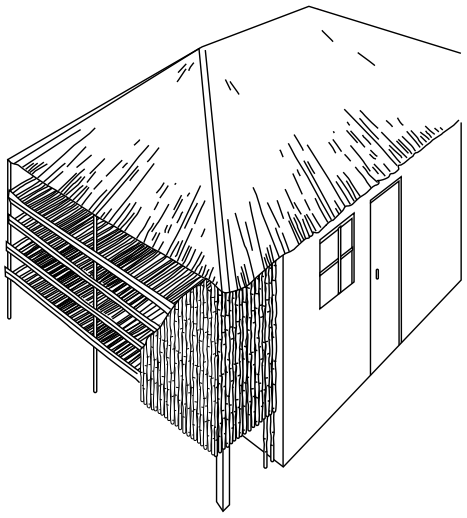


Figure 15.9 **Small-scale chitting racks**

Buildings for use as chitting stores can be very simple. They may be built of poles, blocks, bamboo, reinforcing wire and netting, and are constructed so that the sides let in light and ventilation. The interior is always at ambient temperature and lit by indirect daylight. As a result, once potato dormancy finishes, the tuber sprouts grow, but only slowly, remaining short, green and strong. A medium-sized chitting store is shown in Figure 15.10.

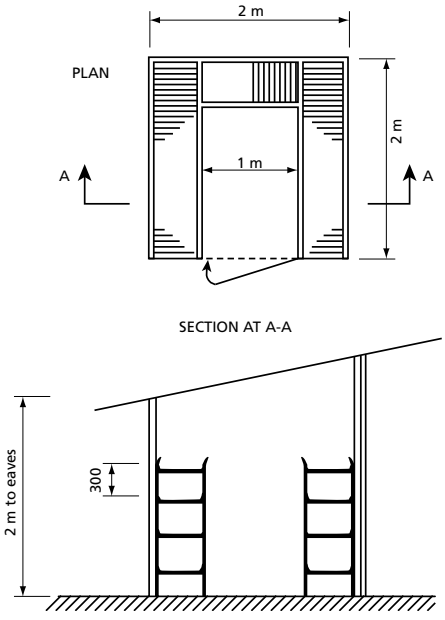


Figure 15.10 **Medium-sized chitting store with shelves**

Direct sunlight must be avoided and, if roof-lights are installed, a shading device should be fitted below the roof to diffuse the light. Whitewashed strip-bamboo curtains suspended about 1 metre below the roof-lights serve this purpose well.

These naturally ventilated ambient-temperature stores are best suited to areas or altitudes with maximum temperatures in the 18–24 °C range. Although results have shown losses somewhat higher than in expensive refrigerated stores, satisfactory seed quality remains after 5–6 months, provided that insecticide has been applied on a regular basis.

Larger stores with similar characteristics can be built to suit the amount of seed to be stored (see Figure 15.11). It is also quite possible to use the maize crib shown in Chapter 16, Figure 16.5 for chitting seed potatoes if it is not needed for maize storage at the time.

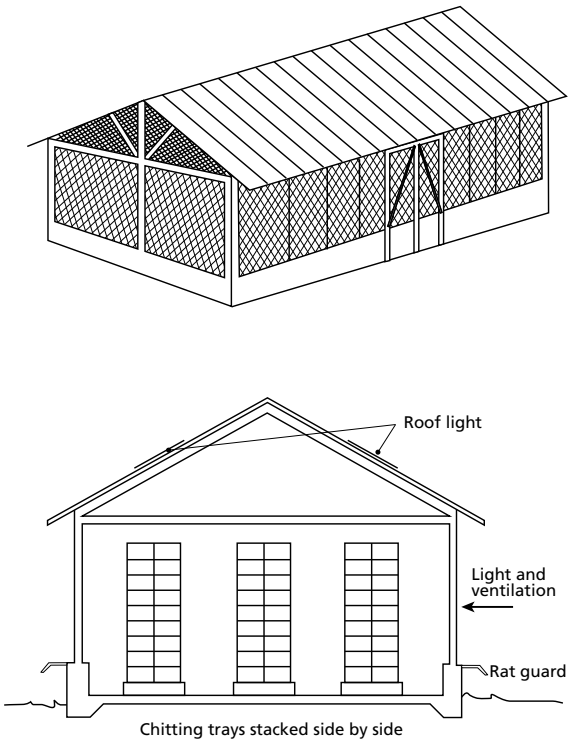


Figure 15.11 **Larger-scale potato chitting store**

PERISHABLE CROPS

Fruit and vegetables

The majority of fruits and vegetables are highly perishable commodities with a short storage life. The exceptions, including apples and potatoes, can last for several months if well stored. Table 15.1 gives the primary differences between non-perishable and perishable crops.

TABLE 15.1
Comparison of cereals and horticultural crops

Cereals and oil seeds	Horticultural crops
Low moisture content (typically 10%–20%)	High moisture content (typically 70%–95%)
Small unit size (typically less than 1 gram)	Large unit size (typically 5 g to 5 kg)
Very low respiration rate, with little heat generation	High to very high respiration rate
Heat production is typically 0.05 MJ/tonne/day for dry grain	Heat production typically ranges from 0.5–10 MJ/tonne/day at 0 °C to 5 to 70 MJ/tonne/day at 20 °C
Hard texture	Soft texture, easily bruised
Stable: natural shelf life is from one to several years	Perishable: natural shelf life is a few days to several months
Losses usually caused by moulds, insects and rodents	Losses usually caused by rotting (bacteria, fungi), senescence, sprouting and bruising

Storage requirements

To store perishable crops, the main requirements are to lower the temperature substantially and to retain moisture in the produce. Table 15.2 illustrates the storage conditions and storage life of some fruits and vegetables.

Mixing commodities

Some crops produce odours in storage, while others emit volatile gases such as ethylene. Ethylene stimulates the ripening of many fruits and vegetables. This is negligible at low temperatures but may be a nuisance at higher temperatures. Consequently, even when two or three crops require the same storage conditions, it is not advisable to store them together.

Products that emit ethylene include bananas, avocados, melons, tomatoes, apples, pears and all fleshy fruits. Lettuce, carrots and greens are damaged when stored with fruits or vegetables that produce ethylene. Even very small amounts can be harmful. It is recommended that onions, nuts, citrus fruits and potatoes each be stored separately. Table 15.3 shows compatibility groups for storage of some fruits and vegetables. More compatibility groups can be found in the literature.

Onions

The following technique has been developed for harvesting, drying and storing onions:

- Onions are harvested when at least one-third of the tops have fallen over.
- If the weather is dry, the onions are left in the field to dry. The neck must become tight and the outer scales should rustle when dry. This is most important, and successful storage depends on full drying or curing.
- If the weather is unsuitable for outside curing, the onions may be placed on slatted shelves in a well-

TABLE 15.2
Ideal storage temperature, relative humidity and expected storage life of fruits and vegetables

Product	Temperature	Relative humidity (percent)	Approximate storage life
Apples	-1–4	90–95	1–12 months
Apricots	-0.5–0	90–95	1–3 weeks
Asparagus	0–2	95–100	2–3 weeks
Avocados	13	85–90	2 weeks
Bananas, green	13–14	90–95	14 weeks
Beans, green or snap	4–7	95	7–10 days
Beans, lima (in pods)	5–6	95	5 days
Beets, bunched	0	98–100	10–14 days
Broccoli	0	95–100	10–14 days
Brussels sprouts	0	95–100	3–5 weeks
Cabbage, early	0	98–100	3–6 weeks
Carrots, mature	0	98–100	7–9 months
Carrots, immature	0	98–100	4–6 weeks
Celery	0	98–100	2–3 months
Coconuts	0–1.5	80–85	1–2 months
Cucumbers	10–13	95	10–14 days
Eggplants	12	90–95	1 week
Garlic	0	65–70	6–7 months
Ginger root	13	65	6 months
Grapes, vinifera	-1 to -0.5	90–95	1–6 months
Guavas	5–10	90	2–3 weeks
Kale	0	95–100	2–3 weeks
Kiwifruit	0	90–95	3–5 months
Leeks	0	95–100	2–3 months
Lemons	10–13	85–90	1–6 months
Lettuce	0	98–100	2–3 weeks
Mangoes	13	85–90	2–3 weeks
Mushrooms	0	95	34 days
Okra	7–10	90–95	7–10 days
Olives, fresh	5–10	85–90	+6 weeks
Onions, dry	0	65–70	1–8 months
Papayas	7–13	85–90	1–3 weeks
Parsley	0	95–100	2–2.5 months
Peaches	–0.5–0	90–95	2–4 weeks
Pears	-1.5 to -0.5	90–95	2–7 months
Peas, green	0	95–98	1–2 weeks
Peas, southern	4–5	95	6–8 days
Peppers, chili (dry)	0–10	60–70	6 months
Peppers, sweet	7–13	90–95	2–3 weeks
Pineapples	7–13	85–90	24 weeks
Plantain	13–14	90–95	1–5 weeks
Plums and prunes	–0.5–0	90–95	2–5 weeks
Potatoes, late crop	4.5–13	90–95	5–10 months
Pumpkins	10–13	50–70	2–3 months
Spinach	0	95–100	10–14 days
Squashes, summer	5–10	95	1–2 weeks
Tangerines and related citrus fruits	4	90–95	24 weeks
Tomatoes, mature-green	18–22	90–95	1–3 weeks
Tomatoes, firm-ripe	13–15	90–95	4–7 days
Turnips	0	95	4–5 months
Watermelons	10–15	90	2–3 weeks
Yams	16	70–80	6–7 months
Yucca root	0–5	85–90	1–2 months

Source: McGregor, B.M. 1989. *Tropical products transport handbook*. United States Department of Agriculture (USDA) Office of Transportation, Agricultural Handbook 668.

TABLE 15.3
Compatibility groups for storage of fruits and vegetables

Group 1: Many products in this group produce ethylene at 0–2 °C, 90–95% relative humidity. *Citrus treated with biphenyl may transfer odours to other products		
Apricots	Horseradish	Peaches
Apples	Grapes (without sulphur dioxide)	Parsnips
Kohlrabi	Pears	Plums
Leeks	Persimmons	Pomegranates
Beets, topped	Longan	Prunes
Berries (except cranberries)	Loquat	Quinces
Cashew apple	Lychee	Radishes
Cherries	Mushrooms	
Coconuts	Nectarines	
Group 2: Many products in this group are sensitive to ethylene at 0–2 °C, 95–100% relative humidity. *These products can be top-iced		
Amaranth*	Cherries	Parsley*
Anise	Daikon*	Parsnips*
Artichokes*	Endive*	Peas*
Asparagus	Escarole*	Pomegranate
Bean sprouts	Grapes (without sulphur dioxide)	Radicchio
Beets*	Horseradish	Radishes*

Source: McGregor, B.M. 1989. *Tropical products transport handbook*. United States Department of Agriculture (USDA) Office of Transportation, Agricultural Handbook 668.

ventilated open shed. Layers should be no more than 10–15 cm deep (the seed potato store can be used for this purpose).

- Onions will keep at higher temperatures than shown in Table 15.2, and this seems practical, particularly in dry areas. This involves placing cured onions in a slatted-floor store that is freely ventilated, except during damp periods.

Storage structures for perishables

A low-cost cool store

A simple, low-cost structure for storing vegetables for the few hours between harvesting and transport to the market should be useful to all types of farmer. The basic construction is similar to that shown in Figure 15.2. A simple frame is constructed with poles or other low-cost materials. A covering of grass or other thatching material provides protection for the produce from excess temperatures and moisture loss until it can be transported to market.

The wall should be extended to ground level on three sides but left open on the fourth (prevailing wind) side, for ventilation. This allows free air movement most of the time, but canvas flaps should be provided for closing the ventilation openings when required.

The grass roof and walls can be kept wet with a sprinkler pipeline or, if that is not available, the thatching can be sprinkled by hand as required. The interior will be kept cool and moist with temperatures as much as 5–8 °C lower than outside. More important, produce harvested late in the afternoon can be cooled during the night, with resulting temperatures at midday on the following day as much as 10 °C below ambient temperature.

Commercial cool store

As Table 15.2 shows, only a few crops, including potatoes, onions, carrots and apples, can be stored for periods longer than a few days or weeks. However, the wholesale merchant will require short-term refrigerated storage for the produce and separate rooms will be needed for crops that are not compatible for storage together. As with refrigerated potato stores, attention must be given to adequate insulation, a good vapour seal and large evaporators to help to maintain high humidity.

To make sure the storage room can be kept at the desired temperature, the required refrigeration capacity should be calculated using the most severe conditions expected during operation. These conditions include the mean maximum outside temperature, the maximum amount of produce cooled each day, and the maximum temperature of the produce to be cooled. The total amount of heat that the refrigeration system must remove from the cooling room is called the *heat load*. The sources of heat include:

Heat conduction: heat entering through the insulated walls, ceiling, and floor.

Field heat: heat extracted from the produce as it cools to the storage temperature.

Heat of respiration: heat generated by the produce as a natural by-product of its respiration.

Service load: heat from lights, equipment, people, and warm, moist air entering through cracks or through the door when opened.

Common cooling methods for produce

Cooling methods include the following:

Room cooling: This involves placing produce in an insulated room equipped with refrigeration units to chill the air. Although room cooling is effective for storing precooled produce, in some cases it cannot remove field heat rapidly enough. Carefully directing the output of the cooling system evaporator fans can improve the cooling rate significantly.

Forced-air cooling: This is used in conjunction with a cooling room and is effective on most packaged produce. To increase the cooling rate, additional fans are used to increase the flow of cool air through the packages of produce. Although the cooling rate depends on the air temperature and the rate of airflow through the packages, this method is usually 75–90 percent faster than room cooling. The fans are normally equipped with a thermostat that automatically shuts them off as soon as the desired produce temperature is reached, to reduce energy consumption and water loss from the produce.

Hydro-cooling: This method can be used on most commodities that are not sensitive to wetting. Wetting often encourages the growth of microorganisms. In this process, chilled water flows over the produce, rapidly removing heat. At typical flow rates and temperature differences, water removes heat about 15 times faster than air. However, hydro-cooling is only about 20–40 percent energy efficient, compared with 70–80 percent for room cooling and forced-air cooling.

Top or liquid icing: This may be used on a variety of commodities. In the top-icing process, crushed ice is added to the container on top of the produce by hand or machine. For liquid icing, aslurry of water and ice is injected into produce packages through vents or handholds without de-palletizing the packages or removing their tops. As the ice has a residual effect, this method works well with commodities, such as sweet-corn and broccoli, that have a high respiration rate. One kilogram of ice will cool about 3 kg of produce from 29 °C to 4 °C.

Vacuum cooling: This system is effective on products that have a high ratio of surface area to volume, such as leafy greens and lettuce, which would be very difficult to cool with forced-air or hydro-cooling. The produce is placed inside a large metal cylinder and much of the air is evacuated. The vacuum causes water to evaporate rapidly from the surface of the produce, lowering its temperature. If overdone, this process may cause wilting from water loss. Vacuum coolers can be energy efficient but are expensive to purchase and operate.

Evaporative cooling: This is an effective and inexpensive means of providing a lower temperature atmosphere with high relative humidity for cooling produce. It is accomplished by misting or wetting the produce in the presence of a stream of dry air. Evaporative cooling works best when the relative humidity of the air is below 65 percent.

Transportation of horticultural crops

Transport vehicles should be well insulated to maintain cool environments for precooled commodities and well ventilated to allow air movement through the produce. Travelling during the night and early morning can reduce the heat load on vehicles transporting produce. Mixed loads can be a serious concern when optimum temperatures are not compatible or when ethylene-producing commodities and ethylene-sensitive commodities are transported together.

A wide range of pallet covers are available for covering cooled products during handling and transportation. Polyethylene covers are inexpensive and lightweight and they protect pallet loads from dust, moisture and some loss of cold. Lightweight insulated covers can protect the load from heat gain for several hours. Heavyweight covers are sometimes used to protect tropical products from the cold during winter shipment.

Refrigerated trailers

For optimum transport temperature management, refrigerated trailers need insulation, a high-capacity refrigeration unit and fan, and an air delivery duct. The condition of the inside of a refrigerated trailer affects its ability to maintain desired temperatures during transportation. Handlers should inspect the trailer before loading and check the following:

- door and door seal damage
- wall damage
- clean floor
- floor drains clean and open
- door and inside height adequate for the intended load
- trailer precooled before loading
- refrigeration unit operates satisfactorily.

Open vehicles

An open-air vehicle can be loaded in such a way as to allow air to pass through the load, and to provide some cooling of the produce as the vehicle moves. Bulk loads of produce should be carefully loaded to avoid causing mechanical damage. Vehicles can be padded or lined with a thick layer of straw. Woven mats or sacks can be used in the beds of small vehicles. Other loads should not be placed on top of the bulk commodity. High transportation speeds and/or long-distance transport run the risk of causing excess drying of the crop.

REVIEW QUESTIONS

1. Describe the operational principle of a refrigeration system.
2. Describe some of the ways in which some semiperishable and perishable crops are stored in your locality, and identify the advantages and disadvantages of such storage systems.
3. Discuss the different crop-cooling methods for produce while in storage.
4. Outline in detail the steps involved in determining the refrigeration load required for a cold-storage facility.

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Chapter 16
Grain crop drying, handling and storage

INTRODUCTION

Although in many parts of Africa certain crops can be produced throughout the year, the major food crops such as cereal grains and tubers, including potatoes, are normally seasonal crops. Consequently the food produced in one harvest period, which may last for only a few weeks, must be stored for gradual consumption until the next harvest, and seed must be held for the next season's crop.

In addition, in a market that is not controlled, the value of any surplus crop tends to rise during the off-season period, provided that it is in a marketable condition. Therefore the principal aim of any storage system must be to maintain the crop in prime condition for as long as possible. The storage and handling methods should minimize losses, but must also be appropriate in relation to other factors, such as economies of scale, labour cost and availability, building costs and machinery cost.

GRAIN DRYING

The handling and storage of grains will be discussed in an orderly sequence. First we discuss the requirements for safe storage, including the principles involved in both natural and artificial drying, followed by drying methods suitable for the small grower, as well as for the larger scale operations of cooperatives and commercial farms. Finally, various types of storage structures and systems, from family size up to commercial units, are discussed, together with management suggestions for preventing damage during the storage period.

Properties of grains

Cereal grains are edible seeds and, as such, would eventually be released from the plant when fully mature. Grains can be divided into three groups; cereals (maize, wheat, millet, rice, etc.), pulses (beans, peas, cowpeas, etc.), and oil seeds (soyabeans, sunflower, linseed, etc.).

Requirements for safe storage

Crops left standing un-harvested start to show diminishing quantitative and qualitative returns through shatter losses and attacks by insects, mould, birds and rodents. It is therefore important to complete harvesting as soon as possible. In addition, it is necessary to remove dust and contaminants, which can include insects, and vegetable material, such as bits of straw and chaff and weed seeds. These will fill up pore spaces within the crop, inhibiting air movement and adding to any possible spoilage problems. The crop must therefore be clean.

One of the most critical physiological factors in successful grain storage is the moisture content of the crop. High moisture content leads to storage problems because it encourages fungal and insect problems, respiration and germination. However, moisture content in the growing crop is naturally high and only starts to decrease as the crop reaches maturity and the grains are drying. In their natural state, the seeds would have a period of dormancy and then germinate either when re-wetted by rain or as a result of a naturally adequate moisture content.

Another major factor influencing spoilage is temperature. Grains are biologically active and respire during storage. One of the products of respiration is heat, and reducing the temperature of the crop can help to diminish the rate of respiration, thereby lengthening the storage life by lessening the possibility of germination. Another major temperature effect is on the activity of insect and fungal problems. With lower temperatures, the metabolic rate of insects and fungi decreases and consequently so does the activity causing spoilage.

A damp or warm spot in grain will increase the rate of respiration. In addition to heat, another product of respiration is moisture. The heat and moisture from such a 'hot spot' can spread by convection, encouraging moulds and bacteria, which in turn respire and give off more heat and moisture. It therefore becomes a self-generating process. Insect activity also increases with a rise in temperature.

These spoilage mechanisms can also affect the viability of grain required for seed or malting, where the inability to germinate would render it unmarketable.

Figure 16.1 shows how the relationship between moisture content and temperature affects the storability of crops. It can be seen that the moisture content of grain must be reduced at higher temperatures.

Moisture content

The moisture content of a crop is normally given on a 'wet basis' (wb) and is calculated as follows (%mcwb):

$$\frac{\textit{Weight of moisture}}{\textit{Weight of wet sample}} \times 100$$

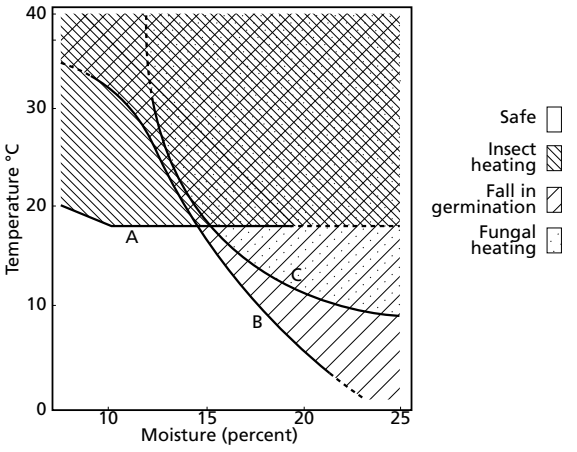


Figure 16.1 **Effects in storage at different temperatures and moisture content**

Occasionally 'dry basis' (db) moisture content is given and it is important to know which has been used.

For example, if 100 kg of moist grain is dried and loses 20 kg of water, the moisture content is:

$$\frac{20 \times 100}{100} = 20\% \textit{ on wet basis (wb)} \text{ or}$$

$$\frac{20 \times 100}{80} = 25\% \textit{ on dry basis (db)}$$

Grain will normally be harvested at a moisture content of 18–25 percent (wb), although it can be substantially higher or lower depending on many factors (such as the stage of maturity, season, weather pattern and drying facilities).

Moisture content measurement

Moisture can be determined in the laboratory by a number of methods, the most accurate of which are the oven-drying method and the distillation method; these are normally taken as references for moisture meters used under field conditions.

Laboratory methods require a representative sample of the grain. As the moisture content is unlikely to be uniform throughout a batch of grain, it is essential that:

- Either several samples are taken and tested, or a sample is taken from several places, thoroughly mixed, placed on a clean surface and quartered, with the procedure repeated until a suitable sized sample is obtained.
- Or the sample taken is kept in a sealed container (e.g. tightly fitting tin, bottle or plastic bag) between the time of sampling and the time of determining the moisture content.

The oven-drying method is the most straight forward and requires an accurately weighed sample of grain to be dried for a period of time and then re-weighed. The scales should preferably be electronic unless a large enough sample is used, in which case good mechanical scales can be used.

The rapid-oven method is one of a number of faster laboratory methods. These methods range from simple, inexpensive pieces of equipment to highly sophisticated and expensive instruments. A typical simple method consists of shining an infrared lamp on a balance pan containing a ground sample of approximately 5 grams. The sample is exposed to the intense heat of the lamp for a predetermined period and the loss in weight is shown on a scale calibrated for percentage moisture content.

The salt-jar method is a simple field method for determining whether maize is dry enough for storage in bags. A teaspoon full of dry non-iodized salt is placed in a thoroughly dry jar (or bottle) with a tight cover. The salt should not stick to the sides of the jar when it is rolled. Then a cob of maize is shelled, the kernels placed in the jar and the cover sealed tightly. The jar is then shaken and rolled gently for 2–3 minutes. If the salt does not lump or adhere to the sides of the jar, the moisture is usually below 15 percent.

Moisture meters measure one or more electrical properties of the grain that are closely related to moisture content. Although acetylene and hair hygrometer measurement techniques have been used in the past, electrical moisture meters are now the most commonly used type of moisture meter. Developments in electronics have led to the manufacture of cheap and easy-to-use electronic meters that are also quite accurate. These are sold under different brand names.

Relative humidity

Relative humidity (RH) as a measure of air moisture is defined in Chapter 12. It is a useful factor for grain drying. The relative humidity of ventilating air indicates how much, if any, moisture can be removed from the grain with unheated air, and is a basis for deciding on ventilation rates and air temperatures.

Relative humidity measurement

Of the devices available for measuring relative humidity, one of the simplest and most accurate is a psychrometer. The temperatures of the wet-bulb and dry-bulb thermometers mounted on the instrument are noted and the values are used with a psychrometric chart. In fan systems, the psychrometer may simply be held in the airstream to obtain a reading.

Drying theory

Equilibrium moisture content

Any hygroscopic material (including grain) has its own characteristic balance (or equilibrium) between the moisture it contains and the water vapour in the air with which it is in contact. This is known as the *equilibrium moisture content* (EMC). When food grains

containing a certain amount of moisture are exposed to air, moisture moves from the grain to the air, or *vice versa*, until there is a balance between the moisture in the grain and in the air.

Each food grain has a characteristic equilibrium curve obtained by plotting a graph of moisture content against the relative humidity and temperature of the air. Curves for some common food grains are given in Figure 16.2. These values must be considered only as a guide because the equilibrium values of different types and varieties of grain vary. The EMC will also vary slightly with temperature. For most cereals, it will drop by approximately 0.5 percent for every 10 °C temperature rise at the same percentage relative humidity of the air.

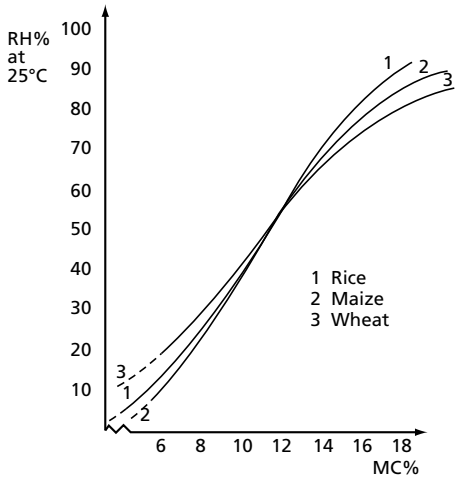


Figure 16.2 **Equilibrium moisture content for different crops**

Table 16.1 shows moisture content equilibrium values for a range of produce at 70 percent relative humidity and 27 °C (the maximum acceptable level for storage of any sample).

TABLE 16.1
Equilibrium moisture content (EMC) values at 27 °C and 70 percent relative humidity

Crop	EMC
Maize	13.5
Wheat	13.5
Sorghum	13.5
Millet	16.0
Paddy	15.0
Rice	13.0
Cowpeas	15.0
Beans	15.0
Groundnuts (shelled)	7.0
Copra	7.0

As sacks are porous and allow air to circulate readily through the crop, it is generally acceptable to allow the grain to be stored at a moisture content that is 1–2 percent higher than in bins or containers with non-porous walls.

The storage of grains can also be affected by the atmosphere, in addition to temperature and moisture content. If damp grain is held in a sealed container, the respiration of grain and insects will consume the available oxygen. As the oxygen is depleted, it is replaced with carbon dioxide. This, in turn, inhibits the activity of the insects and fungal problems, which will decrease to the point that it virtually ceases. However, storage in this manner can cause tainting of the grain, which renders it less acceptable for human consumption.

Storage of seed grain requires conditions that will not only maintain peak viability but will avoid also all possibility of germination while in storage. High moisture content and low oxygen may decrease viability and therefore should be avoided for seed storage. At the same time, to avoid any danger of germination or fungal and insect damage while in storage, seed should be dried 1–2 percent more than for human consumption. Additionally, it is important to keep the temperature of the seed as low as possible.

Temperature and psychrometrics of drying

Grain to be stored in bins or sacks may have too high a temperature or too high a moisture content, or both. If ambient temperatures are low, then air alone may cool the stored grain enough to prevent mould and insect damage while the moisture content is being slowly reduced to a safe level. If the air temperature is too high (over 10 °C), drying may be hastened by heating, as heating the air further increases its capacity to absorb moisture.

Figure 16.3 shows the effect of heating the air, increasing its capacity to absorb moisture.

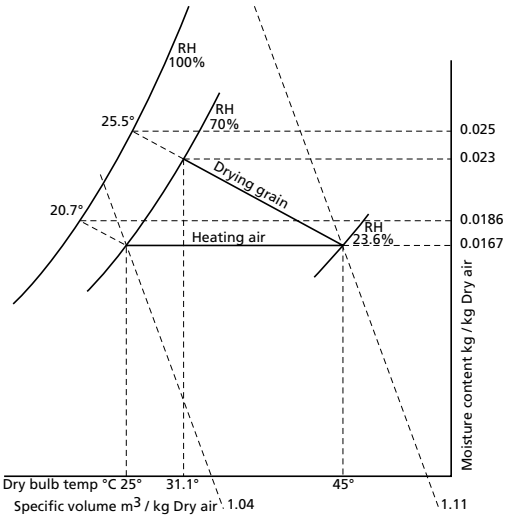


Figure 16.3 **The effect of heating air for drying (from 1500m psychrometric chart)**

Example: The ambient air at 25 °C and 70 percent RH is heated to 45 °C and 24 percent RH. When passing through the grain, it gains enough moisture to again reach 70 percent RH while the temperature drops to 30.1 °C. Each kilogram of air would then have removed (0.023 - 0.0167) = 0.0063 kg of moisture. Whether the air returns to 70 percent RH or to some other level will depend on the air velocity through the grain.

Loss of moisture

As grain dries, it releases its moisture into the drying air and consequently loses weight.

The weight of grain after drying may be found using the following equation:

$$W_2 = W_1 - \frac{W_1 (M_1 - M_2)}{100 - M_2}$$

where:
W_1 = Weight of undried grain (kg)
W_2 = Weight of dried grain (kg)
M_1 = Moisture content of undried grain (percent)
M_2 = Moisture content of dried grain (percent).

For example, if 200 kg of peas at 32 percent moisture content are dried to 19 percent moisture content, what is the weight of the dried peas?

$$W_2 = 200 - \frac{200\ (32 - 19)}{100 - 19} = 200 - 32.1 = 167.9 \text{ kg}$$

When the moisture content of the grain to be dried has been determined, it is possible to check the progress of the drying process by using the following procedure.

Before drying starts, place a weighed sample of the undried grain in a porous sack and bury it in the upper layer of the grain in the grain bin. At any time during the drying process, the sack may be removed, weighed, and returned to the bin. Then, using the initial weight, the initial moisture content and the newly observed weight in the following equation, the current moisture content at that specific level may be calculated:

$$M_2 = 100 - \frac{W_1 (100 - M_1)}{W_2}$$

Drying systems

The range of systems available for drying grains varies from thin-layer drying in the sun or a simple maize crib to expensive mechanized systems such as continuous-flow dryers. The choice is governed by a number of factors, including:

Rate of harvest: The capacity of the system must be able to keep pace with the rate at which the grain arrives at the store on a daily basis. It is essential that loading and drying does not hold up the harvest.

Total volume to be dried: This may not be the total volume of the crop. If harvesting normally starts as the rainy season is ending, it may be necessary to dry the early part of the harvest, but not the later part.

Storage system: In many cases, the storage system and the drying system may be the same structure. For example a ventilated maize crib (see Figure 16.5), used for drying the crop naturally, is likely to be used to store the shelled crop in bags later. Some bin-drying systems have a similar dual purpose.

Cost: Both capital cost and running cost should be taken into account.

TABLE 16.2
Weight of grain after drying (% of original weight)

Initial moisture content (%)	Final moisture content (%)								
	18	17	16	15	14	13	12	11	10
28	87.8	86.7	85.7	84.7	83.7	82.8	81.8	80.9	80.0
27	89.0	88.0	86.9	85.9	84.9	83.9	83.0	82.0	81.1
26	90.2	89.2	88.1	87.1	86.0	85.1	84.1	83.1	82.2
25	91.5	90.4	89.3	88.2	87.2	86.2	85.2	84. 3	83.3
24	92.7	91.6	90.5	89.4	88.4	87.4	86.4	85.4	84.4
23	93.9	92.8	91.7	90.6	89.5	88.5	87.5	86.5	85.6
22	95.1	94.0	92.9	91.8	90.7	89.7	88.6	87.6	86.7
21	96.3	95.2	94.0	92.9	91.9	90.8	89.8	88.8	87.8
20	97.6	96.4	95.2	94.1	93.0	92.0	90.9	89.9	88.9
19	98.8	97.6	96.4	95.3	94.2	93.1	92.0	91.0	90.0
18		98.8	97.6	96.5	95.3	94.3	93.2	92.1	91.1
17			98.8	97.6	96.5	95.4	94.3	93.3	92.2
16				98.8	97.7	96.6	95.5	94.4	93.3

Flexibility: The likelihood of different crops requiring drying should be considered.

Drying systems fall into two main groups:

Natural drying using ambient air temperature and either direct sunlight or natural air movement through the crop.

Artificial drying using mechanical means (e.g. a fan) to move air through the crop, with the air being either at ambient temperature or artificially heated.

Additionally, drying can be considered in terms of the thickness of the bed of grain being dried, i.e. either shallow-layer (or thin-layer) drying or deep-bed drying. Natural drying requires the grain to be in shallow layers, whereas certain fans can push air through grain several metres deep.

Natural drying

The traditional methods used by farmers for drying grain rely on natural air movement to reduce moisture content to a safe level for storage. In addition, they may utilize the extra drying capacity gained by exposing the produce to the sun. With good ventilation through the store, the grain can be harvested just after it is ripe (around 30 percent MC for maize) but most methods allow some of the drying to take place naturally while the crop is still standing in the field.

Natural drying may be divided in three main methods:

- Drying in the field before harvesting.
- Drying in shallow layers and exposing to sun and wind on a surface that prevents moisture from the ground from reaching the produce.
- Drying in, or on, a structure that has open sides to permit air movement through the mass.

Field drying

The method of leaving the crop standing in the field for drying is popular in areas where maturity of the crop coincides with the beginning of a dry season. However, a crop left unharvested is exposed to attack by insects, birds, rodents, wild animals, strong winds and occasional rain showers, which can damage and reduce the crop considerably. These factors are particularly important with the new, improved high-yielding crop varieties, which are often more susceptible to damage from the environment than the traditional varieties. For instance, a hybrid maize cob has less leaf cover than the cob of traditional maize varieties and is therefore more open to attack by insects and birds.

Field drying of the crop will also delay clearing of the field. This should be taken into account in areas where the field needs to be prepared for a second rainy season, or where the humidity is high enough at the end of the growing season to allow for an additional crop, such as beans. It is also not feasible in irrigated fields where higher cropping intensity requires early and/or timely harvesting.

Shallow-layer natural drying

The harvested crop is spread on hard ground, on roofs, on purpose-built platforms or on trays. As the crop is exposed to the sun, it will dry fairly quickly depending on the humidity of the ambient air. The produce should be stirred frequently to ensure even drying. The disadvantage of this method is that the crop has to be brought in or covered every evening or before rain. The labour requirements may be reduced considerably by placing the harvest on a plastic or tarpaulin sheet for easy handling or on a platform/tray covered by transparent plastic, as shown in Figure 16.4.

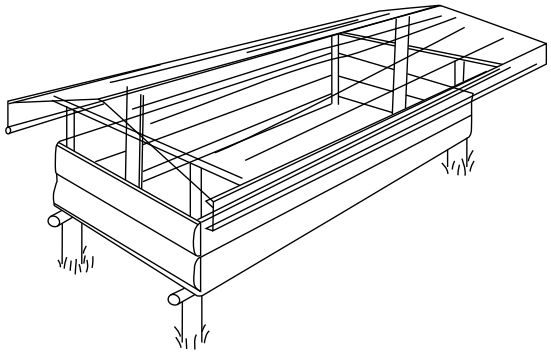


Figure 16.4 **Tray dryer for natural drying of crops in shallow layers. The tray has a mesh-wire bottom and a pitched roof of transparent plastic**

Ventilated structures for natural drying

Very small producers may suspend bundles of the crop from trees or poles so they are freely exposed to the air. With larger quantities, the harvested crop may be heaped on platforms or racks and topped by a layer of straw for rain protection. This method is commonly used for sheaves of paddy and cereals, as well as for cob-maize and groundnut plants. Drying is dependent on the free flow of air through the crop, so the heap should be made as open as possible.

The next step is to have a more permanent ventilated structure in which the crop may be heaped for drying, well protected from rain.

For maize, the tradition in most parts of Africa is to leave the crop in the field until the moisture content has fallen to around 18 percent and then continue drying the maize on the cob (with or without the husk [sheath]) in a granary, which most commonly has the shape of a circular woven basket placed on a platform 0.3–1.0 metres above the ground. The predrying in the field is normally necessary because the basket is too tightly woven or too wide to allow sufficient ventilation.

This 'two-step' drying method worked fairly well with traditional farming systems where farmers used maize with good sheath cover and could break new farmland regularly. However, the fast rise in population

experienced in many countries has resulted in a scarcity of good land, which forces farmers to use the same land for the same crop year after year. In most cases this leads to an accumulation of pests (e.g. insects). This, together with the higher susceptibility to insect attack of most improved high-yielding crop varieties (see the 'Field Drying' section), requires the crop to be harvested as early as possible, just after maturity, and moved away from the field for quick drying and safe storage.

For maize, the circular traditional granary may still be used with some modifications. The basket has to be more loosely woven, or the wall can be made slatted with at least 40 percent airspace and with a diameter of up to 150 cm, depending on the humidity of the air. The width restriction makes it more economical to build a rectangular drying structure if production exceeds a total of 5–9 bags. The rectangular structure shown in Figure 16.5, with slatted walls and a floor, is called a *ventilated maize crib*. Although it can be used with small modifications for any crop that needs to be kept ventilated, it is mostly used for drying maize on the cob without the husk.

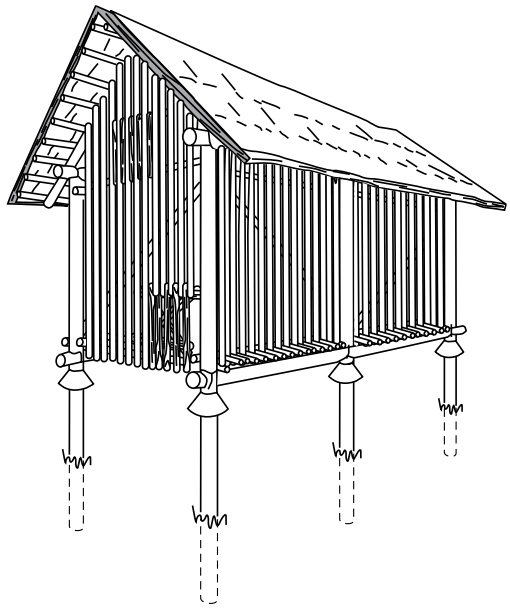


Figure 16.5 **Ventilated maize crib for drying maize on the cob. The structure has slatted walls and should be placed with the long wall facing the prevailing wind**

The crib can be constructed in many different ways, but the most important factor for the drying process is the width and the fact that the long wall should face the prevailing winds. The width may vary from 60 cm in very humid areas to 180 cm in areas with a semi-arid climate. Except for these extremes, a width of 100–150 cm is recommended as being appropriate for many maize growing areas in the eastern Africa region. The walls should not limit the airflow through the maize; this requires at least 40 percent openings.

In areas with rodents, the floor should be raised 90 cm above the ground and the legs fitted with rat guards. If the width does not exceed what is recommended for the area, it is possible to dry maize with an initial moisture content of 30 percent in a ventilated crib without having mould problems, but if it takes too long (more than 10–15 days) to reduce the moisture content to below 18 percent, mould may develop regardless of whether the maize is in the field or in a store.

The drying rate is dependent on the relative humidity of the air and the air velocity. When the moisture content of the produce reaches equilibrium with the humidity of the ambient air, drying will stop. Maize will dry down to approximately 13.5 percent moisture content if the mean relative humidity of the air is 70 percent (Figure 16.2).

TABLE 16.3
Capacities of cribs at different lengths (section length 150 cm)

Crib width 150 cm. Number of sections	Volume in m^3	No. of bags of wet maize on cobs	No. of 90 kg bags of dry shelled maize
1	2.7	26	9.3
2	6.0	58	20.7
3	9.4	91	32.5
4	12.8	124	44.8

Artificial drying

If the air humidity is too high to allow grain to be dried adequately by natural means and storage methods do not facilitate further drying, it is necessary to dry the produce using forced air or heat, or a combination of both. Various local methods have been developed using available materials. In some areas, storage is restricted to the amount that can be dried on a heat supply similar to that available from a kitchen fire. Panicles of paddy and maize stored on horizontal grids are kept dry by heat from a fire lit occasionally underneath the grid, and the heap of panicles is turned at regular intervals to prevent the development of mould. There are also raised granaries beneath which fires are lit to complete the drying process.

The produce acquires a characteristic odour and flavour when exposed directly to smoke from the fire, as well as to the hot dry air. This problem is overcome by using dryers designed with a hot-air chamber or heat-exchange unit and smoke stack or chimney (see Figure 16.6).

The fire is lit at the mouth of the oil barrel tube, and hot air and smoke is exhausted via the chimney. The heated barrels in turn heat the surrounding air, which rises through the crop.

When heat is used to dry grain, there must be some provision for aeration as well. Either very thin layers or frequent stirring is advisable, as natural convection currents seldom move enough air.

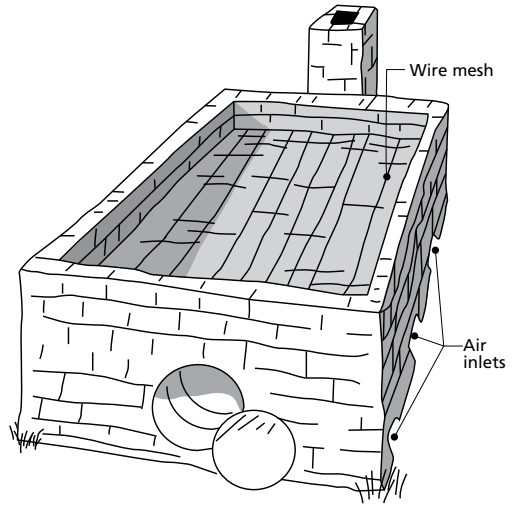


Figure 16.6 **An oil-barrel dryer**

The different forms of artificial drying may be characterized by the depth or thickness of grain being dried. Systems include:

- deep-layer dryers
- shallow-layer (or thin-layer) dryers
- in-sack dryers

Large-scale system dryers can be divided into the following categories:

- storage dryers
- continuous flow dryers
- batch dryers
- sack dryers

They may also be either high-temperature or low-temperature systems.

Air volume requirements

Whatever the system, artificial drying depends on forced-air ventilation, with or without added heat. Knowing the amount of moisture to be removed, together with the moisture-carrying capacity of the air under the existing conditions, makes it possible to estimate the weight of dry air required to complete a given drying operation. The humid volume of air is found on a psychrometric chart and, the total volume for drying can be determined from the chart. Drying will take place as long as the relative humidity of the drying air is below the equilibrium of the produce.

For example, the air described in Figure 16.3 contains 0.0167 kg moisture/kg dry air at 25 °C and 70 percent RH. The holding capacity of this air is 0.0186 kg moisture/kg dry air when fully saturated, and the specific volume is 1.04 m³/kg dry air.

Table 16.2 shows that 1 tonne of grain dried from 22 percent to 16 percent moisture content will yield 71 kg of water (1.000 - 0.929) × 1 000 kg = 71 kg).

$$\textit{Weight of air required} = \frac{71}{0.0186 - 0.0167} = 37\,368 \text{ kg}$$

$$\textit{Air volume is then } 37\,368 \text{ kg} \times 1.04 \frac{\text{m}^3}{\text{kg}} = 38\,863 \text{ m}^3$$

If the same air is heated to 45 °C, the relative humidity will drop to 23.6 percent and the holding capacity when fully saturated will increase to 0.025 kg moisture/kg dry air.

The specific volume is now 1.11 m³/kg dry air (Figure 16.3)

$$\textit{Weight of air required} = \frac{71}{0.025 - 0.0167} = 8\,554 \text{ kg}$$

Air volume is then 8 554 kg × 1.11 = 9 495 m³ or 1 583 m³/tonne and percentage moisture reduction.

From this result, the total volume of air and rate of flow is calculated in order to complete the drying operation in the required time.

Experience shows that the air volume needs to be increased to take into account the air velocity and grain depth. Air leaving a dryer using high air velocity and a shallow grain layer is seldom fully saturated with moisture. Certain minimum airflow rates are necessary to prevent the formation of mould during drying. These rates are given in Table 16.4. It should be noted that these figures are for loose grain through which air can be blown.

TABLE 16.4
Minimum required airflow rates for wheat and shelled maize

	Grain moisture (percent, wet basis)	Airflow ($m^3/s/m^2$)
Wheat	20	0.06
	18	0.04
	16	0.02
Maize	25	0.10
	20	0.06
	18	0.04
	16	0.02

Deep-layer dryers

These consist of beds, bins, silos or rectangular warehouses equipped with ducting or a false floor, through which air is distributed and blown through the grain. The depth of the grain layer may be 30–350 cm.

In deep-layer dryers, unheated or slightly heated air (less than 6 °C) is forced through the grain by a mechanical fan. The grain dries first at the point where

the air enters, a drying front passes through the mass in the direction of the air movement, and the grain at the air discharge location dries last. Most of the drying occurs just below the drying front in a layer called the drying zone, which develops and then moves through the bulk (Figure 16.7). The depth and rate of progress of the drying zone depends largely on the dampness of the grain and the airspeed. A low ventilation rate results in a shallow, slow-moving zone, whilst a higher rate produces a deeper zone that progresses more quickly.

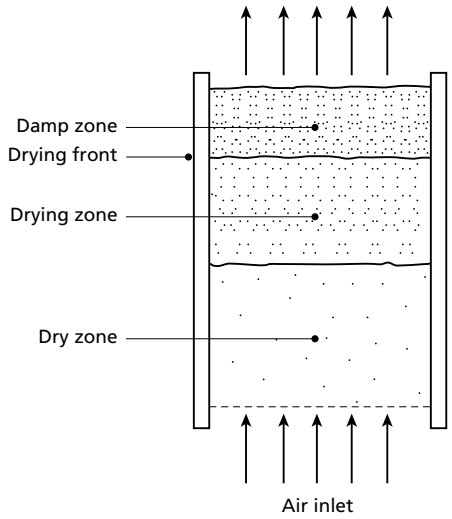


Figure 16.7 **Deep-layer drying**

The grain furthest from the air source will remain wet, and may even become wetter (owing to condensation), until the drying zone begins to move out of the crop. For successful results, the drying zone must reach the surface before the grain in this area deteriorates. Therefore it is normal practice to limit the depth of grain so that the drying front reaches the top in good time.

Although increasing the airflow increases the drying rate, Table 16.5 demonstrates that the static pressure, resulting from the resistance of the grain to the flow of air, rises at a very rapid rate. Therefore it is common practice to limit the airspeed through the crop to 0.10–0.15 metres per second to avoid the need for excessive fan capacity.

TABLE 16.5
Typical resistance to airflow (Pa) per metre of crop depth

Crop	Airspeed through crop (metres/second)				
	0.05	0.10	0.15	0.20	0.25
Wheat	140	330	570	850	1 070
Maize	70	180	320	500	720
Peas	50	110	190	290	410

Note: Values for the other small grain cereals, such as rice, are similar to wheat, and values for very fine seeds, such as herbage seeds, may exceed 2 500 Pa for an airspeed of 0.10 m/s.

Figure 16.8 shows a floor-drying system in a shed or warehouse-type of building. The crop is piled over the lateral ducts, which are fed with air from a main duct. The main duct is often large enough for a person to walk inside in order to close off laterals where the grain is already dry.

The lateral ducts can be installed above or below floor level. The above-ground laterals are cheaper but will have to be removed when unloading the store. Below-ground laterals are left in place and can be driven over.

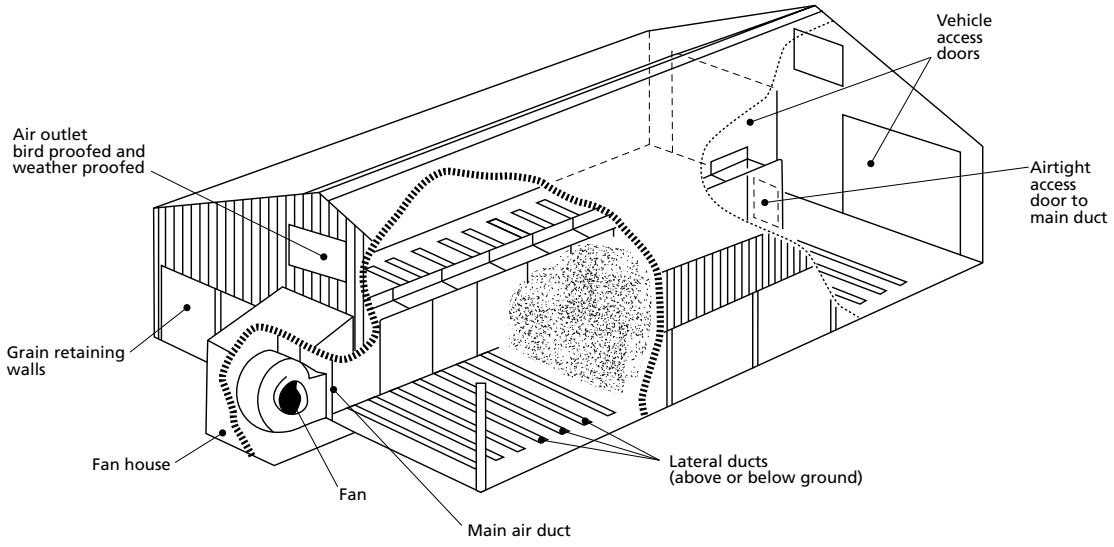
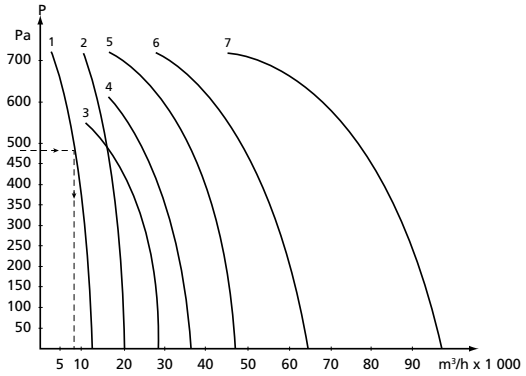


Figure 16.8 **Floor-drying system**

Fan capacities

When planning for deep-layer dryers it is important to keep the fan performance in mind. Figure 16.9 shows typical fan performance curves for modern high-pressure propeller fans.



1	2.2 kW	ϕ	500 mm	2 900 rpm
2	4.0 kW	ϕ	600 mm	2 900 rpm
3	4.0 kW	ϕ	600 mm	1 400 rpm
4	5.5 kW	ϕ	900 mm	1 400 rpm
5	7.5 kW	ϕ	1 000 mm	1 400 rpm
6	11.0 kW	ϕ	1 100 mm	1 400 rpm
7	18.5 kW	ϕ	1 250 mm	1 400 rpm

Figure 16.9 **Fan performance curves for some modern high-pressure propeller fans**

Example

A village cooperative is planning to install a deep-layer dryer. Determine a suitable size for the dryer and choose a suitable fan. The following data is given:

Quantity of grain: 10 tonnes of maize/batch
Time available for drying: 60 hours (6 days)
Initial moisture content (MC) in maize: 21 percent
MC reduction for sack storage: 6 percent
Incoming air at 25 °C and 50 percent RH
Assumed exhaust air at 85 percent RH and 19.5 °C

Air volume required to remove 1 kg water:

From the psychrometric chart it is found that the given air can remove 0.0143 – 0.0118 = 0.0025 kg H_2O/kg dry air. The volume of incoming air is 1.03 m³/kg dry air.

Air volume required to remove 1 kg of water:

$$\frac{1.03}{0.0025} = 412 \text{ m}^3/\text{kg}H_2O$$

Moisture to be removed from maize:

$$W_1 - W_2 = \frac{W_1 (M_1 - M_2)}{100 - M_2}$$

$$= \frac{10 \times 10^3 (21 - 15)}{100 - 15} = 706 \text{ kg}H_2O$$

Total air volume required: 412 × 706 = 290 824 m³

$$\textit{Total air flow/hour} = \frac{290\,824}{60} = 4\,847 \text{ m}^3/\text{h}$$

Minimum air velocity required 0.07 m/s (from Table 16.4)

Try different heights of the layer taking into consideration the airflow resistance.

	Height of layer (metres)		
	1	1.5	2
Floor area required (density of maize 720 kg/m³)	13.9	9.3	6.9 m²
Airflow	$\frac{4847}{13.9} = 349$	521	702 m³/h.m²
Air velocity	0.10	0.14	0.20 m/s
Airflow resistance	180	480	1 000 Pa

Figure 16.9 shows that the 2.2 kW fan can easily manage a 1.5-metre layer, i.e. 4 850 m³/hour at 480 Pa. Under the same conditions, with wheat instead of maize, the airflow resistance would be 330, 860 and 1 700 Pa for the 1, 1.5 and 2m thick layers, respectively. To use the same 2.2 kW fan, the layer should be reduced to 1 metre, otherwise a centrifugal fan with a higher performance would be be required.

The calculations assume ideal conditions and the real moisture reduction may decrease because of other climatic conditions or the moisture content in the grain. The fan performance should therefore be a little higher than calculated.

In the example, the grain depth was given as 150 cm. However, this sort of drying and storage unit may have a capacity of 300–400 cm. To avoid the problem of spoilage in the upper layers, it is normal practice to dry grain in batches of 150 cm before adding more grain. The additional grain will then start drying from this point.

Commercially available bins for drying and storage are normally made of corrugated steel. Round bins have no theoretical limit to the diameter. However, for practical purposes, a diameter of 7–8 metres is likely to be the maximum. The minimum diameter is dictated by the ability to roll the sheet to a tight radius and is likely to be approximately 2–3 metres.

Rectangular bin sizes are limited by the ability of a straight length of wall to resist thrust. The practical limit is around 3 metres and these bins may well be 'nested' together (see Figure 16.10). It is possible to omit the crosswall and replace it with tie-rods.

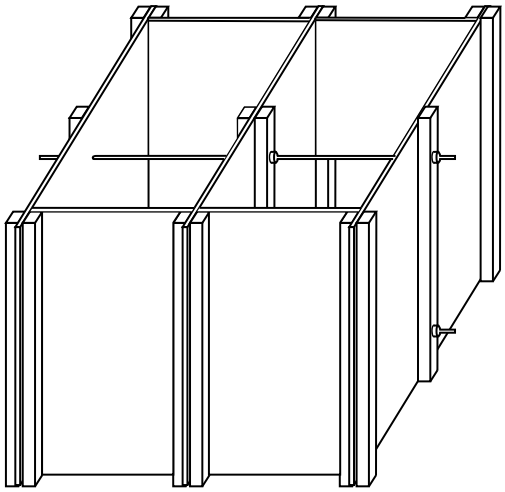


Figure 16.10 **Nested bins with rods replacing crosswalls**

Another type of in-bin dryer is a radially-ventilated bin, in which there is a vertical perforated duct through the centre of a circular bin. The bin wall is of perforated steel or of timber staves alternating with perforated steel strips. The distance between the duct and the bin wall is 1–2 metres, depending on bin size. The air path through the grain is therefore limited to the radius of the bin. The air velocity will also decrease gradually towards the outer wall.

Radially-ventilated bins are normally used as batch dryers, and the grain is then transferred to a store for either bulk or bag storage. When drying wet grain, the height in the bin should be decreased in order to increase the air velocity and to eliminate excessive pressure on grain in the bottom of the bin.

Shallow-layer dryers

Batch dryers

These shallow-layer dryers often take the form of a tray with a perforated base. The dimensions may be 1–2 metres wide and 2–4 metres long, with the grain bed 150–300 mm deep. The dryer can also be built vertically, with channels for both inlet and outlet air going through the grain, as shown in Figure 16.11. Warmed air is blown into the plenum chamber beneath and then up through the grain. These dryers are more suitable for smaller operations than continuous-flow dryers. They may be either mechanically or manually loaded or unloaded.

Continuous-flow dryers

The grain passes through these dryers in a continuous flow at a controlled rate. The grain is kept in a thin sheet approximately 100–150 mm deep and hot air is blown through the crop. Under this system, the air temperature can be substantially higher than in bulk dryers. The rate of throughput can be controlled, and hence the length of time exposed to the hot air. The time is adjusted according to the amount of moisture to be removed. The latter part of the path through the dryer is an ambient-air section to cool the grain. Continuous-flow dryers (see Figure 16.12) are high in cost and are used only in highly mechanized situations.

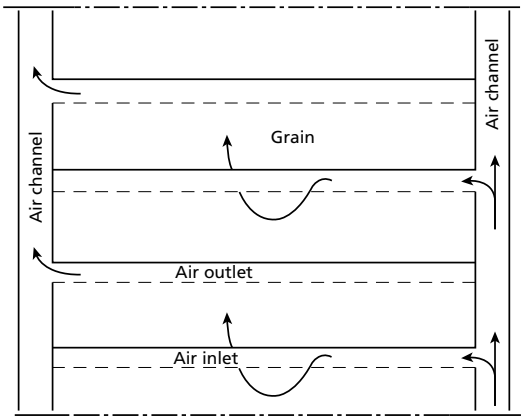


Figure 16.11 **Section showing the principle of a vertical shallow-layer batch dryer**

Grain cooling

Failure to cool grain that has been dried using heat may cause an increase in moisture content that is great enough to shorten its storage life significantly.

As a psychrometric chart will show, for a given air moisture content (absolute humidity), a drop in air temperature causes an increase in the relative humidity. It follows that, if hot grain is allowed to cool naturally, the relative humidity of the air in the bin will rise and, if the saturation temperature is reached or exceeded, condensation can cause the grain moisture content to rise again. To prevent this from happening, the grain should be cooled to ambient temperature after it has been dried. The methods used to cool grain are dependent on the drying system.

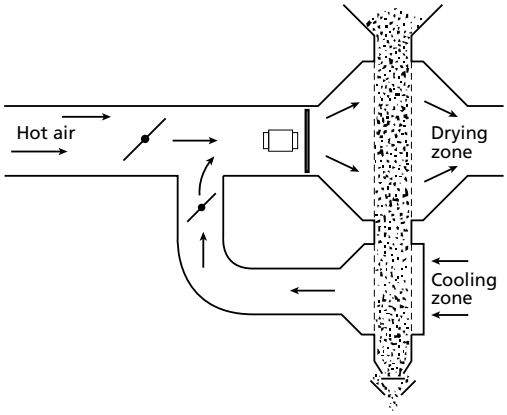


Figure 16.12 **The principles of a continuous-flow dryer**

Sun-dried grain can reach high temperatures in direct sunlight. If the grain is to be stored in any container through which air cannot pass freely, it should at least be left shaded for an hour or more prior to storage.

As air can circulate around sack stacks to some extent, they are able to cool naturally. Even so, it is preferable to ventilate the stacks to cool them.

When using fan-ventilated batch dryers of all types, including sack dryers, the fan should be left running with no added heat until the crop is at ambient temperature before discharging the crop from the dryer. This is most easily determined by comparing the temperatures of the incoming and exhaust air and waiting until there is virtually no difference.

Cooling buffer storage

Low volume ventilation (LVV) or aeration may be employed to cool grain that has been placed in storage. Although it can be used in conjunction with other dryers as a cooling system, the main objective of LVV is to cool the grain positively at harvest time and thus prevent infestations of insects and mites and the development of mould. Loss of viability is slowed and the migration of moisture from warm spots to cooler ones in the grain mass is avoided.

It must be stressed that LVV is not a drying system. Consequently, if grain is too wet at the start (over 18 percent) it will be unlikely to store well and, for human consumption, it would be preferable to start with a moisture content of less than 18 percent.

Principles

Ambient air passed through the grain at the rate of 6–8 m^3/h for each tonne in storage has proven adequate in practice. Depending on the static pressures involved, this range of ventilation rates would require 190–560 W per tonne.

A drop in temperature occurs in three ways:

- removal of respirational heat by the airstream;
- contact cooling of the grain by colder air;
- evaporative cooling when the relative humidity of the cooling air is below the equilibrium moisture content level of the grain.

Airflow may be upwards or downwards and investigations have shown little real difference in the overall effect. Once the grain is cooled and the ventilation stopped, it is advisable to turn the fan on every 2–3 weeks to check for storage problems. A musty odour indicates a moisture and temperature problem.

Equipment

Fans to be used for grain cooling can be either centrifugal or single-stage axial fans. Motors ranging from 370 W to 746 W cover the vast majority of fan sizes used. They are usually small enough to be picked up by hand and operate on 13-amp switched outlets. The volume of air delivered varies with the climate, but should be at least 10 m^3/h. Ducts similar to those used for on-floor storage are satisfactory.

Management

For cooling grain, only air that is cooler than the grain under treatment should be used.

The preferred method of cooling grain is to blow air when ambient air is 3 °C cooler than the warmest grain. This requires knowledge of the temperature of the grain in the bin or heap. A spear thermometer or a thermistor will be needed; the quicker reaction of the latter greatly speeds up the task of taking grain temperatures at several points. In a bin, the hottest spot will be in the centre, some 1.2–1.8 metres below the surface in the case of upward ventilation, or approximately 1.2 metres above the duct in the case of downward airflow. In a natural heap, the hottest places are the apex, the shoulders or at the foot of the sidewall (see Figure 16.13).

Sack drying

Grain in sacks can be dried in a stack or the sacks may be laid in one or two layers on a platform dryer as shown in Figure 16.14.

A platform dryer consists of a plenum chamber with an open top of wire mesh, bamboo or other means of supporting 2–3 layers of sacks. Using an airflow rate of 0.1 m^3/s per m^2 of platform area, air heated to around 14 °C above ambient temperature should reduce the moisture content by around 0.5 percent/h,

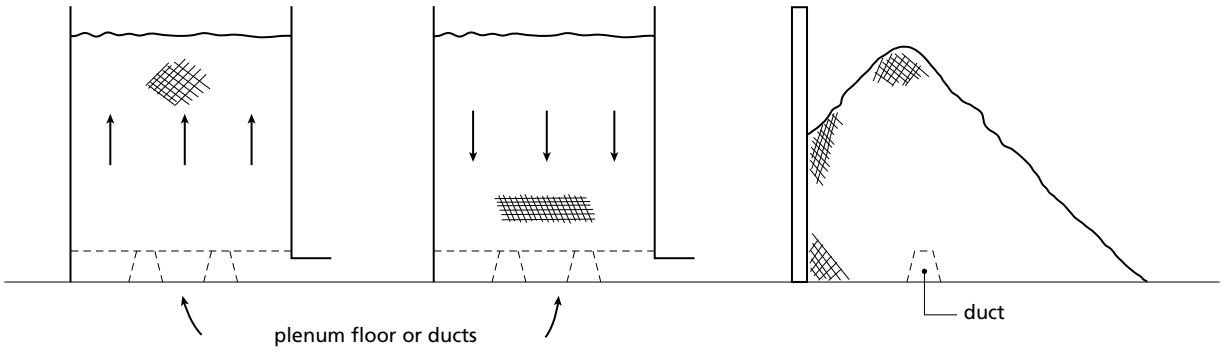


Figure 16.13 **Warmest areas in grain**

although a temperature increase of 6–10 °C may be more usual.

In the stack system, a perforated plenum tunnel is used to form the base of the stack and to distribute the air uniformly (see Figure 16.15). The initial moisture content determines how large the stack can be: 8 sacks high for an initial moisture content of 25 percent and 12–13 sacks high for an initial moisture content of 18 percent. A fan is used to blow air through the stack. This fan is normally diesel powered.

With both platform dryers and sack-stack drying, there are some points that need to be borne in mind. Firstly, any gaps between sacks should be filled with empty bags or straw to minimize air leakage. Secondly, as pointed out earlier, grain should be cooled before being left in storage.

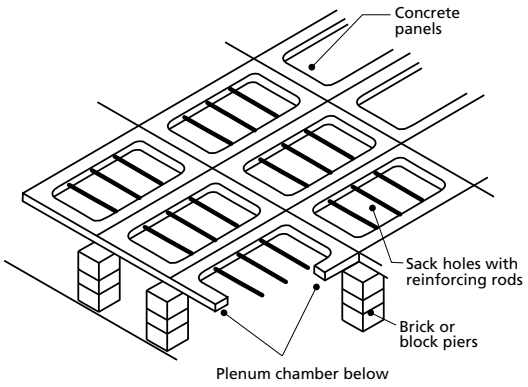


Figure 16.14 **Platform dryer with concrete panels on brick piers**

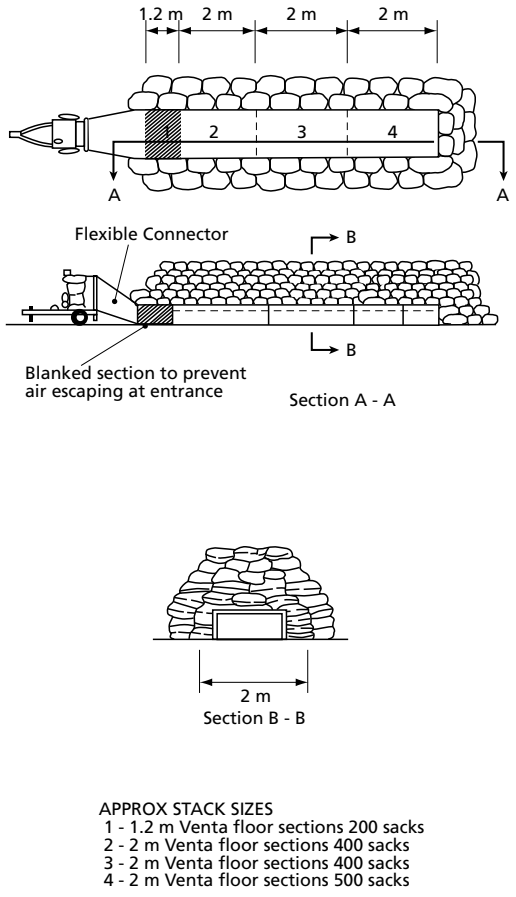


Figure 16.15 **Sack drying with a diesel-powered fan**

Drying problems

Overdrying grain using excessive temperatures can cause stresses in the individual kernels, leading to cracking and loss of viability. Another effect of overdrying is that all moisture lost below the safe-storage moisture content represents a loss in the value of the crop when the grain is sold. For example, 10 tonnes of grain at 15 percent moisture content weighs 340 kg less at 12 percent moisture content.

Air short-circuiting means that the air will always take the path of least resistance which, in the case of grain, is usually the shortest route possible through a batch. Figure 16.16 illustrates this principle and emphasizes the need to level the grain and provide a uniform depth in any forced-air system.

Dirty crops, such as grain with a large proportion of chaff, fine seeds and dirt, are more difficult to dry because the resistance to airflow increases as the spaces between grains become blocked. While Table 16.5 refers to clean grain, it shows the significant effect of small particle size on the resistance to airflow. Therefore it is important for the grain to be as clean and uncontaminated as possible.

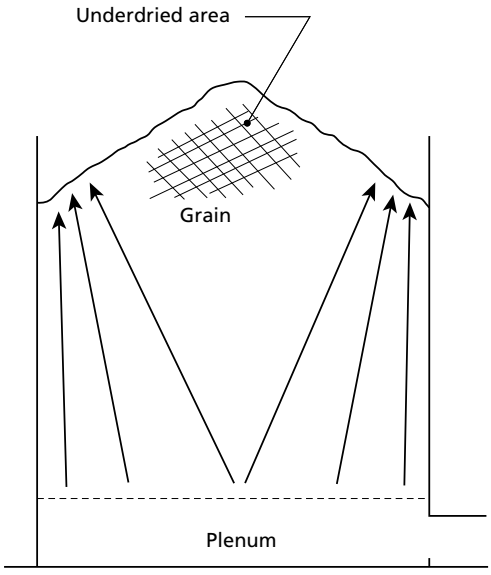


Figure 16.16 **Air taking the shortest path**

Cleaning techniques range from the traditional winnowing of crops by throwing them into the air, to the use of sophisticated, modern, high-throughput

equipment. The two techniques used on small farms are winnowing and sieving.

Sieving is usually a two-stage operation. The first sieve is just coarse enough to let the grain through while rejecting all larger particles. The second sieve is just fine enough to hold the grain being cleaned, but it passes weed seeds and particles that are smaller than the grain.

Grain may sometimes be given a preliminary cleaning prior to storage to remove the majority of contaminants, and then a second, more thorough, cleaning before sale. This would apply in particular to seed grain.

Instruments

Temperature, relative humidity, static pressure and airflow measurement are discussed in general in Chapter 13. Here we discuss in more detail some specific points relating to taking such measurements in the case of grain drying and storage.

Thermometers

Although mercury-in-glass thermometers are fragile and rather slow to react, they are probably the most dependable means of measuring temperature. They may be protected by mounting them in a groove in a wooden or metal probe so that temperatures deep in piles or bins may be checked. Care should be taken to allow several minutes for the temperature to stabilize.

Thermistors and thermocouples are convenient for remote measurements but they are more costly and have adjustment problems.

Airflow meters

Airflow meters similar to the one shown in Figure 16.17 are available to measure the vertical airspeed through grain being dried in bulk. The conical, clear plastic tube contains an aluminium disc that can slide on a wire mounted along the axis of the tube. A metal cone at the base of the plastic tube supports the instrument on the grain and collects the emerging air. The plastic tube is graduated in metres/second and the airspeed is read at the point where the disc is 'floating' on the air flowing upwards through the tube. In order to obtain consistent and accurate readings, the disc should move freely on the wire.

For very simple and rough airflow assessment in a fan-ventilated bin, a square of light material approximately 300 mm square, such as a handkerchief, laid on the surface of the grain should be lifted by the airflow if enough air is passing through the crop.

Manometers

The quantity of air delivered by a fan is related to the static pressure against which the air is being delivered. By measuring static pressure and referring to the relevant fan performance data, an approximate guide to the quantity of air being delivered can be obtained. Figure 13.11 shows a simple manometer.

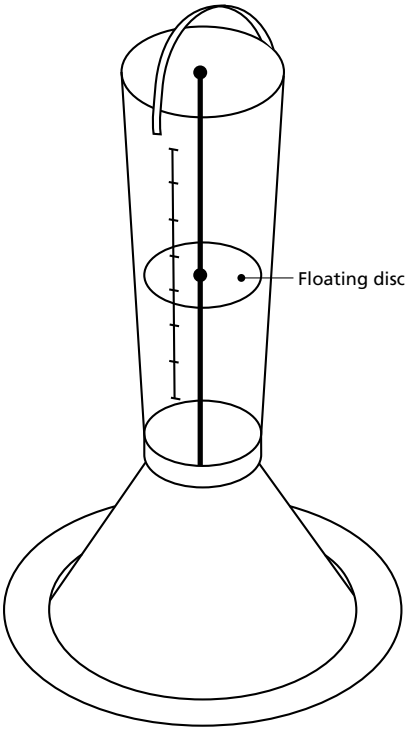


Figure 16.17 **Grain airflow meter**

For all types of manometer, it is important for the sensor head (static tube) to be mounted in a position in the main air duct where the mean static pressure can be monitored. In practice, a position near the top of the main air duct, at a distance of at least twice the fan diameter from the fan, is normally satisfactory. The lower the airflow at the sensing location, the truer the static pressure reading will be.

GRAIN STORAGE

Parameters

The major objectives of crop conditioning and storage have been discussed before. To be able to achieve these objectives, the store must satisfy the following parameters as far as possible: (a) the grain must be kept dry; (b) the grain should be kept at a uniform temperature; (c) the grain should be protected from insect attack; (d) rodents and birds should be excluded.

It is evident from previous sections that, in many cases, facilities for drying and storage are found in one and the same structure. Combining these functions is economical and allows further conditioning at later stages if required. For example, if a hot spot develops in a storage bin, it can easily be ventilated again. It may also be possible to provide some low-volume ventilation in an otherwise pure storage system.

However, there are situations where storage is considered quite separately from drying, ranging from the storage of naturally dried crops to the storage of grain from a continuous-flow or batch dryer.

The size and type of a storage facility is likely to be dictated by:

- total volume of crop/produce to be stored;
- the storage requirements for the crop/produce to be stored;
- the unit cost of various types of storage;
- the form in which the crop/produce is stored, i.e. cob maize versus shelled maize, or bagged wheat versus bulk wheat.

The volume of the store required can be estimated from the expected yield and the land area.

A comparison between different forms of storage is normally made by calculating costs per tonne of capacity. The form of storage depends not only on how the crop is harvested, the volume and the way it is delivered to the market, but also on the overall cost. Where drying is a problem, bag storage has the advantage of allowing a higher moisture content than bulk storage. For maize, the requirement for safe storage is a maximum of 15 percent and 12 percent moisture content respectively.

In general terms, the respective advantages and disadvantages of bag and bulk storage are:

Bags	Bulk
Flexibility of storage	Inflexible storage
Partly mechanizable	Mechanizable
Slow handling	Rapid handling
Considerable spillage	Little spillage
Low capital costs	High capital costs
High operating costs	Low operating costs
Easy inspection	Inspection more difficult

Solid-wall bins and silos for bulk storage

Solid-wall bins may be anything from a small plastered basket to large steel or concrete silos holding several thousand tons. The traditional bins used by African farmers are small with a capacity of 2–3 tonnes, including gourds, clay pots, mud-plastered baskets raised off the ground and mud-walled silos ('rumbus').

Many of these solid-wall bins or silos have limitations, particularly in terms of durability and protection against rodents, insects and moisture from ambient air. Solid-wall bins or silos should be used only in areas where the produce can be dried sufficiently prior to storage. Several attempts have been made to improve on traditional stores to make them more suitable for long-term storage.

Improved traditional bins

Many traditional stores perform excellently in their appropriate climatic conditions, and others can be made to do so with minor changes. Efforts should be made to prevent cracking of the surface of the walls and to seal the entrance to the bin. This can be done, for instance, by adding lime or cement to the mud (i.e. a stabilized-soil technique) or by incorporating an airtight lining (e.g. plastic) in the wall.

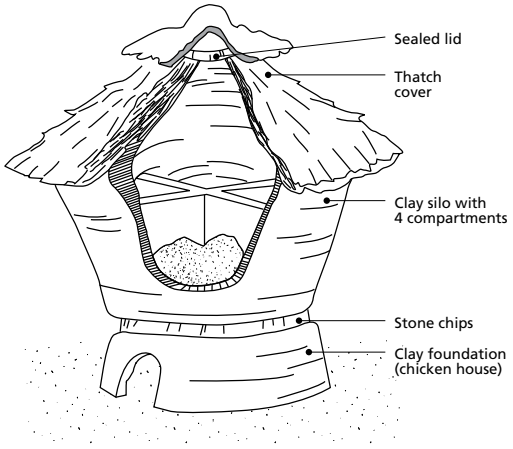


Figure 16.18 **Clay silo for storing grain in four compartments. The stone chips form the moisture barrier**

Figure 16.19 shows a woven basket made of sticks or split bamboo, plastered with mud mixed with cement. The walls slope towards a covered manhole in the top. There is an outlet near the bottom. The bin, which is placed on a raised platform, is covered by a thatch roof, or hat.

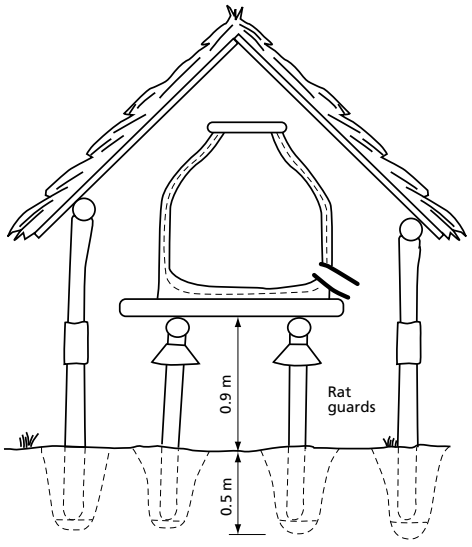


Figure 16.19 **Improved traditional bin**

The major improvements are:

- The floor is raised above the ground to avoid moisture.
- Supporting legs of hardwood are made 90 cm long and equipped with baffles to protect against rats.

- Instead of mud, the walls may be plastered with cement or mud mixed with cement/lime.
- Inlets and outlets should be made with airtight and lockable covers.
- Thatched roof to protect the bin from rain and strong sun.
- The area around the store should be kept clean.

Underground pits

In a few countries (e.g. India, parts of Africa and Latin America), it is claimed that underground pits are able to store grain without damage for many years. The pits keep grain cool, and some of them are relatively airtight. However, the grain on top and around the sides often becomes mouldy.

There are several types of pit, most of them flask-shaped and covered with sticks, cow dung and mud, or a large stone embedded in soft mud. The area should be free from termites and relatively dry.

Improvements to the pit may include:

- better lining of straw and mat;.
- plastic sheets and concrete or ferrocement;
- use of plastic bags in the pit;
- improved covering:
- surface drainage.

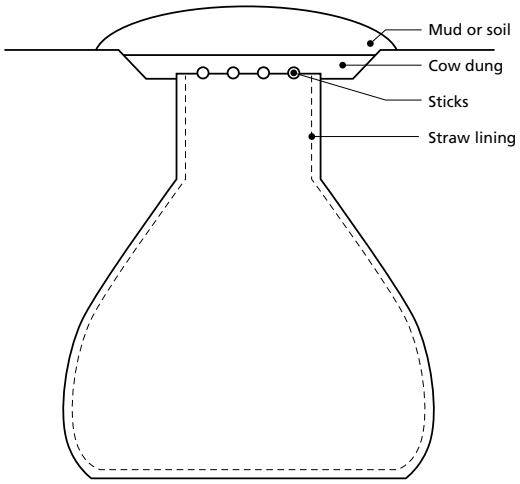


Figure 16.20 **Underground pit**

Brick-walled silo

Brick-walled silos or bins are suitable for small- and medium-size stores. The need for reinforcement makes them uneconomical when the height exceeds 7–8 metres. The wall may be made of bricks or blocks of mud, stabilized soil, burnt clay, stones or cement. To withstand the pressure from the grain, the wall will need reinforcement commensurate with the size and strength of the building materials.

Reinforcement can be reduced, and even omitted, by building thick, heavy walls (gravity walls). Figure 16.21 shows a silo with gravity walls where the bricks are placed radially. While no reinforcement is needed for this size, more building material is required.

Walls made of bricks, mud or cement will absorb moisture from the ambient air. In areas with high relative humidity it is therefore necessary to protect the grain by adding a moisture barrier to the silo walls. It will help considerably to bag-wash or plaster the walls on the outside with a mortar of cement–lime–sand (1:1:5) for burnt bricks or cement, and cement–sand–mud (1:2:6) for mud walls. The walls can then be painted with plastic paint or coal tar if better protection is needed.

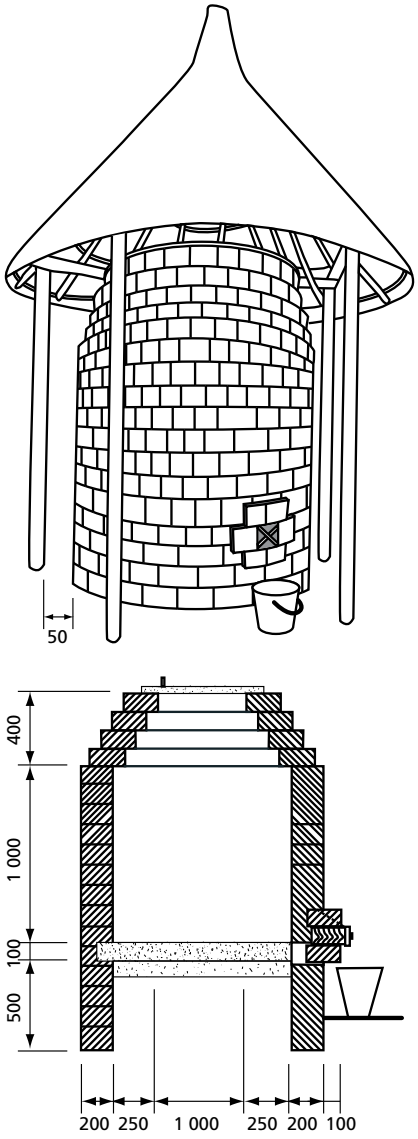


Figure 16.21 **Silo built of bricks laid radially (gravity wall)**

An alternative to plastering and painting the silo is to incorporate a lining of plastic sheeting in the middle of the wall, floor and roof to make the container airtight. The Pusa bin is such a structure and has been developed by the Agricultural Research Institute in

New Delhi. Originally the bin was rectangular with walls of two layers of brick; the floor and the roof are made of two layers of mud. The system can be used for silos of any shape and, if properly constructed, will give good protection against air and moisture.

Reinforced concrete silos

Concrete can take very little tension and needs to be reinforced when used for silos. Small silos suitable for an individual farm may be reinforced with chicken-wire.

The *ferrocement store or 'ferrumbu'* is a typical example (see Figure 16.22). One or two layers of 12 mm chicken wire are tied to vertical sticks or rods placed in a circle. The chicken wire is then plastered from both inside and outside. The verticals are removed after the outside is finished. Taller silos of 3–4 metres or more may be framed by welded mesh wire and with 12 mm chicken wire tied to the outside. With bags or plastic tied to the outside, it is possible to plaster the silo from the inside first and then from the outside a few days later after removing the bags. These techniques make it possible to construct walls with a thickness of 3–6 cm.

Larger concrete silos are built using a sliding mould, which is moved upwards continuously or step by step. Reinforcement and concrete are supplied from the top. Concrete silos can be made airtight if openings are properly sealed.

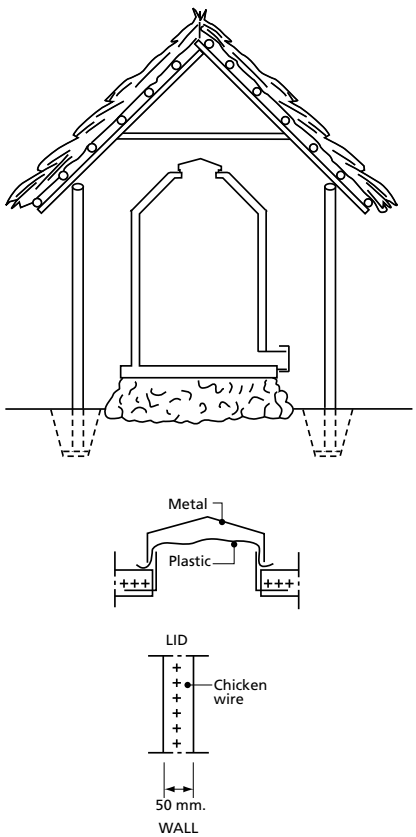


Figure 16.22 **Cross-section of a ferrocement store (ferrumbu)**

Steel bins

Steel bins range from thoroughly cleaned steel oil drums to commercial stores with a capacity of several thousand tonnes (see Figure 16.23). In most cases, steel silos are more expensive than concrete silos but have the advantage of being easy to erect and, for the smaller sizes, possible to move. The welded steel silo is normally airtight if the openings are properly sealed, but even a silo assembled of corrugated iron sheets can be made airtight if all joints are sealed with rubber gaskets or bitumen.

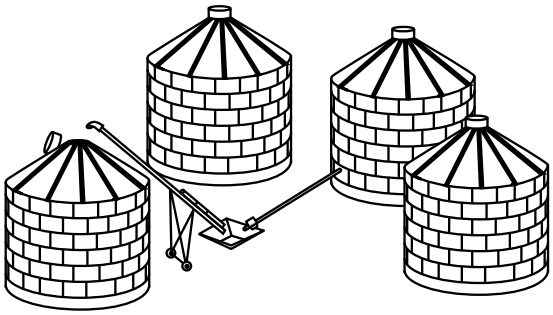


Figure 16.23 **Commercial storage silos**

Bag storage

The most commonly used method of grain storage in many countries is bag storage in any of a variety of buildings, e.g. stone, local brick, corrugated iron and mud and wattle, with or without plastered walls, and with an earth, stone or cement floor and a corrugated iron or thatched roof.

As mentioned before, the form in which the produce should be stored will depend on the quantity, harvest method, handling method, moisture content and costs.

The advantages of bag storage were listed earlier. The disadvantage is that jute bags give no protection against insects, which means that an insecticide has to be used. In some countries with a dry climate, it is common practice to stack the bags on plinths and cover them with a tarpaulin for temporary storage. Examples are the hard stands used in Zambia and the groundnut pyramids used near Kano in Northern Nigeria.

However, if the grain is to be kept for some time, it is recommended to store the bags in a building. A simple store makes use of the ventilated maize crib that is used for drying, the only difference being that the walls should be covered for protection against rain (see Figure 16.24). If the bags are stored in a multipurpose farm shed, or even in the farmer's dwelling, they should be kept out of reach of rats and mice. A raised, free-standing platform equipped with rat guards will serve this purpose.

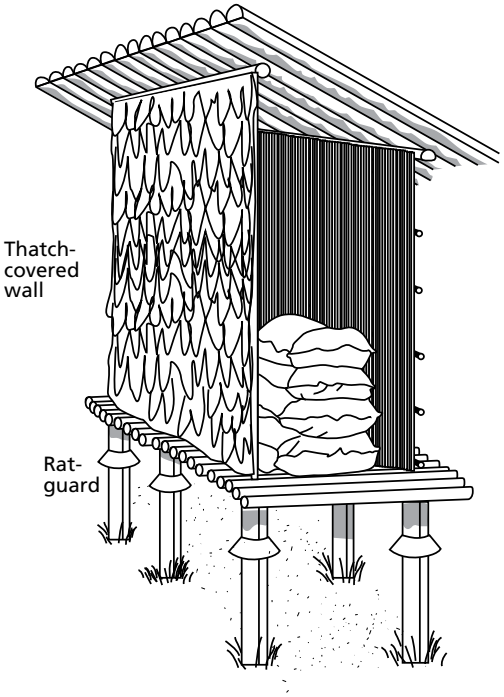


Figure 16.24 **Ventilated maize crib used for storing shelled maize in bags**

For larger quantities, a special building is recommended. Figure 16.25 shows a small block-built bag store (20 m²) with the capacity to store approximately 15 tonnes of cereals.

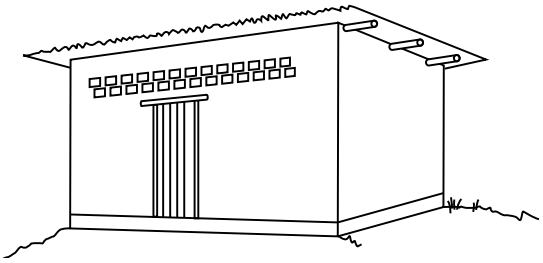


Figure 16.25 **Small block-built bag store**

Whatever the size of the bag store, the floor should be made of good quality concrete, the door should fit tightly to protect against rodents, and ventilation openings should be screened to keep out birds. The gaps between the wall and the roofing sheets must be closed using a material such as cement.

If fine mesh is used to prevent insects from entering through the ventilation openings, it must be maintained regularly; dust should be brushed away and holes repaired immediately. Figure 16.26 shows a multipurpose store with 90 m² (extendable) storage space suitable for cooperatives and villages.

Storage warehouses

A warehouse (see Figure 16.27) is built for the storage and physical protection of goods or bagged grain. It may also include materials and equipment required for the packaging and handling of bagged grain, and chemicals to control storage pests. Factors

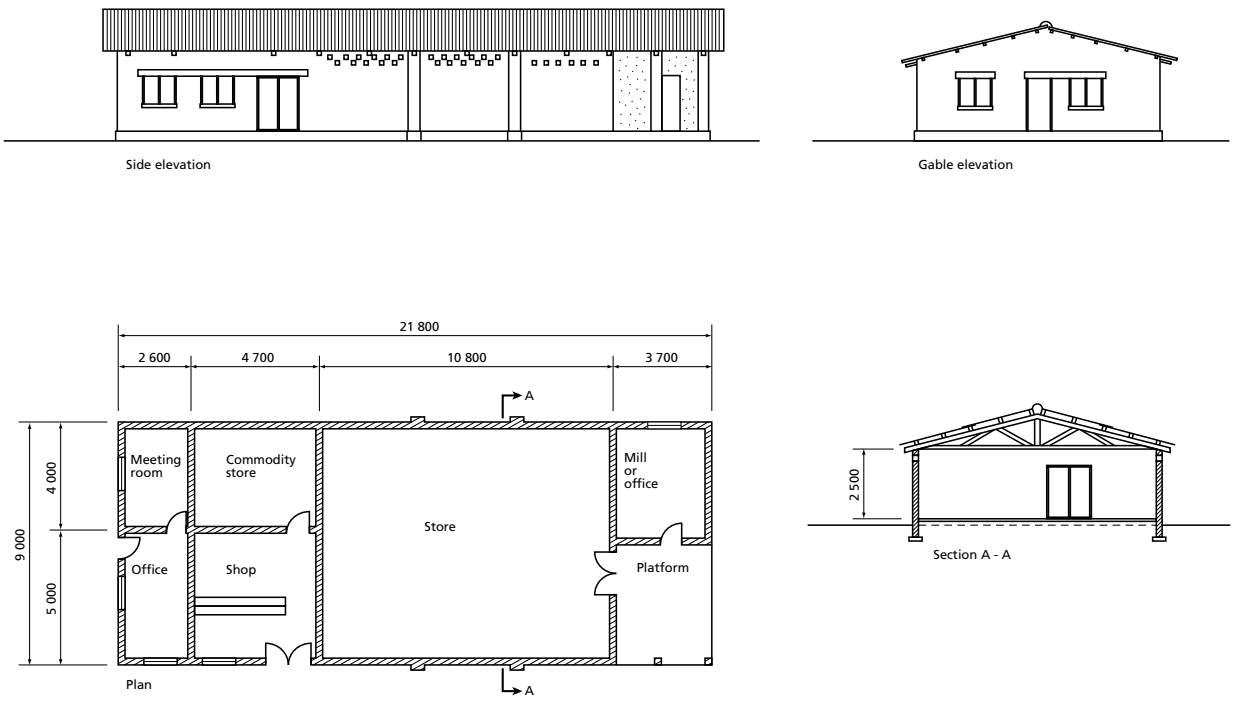


Figure 16.26 **Multipurpose store (196 m²)**

such as topography, soil characteristics, accessibility, orientation and proximity to human dwellings should be considered when locating the warehouse.

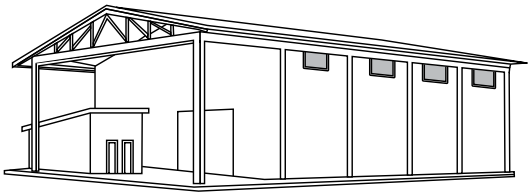


Figure 16.27 **A typical low-scale warehouse**

When determining the dimensions of the warehouse, the following information is important:

- the specific volume of the principal product to be stored (m^3/tonne)
- the maximum tonnage of the product to be stored
- the maximum stack height desired
- the extent to which separation of lots is desired.

Example

Determine the dimensions of a rectangular warehouse to store 1 000 tonnes of maize in bags in four separate lots. The length should be approximately twice the width. The specific volume of maize is 1.80 m^3/t. Each lot should measure 6 m × 15 m.

Solution

The total stock volume = 1 000 t × 1.8 m^3/t = 1 800 m^3

Assuming the bags of maize are to be stacked 5 metres high, the floor area required will be:

$$\frac{1\,800}{5} = 360\ m^2$$

If length (L) = 2 × width (W), then:

2 W^2 = 360 m^2, or W = 13.4 metres

To simplify, let W = 12 m; then, the area being 360 m^2 implies that L = 30 m.

As the stock is to be kept in four separate lots, each measuring 6 metres × 15 metres, the floor space required will be:

- a main handling area, 3 metres wide, along the axis of the warehouse;
- a gangway, 2 metres wide, across the centre of the warehouse;
- an inspection space, 1 metre wide, around the entire stacking area (this information should be known to the designer beforehand).

The internal dimensions of the warehouse will then be:

- Width (W) = 1 m + 6 m + 3 m + 6 m + 1 m = 17 metres
- Length (L) = 1 m + 15 m + 2 m + 15 m + 1 m = 34 metres

This gives a total floor area of 578 m^2.

Most warehouses in the tropics have a trussed roof, so the walls should be at least 1 metre higher than the intended stacking height: in this example 5 metres + 1 metre = 6 metres.

The percentage utilization of the building will then be:

$$\frac{1\,800\ m^3}{578\ m^2 \times 6\ m} \times 100\,\% = 52\,\%$$

Storage management

Storage management is important for all types of storage functions. For bag storage, the three main points are:

1. Prevent damp (moisture) from the floor and walls reaching the produce by stacking the bags on pallets off the ground and away from the walls.
   - Damp from the roof is avoided through proper ventilation and using damp absorbing materials.
2. Stack the bags properly to allow:
   - Optimal use of space.
   - Ease of sweeping the floors.
   - Ease of inspection of produce for rodents and insects.
   - Ease of counting the bags.
3. Control insects and rodents
   - Make sure the building is rodent-proof.
   - Treat the building and protect against pests.
   - Keep the warehouse clean.
   - Close all holes in doors, roof, etc. where pests can enter.
   - Repair cracks in walls where pests can hide.
   - Remove and destroy any infested residues that could contaminate newly introduced produce.

Bag stacks should be carefully constructed to maximize the use of space, to maintain hygienic conditions and to facilitate good management. If the bags are laid exactly one on top of the other in successive layers, the stack will be extremely unstable. To overcome this, ensure that there is an overlap in each successive layer (see Figure 16.29).

Insect control

Losses caused by insects:

(i) Weight loss: as insects develop they will feed on the produce. Losses vary with the commodity, for grain and legumes.

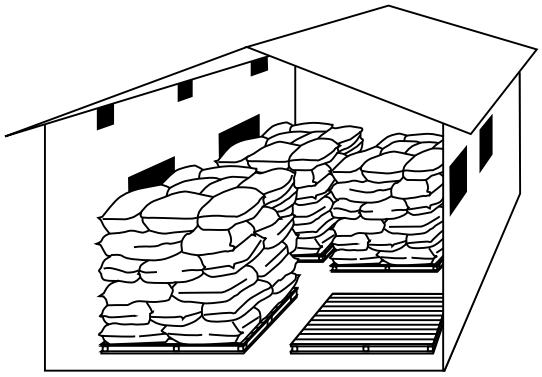


Figure 16.28 **Proper stacking for easy management. The bags are placed on dunnage**

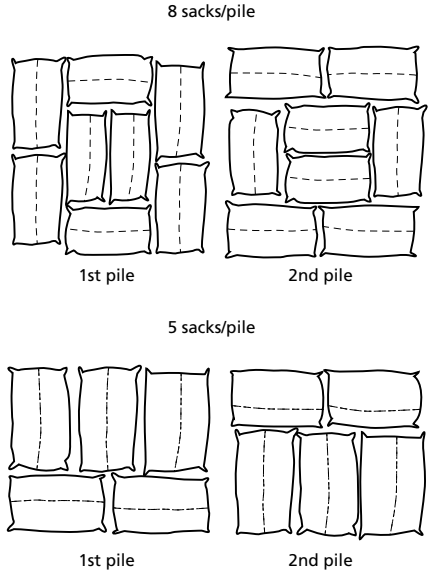


Figure 16.29 **Bags stacked in five- and eight-bag layers**

(ii) Losses in the range of 10–30 percent can be expected over the storage season.
(iii) Loss in quality and market value. Damaged grains will have reduced market value.
(iv) Promotion of mould development. 'Respiration' water from insects leads to mould formation in poorly ventilated stores.
(v) Reduced germination in seed material. Many insects prefer to eat the embryo because it is the most nutritious part of the grain.
(vi) Reduced nutritional value. Removal of the grain embryo reduces the overall protein content of the grain.

Sources of infestation

- Insects can survive from one season to the next in:
  – infested residues in the field
  – the structure of the store
  – natural habitats such as natural vegetation.
- Fresh produce can be infested by:
  – active migration to the crop in the field and store;
  – infested produce placed in the store.

Control measures

A wide variety of techniques are used to control insect pests in stored produce, from sunning and smoking at the traditional farm level, to irradiation in the largest bulk-handling facilities. This paragraph is concerned with various proven techniques, suitable for use in small- to medium-scale storage under tropical conditions. Specific recommendations are difficult to make; a technique must be tested for a particular situation depending on the value of the crop, the occurrence and resistance of the pest, the farming system used and the availability of insecticides. When selecting a technique, it is important to consider its effectiveness against the target pests, the hazards to the farmer and the consumer, and whether the result will pay for the cost of treatment.

Insect control techniques

- Sanitation: Do not mix new grain with old. Old, infested material should be removed or thoroughly fumigated. Clean the storage structures and machinery, and disinfect bags and baskets by sunning or chemical treatment. Large structures will require chemical treatment, while smoke may be adequate for small stores.
- Natural resistance: Crop varieties differ in their susceptibility to storage pests. Traditional varieties are usually more resistant to storage pests than new varieties. For instance, maize with good husk cover can reduce field infestation.
- Hermetic storage: In airtight conditions, reduced oxygen and increased carbon dioxide will arrest insect and mould development.
- Chemical control: The traditional method for preserving the crop in storage is to treat the grain with smoke and special plants or, when stored in closed containers, to mix the grain with ash or sand. While this method is widely used for small volumes, such as seed, for larger quantities the method becomes cumbersome.

In most cases, chemical control involves the use of an insecticide, which can be applied to the produce in the form of:

- dust
- spray
- fumigants

In addition to killing the insects, all insecticides are toxic to mammals to varying degrees. The toxicity is usually expressed as a 'LD_{50}'. Technically, this is the dose required (measured in milligrams of active ingredient per kilogram of body weight of the consumer, for

specific conditions, application method and time span) to kill 50 percent of the test population (usually rats).

Most insecticides do not kill all insects and mites. Choose a chemical that is either 'broad spectrum' or one that specifies toxicity to moths and beetles; mites may require special treatment.

With regard to persistence, insecticides will tend to lose their effectiveness when exposed to high humidity, high temperatures and sunlight.

It is important to apply the insecticide in the correct dosage. Excessive and/or inappropriate use of chemicals will lead to the insects becoming resistant and can be a hazard to human health.

Application

- Dusts are usually admixed with the grain in diluted form, at 10–15 parts per million active ingredient (ppm AI) at the time of loading/bagging. Suitable chemicals include organophosphorus insecticides, pirimephos-methyl (Actellic) and pyrethroids.
- Sprays may be added to bagged produce by spraying each layer of bags as the stack is built. This will give protection for several months but, in the case of reinfestation, the surface of the stack can be resprayed.

  For bulk storage, the sprayer may be mounted on a belt conveyer used for loading the bin. Liquid insecticides are also very suitable for both space and surface treatment. For application, a small domestic applicator (shelltox type) is sufficient for the small farmer, but a knapsack sprayer will reduce the labour required. The liquid form of the insecticides mentioned in point 1 may be used.
- Fumigation can be used for killing all pests where airtight conditions can be provided for at least 3 days when applying Phostoxin, or one day for Ethylene dibromide, after adding the chemical. The treatment can be used for closed containers, as well as for bagged produce, if they are covered by tarpaulin or plastic sheets. As fumigation is effective only at the time it is applied, subsequently the grain must be protected from reinfestation.

  Common chemicals include phosphine gas (e.g. Phostoxin is supplied in tablets of aluminium phosphide, which release phosphine on contact with moisture in the air); ethylene dibromide, metyl bromide, carbon tetrachloride (various combinations and formulations are available, such as Trogocide) – all volatile liquid fumigants. Capsules and sachets are available for small-scale applications and pressure cylinders for large-scale operations.

Commercial insecticides usually consist of a small quantity of the toxic compound – the active ingredient (AI) – with other substances called the filler. It is important to be able to convert from one basis to another. For example 'Actellic should be applied at 15 ppm AI' means that we should apply 15 grams of active ingredient to every million grams of produce, i.e. to one tonne.

Example

If we start with 5 percent dust, this means that 100 grams of crude product (CP) contains only 5 grams of AI. The dose of chemical to be applied will be:

$$q = \frac{15 \text{ ppm} \times 100}{5\%} = 300 \text{ gr/tonne of produce}$$

Rodent and bird control in stores

Apart from consuming large quantities of stored grain and food, rodents contaminate stored produce through droppings, urine and hairs, and may spread human diseases. Rodent control requires an integrated approach because no single method is completely effective. It should focus on creating an unfavourable environment and excluding rodents from stored grain. Methods used to minimize the damage caused by rodents include good housekeeping, proofing, repelling, trapping and poisoning. Keeping a cat around a grain store is another effective control method.

The requirement for good housekeeping is the same for rodents as for insect control; the store should be kept clean inside and out and be easy to inspect. In the following paragraph we focus on how construction can be improved to keep rodents out.

Birds are likely to be a nuisance in warehouses if no precautions are taken.

Construction details

- Local granaries, cribs and other small stores can be made rodent-proof if the floor is raised a minimum of 90 cm from the ground and the legs equipped with conical sheet-metal rat guards (see Figure 16.5).
- All openings between the floor and the walls should be closed. This is especially important in warehouses with walls of corrugated iron sheets. The floor should be made from strong concrete to prevent rodent penetration.
- The door should fit closely to the frame and be covered with sheet metal for added protection. Boards dropped vertically into slots on either side of the door, approximately 50 cm high, will form a barrier while the door has to be kept open.
- Ventilators and windows should be covered with wire mesh ,with openings not exceeding 12 mm. This will also form a barrier against birds.
- To keep birds out, other openings, such as the gaps between the walls and the roof, should be closed or covered with wire mesh with 12 mm openings, and the door should be kept shut as much as possible.

- Ideally, the proofing of large central storage depots should be considered during the planning stage; this allows it to be incorporated at very low cost into the construction of each building.
- In many cases, existing stores can be protected by a rodent-proof fence at least 90 mm high. This should be constructed of small-gauge wire netting, topped by a horizontal metal sheet, which should completely encircle the store. The bottom of the fence should be buried to a depth of at least 30 cm.

Using the protective measures described above, it is possible to reduce, and even eliminate, the rodent problem if the measures are properly maintained.

Storage management, hygiene and safety

Condensation and moisture movement

If bins, especially silos, are exposed to direct sunlight, or if the grain inside the silo is warmer than the external air, convection currents can form. This leads to the moist air being carried through the grain and, where it meets a cooler surface, such as the silo wall, the moisture will condense and dampen the grain in the immediate vicinity. Clearly this can be a major problem with grain stored in steel silos in hot climates, particularly in areas where the sky is clear during both day and night. A clear sky results in high daytime temperatures and cool nights.

For small silos, the problem can be reduced by covering the silo with a roof, or hat, to prevent the sun from heating the surface. For larger silos, other solutions have to be found, either by ventilating the grain in the store or by moving the grain from one silo/cell to another. This will mix the grain enough to even out the moisture content. If the moisture content is too high, the grain will need to be run through a dryer.

Hygiene

Insect and rodent control was discussed earlier in the section on bag storage. However, for all types and sizes of grain store, cleaning will have to be carried out when the store is empty. If the insect population is building up, the entire store may have to be fumigated or sprayed.

Safety

Dust is stirred up when grain is handled. Inhalation can cause respiratory problems, especially exposure to slightly mouldy grain. Breathing filters should be used. As grain dust is explosive, it is important to enforce a no-smoking rule and ensure that all light bulbs and

TABLE 16.6
Grain-handling equipment

Type of equipment	Fixed (F) or portable (P)	Horizontal (H) or vertical (V)	Capacity range	Power requirement	Cost	Advantages	Disadvantages
Belt and bucket elevator	F	V	Medium to high	Low	Medium to high	1. Efficient 2. Minimum maintenance 3. High capacity 4. Cleanable	1. Can be difficult to erect 2. Expensive
Auger (screw conveyor)	F P	H + V	Medium	Medium	Medium	1. Wide range available	1. Can damage some material 2. Medium to heavy wear
Belts	F	H (if belt is ribbed maximum 30° angle)	High	Low	High	1. Long distances 2. Low power 3. Self-cleaning	1. Expensive 2. Angle very limited
General-purpose elevator with belt or chain with slats	F P	H and inclined with ribs	Medium	Low to medium	Medium	1. Multipurpose 2. Inexpensive	1. Noisy with chain
Tractor shovels	P	H	Medium to high	On tractor – high	Low	1. Flexible 2. High output in short time – for loading lorries	1. Requires space in which to operate
Sweep augers	F P	H	Medium	Medium	Medium	1. Unloading round bins	-
Sack barrows	P	H	Depends on distance	-	-		1. High labour requirement
Pneumatic	P	H + V	Low to medium	High	High	1. Flexible	1. Noisy 2. Much dust 3. Reduced capacity for wet grain

electrical equipment are shielded. Good ventilation is recommended.

Falls: All catwalks where a person could fall more than 150 cm should have guard rails 100 cm high, with 15 cm toeboards.

Crusts can form in damp grain beneath which the grain has run out. Walking on bridged grain can cause failure of the crust, resulting in burial and suffocation.

Machinery: All moving parts should have guards fitted and all wiring should be maintained regularly.

Grain flowing out of a container tends to form a funnel at the centre. This highly unstable surface can suck a person in within seconds.

GRAIN-HANDLING EQUIPMENT

There is a wide variety of grain-handling equipment available on the market, and Table 16.6 attempts to categorize their ability to move grain.

Belt-and-bucket elevators

A flat belt is carried between a crowned pulley at the top and bottom of the casing. Small buckets or scoops are fixed to the belts at regular intervals and these carry the grain from the elevator bottom to the top. The capacity depends upon the width of the buckets, the spacing and the belt speed. Elevators up to 20 metres in height and with a capacity of 50 tonnes per hour are available.

Auger (screw conveyors)

Auger elevators are reasonable in cost, comparatively light in weight, and dependable in their operation. They are available in a wide range of lengths and capacities and are usually powered by an electric motor. Long augers may be mounted on wheels for easy transport. The angle of operation is adjustable but the capacity declines as the auger is raised (see Table 16.7). High moisture content also reduces the capacity.

TABLE 16.7
Example of auger capacity and power requirements per 3-metre length of auger (diameter 150 mm)

Moisture content (percent)	Angle of elevation									
	0°		22.5°		45°		67.5°		90°	
	t/hr	kW	t/hr	kW	t/hr	kW	t/hr	kW	t/hr	kW
14	27	0.42	25	0.61	21	0.64	17	0.62	13	0.52
25	17	1.32	15	1.40	13	1.33	10	1.08	7	0.52

Note: Auger speed 400 rpm; power requirement is directly proportional to the auger length.

Flat-belt conveyors

In practice flat-belt conveyors are used horizontally, although up to 15° inclination is possible. With ribs, the angle can be increased to 30°. The capacity is high, and grain can be loaded or unloaded anywhere along the belt. It does not cause any damage to the crop and raises little dust.

Chain-and-slat conveyors

These consist of a chain carrying traverse slats that drag the grain along a metal or wooden trough. Slat widths up to 300 mm, spaced 150–300 mm apart, and chain speeds of 10–77 cm/s are used to give an output of up to 30 tonnes per hour. Small models have no support frame and can be carried by two people.

Sack elevators

This may be a continuous belt with ribs or a chain conveyor with slats.

Dumping pits

An effective system for receiving grain must be used if high capacity is to be achieved when using tractors and trailers to take grain to the store. Ideally, it should be possible to dump a trailer load and pull away within minutes. Such a reception facility will normally be associated with an elevator to raise grain for conditioning or storage.

Reception pit with an elevator

A pit lined with concrete, wood or steel with an inverted pyramid or V-shaped bottom is built in the ground (see Figure 16.30).

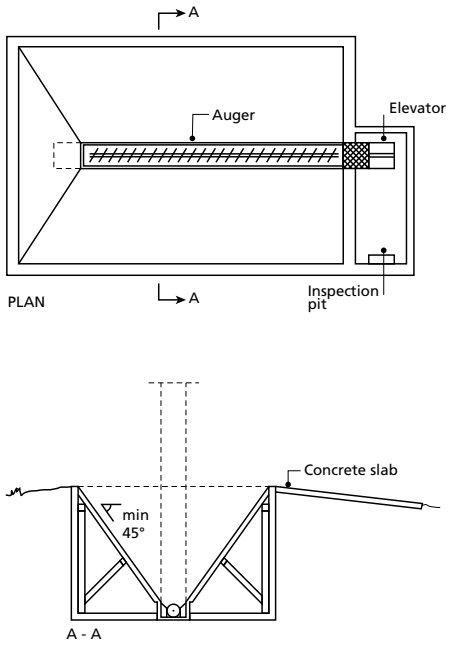


Figure 16.30 **Dump pit with an auger moving the grain to the elevator**

The crop is dumped from a trailer into the reception pit, from where it flows by gravity, or with the help of an auger, into a second pit containing the bottom end of an elevator. Having a 'run-over' pit saves much time as it avoids the need for farm transport to reverse to the tipping pit. A run-over pit requires a safety grid, which must be strong enough to carry a loaded trailer.

Shallow-surface pits

These pits are usually used in conjunction with an auger. Two simple shallow-surface pits are shown in Figure 16.31.

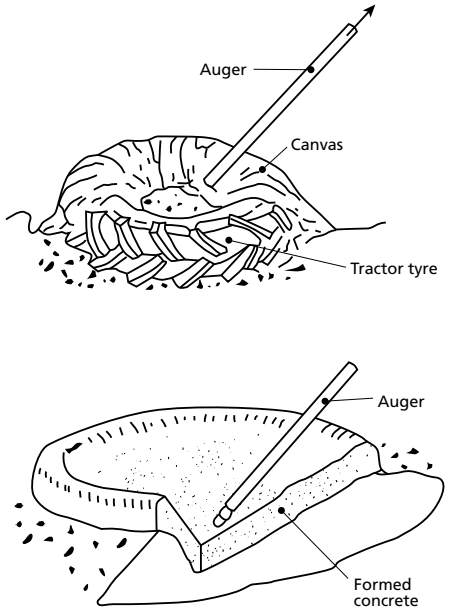


Figure 16.31 **Small simple reception pits**

Overhead grain-loading bins

Hopper-base gravity-discharge bins, when erected at a suitable height, facilitate high-speed loading of transport vehicles. This will cut the waiting time and should therefore be considered where the capacity of the loading equipment is low compared with the load capacity of the vehicle.

REVIEW QUESTIONS

1. Discuss the factors to consider for safe storage of grain.
2. Three tonnes of maize is dried and its final mass is measured and recorded as 2 600 kg. Calculate the moisture content of the maize on both a wet and a dry basis.
3. If Bambara groundnuts weighing 650 kg at 28 percent moisture content are dried to 12 percent moisture content, what is the weight of the dried Bambara groundnuts?
4. Discuss the principles of cooling the grain while in storage.
5. Discuss the major differences between traditional storage and modern storage mechanisms.
6. Discuss the key issues that must be addressed in the management of stored grain.

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Chapter 17
Rural roads

INTRODUCTION

Rural roads play a critical role in agricultural and rural development in general. While most roads pass through rural areas, the roads considered in this section are those that link farms, villages and rural markets; trunk roads and district roads are beyond the scope of this book. Inadequate rural road infrastructure, in particular what is often called *the last mile* (i.e. the section of the road nearest to the farmstead), is regarded as one of the greatest constraints on improving agricultural productivity, especially in tropical regions. These rural roads provide critical links between the farms and rural households and the input and output markets, thereby increasing the profitability of any investments in rural areas.

In many countries, rural roads fall under the jurisdiction of the local authorities. In this regard, farmers or their associations, the village, ward and subdistrict authorities have inordinate power over decisions on where to construct such rural roads, the levels of capital investment and maintenance resources. The cost of construction can be quite high and adverse weather conditions (e.g. floods) result in high maintenance costs. Building local capacity to construct and maintain such roads therefore contributes significantly to lowering costs.

Rural access roads range from the simplest earth roads to bituminous surfaced roads. In most cases, earth roads are the only ones that can be justified for access to rural homes and farmsteads. These roads, designated in many countries as unimproved earth roads, are generally suitable only for light traffic: up to a few dozen vehicles per day. In the wet season, especially in high rainfall areas, they often become impassable. Although, in most cases, there is no need for structural design for such unimproved roads, there are some principles which, if followed, will result in a reasonably good road that justifies the modest investment. The aim of this chapter is to explain some of these principles.

Road location

While some roads are constructed entirely from scratch, more often than not a sequence of communication routes evolves as the area develops. This may start with a footpath, which later turns into a track and, through gradual improvement, becomes an earth road that is passable for most of the year. It is therefore advantageous to choose a road line at an early stage in the planning process that will allow for gradual improvement of the road without having to make long and costly diversions.

A survey to determine the best location for a road line starts by identifying areas through which the road must pass (for example, a gap between hills), the best location for a river crossing, and the points to be linked by the road. Places to be avoided include soft ground, steep slopes and areas with big rocks. For large-scale road projects, the terrain is viewed from aerial photographs, but for smaller projects this is too costly and an overview of the proposed road line must be obtained from adjacent hills. Although such an overview provides valuable information on natural drainage, it should always be supplemented by a detailed examination on foot.

Once the points through which the road must pass have been established, the road line is laid out to run as directly as possible between these points. Wherever possible, roads should be located on sandy soils in well-drained locations, avoiding wet and low-lying areas prone to flooding. To take full advantage of natural drainage, it makes sense to locate the road along the backbone of a watershed if it runs roughly parallel to the road line. This will ensure the best possible drainage away from the road, and expensive bridge, culvert or drift construction can be avoided. However, an attempt to avoid all the difficult spots may result in a longer road, and the additional cost of construction and maintenance should always be weighed against the cost of a road built in a more direct line.

Gradients

A steep gradient not only slows down traffic and increases the load on vehicles, it also complicates road construction and increases the cost because care must be taken to avoid erosion from storm water flowing on and alongside the road. A gradient can be expressed in three ways:

- units of rise relative to units of horizontal distance (e.g. 1:40);
- percentage (e.g. 2.5 percent);
- angle to the horizontal (e.g. 1° 26‘).

Although the *recommended gradient* standards for unimproved roads differ between countries, generally, for roads used mainly by motor vehicles, the gradient should not exceed 1 in 17 in flat or rolling terrain, 1 in 13 in hilly terrain, or 1 in 11 in mountainous

terrain. In exceptional cases, it may be necessary to have steeper gradients, but their maximum length should be limited. In hilly terrain, 1 in 11 may be permissible over a maximum of 500 metres and, in mountainous terrain, 1 in 9 over a maximum of 150 metres.

Roads used frequently by draught animals should have a gradient not exceeding 1 in 20 or, in exceptional cases, a maximum of 1 in 10 over short distances. Pack animals can manage steeper gradients: 1 in 10 with a maximum of 1 in 8. The ability of trucks to climb steep gradients in wet conditions will improve if the surface is gravelled, although that is expensive.

Curves

While a straight road is the shortest distance between two points, as noted earlier, this may not be the most economical line for a durable, easily constructed road that is passable throughout the year. Long, gentle curves are preferred because they provide better visibility and require less speed reduction than sharp corners. The minimum radius for a horizontal curve is 15 metres, but 30 metres or more is preferable. Banked curves are seldom a consideration when building earth roads because traffic speeds are generally low. Sharp ridges, which may reduce visibility or require cutting, can almost always be avoided.

Slopes

Only occasionally will an unimproved road require embankments or cuttings but, where they cannot be avoided, the side slopes should not exceed 1 in 1 on well-drained soil. In wet soil, it should not exceed 1 in 3, i.e. one unit rise for every three units of horizontal distance. These are maximum values and should only be used where the depth of the cut or fill is so large that to reduce the slope would be too expensive.

Camber

The camber is the slope of the road surface to the sides, designed to shed water into the side drains. A simple earth track has no camber and no side drains. All other roads should have a camber of 5–7 percent from the middle of the road, shedding water into drains on both sides. In deep cuts (where the road is dug into a hillside) or on sharp curves, the camber is designed to drain water from the entire surface inwards towards the cut or to the inside of the curve.

Cross-section of a simple earth track

The simplest earth track is obtained by merely clearing vegetation and stones from the natural soil surface. It may run between fields within a farm, from the main road to a farmstead or between small villages where the traffic volume is very low. Earth tracks are based on single-lane traffic in one pair of wheel tracks, but vegetation should be cleared far enough to each side to allow two small cars to pass.

The road surface should be level with the surrounding terrain to enable water to flow across it in any direction. If the tracks deepen, they should be filled to allow any water running down a slope to pass across the road at any point, preventing water from accumulating in the tracks and causing erosion or reducing the bearing capacity.

Where the road runs with the gradient, low, gentle humps across the track will direct water flowing along the road into the surrounding terrain. In wet spots or in areas with high rainfall, it may be impossible to maintain the simple earth track in a passable condition. The cheapest way to increase the carrying capacity in such areas is to raise the level of the road and camber it, as described in the next section.

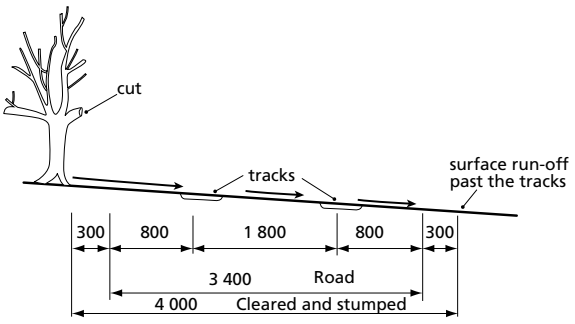


Figure 17.1 **Cross-section of a simple earth track**

Cross-section of an upgraded earth road

Upgraded earth roads may be used to connect rural market centres and villages where the traffic volume is 10–20 vehicles per day, including several heavy trucks during the dry season. In most cases, the only affordable surface material is the soil found on the line of the road or in its immediate surroundings.

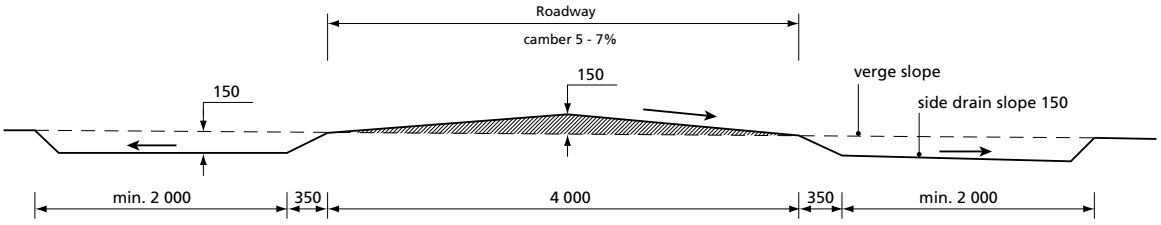


Figure 17.2 **Cross-section of an upgraded earth road**

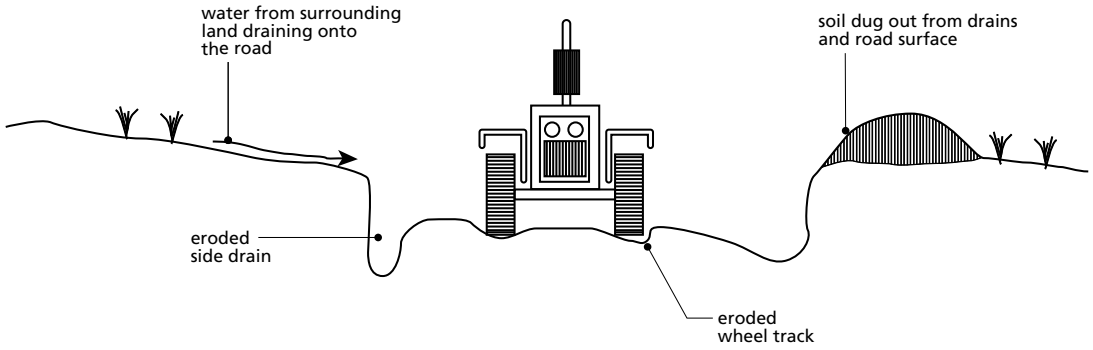


Figure 17.3 **Road erosion resulting from incorrect construction and maintenance**

The bearing capacity of the road depends on the type of soil and the prevailing climatic conditions. The road is constructed by digging out soil from the sides and throwing it onto the road until the cross-section illustrated in Figure 17.2 is obtained. The 30 cm difference in level between the road surface and the bottom of the side drains, combined with the camber of the road surface, will ensure a much drier roadway with a higher carrying capacity than a simple earth track.

Wet spots soon turn into mud if there is frequent traffic, making the road impassable if wet weather continues. Although gravelling reduces the risk of mud forming, a 50–70 mm layer of gravel may more than double the cost of the road. It is usually far cheaper to make the level of the roadway higher. Up to a point, depending on the type of soil, the higher it is raised, the drier the road will be. This means that gravelling will be necessary only if mud still tends to form in wet spots, and then only in those spots.

EROSION OF EARTH ROADS

Soil is eroded from a road by traffic, wind and water. Depending on the soil conditions, the climate and the volume of traffic, soil erosion may cause considerable deterioration of the road and increase the cost of maintenance. While erosion from wind and traffic is normally of minor importance, erosion caused by water run-off from heavy rains can cause such deterioration in just a few years that it is no longer worth repairing the road, unless the erosion is controlled by proper drainage and maintenance.

Properly installed drainage and road maintenance go hand in hand to ensure the durability and carrying capacity of an earth road. If deep tracks are allowed to form, water will accumulate in them and, as most roads have at least a slight gradient, the water begins to flow. As the volume of water increases, either through rainfall intensity or inadequate side drains, its speed and erosive action will increase. Side drains, if not properly installed, will also erode.

Clearly the drainage of earth roads is of primary importance. It is essential to remove rainwater that falls onto the road itself and to prevent rain that falls onto adjacent land from washing over the road. As far as possible, natural drainage should be used to achieve these goals, but an engineered drainage system may be required for adequate protection of the road.

Rainwater that falls onto the road is shed from the curved surface (camber) into shallow side drains and diverted away through mitre drains into the bush. Where necessary, catchwater drains should be constructed to collect water flowing towards the upper side of the road, directing it across the road and back into its natural channel in a controlled way.

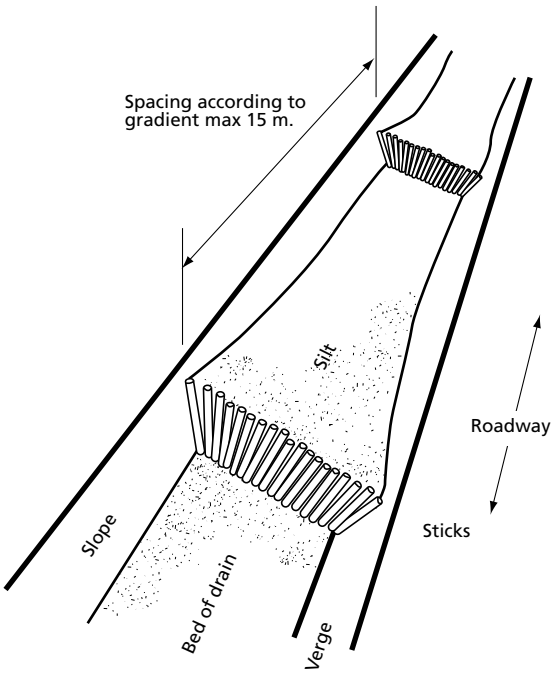


Figure 17.4 **Scour checks will slow down the water flow in side drains with a steep gradient**

Side drains

When side drains are dug, care should be taken to make them shallow but wide. Water in thin layers flows slowly without causing much erosion and the grass that

will gradually grow in the drain will further slow the flow. Gradients no steeper than 1 in 250 are unlikely to cause erosion in ordinary soils. Where steeper gradients are necessary, the drains should empty onto surrounding land at frequent intervals. Where a side drain has a very steep gradient, additional measures in the form of checks or gabions may be necessary. These checks will silt and form steps, thereby decreasing the gradient and slowing the flow.

Mitre drains

Mitre drains are used along high-level roads to prevent water build-up in the side drains. Depending on the gradient, mitre drains should be spaced 20–250 metres apart, with closer intervals where the rainfall is heavy, the soil is prone to erosion or the gradient is steep. The mitre drain should block off the water flow in the side drain with a bolster block at an angle of approximately 30 degrees and lead the water well away from the road through a wide, shallow channel with a gradient of 1 in 125. The water is discharged 30–40 metres away from the road over as large an area of land as possible to minimize erosion. Figure 17.5 shows the use of mitre drains.

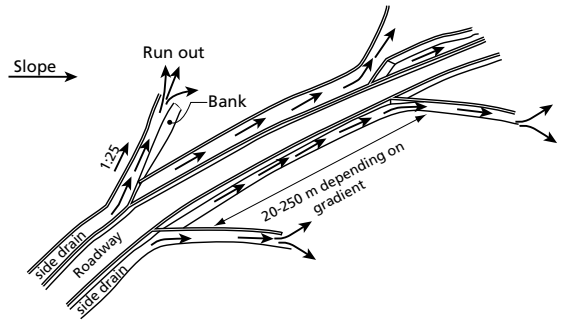


Figure 17.5 **Mitre drains**

Diversion banks

Simple earth roads that do not have side drains should have diversion banks at 30–250 metre intervals to divert water flowing along the tracks. Natural bumps in the road can sometimes be used as diversion banks if they can be improved to a suitable shape. These banks along the road, measuring 30 cm high and approximately 12 metres in length, should have a smooth contour allowing vehicles to pass easily at moderate speeds. The bank is connected to a mitre drain that feeds the water onto the adjacent land.

Catchwater drains

Where a road is constructed along the lower part of a slope or cut into a hillside, a catchwater drain will divert the excess water flow down the hill and across the road line. Wherever possible, the catchwater drain should be constructed on the upper side of the road, at least 3 metres from the edge, and be separate from the side drain. This construction prevents the side drain from being overloaded with water from the slope.

The water in the catchwater drain must be lead off across the road line back to its natural channel in a controlled manner. Wherever possible, a natural waterway crossing the road should be used. If a controlled lead-off cannot be arranged easily, then it is better not to use a catchwater drain because the collected water flowing uncontrolled across the road will cause serious erosion and form gullies.

ROAD CONSTRUCTION

When the land has been surveyed and the most feasible road line has been identified, the centre line of the road is set out with pegs inserted at 15–20 metre intervals and tall enough to be clearly visible. Additional pegs may be installed to mark the width of the roadway, side drains and the area to be cleared.

Stumping and clearing

To construct a simple earth road, trees and rocks must be cleared from the road line and moved well back from the road so that sun and wind can dry the road surface. In heavily wooded country, trees should be cleared from the roadway to a distance equal to the height of the tree cover, or even 1.5 times that height on roads with north–south orientation. Wider clearing ensures visibility through bends and road safety in areas densely populated with wild animals.

Tree stumps can be removed by digging them out, burning them or dragging them away with draught animals or a tractor. Rocks are either dug out and removed, buried, or broken down to ground level with a sledgehammer or by the hot–cold (fire–water) treatment. All holes are then filled and compacted and any bumps levelled. Stumps and rocks should be cleared well away from the roadway because the verges are likely to be used when vehicles meet.

Any stones lying beside the roadway that cannot be removed should be clearly and permanently marked with paint or a tall white peg. The final step in constructing a simple earth track is the building of diversion banks at suitable intervals. If the objective is to construct a high-level earth road, the work will continue with the construction of side drains.

Construction of side drains

Using wooden pegs and string as a guideline, the edge of the road should be established 1.8–2.0 metres from the centre line. On roads with no crossfall, side drains are dug out on either side to a depth of 150 mm and half the width of the roadway. All excavated soil is thrown onto the road and spread to form an even road surface with the correct camber.

It can be advantageous to excavate the side drains in several stages, allowing some traffic to pass on the road between each step, as some unevenness of the surface

can be corrected during later stages when the high and low spots become visible.

The side drains are then shaped with a gentle slope of 1 in 150 away from the road. The verge and back edge of the drain are shaped with a slope of approximately 1 in 3, avoiding the need to install meeting bays as vehicles can use the verge when they cross.

On sections of the road with a steep crossfall, the side drain on the upper side of the road is started at a depth of around 150 mm and then dug slightly sloping away from the road into the hill. Where the crossfall is steeper than 1 in 30, no drain is required on the lower side of the road and, in this case, the road level and camber is formed with material taken only from the upper side drain.

Mitre drains should be installed without delay, especially when working in wet areas. Boning rods may be used in uneven terrain to give the mitre drains an even gradient of 1 in 125. Catchwater drains may be installed later, on slopes where it proves necessary, to drain off surface water and divert it away from the road. Much of this water often flows down footpaths and cattle tracks and, if small diversion banks are installed on these to divert the water into the bush well away from the road, the catchwater drain may become unnecessary.

Road maintenance

The most important maintenance job on any type of earth road is to ensure that all drains work properly and that additional drains are installed wherever necessary. Secondly, rutted wheel-tracks should be filled with soil from outside the road bed. If the road surface deteriorates significantly, it will be necessary to resurface the road by adding more soil from the side drains. Earth should never be removed from the road surface because this will lower the road level and make efficient drainage difficult, or even impossible.

Soil should be taken from the side drains to make them wider rather than deeper. On crossfalls, soil should be taken only from the upper side drain. During the first years after construction it may be necessary to control shoots from tree roots. When vehicles start using the road, bumps (other than diversion banks) and holes will soon become apparent. These holes and any other unevenness should be repaired promptly by filling.

MINOR RIVER CROSSINGS

Where the road crosses a natural waterway, a splash, drift, culvert or bridge should be built. Even if the waterway only carries water occasionally during the rainy season, some kind of structure is necessary to keep the water that flows across the road from scouring and forming a gully. It is cheaper to build a splash or drift than a culvert.

Bridge construction requires complex design calculations and is generally the most expensive alternative. The problem can often be simplified by choosing a road line closer to the watershed line, or at an alternative crossing point where conditions permit a splash or drift to be constructed rather than a more expensive structure.

Splashes and drifts

Splashes and drifts are the same type of construction but they differ in size. Splashes are associated with small local run-offs, whereas drifts are built where a road crosses a stream or river bed. Splashes are frequently used where water collected by a catchwater drain is

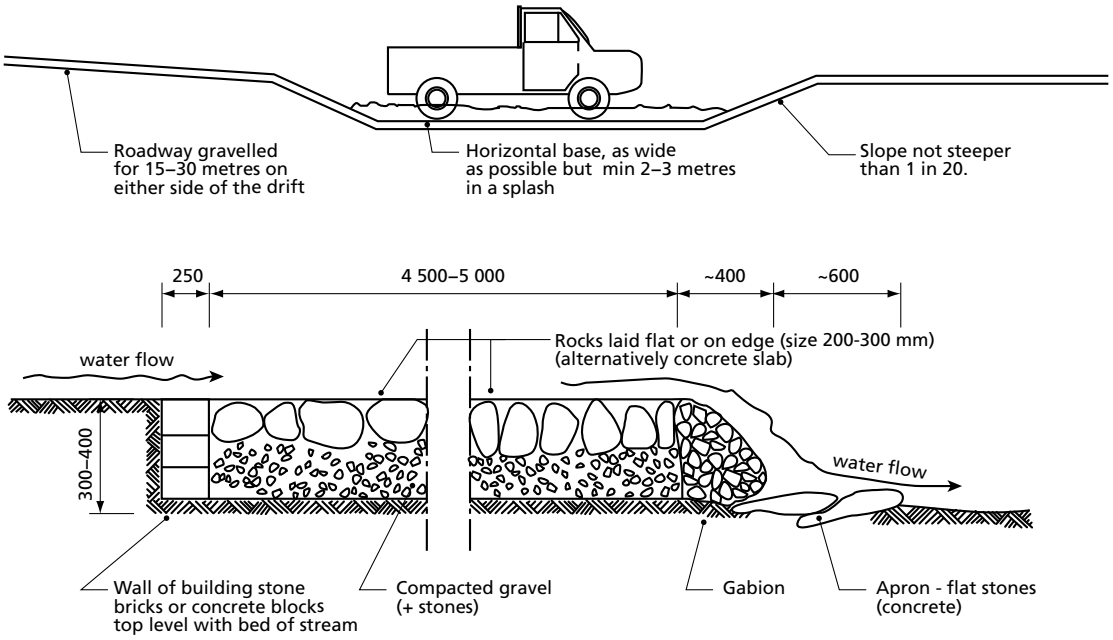


Figure 17.6 **Sections of a splash or drift**

directed across the road. The information given for drifts in the following paragraphs also applies to splashes.

A drift is best suited to a crossing where the river banks are relatively low and gently sloping and the stream is shallow. Concrete is the best material for surfacing the crossing, but in many cases it is too expensive. Stone and gravel are used to surface most drifts, but if the water flow is rapid, the surface may soon be eroded. In some cases grass can be planted for stabilization or the flow can be slowed by widening the water course.

A drift should allow motor vehicles to pass at a reasonable speed during the dry season when there is little or no water. It should also be designed to allow traffic to pass during flood conditions, perhaps with the exception of a few hours or a day when the water flow reaches its highest level. However, such flows should not cause any major damage to the drift. For safety reasons a drift should be designed as nearly perpendicular to the flow of water as possible and the road approaching and crossing the drift should be straight for 20–30 metres on either side.

To maintain a uniform depth throughout its length, a drift must be constructed with a level roadway across the stream. While the dimensions of a drift are largely determined by the stream width and flow, a long level section will spread the flow and reduce the water depth and velocity to a minimum. For small splashes needing only a short level area, a minimum of 2–3 metres should still be allowed to avoid interfering with traffic flow during periods of no water.

The gradient of the road leading down to the drift should not be steeper than 1 in 20 and should preferably be gravelled for 15–20 metres on either side of the stream to avoid mud forming from the water that is carried up the slopes by passing vehicles. Where the road has to be cut into the river banks to decrease the gradient, run-off water on the road surface and in the side drains should be led away by diversion banks and mitre drains immediately before the road goes into the cut.

The edges of the drift must be stabilized with concrete blocks, big stones or gabions (stones wrapped in wire netting). The top edge on the upstream side of the drift should be laid level with the bed of the stream to prevent turbulence in the water flow and subsequent scouring and washing away of the road material. For the same reason, the downstream edge should be level with the road surface, and if a free-fall is created, the river bed may need to be strengthened with an apron of flat stones to prevent undermining.

Finally, the edges of the roadway should be clearly marked with stones or stakes that have been painted white. Depth markers are also desirable. They should be painted white up to the maximum safe depth and red above that to serve as a warning.

Embanked drifts

Motor vehicles and other road traffic can tolerate shallow water better than deep water, even if the flow is faster. In some cases the depth of water can be decreased by raising the roadway on an embankment. In streams with a low gradient (flat country) the water

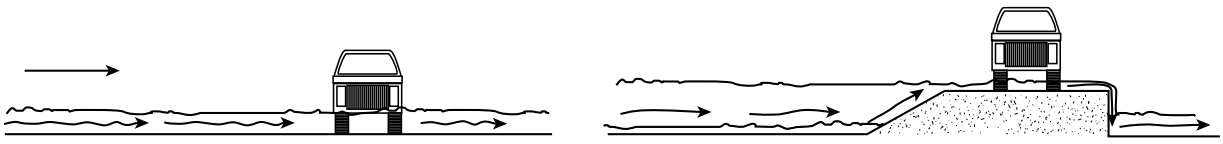


Figure 17.7a **An embankment drift in a stream with deep water flow because of a slight gradient will create a shallow rapid flow across the top of the drift**

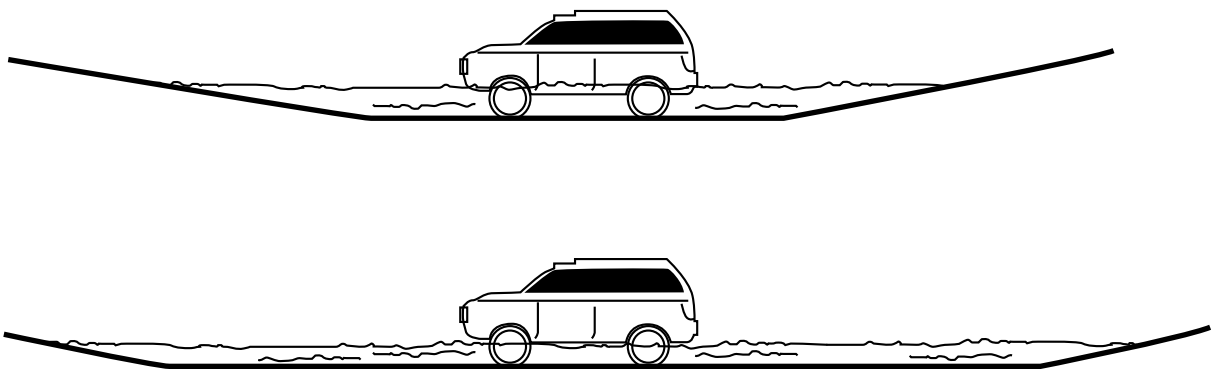


Figure 17.7b **An embankment drift in a narrow, deep watercourse can spread the flow to make it shallower**

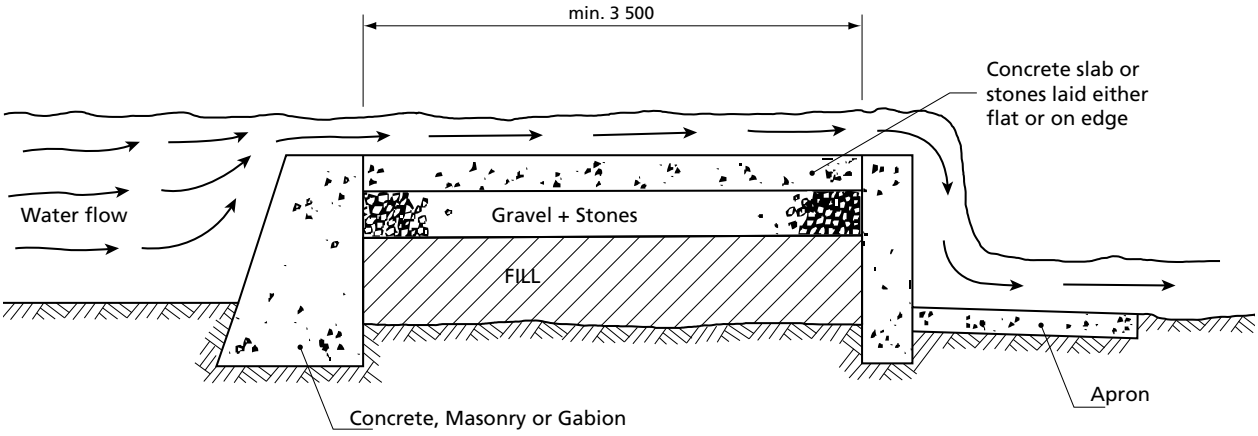


Figure 17.7c **Cross-section of an embanked drift**

tends to bulk up in a deep, slow flow. An embankment drift with a free fall on the downstream side will cause a rapid but shallow flow over the embankment.

The increased water speed may, however, require the road surface to be concreted to avoid scouring. The edge of an embanked drift facing upstream will normally have to be constructed in concrete or masonry work and be designed as a dam. The structure should preferably be carried down to a solid base on the bottom of the river bed to avoid undermining.

Culverts

Culverts are best suited to streams with steep banks because their construction requires some difference in height between the level of the road surface and the bed of the stream. Culvert construction consists of the following:

1. The actual culvert (one or more pipes) that carries the water under the road.
2. The embankment, which carries the road across the water course.
3. Wing walls, which protect the embankment from flood water and direct the flow into the culvert.
4. The apron at the discharge end, which prevents erosion of the stream bed.

Culverts may also be combined with embanked drifts. The normal water flow is carried by the culvert, but large flows of storm water are allowed to flow over the top of the embankment.

Concrete pipes measuring 400–900 mm in diameter are often used for culverts. The diameter and number of pipes is determined by the expected water flow. Alternatively, corrugated steel pipes or masonry work in burnt bricks, concrete blocks or stone may be used to form the culvert. Temporary structures may be constructed with logs, which are notched and fitted together. The bottom of the culvert should be laid on, or slightly above, the bed of the stream to avoid silting. Regular maintenance to clear the culvert of any silt or debris is essential.

Where concrete pipes have been used for a culvert, the embankment must provide for soil cover above the pipe to a depth at least equal to the diameter of the pipe in order to protect the pipe sufficiently from heavy vehicle loads. The beams in the ceiling of a square-shaped culvert with masonry walls may be designed to carry vehicle loads, thereby reducing the need for soil cover to spread the load in the embankment.

Many culvert installations have failed because the embankment has not been sufficiently protected by wing walls and have been washed away. In some cases, the embankment can be built adequately with materials found at the site but, in most cases, the extra protection of concrete work or a masonry wall is required.

Water will tend to bulk up in front of the culvert and the height of the walls must allow for this. Wing walls, built at an angle, guide the water flow into the culvert and reduce the bulking tendency. As any culvert construction is likely to be overtopped by an extreme storm flow or when the pipe is blocked, provision should always be made for a controlled overflow through emergency spillways.

Simple bridges

The ideal site for a bridge is where the river is narrow and the banks are solid. The bridge should be designed to interfere as little as possible with the natural flow of water. The highest level that the river is known to have reached is determined and the bridge is designed to give at least half a metre of clearance above that level. A bridge includes the following.

Abutments are the structures provided to strengthen the stream banks and to support adequately the shore end of the road-bearing beams. They can be constructed of concrete, masonry (stone, brick, concrete blocks) or timber. The lower part of the abutments will normally require wing walls to protect them from the action of the stream.

Intermediate supports are installed where the stream is too wide to be bridged in a single span. Timber

trestles, masonry piers and reinforced concrete columns are the most common types of support. Intermediate supports must be designed to withstand the combined loads of the weight of the bridge and vehicles moving on it, plus the action of the flowing water and any debris floating in the water.

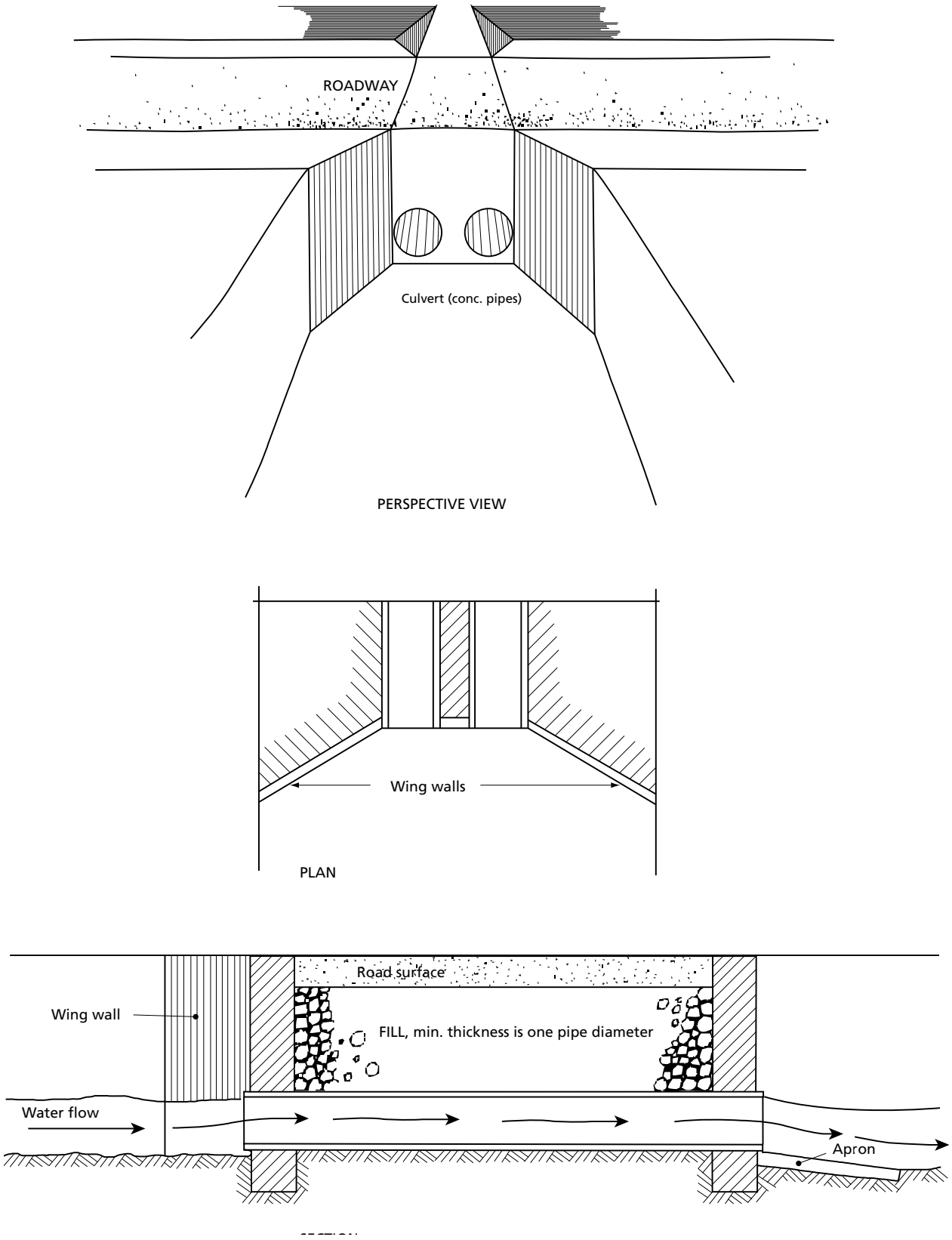


Figure 17.8 **A culvert**

Road-bearing beams carry the weight of the roadway and traffic between abutments and any intermediate supports. Simple bridges have road-bearing beams consisting of round or sawn timber or universal steel beams spaced approximately 600 mm centre-to-centre across the roadway. For example, a bridge 3 metres wide requires six beams; a bridge 3.6 metres wide requires seven beams, and so on. The beams are usually designed as simple beams supported at each end.

Decking or flooring makes up the road surface on the bridge. Where poles or other rough materials have been used for decking, a smoother surface can be obtained by placing planks along the bridge for the wheel tracks. The decking should be strong enough to spread the load from one wheel over at least two road-bearing beams. Wooden decking should never be covered with soil because that would increase decay and conceal any weakness in the bridge.

Curbs made from poles or pieces of timber should be secured to the edges of the decking. Curbs reduce the risk of vehicles slipping over the edge and, if they are positioned over the outer road-bearing beams and are well secured to them, curbs also contribute to the strength of the bridge.

Rails should be installed along the edges of the bridge for safety.

The bridge must be designed to carry the weight of the members of the bridge (dead load) and the weight of any traffic moving across it (moving load). In order to simplify calculations, the moving load is often converted to an equivalent live load by multiplying it by two. When a heavy truck moves across the bridge, the bridge will carry concentrated loads from the wheels with spacing equal to the wheelbase and tread width.

In a short-span bridge, the largest bending moment in the road-bearing beams will occur when the back wheels that carry the greatest weight are at the centre of the span and will be determined by half the weight on one wheel, because the decking is designed to distribute the load to at least two beams. In a longer span bridge where both front and rear wheels may be on the span at the same time, the maximum bending moment will occur when the centre of the wheel base is a short distance from the centre of the span.

In addition to bending, shear may have to be considered for short spans, and deflection for long spans. Where bridges are constructed with rough materials under unfavourable conditions, a larger factor of safety should be used.

VEHICLE ACCESS TO FARMSTEADS

Although the types of vehicle found around any farm building depend on the scale of the farm operation, there is likely to be an increasing need to allow for larger vehicles delivering supplies or collecting produce. On smaller farms, this may be limited to pickups, light vans and tractors, but on larger farms and around village or cooperative buildings the vehicles may be up to the maximum sizes allowed on roads.

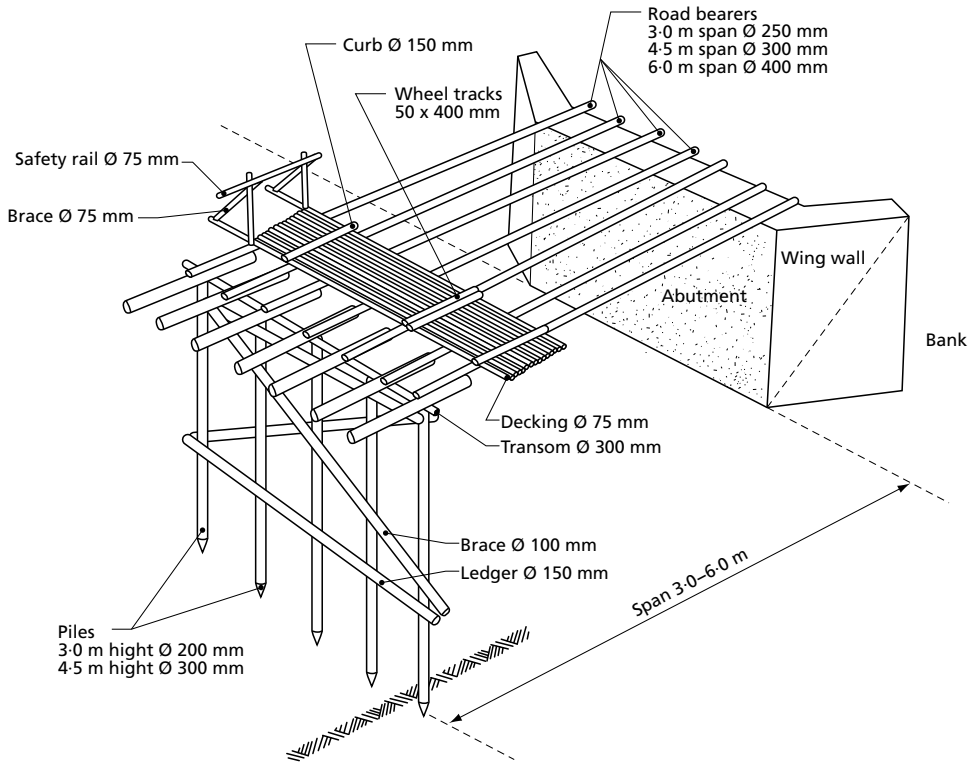


Figure 17.9 **Simple bridge constructions using round timbers (carrying capacity for moving loads up to 10 tonnes)**

Vehicle dimensions

The overall width and height of vehicles are important factors when designing door openings and gateways, and when clearing vegetation for roads and driveways. The minimum requirement is an opening 0.6 metres wider and 0.5 metres taller than the vehicle to allow for manoeuvring, uneven ground surface, deflection of lintels, etc. Big trucks will therefore require a minimum opening with a height of 4.8 metres and a width of 3.2 metres, provided there is straight access to the opening. If the free space in front of the opening is limited (e.g. smaller than 1.2 times the overall length of the vehicle), a wider opening will be required.

High vehicles should be prevented from moving too close to buildings with roof overhangs or other projections less than 5 metres above ground level. Vehicles with lift bodies may require a clearance height of 7 metres or more.

Drives near the corners of buildings must make an allowance for the vehicle to swing out on the curve, so that the centre of the turning circle is at the corner of the building, or preferably well away from the corner. The space required for a U-turn is an area with a width equal to the outer turning diameter and a length equal to the outer turning diameter plus one vehicle length.

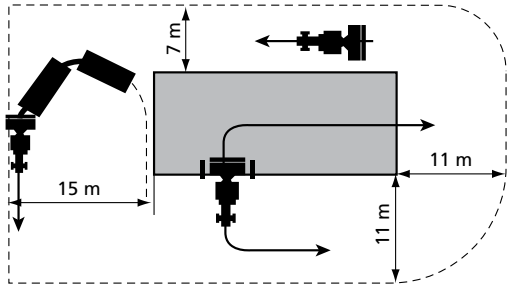


Figure 17.10a **Space requirements for tractor movements around a building**

Planning space for vehicles in farm drives and courtyards

Drives and farm courtyards are part of the internal transport system on a farmstead. They indicate where the vehicles are expected to move or be parked. A single entrance drive is usually desirable for traffic control so that vehicles can be readily observed from the house and farmstead.

The turnoff from the main road to the entrance drive should be located at the top of a hill, or far enough from the top for safe visibility. Visibility must not be obstructed by trees, banks, signs, etc. A gate located in the entrance drive should be at least 10 metres – but preferably 20 metres – away from the main road, to permit cars and trucks to wait off the road while the gate is being opened.

The farmstead courtyard is usually an extension of the entrance drive intended to provide space for parking and for manoeuvring machines and trucks. Proper parking space discourages visitors from blocking farm

TABLE 17.1
Dimensions and outer turning diameters for some common types of vehicle and vehicle combinations

Type	Overall dimensions (metres)			Outer turning
	Width	Height	Length	Diameter (metres)
Saloon car	1.8	1.5	4.0	11.0
Pickup	1.8	1.6	4.8	11.5
Light delivery van	2.1	2.4	6.0	12.0
Two-axle truck	2.6	3.4	10.0	23.5
Three-axle truck	2.6	3.9	12.0	25.0
Articulated truck	2.6	4.6	15.0	24.0
Truck with trailer	2.6	4.6	22.0	26.0
Tractor	2.3	2.8	4.3	10.0
Tractor with trailer	2.4	2.8	12.0	13.0
Tractor with two trailers	2.4	2.8	20.0	15.0

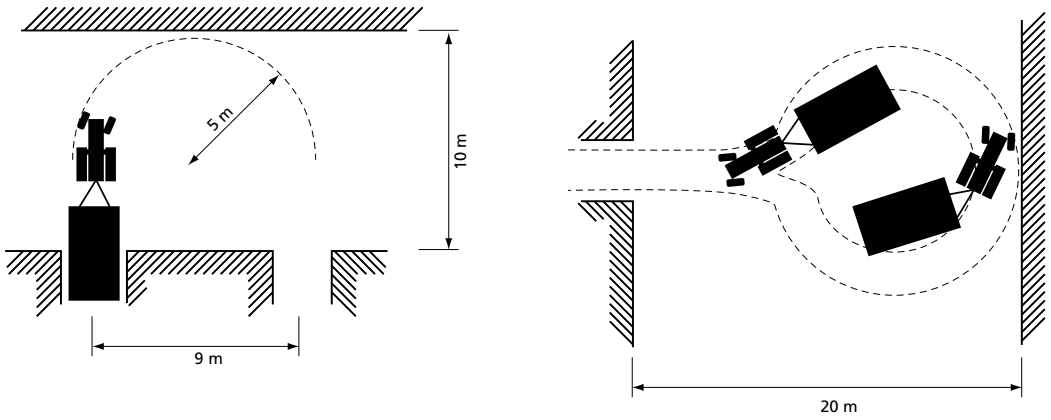


Figure 17.10b **Space requirements for tractor movements in and out of buildings**

vehicles and directs them to the house or office. The safety of drivers, farm workers and children should be a primary concern in the overall scheme.

When planning the layout of farmstead buildings, drives and courtyards should be designed to accommodate the vehicle types and sizes used in the farm operation in an effective circulation system. When a vehicle moves through a turn, the rear wheels track with a reduced radius. The road or drive therefore needs to be wider at curves. Articulated vehicles can almost pivot around the centre of the turning circle in a sharp turn or U-turn.

Gravelling the most frequently used areas will improve drainage and keep drive surfaces firm and durable throughout the year. Extra parking space for storing machines and supplies can be stabilized by turfing. Heavy vehicle traffic close to retaining walls, tanks and similar structures should be kept to a distance equal to or greater than the height of the wall or structure.

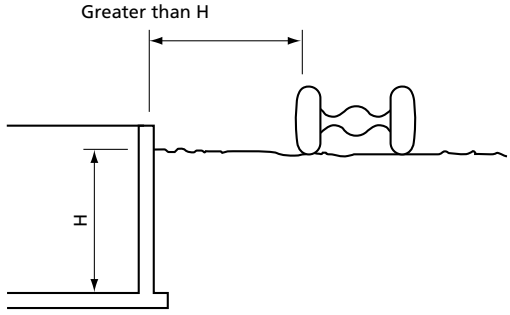


Figure 17.11 **Protect retaining walls from heavily loaded vehicles causing shearing of the soil**

REVIEW QUESTIONS

1. Why are rural roads refered to as 'unimproved roads?
2. Briefly describe factors which need to be considered in the location of rural roads.
3. Why is choice of the gradient of a rural road under construction important?
4. What are wet spots and how would you eliminate them from a rural road?
5. Outline some of the methods you would use to prevent erosion of a rural road.
6. Describe three types of drains usually used with rural roads.
7. Outline the steps followed in the construction of a rural road.
8. Distinguish between splashes and drifts as used in rural roads.
9. Describe factors taken into consideration when siting culverts and simple bridges.
10. Outline factors that must taken into consideration when planning space for vehicles in the farmstead.

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Chapter 18
External facilities

This chapter deals with rural structures that are only indirectly related to buildings but are of great importance to agricultural production and the provision of services in rural areas. These include fences, farmstead courtyards, fencing and animal-handling yards.

FENCING

The two main objectives of fencing on a farm are to improve security and livestock management, but fences may also be used as windbreaks, to provide privacy and to enhance appearance. The type of fence chosen for a specific situation is normally determined by the objective, or the combination of objectives, for which it is built.

Security

Fencing is often used to protect property and growing crops from theft and damage by people or animals. It is also useful in pasture management when used to divide paddocks. Where the objective is solely to demarcate boundaries, very simple structures may suffice. On the other hand, fences that are designed to stop intruders from entering must be high, dense and sturdy, and be topped with spikes or barbs. As secure fences can be quite expensive, their use is limited to enclosing particularly valuable property.

The three most widely used types of fence for this purpose are:

1. Round or square vertical bars of wood or steel, secured to horizontal rails and fixed to posts set 2–3 metres apart. These are very difficult to climb.
2. Chain-link (diamond-mesh) netting, about 2 metres high and fixed to posts set 3 metres apart. In both types of fence, stays may be used for extra strength, with a barbed-wire top for extra security.
3. Thorny hedges.

Fencing is also used for protection around ponds, along steep slopes or in other hazardous locations.

Improved livestock management

Herding is the traditional method of controlling livestock movements during grazing. In the past, fencing was used only to exclude animals from certain areas, such as homesteads and cultivated fields, and to safeguard them at night.

With 'extensive' livestock production, fencing is likely to be so costly that the practice of herding must continue. However, it is not uncommon to enclose the land with a boundary fence. With 'intensive' livestock production, it is often feasible to subdivide the land. The greater number of paddocks allows for flexibility in herding livestock and dividing them into different classes or age groups. It is seldom economical to subdivide the land beyond what is necessary for efficient grazing.

In Africa, some of the worst livestock diseases are tick-borne, and fencing can play an important role in breaking the disease cycle by maintaining the disease-free condition of livestock once enough ticks have been eradicated by regular spraying or dipping. Fencing also helps to limit the spread of other infectious diseases, and to reduce problems with parasites. In addition, fencing can be used to prevent improved animals from breeding with animals from outside the farm.

In intensive dairy production, the animals are often grouped according to production to allow for more efficient feeding of concentrates and for improved management practices. The various groups of animals are kept separate by fences and other structures, such as feed racks.

TYPES OF FENCES

Any type of structure that forms an effective barrier to livestock movements, or restricts human movements, can be termed a fence. The following are the most common types of fence on farms.

Wire fences, such as:

- plain-wire fences
- barbed-wire fences
- suspension fences
- wire-netting fences
- electric fences

Other types of fence, such as:

- post and rail fences
- hedges
- log fences
- walls
- movable fences

Wire fences

Types of wire

Plain- or barbed-wire fences are best suited to fencing large areas. Although plain wire is cheaper than barbed wire, it requires a higher standard of assembly and construction for posts because the wires must be permanently strained to be effective. The thinner but stronger high-tensile steel wire is cheaper than plain wire but more difficult to install. Fencing wire is galvanized for corrosion protection. However, significant thermal variations may crack the protective cover. The salt air in coastal districts, and applications below ground level, also reduce the effectiveness of the galvanizing. Barbed wire will generally rust faster than plain wire.

High-tension wire will maintain its tension longer than plain or barbed wire, but will rust faster than plain wire once the galvanizing is broken. Barbed wire may cause serious injury to animals, resulting in lower pelt value. The most justifiable use of barbed wire is as a top wire above other types of fence to discourage stock from leaning over the fence and breaking it down.

Even though fencing wire should be strained to be effective, care should be taken not to overstrain it. The elasticity of the wire will cause it to return to its original position after being stretched by the impact of animals or by temperature changes, provided the yield-point stress has not been exceeded. Furthermore, it will be difficult to maintain very high tension over several years. Generally the elasticity will not be damaged and the fence will retain resilience and tension if the wires are stressed to about 30 percent of the yield point, or about 1 500 N for common types of fencing wire.

Wire applications for various animals

It is recommended to use 4–5 lines of barbed wire, or 5–7 lines of plain wire, for a cattle fence. However, on large ranges with low stocking density, 2–4 lines of barbed wire, or 3–5 lines of plain wire, may be adequate. The top wire should be at least 1.2 metres above ground level.

Fencing for poultry runs should be about 2 metres high. A thin-gauge, hexagonal, relatively open mesh is adequate to control adult birds, but smaller mesh netting, dug 20–30 cm into the ground and with a total height of about 1 metre, is often fitted at the bottom of the fence to prevent young birds from escaping and predators from entering the run.

Although barbed or plain wire can be used for pig fencing, because the wires must be closely spaced, in most cases it will be more economical to use a heavy-gauge, woven-wire fence or a chain-link (diamond-mesh) fence. A mesh smaller than 15 cm is recommended, although 20 cm mesh can be satisfactory for adult pigs in large runs. Where sows with litters are to be fenced, smaller mesh must be used at the bottom.

The height of the fence should be at least 90 cm. Unless the pigs' noses are ringed, it is difficult to make a fence pig-proof, but it will help to dig the bottom of the fence about 25 cm into the ground. However, this will increase the maintenance cost because of rusting of the wires. Alternatively, a single line of barbed wire can be fixed at the bottom of the fence, just above the ground.

Barbed wire is not considered suitable for sheep because it tears their fleece. A good sheep fence needs to be 90–110 cm high, depending on the breed. It can consist of either 6–10 lines of plain-wire or woven fencing, 80–90 cm high, and 1–2 barbed wires at the top to make up the height. However, sheep fences in small paddocks or yards should be built at least 2 metres high to keep out predators.

The mesh should be 15–30 cm. The larger mesh will prevent the sheep from catching their heads if they attempt to reach through, but may not be sufficiently dense for lambs and for breeds with a special liking for breaking through fences. For plain-wire fences, batten and wire spacing seem to be more important than tension in the wires. Wires spaced 15 cm apart require battens every 2 metres, whereas wires at 10 cm can have battens spaced 2.5 metres.

Fencing posts

Just as important as the wires in a fence are the posts that support them. Strainer posts and corner posts need to be strong and fixed firmly in position because the stability of the fence and the tension in the wires depend on them. Intermediate posts, battens and wires may be replaced as necessary.

Naturally durable and termite-resistant hardwood, or less durable wood treated with a preservative, should be used for strainer and corner posts. Note that some wood preservatives may cause the wires to deteriorate quickly, especially in the atmosphere of coastal areas. Knots are potential sources of weakness. Sometimes galvanized steel or concrete posts are used, but they are generally more expensive than wooden posts.

Concrete posts, although easily broken, are long-lasting, fire- and termite-resistant and can be made at the farm using a simple mould. A 1:2:2 concrete mixture, reinforced with four 6 mm steel bars, wired together at 50 cm intervals, is satisfactory. Strainer posts should be 20 cm by 20 cm at ground level, and other posts should be 15 cm by 15 cm.

Wooden posts may be set in dug or bored holes and fixed firmly with tamped soil. Alternatively, they may be driven into the soil or into undersized bored guide holes. Driven posts are generally 1.5 times firmer than posts rammed into oversized holes, and will withstand greater lifting forces. A hand driver can be made from a 900 mm length of 200 mm steel pipe. The top end is closed with a steel plate, while handles are welded to the bottom end. The total weight should be about 15 kg for a one-person driver, and about 30 kg for a driver operated by two people. Driven posts should be pointed before they are given a preservative treatment.

Intermediate posts should be set 40–60 cm deep, whereas strainer, corner and end posts requiring greater rigidity should be embedded up to 80 cm deep. Metal strainer posts should always be set in concrete, and wooden posts are sometimes set in concrete for extra rigidity.

Live posts consisting of trees growing on the fence line, or specially planted posts, are cheap and long-lasting. Suitable species can also act as shade trees and provide browse. Live posts should be planted some time before they are to be used to give adequate time for rooting. It can be difficult to establish live posts in arid areas.

Battens (droppers) are used to compensate for sag in the wires where the distance between intermediate posts is necessarily long, and also to keep stock from pushing between the wires. Wood battens should have a diameter of 25–40 mm and will last longer if treated with a preservative. Alternatively, wire lashings may be used to maintain the distance between the wires, or extra wires can be supplied to decrease the spacing, thereby reducing the need for battens.

Stapling is the most common method of fixing wires to posts. Alternatively, they may be secured with 2 mm galvanized mild steel ties. However, it is difficult to make such a tie secure against sliding on the post. When stapling, the wire should be stapled loosely to the intermediate posts. Staples driven too far will bend and hammer out the wire, creating a weak spot. Splitting of the posts can be lessened if the staples are driven diagonally into the grain.

Plastic poles

Plastic lumber is currently one of the major products manufactured from waste plastic. Most of the plastic lumber is composed of thermosetting plastics, such as high density polyethylene (HDPE), low density polyethylene (LDPE) and polyvinyl chloride (PVC). They act as adhesives and encapsulate high-melt plastics and other additives, such as fibreglass and wood fibres, within a rigid structure. The following processes are used in the manufacture of plastic lumber:

- Sorting and precleaning of plastic waste.
- Homogenization and melting.
- Additives such as foaming agents; ultraviolet (UV) stabilizers and pigments are added to improve the performance and appearance of plastic lumber.
- Pouring into moulds – extruders push melted feed stock through different die sizes to produce lumber of different dimensions.

Advantages of plastic lumber

1. Resistant to insects, rot, moisture and many chemicals.
2. No defects, although standards are still being developed to ensure uniformity.

Disadvantages of plastic lumber

1. Very sensitive to temperature (dimensional changes).
2. High creep rates.
3. High flammability.
4. UV degradation.
5. Grading system needs to be developed.
6. The engineering properties are inferior to those of timber, as they are subject to UV radiation and deformation under constant load.
7. As plastic lumber has a low modulus of elasticity, more members are used per unit area, increasing the need for material.

Wire fence construction

The length of fencing required per hectare will vary greatly with the size and shape of the fields. Square fields have the lowest fencing cost per unit area and, the larger the field, the lower the fencing length per hectare. Fence lines should be as long, straight and unbroken as possible, because corner posts and gate posts require bracing and increase the cost.

When the fence line has been laid out, the ground area over which the wires will be stretched should be cleared. Next, the strainer assemblies are installed. As these will take the whole strain of the stretching of the wires, it is very important for them to be firmly set and well braced. Although strainer assemblies are normally located next to corner and gate posts, on long, straight stretches of fence, additional strainers should be installed at up to 200-metre intervals if the ground is even, or at the top and bottom of each slope in hilly terrain.

Figures 18.1a, 18.1b and 18.1c show three types of strainer assembly in general use. The double horizontal stay strainer assembly is extremely rigid in all types of soil but, for most purposes, the single horizontal stay assembly will be sufficient. On firm but easily dug soil, the traditional assembly with one diagonal stay will be adequate and is the cheapest in terms of material.

Corner posts should have a diameter of at least 150 mm and be braced in the direction of both fencing lines. Corner posts, where the fence angle is less than 45°, will be sufficiently rigid if braced with a single diagonal stay or diagonal tie-back.

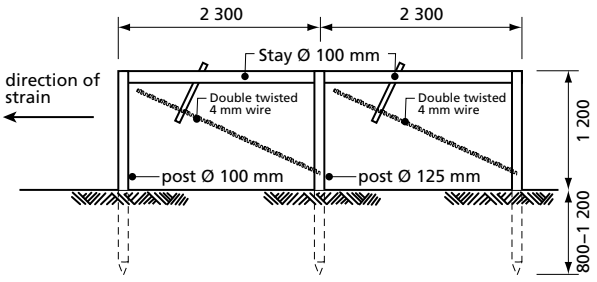


Figure 18.1a **Double horizontal stay**

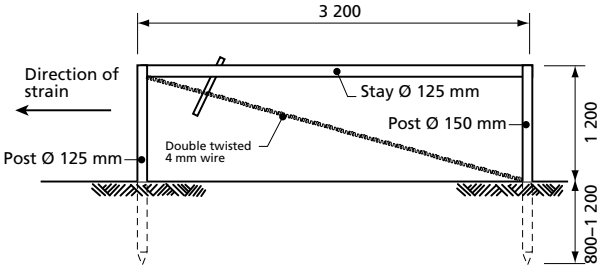


Figure 18.1b **Single horizontal stay**

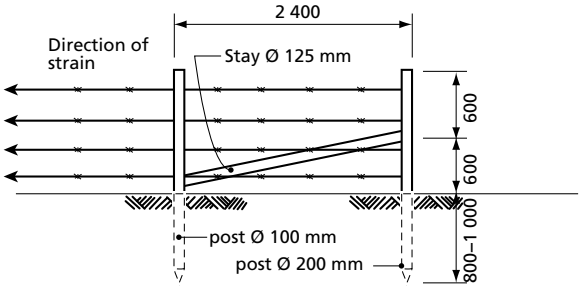


Figure 18.1c **Traditional strainer with diagonal stay**

Intermediate posts, with a diameter of 75–125 mm, should be set exactly in line to avoid any horizontal forces caused by strain in the wires. Where there is a pronounced low spot in the fence line, one or two of the intermediate posts in the low area may require extra support against uplift by being driven deeper, or set in concrete. For a plain-wire cattle fence, no battens are required if the intermediate posts are spaced no more than 3.5–5 metres apart, but the posts can be set up to 15 metres apart if battens are used at 3.5–4 metre intervals. Woven wire fence requires intermediate posts every 4–5 metres, and chicken wire, every 2 metres.

The wire, or wire netting, is then attached to the posts. Starting with the bottom wire, first it is secured to a strainer post, then stretched using a tackle-block stretcher, chain stretcher or, for single plain or barbed wires, using a simple wooden lever. When the wire has been stretched tightly enough, it is secured to the next strainer post by wrapping and stapling.

The wire should be placed on the inside of all posts, and wrapped one turn around any corner post. After the fence stretcher has been released, the wires are loosely fastened to the intermediate posts and finally battens are fixed as necessary. When the fence is erected, all surplus wire, nails and staples should be collected to avoid 'hardware disease' caused by the animals eating the scrap metal.

Suspension fences

A suspension fence can be cheaper than a conventional plain- or barbed-wire fence because the number of posts is reduced. Nevertheless, it will require one or two more wires than the corresponding conventional fence. Its effectiveness relies on the strain in its high-tensile wires, which causes them to vibrate when an animal nudges the fence.

If an animal charges against the fence with a force that would seriously damage a conventional fence, the suspension fence heels over and returns undamaged to its original position after the animal has retreated or passed over. Strainer assemblies are set as for conventional fences, but intermediate posts may be spaced up to 40 metres apart where the fence line and contours permit. Wood or wire battens, which must not touch the ground, are spaced approximately 4.5 metres apart.

Electric fence

An electric fence can be made from either plain or barbed wire. It can be simple in design, since it need not be a physical barrier to the animals, but instead relies on an electrical pulse sufficient to shock, but not kill. The wires are stretched between insulators at the strainer posts with intermediate posts spaced 12 to 15 metres for cattle or 7 to 12 metres for sheep and pigs. Battens are not needed. Barbed wire is often preferred since the barbs will penetrate the fur of animals and make good contact with the skin. However, plain wire is satisfactory in most cases.

As the hot wires must be insulated from the ground, they are fastened to the posts with insulators and should not come into direct contact with weeds, grass or the posts. The most common type of energizer (controller) operates by charging a capacitor with electrical energy and then discharging it to the fence in the form of a pulse of high voltage. It can be powered from the mains or a battery. Solar recharging units are also available for battery-powered energizers.

The electric fence may be single hot wired (Figure 18.2) or multi hot wired (Figure 18.3). In a single hot wired system, a single wire is placed at a suitable height where the animal cannot avoid touching it, if it attempts to escape. The recommended height is 60 cm for cattle and 25 cm for sheep.

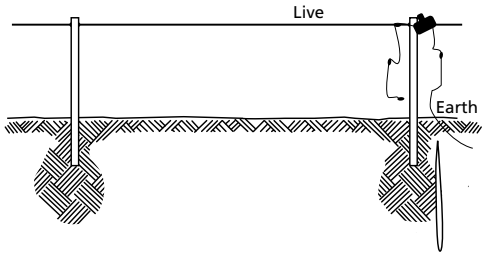


Figure 18.2 **Single-wire electric fence**

A single hot wire can also be used to increase the animal's respect for a conventional fence and to protect

it from damage. The line can be carried on insulators in the fence or on outriggers.

Multi hot wired systems offer two possible ways for the electrical impulse to travel back to the energizer. Just like the single wire fence, if the animal touches only a live wire, the electrical impulse will travel back to the energizer through the moisture in the soil via the closest earth electrode.

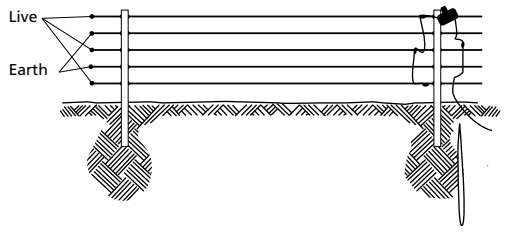


Figure 18.3 **Multiple-wire electric fence**

Temporary electric fences are often used for strip grazing within a permanently fenced field. These consist of a single hot wire at a level about three-fourths the height of the cattle. Two hot wires are provided for sheep and pigs.

Electric fences rely on the soil to conduct the current back to the earth (ground) terminal on the energizer, but soil is a poor conductor under dry conditions. Therefore, in the dry season an electric fence may be ineffective since an animal may not get a shock because of insufficient current flow. Adding earth-return wires from the energizer to the fence will make it effective during dry conditions. This is also the typical arrangement for permanent electric fences which have two hot wires and one or two neutral wires spread between them.

Other types of fence

Post-and-rail fences

Post-and-rail fences consist of wooden posts with wooden, or split bamboo, rails attached to them. They are used mainly to fence areas where the stocking density is very high, as in collecting yards and handling areas. They are also used in farmstead areas because of their attractive appearance and the fact that humans can cross them easily. Their main advantage of post-and-rail fences is that animals are unlikely to be injured by them but, to be effective as physical barriers for stock, they must be strong and properly constructed.

The posts should be at least 125 mm in diameter, be firmly fixed in holes 500–800 mm deep and be set no more than 3–4 metres apart. Three to four 100 mm rails are then fixed to the posts. Where post-and-rail fences are used in animal handling yards or other similarly crowded situations, the rails should be joined only on posts for extra strength, but the same post should not be used to join all the rails.

In a four-rail fence for cattle, the rails are usually spaced at a height of approximately 125 mm, 175 mm, 225 mm and 275 mm from the ground. With 100 mm rails, the top rail will be 1 200 mm above ground level. Where the stocking density on pastures is high, single wooden rails are sometimes used at the top of barbed-wire fences. The rail increases the visibility of the fence and protects the wires from damage by animals leaning over the fence, without any risk of injury to the animals.

Hedges

Although live fences have the advantage of low capital cost if planting material is available at the farm, they require labour for planting. In the humid tropics, most species used for hedging grow quickly and may require cutting twice a year. Therefore, the maintenance work

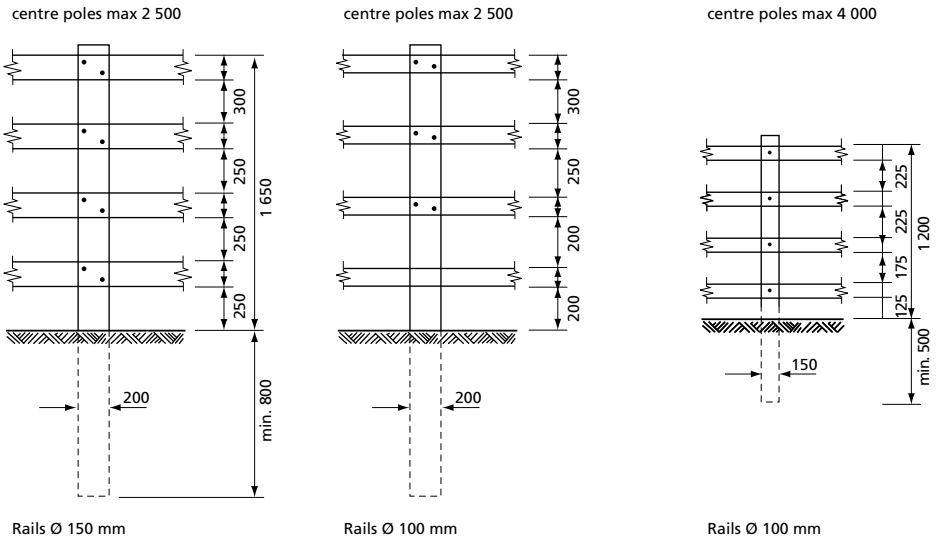


Figure 18.4 **Post-and-rail fences for cattle**

can require more labour than is available on the farm, in spite of underemployment during part of the year.

For a hedge to be stockproof, it may be necessary to include one or more barbed wires in the fencing line. Although hedges require more space than fences and encourage weeds and vermin, they may preserve wildlife, act as windbreaks and serve as an attractive feature of the landscape.

Log fences

Where land is being cleared, thorn bushes or the waste from tree felling can be laid in a line to make a stockproof fence that will last for some years. Piled logs and wooden palisades can also be used for fencing, but are quite wasteful of material. Unfortunately, log fences are very susceptible to attack by termites and, in humid areas, by rot as well.

Walls

Stone walls are an attractive alternative in localities where wood is scarce and stones are plentiful. Although construction is labour-intensive, the maintenance cost is low. They may be constructed with stones placed in mortar, as described in Chapter 8, or simply by piling stones loosely in a wall 0.7–1.2 metres wide at the base. Adobe or stabilized-soil blocks can also be used for low-cost wall construction, especially in very dry areas.

FENCING ACCESSORIES

Fencing accessories include various structures such as gates, stiles and grids, which allow people and/or vehicles to pass a fencing line, but still restrain animals. The purpose of wheel splashes is mainly to restrict the spread of disease.

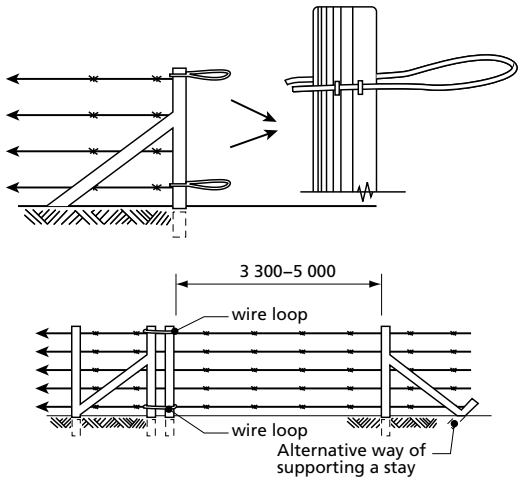


Figure 18.5 **Wire gate**

Wire gates

Although a wire gate is not expensive in itself, the strainer assemblies required for the gate posts in a wire fence should be included in the total cost. The normal width for a gate where vehicles have to pass is 3.3 metres, but may be up to 5 metres if traffic is frequent.

Pole-and-chain gate

A pole-and-chain gate is less tedious to open and shut than a wire gate, and is also quite inexpensive. Neither the pole-and-chain gate nor the wire gate imposes a lateral load on the gate posts other than the strain of the fence.

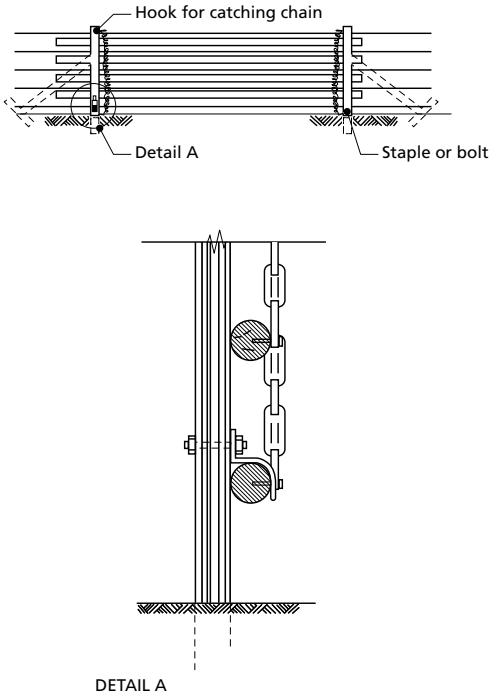


Figure 18.6 **Pole-and-chain gate**

Field gates

Field gates are constructed with wood or metal frames and a face of open boards, netting or wire. As a gate will generate a sideways bending moment on the post when the gate is open, the post must be extrastrong and firmly installed. The gate can be made self-closing by arranging the hinges so that the centre of gravity is lowest when the gate is closed. Gates wider than 3.5 metres should be given extra support with a wire running from an extended gate post down to the free end of the gate, as shown in Figure 18.7b.

Stiles

Stiles provide easy passage over a fence for humans without breaking the fence line. The stile shown in Figure 18.8 can be moved easily.

Person-pass

There are several methods to make passages for persons through a fence line. The one illustrated in

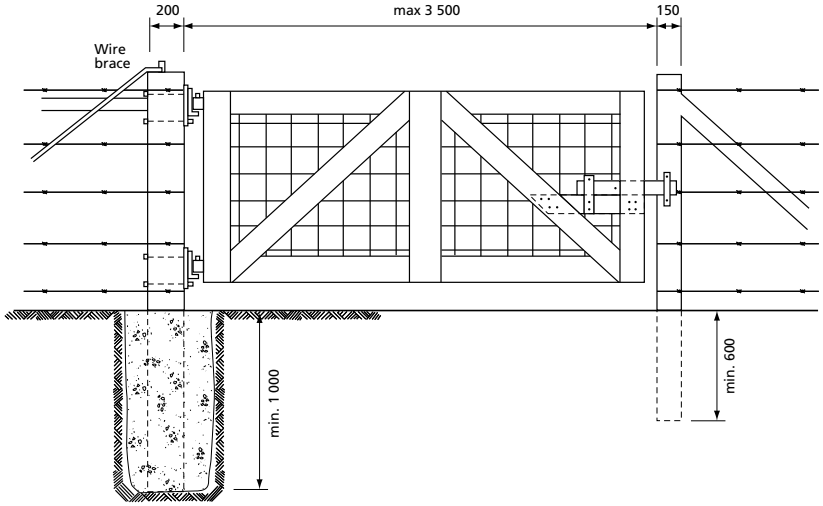


Figure 18.7a

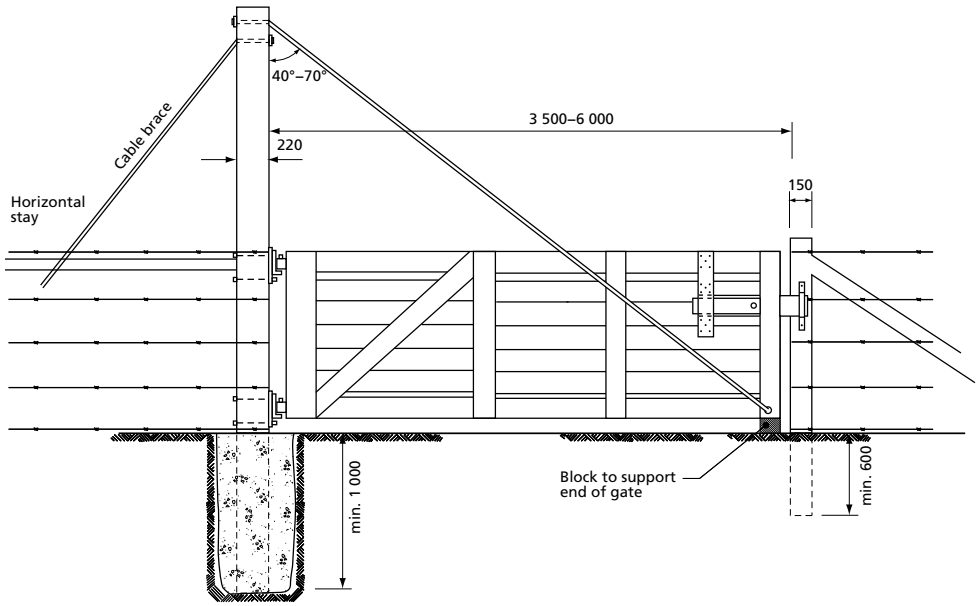


Figure 18.7b

Figure 18.7 **Two types of field gate**

Figure 18.9a has an opening protected by doors, which are permanently fixed in a half-open position so that cattle are restrained. The strain in the fencing lines is transferred overhead with a tie rod. The posts should be strong enough to resist the bending load from the strain in the wires. Another type consists simply of an opening 250–300 mm wide, just enough to let a person pass but too narrow for cattle.

Cattle grid

A cattle grid is a grid in the roadway that serves as an alternative to a gate. Although it eliminates the need for frequent opening and closing of a gate, it is more

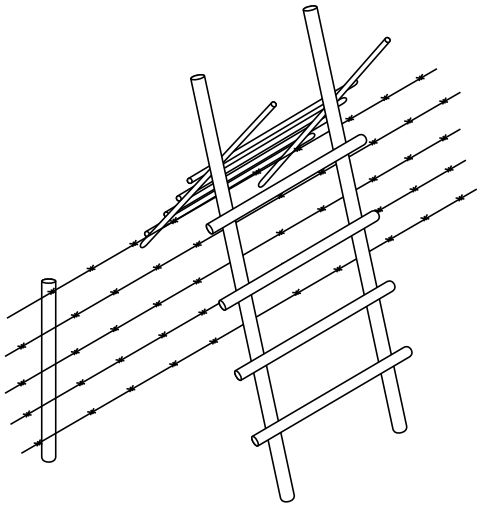


Figure 18.8 **Stile**

expensive to construct. The cattle grid may be made of pressure-treated wood, but steel or concrete are best for use in places where wood is likely to be attacked by pests. Although the minimum length of a cattle grid (in the roadway) is 1.5 metres, 2.4 metres is recommended, to discourage animals from jumping across.

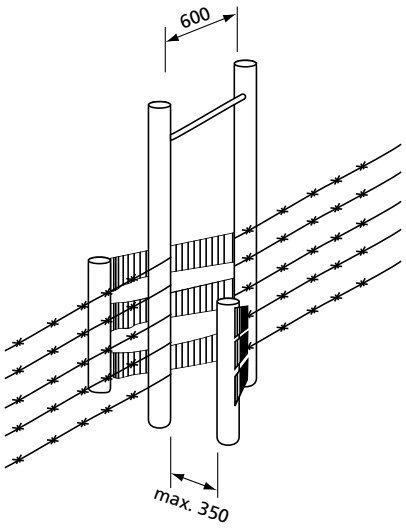


Figure 18.9a

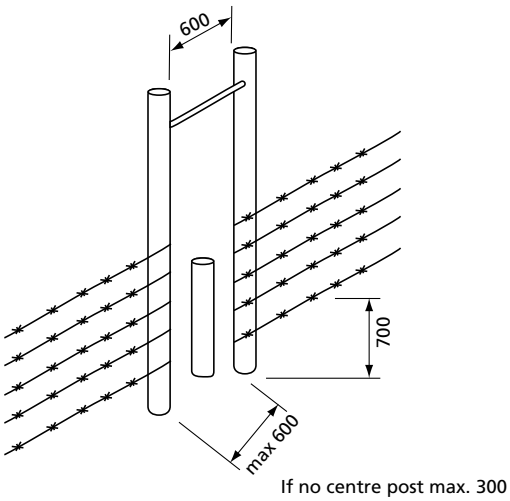


Figure 18.9b

Figure 18.9 **Two types of person-pass**

The load-bearing members should be made of round timber with a minimum diameter of 200 mm, or larger if heavy trucks may have to pass. The grid can be made of 50 mm by 125 mm sawn timber, or of 100 mm round poles spaced 100 mm apart. The width of the cattle grid is usually 3–4 metres. The narrower width is satisfactory if sloping ends are used, as shown in Figure 18.10.

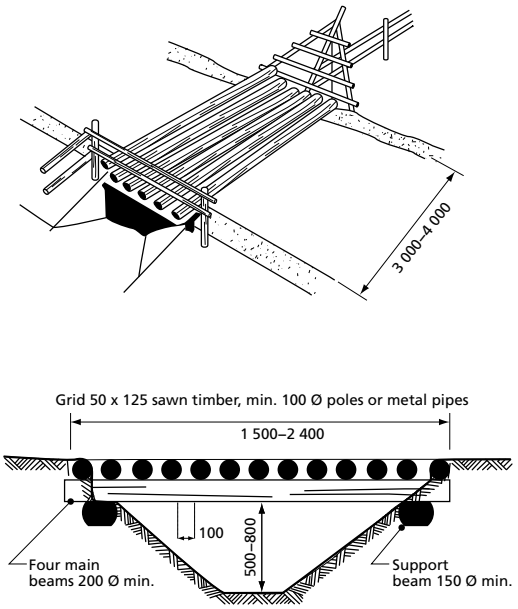


Figure 18.10 **Cattle grid**

Wheel splashes

The purpose of a wheel splash is to disinfect the wheels of vehicles moving into the farm area, thereby limiting the spread of diseases and parasites. Wheel splashes are relatively expensive to construct and maintain and, to be effective, they must be kept filled at all times with a disinfecting liquid. A wheel splash is a shallow basin made of waterproof concrete with 2-metre long entrance and exit ramps sloping 1 in 8. The centre section of the splash containing the disinfecting liquid should be long enough to allow the largest wheel of a tractor to make at least one full turn before reaching the other ramp (4–6 metres).

ANIMAL-HANDLING FACILITIES

Animals that are handled regularly are normally very docile and can be managed easily with very limited facilities. Larger herds with less individual handling of the animals and new management practices, such as artificial insemination, castration, inoculation, dehorning and weighing, will increase the need for handling yards.

A simple handling yard should include a holding pen, a forcing pen, a race, a crush with a head restraint and a loading ramp. A more complete handling yard may also include drafting facilities and several holding pens for the sorted animals. A dipping tank or spray race can also be included. The size and complexity of the yard depends largely on the number of animals to be handled at any one time.

While handling facilities can be built of inexpensive materials, they should be of a good enough standard for tasks to be carried out easily. All fences in the handling yard should look strong and be strong, and be clearly visible to the animals to prevent bruising. Post-and-rail

fences fit these needs best. Wire fences are suitable only for receiving yards where the animals are held prior to entering the main yard.

Main yard

The handling yard should be situated centrally to the grazing paddocks in a village, and must be on a site with good drainage. Shade and drinking water should be available. The site should also be accessible to trucks throughout the year.

The fences of the holding and forcing yards should be at least 1.65 metres high if large, active zebu cattle are to be retained. Posts 150–200 mm in diameter should be set at least 0.8 metres into the ground and spaced no more than 2.5 metres apart. Four 150 mm, or five 100 mm, rails are attached to the inside of the posts, with slightly larger spacing at the top of the fence. Holding yards for sheep can have lower fences, but they need closer rail spacing, especially if lambs are to be handled.

TABLE 18.1
Space requirements for holding and forcing pens

Animal category	Holding yard (m^2/animal)	Forcing yard (m^2/animal)
Cattle		
100–300 kg	1.3	0.6
300–550 kg	1.6	1.0
More than 550 kg	2.0	1.2
Sheep		
Dry ewes	0.5	
Ewes with lambs	1.0	

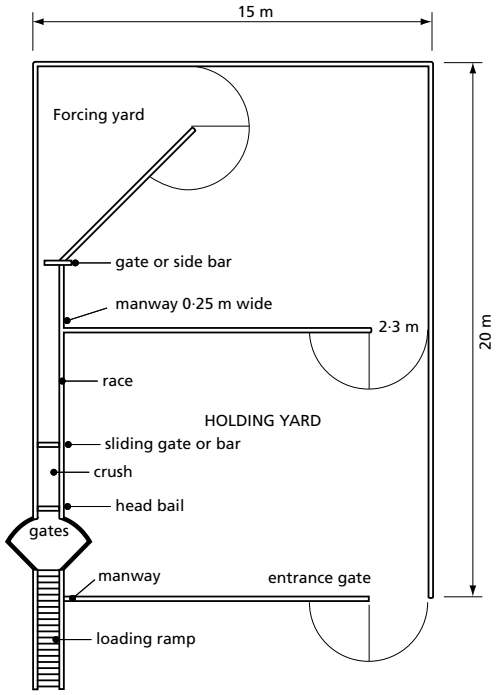


Figure 18.11 **Simple cattle yard**

Cattle races and crushes

Quick operations, such as branding, spraying and giving injections, need only a race to position the cattle. More specialized tasks, such as earmarking, dehorning, castration, foot trimming, weighing, artificial insemination, pregnancy testing and veterinary operations, require a crush to firmly restrain an animal. The crush is best located as an extension of the race.

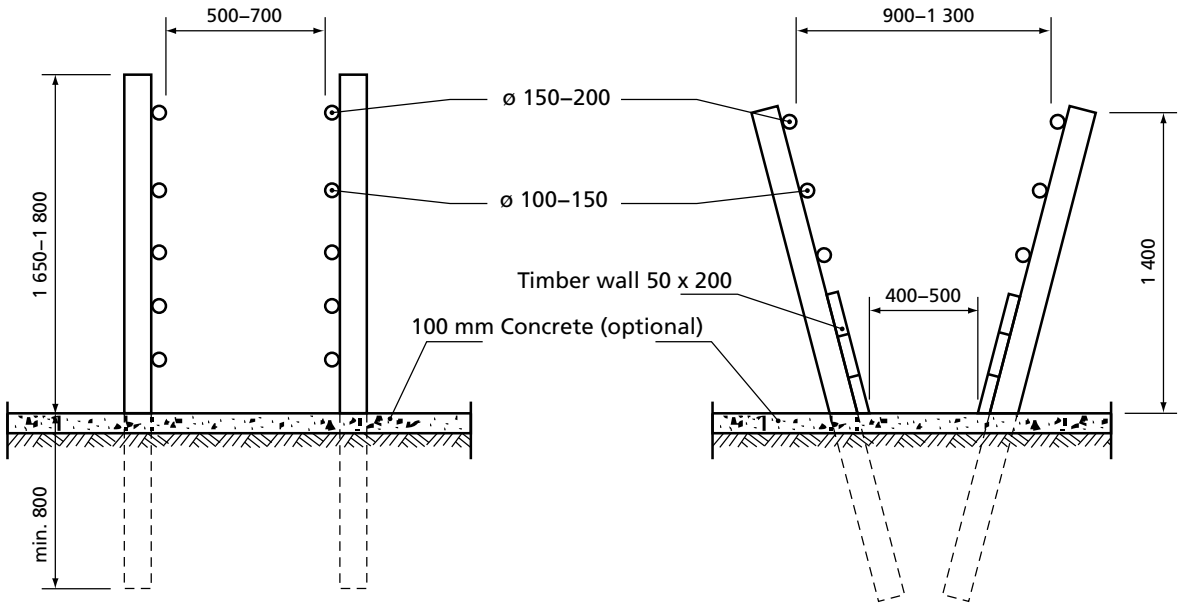


Figure 18.12 **Alternative sections for a cattle race**

Although it is often a slow process to move cattle into the race, once a few animals have entered, others will readily follow. The race should therefore be long enough to hold three animals waiting to enter the crush, or be at least 6 metres long.

The same type of post-and-rail fences are used for the race as for the holding yard, but the height should be increased to 1.8 metres. Where round timbers are used for rails, they should be arranged so that the thick end of the pole faces the front of the race, to minimize the risk of animals injuring themselves on projecting butt ends. The rails should be joined on posts for extra strength. It is important to have the correct width for the race so that animals can move easily but cannot turn around, i.e. 500–700 mm between rails, depending on the size of the cattle. Cattle with very large horns are a problem. The only real solution is to build a race with sloping sides and reduce the height of the fence.

It is desirable for the entire length of the race and crush to be floored with concrete. A solid wall about 600 mm high at the bottom of the fences will reduce the risk of leg injury if the cattle should slip. Such walls are especially necessary in races with sloping sides.

A simple crush need only consist of a head bail at the end of the race and a side-opening gate in the last panel of the race. To improve access to the side of the animal, the gate can be split horizontally in halves to enable the top half to be opened while the bottom half restrains the animal. It is also advantageous to have a sliding gate or tail bar at the entrance of the crush to hold back animals and give easier access to the rear of the animal in the crush.

The animals should not have to back up to leave the crush. This can be solved by having a side gate that opens at the front of the crush, or by constructing the head bail in a gate, or else constructing a head bail so that it can be opened wide enough for the animal to walk through.

The head bail should fix the head of the animal with vertical bars because horizontal bars may cause choking if the animal should collapse or slip. However, dehorning will require the head to be restrained both vertically and horizontally. In such cases, a bar at the top and a quick-release chain at the bottom will hold the head adequately.

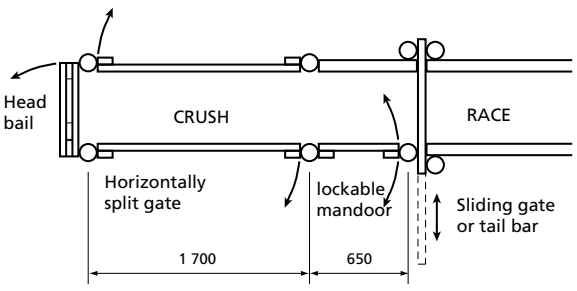


Figure 18.13a **Cattle crush**

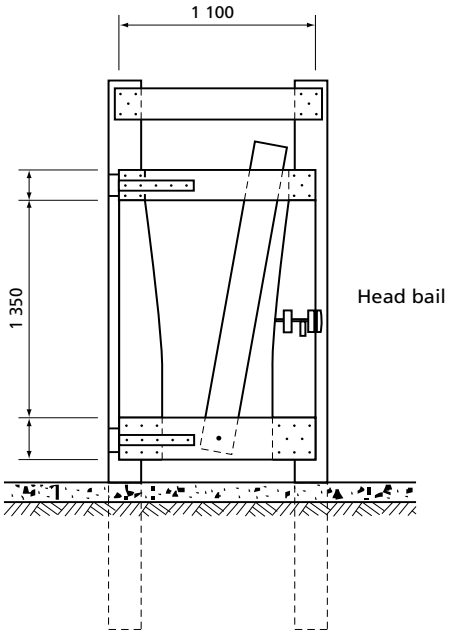


Figure 18.13b **Head bail**

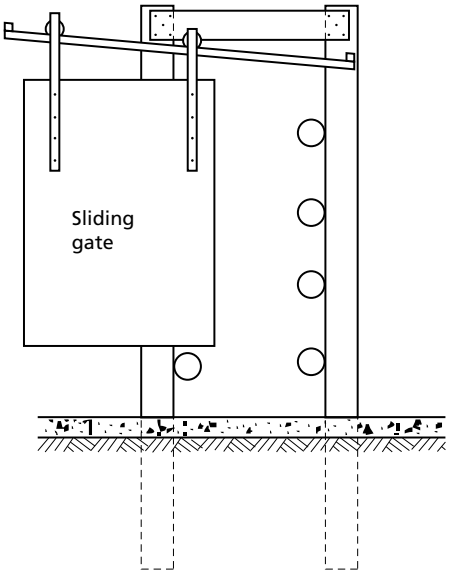


Figure 18.13c **Sliding gate**

Loading ramps

A loading ramp is necessary for loading stock into trucks for transport to market or for transfer to other grazing areas. Figure 18.14 shows typical dimensions for a cattle loading ramp. Note that the ramp floor has cross-battens every 20 cm to prevent slipping. The catwalk along the outside is convenient for the workers urging the animals along. A height of 1.1 metres is a little low for articulated trucks and a little high for most two-axle trucks, however, it should be adequate for either. A ramp slope of approximately 30 cm/metre is suggested.

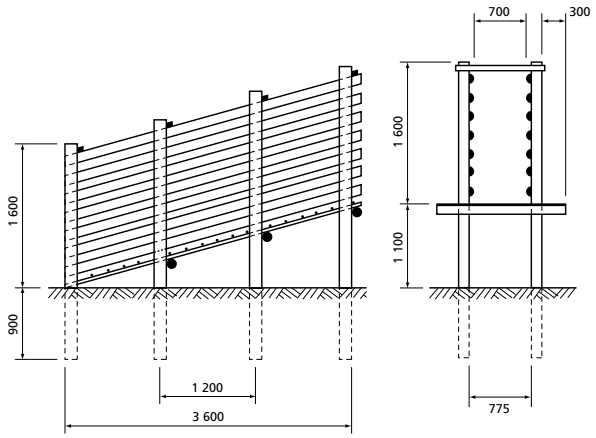


Figure 18.14 **Loading ramp**

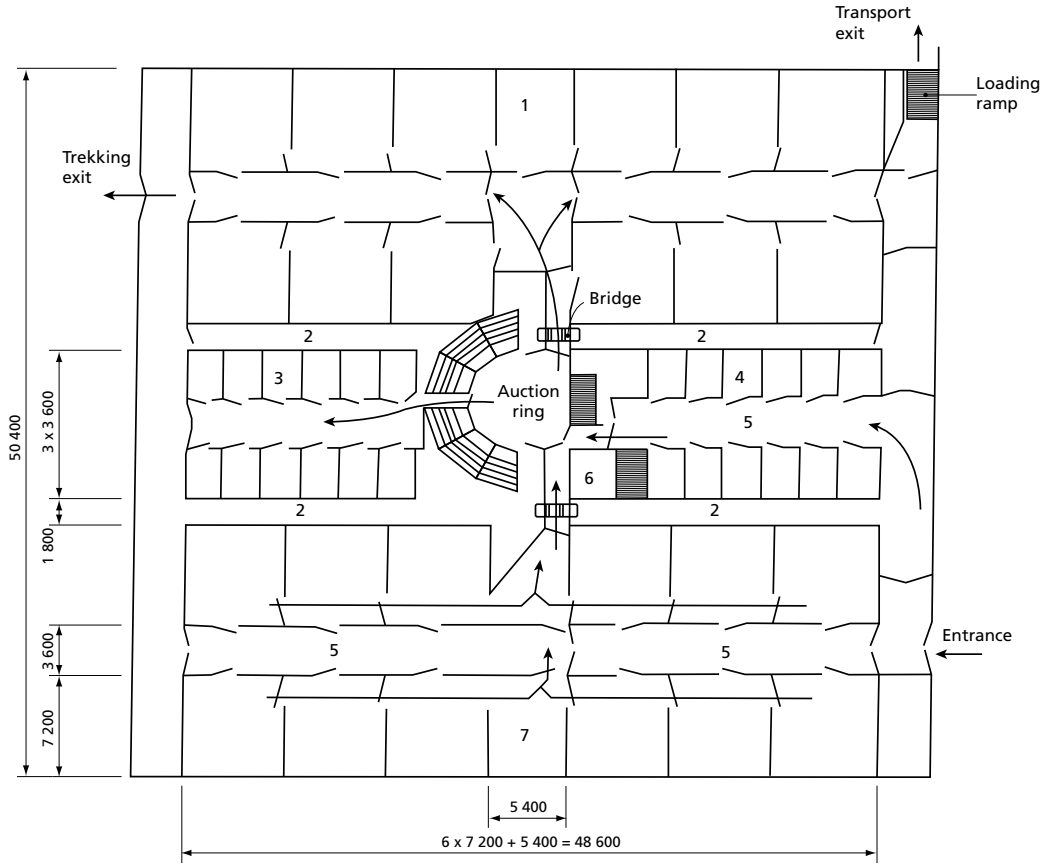
Sorting alley

A sorting alley is useful in a handling yard where large herds must be drafted frequently into several different groups. A sorting alley is basically a race with side gates that can be swung into the race, thereby directing the animals into holding yards, one for each class of animals. The yards can be located on one or both sides of the race.

Sales yard

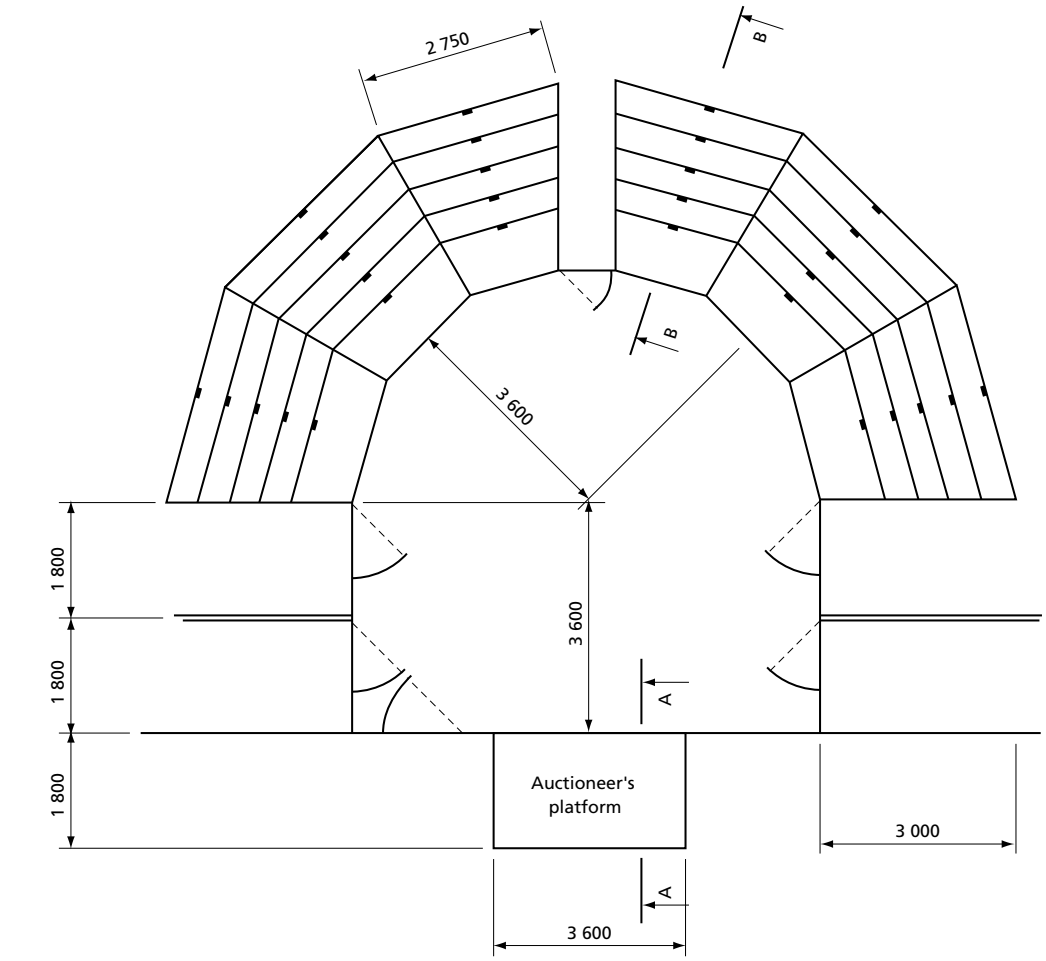
Animal auctions have the advantage of establishing the market price for animals of the same quality. This encourages farmers to market better animals and buyers will have access to a central market instead of travelling around to many different farms (producers).

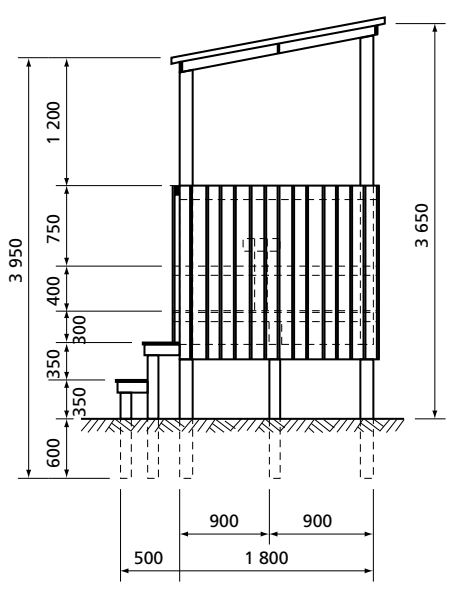
The auction system demands both good management and a well prepared sales yard. Figure 18.15a shows the principles of a sales yard for approximately 500 cattle and 350 sheep and goats. The yard is calculated for 40 cattle/sheep in each pen, or 1.3m²/cattle and 0.25m²/sheep or goats.



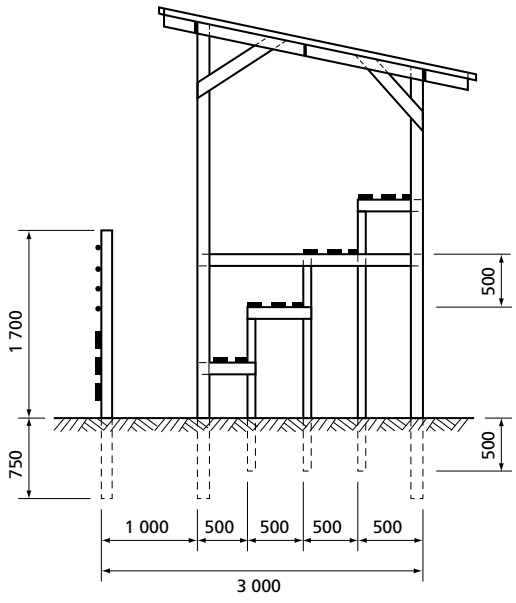
1 - Buyers' pens cattle
2 - Public access
3 - Buyers' pens sheep and goats
4 - Sellers' pens sheep and goats
5 - Sorting and throughout fare
6 - Office
7 - Sellers' pens cattle

Figure 18.15a **Sales yard**





SECTION A -A



SECTION B - B

Figure 18.15b **Auction ring in sales yard**

Management

Normally cattle are registered and marked before they are sorted by size and sex. Each category can then be sold in groups or individually. Note that, if sold one by one, a maximum of 250–300 cattle can be sold in a single day.

A monthly auction will create widespread interest, and buyers and sellers may come from a large area. As a market will normally establish itself near the auction area, this should be considered when choosing the site.

The auction should start with the largest cattle first, taken in groups to the collecting point, from which 12–15 cattle at a time walk into the auction ring. When sold, the cattle go to the respective buyers' pens.

Maintenance has to be carried out regularly because of heavy wear and tear. The gates are particularly weak points. Access to water in each pen is necessary, especially when selling dairy cattle.

REVIEW QUESTIONS

1. Describe the role of fences in a farmstead.
2. Outline five types of fences that may be used in a farmstead.
3. Discuss wooden and plastic posts as used in fencing.
4. Outline five factors you would consider when constructing a wire fence.
5. What is 'hardware disease' and how can it be prevented?
6. Briefly explain the working principles of an electric fence.
7. Outline the advantages of the post and rail fences.
8. Describe four types of fencing accessories.
9. Briefly describe three animal handling facilities.

FURTHER READING

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Chapter 19
Water supply and sanitation

Water, along with food, is one of the essentials of life. Perhaps because of its importance and scarcity in many locations, in most societies the use of water is encompassed by very strong cultural/social precepts. The success of projects aiming to improve water supply and water quality therefore depends on the full participation of the village population, in particular the women, as they are the main users of water.

While relatively small quantities will sustain human life, much more is needed for cooking, personal hygiene, laundry and cleaning. Water for a sanitary system is desirable, although not essential if it is scarce. Water is also required for livestock and perhaps for irrigating crops. Types of water required for the farmstead include: (a) clean water for use in the home; (b) reasonably clean water for livestock; and (c) water for irrigation.

WATER REQUIREMENTS: QUANTITY AND QUALITY

Quantity for domestic use

Location and convenience are significant factors in determining the volume of clean water for domestic use, as Table 19.1 below shows.

TABLE 19.1
Domestic water consumption per person

Water source several kilometres away	2–4 litres per day
Water source up to 1 kilometre away	4–8 litres per day
Water next to the house	10–20 litres per day
Water in the home for toilet, tap and shower	60–100 litres per day
Water in the home for toilet, bath, kitchen and laundry	100–250 litres per day

The range of consumption given in Table 19.1 varies by a factor of over 100. It seems obvious that people adapt their needs to the supply. At the low extreme, the bare minimum is used for cooking and drinking, while at the upper extreme water is used with abandon. When there is a shortage, much lower quality water may be used for personal hygiene and for washing clothes. The suggestions that follow are intended to improve both the supply and the quality of water.

Quantity for livestock

Table 19.2 gives the estimated water requirements for various classes of livestock. This can be used to determine the total requirements.

TABLE 19.2
Water requirements for livestock

Type and number		Daily needs in litres	Total for each type
Upgraded dairy cow	.....	× 70 =	.....
Upgraded beef cows	.....	× 50 =	.....
Local cattle	.....	× 20 =	.....
Sheep	.....	× 5 =	.....
Goats	.....	× 3 =	.....
Poultry, dipping, biogas, etc.			.....

If water for dipping livestock is to be drawn from the same source, 3 litres per head of livestock per week must be added to the estimated amount needed.

Fish can be raised in a reservoir without any additional volume of water. Although chickens, pigeons and turkeys can live on used water from the house, ducks and geese need approximately 1 litre of fresh water a day per bird.

For the production of biogas, a weekly consumption of around 100 litres must be included in the total requirement of water for livestock.

Quality of water

Water from a protected well is nearly free from harmful bacteria although it may contain dissolved salts that make it less than desirable for drinking. A protected well is located upgrade from sources of pollution such as animal yards and privies. Twenty metres is an adequate distance in areas with fairly heavy type soils, while double that distance is necessary for light soils and even more in areas with limestone formations. “Protected” also implies a well head that extends high enough above the ground level to prevent anything from washing or blowing into the well mouth and narrow enough to discourage the users from standing on it. The other essential feature is a concrete apron sloping away from the well on all sides. A sanitary means of lifting the water is also necessary.

Water from roof catchments is generally safe for drinking and other domestic purposes. The dust and bird droppings that accumulate on the roof during dry times are usually carried away at the start of the first rain and should be diverted away from the storage tank. A paved catchment to collect water for domestic use must be fenced to restrict animals and people. It should also be allowed to clean itself before the water is saved. Water that is stored for a week or more in a catchment tank will generally be free of any harmful bacteria such as those causing cholera, typhoid and diarrhea in children as these bacteria cannot live for long outside the human body.

Streams and ponds, whether artificial or natural, are very likely to be contaminated and should be used for domestic purposes only as a last resort.

When the only water available is turbid (cloudy) and suspected of being polluted, it should be filtered through a well-designed sand filter. Even then, the safety of the water for drinking is questionable and boiling or other purification is recommended for complete safety.

WATER STORAGE

Long-term storage of drinking water may give rise to contamination because the tank may not always have been cleaned properly before the start of the rains, and because it not possible to block entry to the tank by small animals and microroganisms altogether. The use of chemicals, cooking or biological treatment of the water may be necessary to obtain good quality drinking water.

Catchment areas

The success of rain catchment depends on two factors:

1. The amount of rainfall.
2. The area and character of the catchment surface.

The type of surface determines both the quality and quantity of water saved.

Types of catchment area include:

Total runoff areas such as a hard roof surface or a protected paved area, which allows the collection of nearly all the rain that falls on them. If surface dust and impurities are flushed away first, the water collected should be good for domestic use.

Partial runoff areas are hard surfaces such as rocky outcrops, roads and pavements, which allow the collection of up to half the rain falling on the area. Obviously the water will not be as clean as water from total runoff surfaces but, if stored properly, it should be satisfactory for livestock requirements.

Other surfaces include open land surfaces, road drains and ends of ridges. Water from these sources is likely to carry a considerable amount of sediment into the storage, making the water suitable only for crop irrigation.

If wells are dug close to surface water storages they can provide high quality water.

Roof catchments

The advantage of roof catchment systems is that even light rain showers will supply clean water, and the total runoff is easily stored in a tank situated next to the house.

Types of storage for roof catchments

A *granary basket tank* (design by the United Nations International Children's Emergency Fund [UNICEF]) is a type of tank that uses a granary basket of woven sticks as a built-in framework for a cement–mortar plastered tank. The cost of the framework is only the labour of cutting and weaving sticks into an open weave basket. To improve strength and allow the construction of larger tanks, the outside of the basket can be covered with a layer of chicken wire, after which barbed wire is wrapped around with 150 mm spacing before the basket is plastered inside and out.

A rich mortar of approximately 1:3 portland cement-to-sand ratio should be used and mixed with just enough water to make the plaster easy to apply. Without wire reinforcement, the tank size should not exceed a diameter of 1.5 metres and a depth of 2 metres. If it is reinforced with barbed wire, it should not exceed a diameter of 2.5 metres and a depth of 2 metres. A cover is desirable and can be made of mortar reinforced with chicken wire.

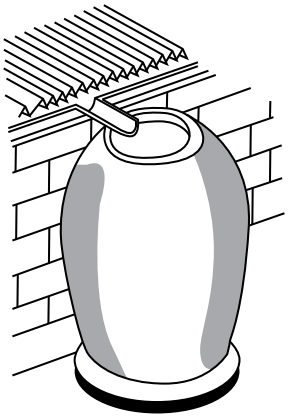


Figure 19.1 **Reinforced mortar tank (courtesy of Erik Nissen-Petersen)**

A *large cement jar* tank is a large bag with a framework made of cloth or sacks and stuffed with sawdust, sand or rice hulls. Mortar is then plastered onto the bag, after which chicken wire and barbed wire are tied onto the plaster, and another layer of plaster is applied. The bag is removed from the inside of the jar after 24 hours, and plaster is applied to the inside to make it waterproof.

The bag can be used to make many water jars, with the result that the cost per tank is minimal. A 1:3 portland cement to sand mortar is essential. The same size restrictions apply as for the granary basket tank. In both the large cement jar tank and the granary

basket tank, the curved sides contribute to the strength and life of the tank. A cover is desirable.

Concrete ring tank sections can be used to form water tanks with a capacity of around 2 000 litres. The small tank volumes are suitable for rain catchment from small roofs scattered around a compound and for areas with relatively even annual distribution of rainfall. A reinforced concrete cover should be installed. Concrete ring tanks are particularly suitable where a form can be obtained for community use. When the casting is carried out on site, expensive transportation is avoided.

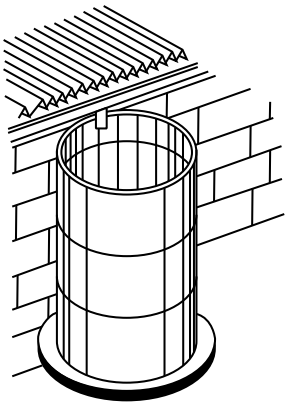


Figure 19.2 **Concrete ring tank (courtesy of Erik Nissen-Petersen)**

A *concrete block tank* must have steel reinforcing incorporated into the walls. Two barbed wires woven completely around the tank and embedded in the mortar between each course of blocks are adequate. The blocks must be of good quality to be relatively impermeable to keep leakage and evaporation to a minimum. The site for a tank of this size must be on firm ground with a reinforced concrete base. If the original ground is sloping, it is necessary to dig out the high area but not to fill in the low side.

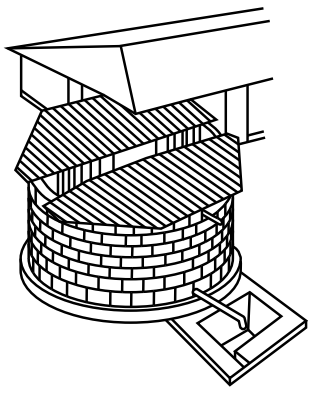


Figure 19.3 **Roof catchment (courtesy of Erik Nissen-Petersen)**

Corrugated galvanized steel tank: The quickest and easiest way of providing roof catchment storage is to buy and install a corrugated steel tank. Although the steel sheets are rather easily damaged, if they are handled carefully and protected from corrosion by coating them both inside and out with bitumen and then installing them on a concrete base, corrugated galvanized steel tanks provide very good storage.

Partial run-off catchments

In areas with heavy rainfall during relatively short periods, the runoff can be considerable if the ground-level catchment areas are well sloped and hard surfaced. While as much as three-quarters of the annual rainfall may be collected from sloping areas, where there is little slope and a permeable surface, only approximately one-quarter can be saved.

To compensate for a gentle slope, a soft surface, or to meet the need for additional water, the catchment area can be extended or covered with a hard surface material. For a small group of farmers, a compound catchment tank can be enough, while dammed reservoirs are more suitable for communal use. Table 19.3 compares different storage systems.

TABLE 19.3
Storage tank selection and sizes

Type	Range of capacity (litres)	Relative cost	Notes
Water jar	< 1 000	Low	No reinforcement needed, filled sack used as form.
Water jar	< 5 000	Low	Reinforced, sack form.
Granary basket tank	< 10 000	Low	Woven stick form, reinforced with chickenwire and barbed wire.
Precast concrete rings	2 000–3 000	Medium	Simple to install. Less expensive if cast on site.
Concrete block	< 20 000	Medium	Requires good base and reinforcing.
Corrugated steel	> 1 000	High	Simple to build, needs good base and corrosion protection.

Storage requirements

If a dependable, continuous source of water is available, no storage facilities are required. However, with an intermittent supply, storage is absolutely essential. The theoretical size of the storage required is determined by multiplying the total daily needs, for the family, livestock and irrigation, by the forecast number of days without rain.

Selection of tank size

This section describes four methods of rainwater roof tank sizing, to answer the question: "What tank size do I need to satisfy my water needs?"

To illustrate these methods, it is assumed that a person uses a minimum of 15 litres of water per day for drinking and cooking. Therefore assuming a family of 8 people:

Daily demand = 8 × 15 = 120 litres

The roof water supply for a given building is estimated by:

Supply (litres) = roof area (m^2) × rainfall (mm) × 90 percent (loss factor)

1. Balance method

This method balances the supply of water with the demand at the end of each month and calculates the storage left in the tank. Assuming that the storage at the end of each month can never be less than zero, this method can be used to determine the minimum tank size needed to satisfy the family's water requirements. Table 19.4 presents the result of using this method, given the data above and the following additional information:

annual rainfall	731 mm
roof area	75 m^2

The basic formula (balance equation) is

$$S_E = S_P + R_M - D_W$$

where:
S_E = Storage at the end of the month
S_P = The amount stored at the end of the previous month
R_M = Monthly rainfall × roof area × loss factor
D_W = Amount of water used by a family in a given period

Using this method, the supply and demand are calculated and the cumulative supply and demand for each month is also calculated. The maximum difference between the cumulative supply and demand is determined either graphically or by calculation. This difference is the optimum tank size. For the balance method, the optimum tank size is 18 060 litres. This can be seen in the column labelled 'cumulative (R_M - D_W)' in Table 19.4.

2. Dry-season storage method

This is perhaps the simplest method for determining the size of a roof catchment tank. First, estimate the longest period during the year without rain. For example: November, December, January and February constitute the dry period in some parts of eastern Africa. This is approximately 120 days without rain.

Secondly, estimate the daily water use. For example, for a family of eight people using 200 litres per day (one drum per day is an average use), the size of storage tank can be determined as follows:

Tank size = Number of dry days × daily water use
= 120 days × 200 litres
= 24 000 litres (24 m^3)

If the annual yield is less than the dry-season storage tank size, the tank will have to be reduced to the value of the annual rainfall yield. For example, if the rainfall is 500 mm per annum and the effective roof area is 40 m^2, a maximum yield of 18 m^3 (500 mm × 40 m^2 × 0.9 = 18 m^3) is obtained. This is less than the ideal tank size, so the tank size would be reduced to 18 m^3.

Using as input the data from Table 19.4, the tank size for this method would be:

TABLE 19.4
Balance method for sizing a roof tank

Month	Average rainfall (mm)	Rainfall supply, R_M (litres)	Demand, D_W (litres)	R_M - D_W (litres)	Cumulative (R_M - D_W) (litres)	Calculated Storage at end month, S_E (litres)
January	45	3 038	3 720	-683	-683	0
February	60	4 050	3 360	690	7	690
March	77	5 198	3 720	1 478	1 485	2 168
April	198	13 365	3 600	9 765	11 250	11 933
May	156	10 530	3 720	6 810	18 060	18 743
June	40	2 700	3 600	-900	17 160	17 843
July	0	0	3 720	-3 720	13 440	14 123
August	0	0	3 720	-3 720	9 720	10 403
September	0	0	3 600	-3 600	6 120	6 803
October	50	3 375	3 720	-345	5 775	6 458
November	45	3 038	3 600	-563	5 212	5 895
December	60	4 050	3 720	330	5 542	6 225
	731	**49 343**	**43 800**	**5 543**		

Dry days = 3 months (July to September) = 92 days.
Tank size = 92 days × 120 litres/day = 11 040 litres
= 11.04 m^3

3. Collecting and storing all the rainfall

This involves collecting all the rainfall from the roof and storing it until there is an acute shortage. This implies that the tank size will be equal to the total supply for the year.

Tank size = Annual rainfall × roof area × 90 percent
= 49 343 litres (refer to Table 19.4 in the column labelled 'Rainfall supply, ')

This method is common in arid and semi-arid land (ASAL) areas, where it may rain only once a year.

4. Graphical method

Figure 19.4 illustrates a method for determining the maximum potential storage capacity using the graphical procedure:

1. Plot the mean monthly rainfall for the area.
2. Calculate the amount of rainfall that can be collected each month. This is determined by the amount of rain that falls and the area of the roof. (For a rectangular roof the area is the length of the roof times the width between the eaves.) Thus the amount of water collected each month is the product of the amount of rainfall and the area of the roof.
3. Starting with the first month after the dry season in which there is a chance to accumulate water in the tank, plot the amount of water that can be collected each month, without regard to the amounts used. In the example, the first month is November.
4. Draw a line from zero on the left to the highest point on the right, making sure the line never goes above the amount of water accumulated to date. The slope of the line represents the average number of litres that can be used daily.
5. Finally, the maximum difference in litres between the water usage line and the water accumulation line indicates the theoretical size of the storage tank required, which in the example is a little over 16 000 litres. It should be noted that these calculations are based on average rainfall records. There will be dry years when the tank will not come close to filling, and other years when water runs to waste from an overflowing tank.

The accuracy of the first two methods depends on the accuracy of the rainfall data. Mean monthly data is used in most cases. However, as there is wide variation in rainfall (mostly in the ASAL area), both geographically and over time, mean monthly data may not reflect the actual rainfall distribution.

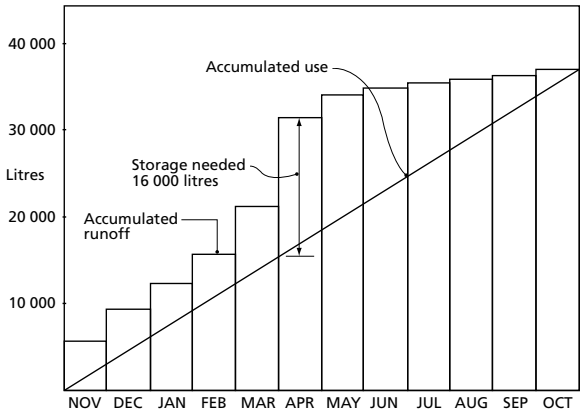


Figure 19.4 **Estimating storage tank size**

The balance method allows for a minimum tank size to be determined to satisfy daily needs and will be of great use in a situation where money for building tanks is limited. It is suitable for the majority of rural people who are interested in rainwater as a clean and safe (and possibly the only) source of water.

The cumulative supply/demand method enables the ideal tank size to be determined, especially where funds are not limited. The dry-days method is quick and easy but does not reflect rainfall patterns accurately. Any method works well only if the following key points for the management of a successful rainwater catchment system are adhered to:

- Install gutters on the maximum roof area.
- Maintain the gutters to collect the maximum amount of rainfall.
- Use the water carefully (economically), especially towards the end of the rainy season when the tank is full, to conserve water for the dry season.
- Clean the gutter and the tank at regular intervals and maintain proper standards of sanitation. If possible, install a foul-flush system or self-cleaning gutters (inlets).

Calculation of tank and reservoir volumes

Roof catchment tank

One of the strongest and least expensive tank shapes for a roof catchment is cylindrical, with a diameter greater than its height. The height is usually determined by the distance between the surface of the tank foundation and the lowest point of the gutters.

The formula for calculating the volume of a cylindrical tank, using interior dimensions, is as follows:

$$V = \pi \times r^2 \times h \times 1\,000$$

where:
V = volume, litres
r = radius, metres
h = height, metres

Example:
Calculate the volume of the tank shown in Figure 19.5

$V = 3.14 \times 2.25^2 \times 2.0 \times 1\,000 = 31\,792.5$ litres

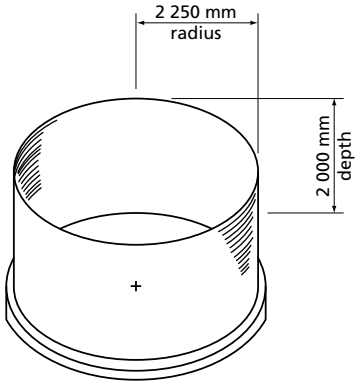


Figure 19.5 **Capacity of a cylindrical tank**

TABLE 19.5
Cylindrical tank capacities in thousands of litres (interior dimensions)

Diameter	Height			
(m)	1 metre	2 metres	3 metres	4 metres
1.0	0.785	1.570	2.356	3.142
1.5	1.767	3.534	5.300	7.068
2.0	3.141	6.283	9.425	12.566
2.5	4.910	9.817	14.726	19.635
3.0	7.070	14.137	21.206	28.275
3.5	9.621	19.242	28.863	38.485
4.0	12.566	25.132	37.700	50.265

Catchment tank for the compound

Where a storage tank must be dug into a relatively level area of ground, an approximate half-sphere shape is easiest. The volume of a half sphere can be found by using its radius in the following formula:

$$V = \frac{2}{3} \times \pi \times r^3 \times 1\,000$$

where:
V = volume, litres
r = radius of half sphere, metres

Example:
Calculate the volume of the half sphere tank shown in Figure 19.6.

$$V = \frac{2}{3} \times \pi \times 2.13^3 \times 1\,000$$

= 20 239.4 litres

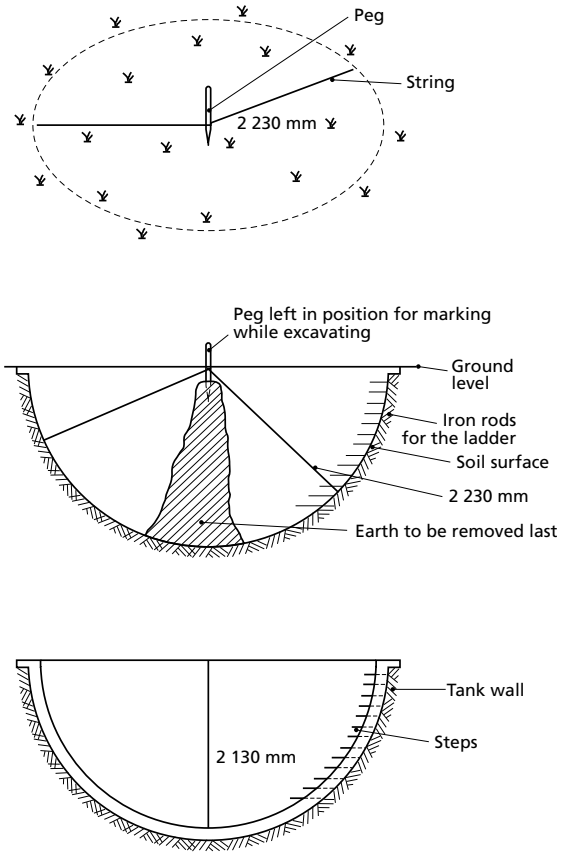


Figure 19.6 **Half sphere tank**

Dammed reservoir

Water that drains from the compound, or from a large area, may be stored in a pond or reservoir behind a dam. It is difficult to estimate the quantity of water behind a dam because of the uneven topography below the water level. Two formulas that will help to make a rough estimate are as follows:

For a long, narrow pond, perhaps a dammed-up stream:

$$V = \left(l \times w \times \frac{d}{8} \right) \times 1\,000$$

where:
V = volume (litres)
l = length of pond (metres)
w = width of pond at dam (metres)
d = depth of pond at dam (metres)

For a circular pond with an area in the middle that is quite uniform in depth, the volume is determined in two steps, and the results are combined.

$V_1 = \pi \times r^2 \times d$

where:
V_1 = volume in uniform depth area (m³)
r = radius of the area of uniform depth (metres)
d = depth of the uniform area (metres)

$$V_2 = \frac{1}{2} \times w \times d \times c$$

where:
V_2 = volume of sloping edges of pond (m³)
w = width of sloping edges (metres)
d = depth (metres)
c = circumference or length of sloping edge (metres) (3 × the diameter is a good approximation)

$$V_t = (V_1 + V_2) \times 1\,000$$

where:
V_t = total volume (litres)

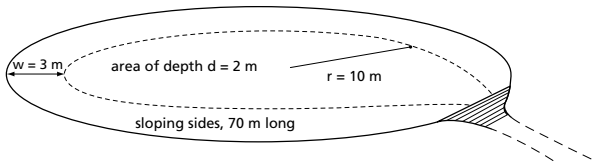


Figure 19.7 **Volume in a circular reservoir**

Example:
Assume a pond roughly 26 metres in diameter with a uniform depth of 2 metres in the centre covering an area estimated to have a radius of 10 metres. The approximate volume can be found using the method described above.

$$V_1 = \pi \times 10 \times 10 \times 2 = 629\ \text{m}^3$$

$$V_2 = \frac{1}{2} \times 3 \times 2 \times 70 = 210\ \text{m}^3$$

$$V_t = (629 + 210) \times 1\,000 = 839\,000 \text{ litres}$$

Plastic-lined reservoirs

One of the easiest and cheapest methods of water storage is a plastic-lined reservoir. It involves excavation of a hole on the ground of a size equivalent to the storage required. Care must be taken to have sloping sides to avoid landslides. Once the reservoir has been levelled smooth to avoid stones and other sharp objects, the plastic lining material is placed in the excavation with a 10 percent allowance for shrinkage.

The plastic is normally 0.5 mm–1.2 mm in thickness and the most common type of material used is high density polyethylene (HDPE). Water can then be stored in the reservoir from roof catchment or ground runoff. To avoid people and animals falling accidentally into the reservoir, it should be covered with an iron sheet roof (which also minimises evaporation) the reservoir must be fenced. When water is diverted from road runoff, a siltation tank as well as a filtration mechanism must be included in the path of the water before it enters the reservoir.

SAND DAMS

The terms 'sand dams', 'subsurface dams' and sometimes 'sand weirs' are often used interchangeably to refer to the same, or different, kinds of structure. In a sand dam, the dam wall protrudes above the surface of the sand, while in a subsurface dam, the dam wall is level with the sand surface. It should be noted that these structures are feasible only in certain areas. The type of soil in an area is important because it determines the types of sediment deposited in a dam and consequently its water storage capacity.

Subsurface dams are used in many parts of the world, including Thailand, Japan, southern India, Arizona, California, Morocco, Algeria and Ethiopia. In the past, people in the Machakos district of Kenya have been known to obtain water from holes dug in dry river beds, usually at a depth of 60–100 cm below the sand surface. They are able to do so because water has been deposited in sand under natural conditions, where there are large natural rock barriers across riverbeds and where the channel gradient is low. This natural phenomenon provides water storage, albeit in limited quantities.

Development of sand dams

Site selection for sand dams
Suitable sites have the following features:

- The river is naturally confined between banks, even when flooding.
- There is a rock bar through the river bed that is not fractured. The rock bar provides the best foundation and reduces the risk of failure.
- The size and shape of catchment should be such that reasonable runoff and recharge rates are obtainable.
- The bedrock should be free from fractures, especially major ones, which may be difficult to seal.
- The width and slope of the river bed should be able to provide adequate sand storage volume.

The design and construction procedure of sand dams is variable because virtually no two sites are the same. Rivers vary in width and discharge, while rock foundations vary in depth and susceptibility to leakage. Riverbanks vary in height, and the need for wing walls has to be carefully assessed. There are predesigned standard cross-sections to be used in the construction

of sand dams. However, the dimensions of a sand dam have to be adjusted to suit the specific site conditions. Provision for a draw-off pipe is made at the bottom of the dam wall. Construction in multiple stages along the river has no significant effect on the quality of the deposits.

Structural design criteria

The conditions prevailing at a selected site for a sand/subsurface dam determine which type of dam and which materials will be most suitable. The criteria include such factors as the height of the river banks, the depth of sand and the cost implications.The height of the dam wall, or crest, for a sand dam is determined by the maximum height of flash floods. The maximum allowable height of the crest of a dam wall is the difference between the maximum flood level and the height of the lowest bank.

Before a choice is made between two sites, the economic viability of a sand/subsurface dam should be assessed based on the expected water yield. For a subsurface dam built of clay, the following specifications must be determined:

- quality of clay;
- location of clay soil;
- thickness of dam wall and its key;
- depth of dam wall into river floor;
- length of key;
- crest of dam wall;
- spillway;
- reinforcements.

Sand dams built of stone masonry are more complicated than subsurface dams in terms of hydraulics, and structural aspects such as structural stability are a major consideration. The dam must have sufficient own weight and a wide enough base to counteract the overturning moments and sliding pressures exerted by water and sand.

The gravity design has proved itself over a period of 40 years. In the design:

Base width = 0.75 × height of dam wall from its base
Crest width = 0.2 × height of dam from its base

Estimating the yield of water from a sand dam

The extractable yield of water can be estimated using the following procedure:

1. Volume of sand in reservoir.
This is given by: (length × maximum width × maximum depth) divided by 3.

2. Porosity or water-holding capacity of sand.
The test procedure is as follows:

(a) dry the sand until all moisture is removed;
(b) fill a container of known volume with the dried sand;
(c) pour a measured volume of water into the sand until the sand is fully saturated;
(d) upon full saturation of the sand, record the total volume of water poured into the sand.

Then porosity = volume of water required for full saturation of sand (litres) × 100 percent total volume of dried sand sample in the container (litres)

3. Extractability of water from sand

This is given by:

Total volume of water flowing out of container (litres) × 100 percent
Total volume of dried sand sample in container (litres).

Methods for abstracting water from sand dams

Scoop holes

The most common and simplest method of extracting water from sand dams is to use scoop holes. Separate holes are dug for people and livestock. As the water level goes down during the dry season, wider holes are required to avoid the risk of sand caving in. This method of water extraction is risky to both people and livestock, inefficient and encourages contamination of the sand-dam water.

Shallow wells

The shallow-well abstraction method is an improvement on the scoop-hole method above. The well should be sited high enough to prevent river water from entering during peak flow. The location should be on one side of the river, and between 10–20 metres upstream of the dam wall. Scoop holes near the dam wall can serve as livestock watering points without any danger of polluting the shallow well-water source. Water can be abstracted from wells using a simple rope and bucket, a windlass or a hand pump.

Draw-off pipes

Draw-off pipes are passed through the bottom of the dam wall. They have been largely unsuccessful because of poor operation and management of the tap and intake components.

Quality status of water from sand dams

Water stored in sand dams is assumed to be of suitable quality for drinking because of the filtration process it undergoes in the sand reservoir. However, the chemical quality is usually localised and more dependent on hydrological factors. Sand filters are capable of purifying the water bacteriologically, as well as physically. Slow sand filtration has proven efficient in improving the physical, chemical and bacteriological quality of surface waters and in removing turbidity, tastes and odours.

How to ensure that the quality of water in sand dams is maintained

River barrages increase the quantity of water available, but other measures are needed to improve the quality of water. Although water drawn from scoop holes may look reasonably clean, it is likely to contain pathogenic micro-organisms. The following measures are suggested to protect against contamination:

- Keep the places where livestock come to drink separate from places where people extract their water.
- Construct pit latrines at all homesteads so that runoff water does not carry human waste into the river during rainy periods.
- Boil water for drinking.

ROCK CATCHMENT DAMS

A rock catchment is a reservoir located on a bare rock surface with sufficient surface area to capture enough rainwater in the rainy season for use during the dry season. The rock catchments may be natural or artificial. Natural rock catchments are formed when weak rocks are embedded in resistant rock.

When weathering occurs, the weak rock is removed, leaving a depression in the resistant rock. These depressions act as reservoirs. It is important for the base of the reservoir to be free from cracks or permeable rocks. Essentially, the only way in which rocks can act as natural reservoirs is where there are depressions in the rock.

There are three types of artificial rock dam. All types of artificial rock dam have a water trapping/diversion mechanism, a route through which water flows to the storage and a storage tank. The methods used to trap water depend on the shape and orientation of the rock catchment.

When the rock has a flat, sloping surface similar to a roof or is dome shaped, water may be harvested using flat stone gutters constructed around the surface. As there is no large storage surface behind the stone gutters, it is usually necessary to construct a storage tank for the harvested water. When the rock has a valley or funnel-shaped depression, a long wall may be built across the valley to trap water. It may be necessary to include a spillway in the design, which will guide any overflow into a tank.

The third type of artificial rock dam is similar to the second type, apart from the fact that it has a ferrocement roof above the dammed water. The purpose of this roof is to minimize evaporation (as these dams are usually constructed in arid areas) and to prevent the entry of dust, insects and birds.

WELLS

A properly constructed and protected well can provide an excellent source for domestic water needs. The terms *borehole well*, *dug well* and *tube well* describe the manner in which water is reached. A borehole well is drilled with a cable or rotary drill. It is small in diameter and can be 200 metres or more in depth. A dug well is a hole dug with a diameter large enough to allow a man to work, usually to a maximum depth of approximately 30 metres. A tube well is a perforated pipe with a pointed end, which is either hammered or jetted into the ground.

When a well is less than 7 metres deep, it is called a shallow well, and when it is more than 7 metres deep, it is called a deep well. An earth well is unlined; a masonry well is lined with concrete blocks or stone; and a sinking well casing is constructed and sunk in stages from the ground level as the well is being excavated.

Location of well site

Water may often be found in one of the following locations:

1. Near a pond or reservoir.
2. In the foothills near mountains, and especially near green trees or holes dug by animals.
3. In areas of green vegetation during drought.
4. Near existing wells or waterholes.
5. In sandy river beds, especially upstream from bedrock, where temporary wells may be dug.

Types of well casing

There are several methods of constructing well casings; the choice depends on the purpose, soil structure, water source and local skills.

An *oil barrel* can be used to form an inexpensive well casing. The barrels are perforated to allow the entry of water. The life of this casing will be shorter than with other materials, and the residue in the barrels may pollute the water, making it unfit for domestic use.

A *ferrocement* well is a type of earth-wall well that is excavated to a straight and smooth surface, which is then plastered with a layer of mortar, reinforced with chicken wire, and finally plastered a second time. A wellhead is built above ground level to limit the risk of children and animals falling into the well. To prevent contamination of the well, a concrete apron sloping away from the wellhead is constructed on the surrounding ground.

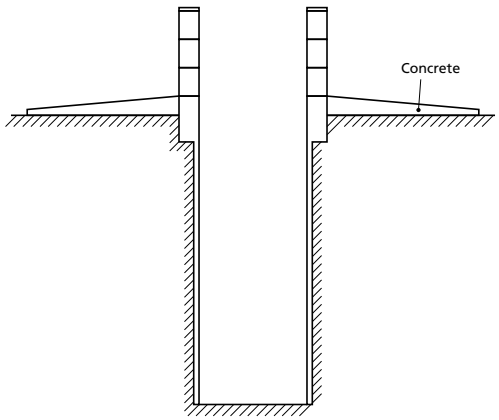


Figure 19.8 **Ferrocement well (courtesy of Erik Nissen-Petersen)**

Sinking wells are so named because the casing is sunk into place. The method works well in sandy soils. Figures 19.9 and 19.10 show casings that can be sunk into place.

A *concrete ring well* is a method that requires either a steel casing ring mould for casting the concrete rings on site, or precast rings purchased and transported from the factory to the construction site. While both these alternatives are expensive for a single well, they are feasible when a number of wells are being constructed in a local area. The rings, measuring 0.9 metres in diameter and 0.5 metres in height, are stacked on top of each other in an excavated well hole, or they can be used for sinking wells, or for a combination of the two procedures.

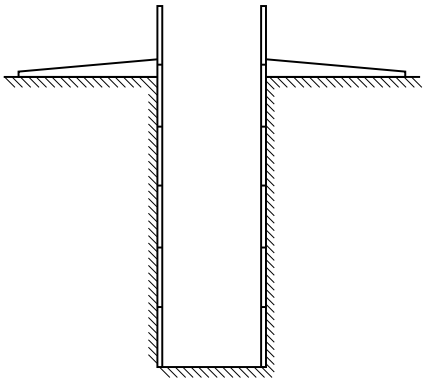


Figure 19.9 **Concrete ring well (sinking well)**

A *concrete block well* is a less expensive alternative to concrete rings, using concrete blocks that have been shaped in a wooden form. These blocks are stacked on a concrete foundation ring, which can be cast in a wooden form or, more cheaply, in a hole in the ground at the construction site.

With either type of casing, the whole structure will be allowed to settle by digging out soil from under the bottom of the casing. When the top of the well casing has reached the surface of the surrounding soil, another section is added to the top. Thereafter, digging is repeated until another section can be added onto the well at ground level, and so on until a satisfactory depth has been reached. The blocks must be tied together with vertical reinforcing rods to ensure that the casing sinks as a single unit.

Lift for wells

The simplest means of lifting water from dug wells, such as a rope and calabash or a bucket and windlass, have been used for centuries and, unfortunately, they continue to be used today in many parts of the world. The objection to their use is that, all too often, they are a source of pollution because the top of the well is open and the water vessel is frequently set down on a badly polluted surface. An improvement on these methods uses a bucket with a hose attached to the bottom and to an outlet at the wellhead, as shown in Figure 19.11. When the bucket is lifted, water is discharged from the outlet while the top of the well remains covered.

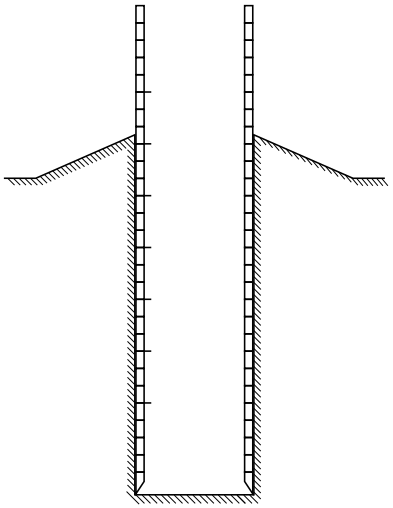


Figure 19.10a **Concrete block well (sinking well)**

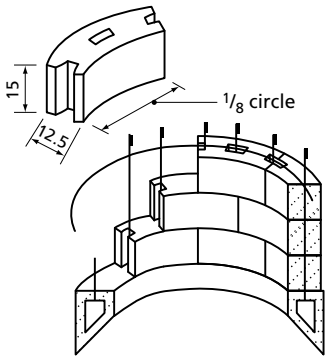


Figure 19.10b **Section of foundation and reinforcement (courtesy of Erik Nissen-Petersen)**

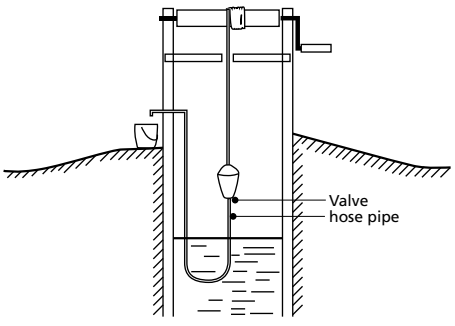


Figure 19.11 **Bucket lift in closed well (courtesy of Erik Nissen-Petersen)**

PUMPS

A pump is the most convenient and sanitary means of lifting water from a well or any other low-level water supply. Pumps may be hand- or power-operated, designed to lift only, or to lift and discharge against pressure, and to lift from either shallow or deep wells.

As mentioned earlier, shallow wells are those in which the low water level is 7 metres or less below the pump. In deep wells, the water level may drop well below the 7-metre mark. The maximum suction lift for shallow-well pumps of any type is reduced by approximately 1 metre for every 1 000 metres of site elevation.

Hand pumps

The simplest hand pump, often referred to as a pitcher pump, is satisfactory for use on wells or cisterns in which the water never needs to be lifted more than around 6 metres. A cross-section of a pitcher pump is shown in Figure 19.12. If pitcher pumps are maintained in good condition, they are easily primed and will hold their prime from one use to the next. However, if the valves leak, the pump will need to be primed each time it is used. Not only is this a nuisance, it can also be a source of pollution from the priming water.

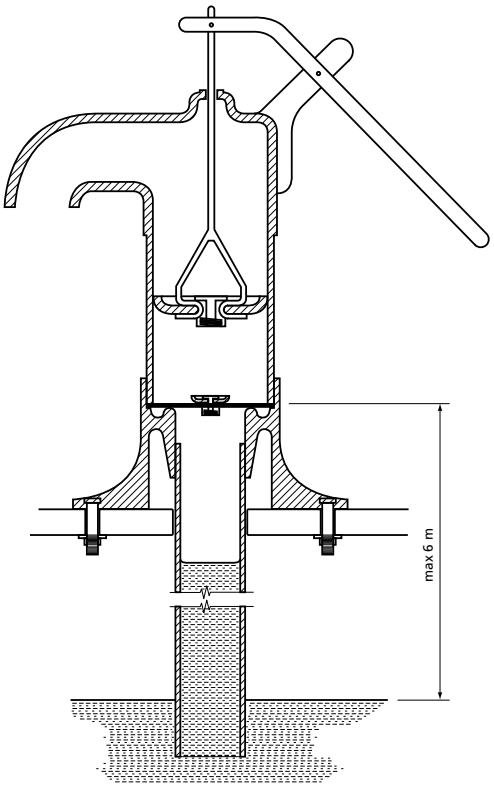


Figure 19.12 **Shallow-well handpump**

Water from deep wells is lifted with a similar plunger-type pump in which the cylinder, including the plunger and valves, is supported on the discharge pipe deep enough in the well to be submerged in water at all times. The pump handle is connected to the plunger by means of a long rod. While this type of pump is self-priming because the cylinder is submerged in the water, it must nevertheless be maintained in good condition to work effectively. Figure 19.13 illustrates a deep-well pump. Both of these pumps allow the well top to be completely covered for maximum protection against pollution.

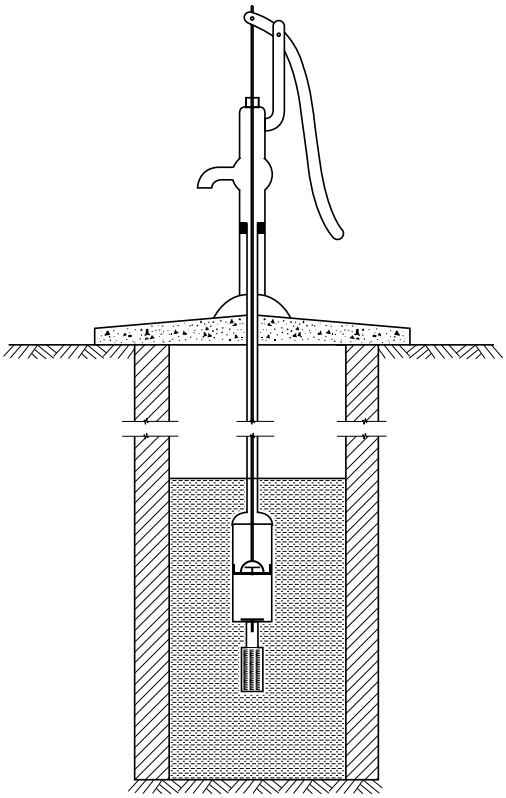


Figure 19.13 **Deep-well handpump**

Occasionally it is necessary to use a hand pump to force water above the level of the pump. Models are available with packing around the lift rod and a pipe connection at the point of discharge, enabling them to force water to a tank higher than the pump. An even more sophisticated model is equipped with a small 'differential' cylinder that causes the pump to discharge on both the up- and down-strokes.

Power-driven pumps

There is a selection of pumps on the market to suit different applications. They all have characteristics that influence their suitability for a specific water supply, as well as the volume and pressure required.

Centrifugal pumps are simple (with only one moving part), durable and relatively inexpensive for a given capacity. However, they are suitable only for low lifts of 3–4 metres and are prone to losing their prime unless the suction pipe is equipped with a good foot valve

(check valve). They will not discharge against a very high head (pressure).

There are several centrifugal pumps designs that further complicate the choice. The impeller may be an open type with a relatively large clearance between it and the casing, or it may be a closed type with very small clearances. The open type will tolerate sand or silt in the water much better than the closed-impeller type (see Figure 19.14 and Figure 19.15).

A centrifugal pump may have an integral electric motor or a petrol-powered engine, which the manufacturer will have sized correctly, or it may have a belt drive. If it has a belt drive, great care must be taken to drive the pump at a suitable speed and with a motor or engine of adequate power.

As with the propeller fans described in Chapter 13, centrifugal pumps have volume, pressure and power requirement characteristics that vary with speed, as follows:

- The volume changes directly with the speed.
- The maximum pressure changes directly as the square of the change in speed.
- The power required changes directly as the cube of the change in speed.

This means that, for a pump designed to run at 2 000 rpm and to be operated by a 1 000 W motor, if the motor pulley is exchanged for one that is 1.5 times the original diameter, the pump will then turn at 3 000 rpm. The corresponding changes in volume, maximum pressure and power required will be:

- Volume = 1.5 times greater.
- Maximum pressure $(1.5)^2 = 2.25$ times greater.
- Power $(1.5)^3 = 3.375$ times greater.

Consequently, the motor will be badly overloaded and may be damaged.

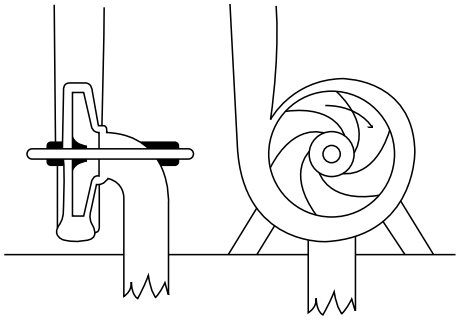


Figure 19.14 **Open impeller**

Jet pumps are centrifugal pumps for a shallow well that may have a jet (ejector) built into the pump housing. This will improve both the lifting and discharge efficiency. Shallow-well jet pumps are suitable for lifting up to approximately 6 metres.

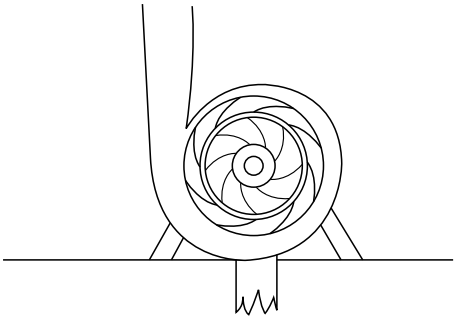


Figure 19.15 **Closed impeller**

A deep-well jet pump will have the ejector installed below the low-water level in the well. Two pipes of different dimensions connect it to the pump, which may be located at the top of the well or even some distance to one side. The smaller of the two pipes carries water to the ejector, while the larger one delivers water to the pump housing, where most of the water is discharged, but some is returned to the ejector. These deep-well jet pumps are suitable for wells in which the water level drops to 30 metres. The correct ejector for maximum efficiency is chosen on the basis of the lowest expected water level in the well (see Figure 19.16).

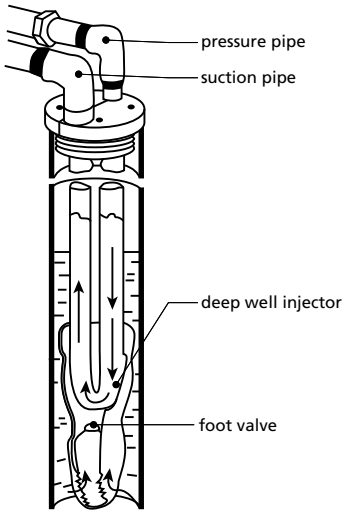


Figure 19.16 **Deep-well jet**

Deep-well turbine pumps are multistage centrifugal pumps that may be driven either by a long vertical shaft from a drive head at the top of the well or by a submersible motor below the pump in the well. These shaft-driven units are large, expensive pumps designed to supply sizeable volumes of water for irrigation or community use.

On the other hand, the submersible pump is available in a range of sizes and is an efficient, trouble-free design for medium-sized installations. Obviously

it is a major operation to remove the pump from the well if something goes wrong. It should be noted that the motor is installed below the pump to ensure that, if the water level is reduced to the pump level, the motor will still be submerged in water, which is essential for cooling.

Reciprocating pumps are available for both shallow wells and deep wells. They are capable of delivering water at quite high pressures. The shallow-well type is usually reasonable in cost, but the deep-well type tends to be expensive and must be installed over the top of the well.

In *diaphragm pumps*, the piston and cylinder are replaced by a diaphragm. As there are no sliding parts to wear, diaphragm pumps are suitable for pumping muddy water or high-moisture slurries, such as the waste from a biogas generator (see Figure 19.17). These pumps may be either hand- or power-operated.

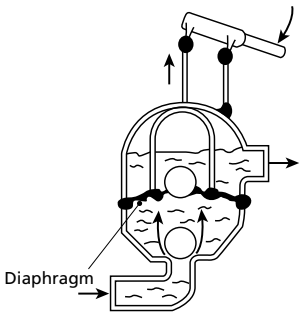


Figure 19.17 **Diaphragm pump**

Hydraulic rams require no electricity or human power to operate, relying instead on the energy from flowing water. A minimum flow of 10 litres per minute, with a head of at least 1 metre, is required. As water flows through the ram, the waste valve opens and closes alternately. Each time the valve closes, water is forced up the delivery pipe by the inertia developed in the flowing water, which is abruptly stopped when the waste valve closes. Small quantities of water are thus lifted well above the original source. A ram can be useful for pumping domestic or livestock water to a storage reservoir.

Commercial rams are available in a number of sizes, with supply-flow rates of 10–400 litres per minute, and can discharge to maximum heights of 100–150 metres. Although a ram will operate with as little as 1 metre of head, larger heads will increase discharge rates considerably, e.g. increasing the supply head from 1 metre to 10 metres can increase delivery by a factor of 20. Before purchasing a ram it is necessary to know the flow rate of the water supply and the head available. Although the initial cost is substantial, maintenance is low, life is long and the operating cost is nil so, if suitable natural conditions are available, a hydraulic ram can be a very good investment.

Choosing a pump

Five main factors must be considered when selecting a pump:

1. The total water required per day.
2. The maximum rate of flow desired.
3. The maximum flow from the water source.
4. The vertical distance the water must be lifted to the pump.
5. The total head against which the pump must operate.

The terms 'head' and 'pressure' are used interchangeably. The unit of measurement for pressure is the pascal (Pa) while the unit of measurement for head is the metre (m). One metre of water column equals

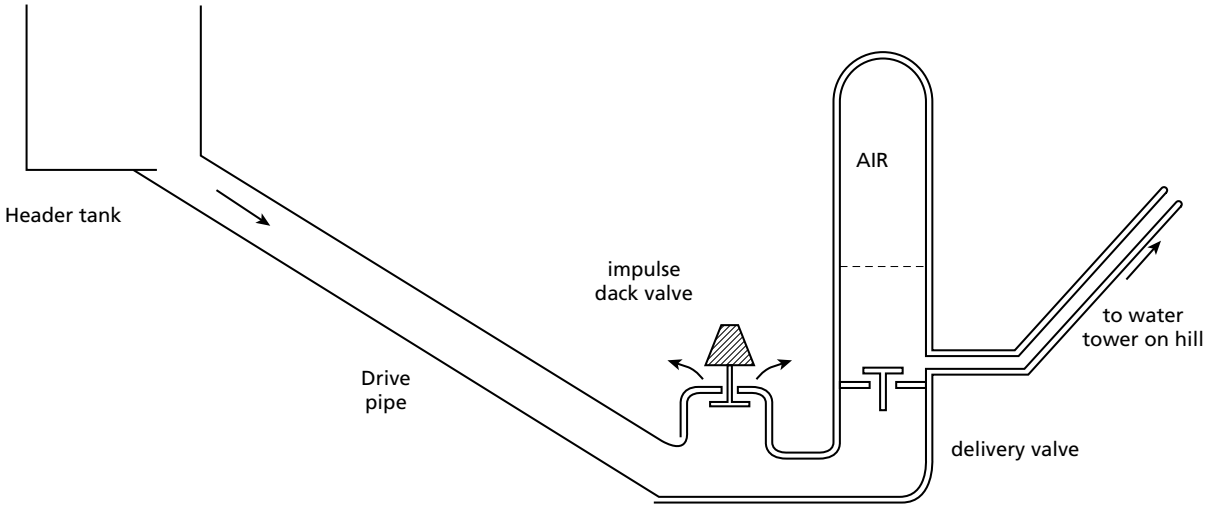


Figure 19.18 **Hydraulic ram**

9.8 kPa. Head is frequently used in discussing pump installations because there will be vertical distances from water level to pump, and from pump to point of discharge. Pipe friction tables are often given in terms of loss of head per unit of pipe length.

The daily water requirement influences pump size, as it is desirable for the pump to operate no more than 25 percent of the time.

The maximum rate of flow is determined by totalling suitable flow rates from all the discharge openings that may be operating at one time. If the source of water is a dug well, pond or stream, the desired flow rate can be used when choosing a pump. However, if the source is a borehole or driven well with very low storage capacity, there is no alternative but to choose a pump with a capacity that does not exceed the flow rate of the well.

The vertical distance between low-water level and the location of the pump is the primary factor governing the type of pump chosen, although the total head is also significant. Total head is made up of: (a) lifting head from well to pump; (b) vertical discharge head from pump to point of use; (c) working head or pressure at the point of use; and (d) friction losses from the flow through pipe and fittings.

Pump storage tanks

Regardless of the type of pump chosen, it must either discharge into a tank or have an open-pipe discharge into an irrigation channel. Operating any of the centrifugal pumps against a closed line results in overheating and damaged shaft seals. Operating a reciprocating pump against a closed line will result in a stalled motor or the physical breakage of some part of the pump.

Hydropneumatic systems

Hydropneumatic systems consist of an enclosed tank combined with an automatic pressure switch that turns on the pump motor when tank pressure drops to a preset level. As the tank is approximately half full of air, several litres of water can be pumped into the tank before the air is compressed and the stock cut-off pressure is reached. The amount of water pumped into the tank can then be used as required before the pump needs to operate again. There are several advantages to the hydropneumatic system:

(a) The tank can be located in any convenient place.
(b) Optimum discharge pressure is available at all times.
(c) The system is completely automatic.
(d) The tank may be relatively small.

As air is soluble in water, a small, continuous supply of air is required to prevent the tank from becoming waterlogged. Each type of pressure pump discussed will have an air-volume control suitable for its mode of operation to provide the necessary supply of air. Alternatively, tanks may be equipped with rubber air bags or foam plastic floats for permanent air retention.

The operation of a pressure tank is governed by the universal gas law, which states that:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

where:
P = absolute pressure (Pa)
V = volume (litres)
T = absolute temperature (K)

Although it is the water charge and discharge that is of interest, it is the pressure and volume of air that must be considered. Although the operation of the tank is essentially an isothermal process (constant temperature), as fresh water is pumped into the tank the temperature is likely to change a little. For optimum operation, the tank should be approximately half full at the cut-in pressure. Water-system problems are discussed later.

TABLE 19.6
Pump applications

Type of pump	Vertical distance from pump to water	Quantity of water required	Operating pressure	Applications
Centrifugal	Up to 4 metres	Large	Low	Stock or irrigation
Shallow-well jet	Up to 6 metres	Medium	Medium	Domestic or stock
Deep-well jet	6–30 metres	Medium	Medium	Domestic or stock
Shaft-driven deep-well turbine	4–40 metres	Large	Low to high	Irrigation
Submersible deep-well turbine	6–40 metres	Medium	Medium	Domestic, stock, irrigation
Reciprocating shallow-well	Up to 7 metres	Low to medium	Medium	Domestic, stock
Reciprocating deep-well	6–40 metres	Medium	Medium to high	Domestic, stock
Diaphragm	Up to 5 metres	Medium	Low	Slurries
Hydraulic ram	(- 1 metre)	Small	Medium	domestic

Gravity system

A second system for storing pumped water is a gravity tank, with the pump operation controlled either manually or by a float switch. The tank must be elevated above the highest point of water use, frequently on the roof of the building where the water is used. The tank is usually considerably larger than a pressure tank. This is an advantage in that, in the event of a power failure or pump breakdown, there will be a larger reserve of water available for use. However, the need to support a large tank on the roof requires strong structural supports that will add to the cost of the installation. Finally, water pressure is seldom very high and may be barely adequate near the level of the tank.

Pipe flow

If the rate of water flow in a pipe system remains constant, the equation of continuity of flow applies:

$$Q = A \times V$$

where:
Q = flow (m³/s)
A = cross-section area (m²)
V = velocity (m/s)

If the area of the pipe is halved, the velocity of flow will double, and so on. Although the velocity is not uniform across a cross-section of the pipe because of the friction affect of the pipe walls, average velocity is used for calculations.

Friction losses occur when water flows through a pipe. The amount of loss is related principally to pipe size, velocity of flow and the roughness of the interior pipe surface – and to a lesser extent to temperature. As the friction is proportional to the square of the velocity, the resistance, which is small at low velocities, builds up quickly as the velocity increases.

Roughness in pipes can change with age. Galvanized steel pipes may form rust or scale with age, increasing the roughness and friction and reducing the rate of flow. A smooth pipe, such as one made from plastic,

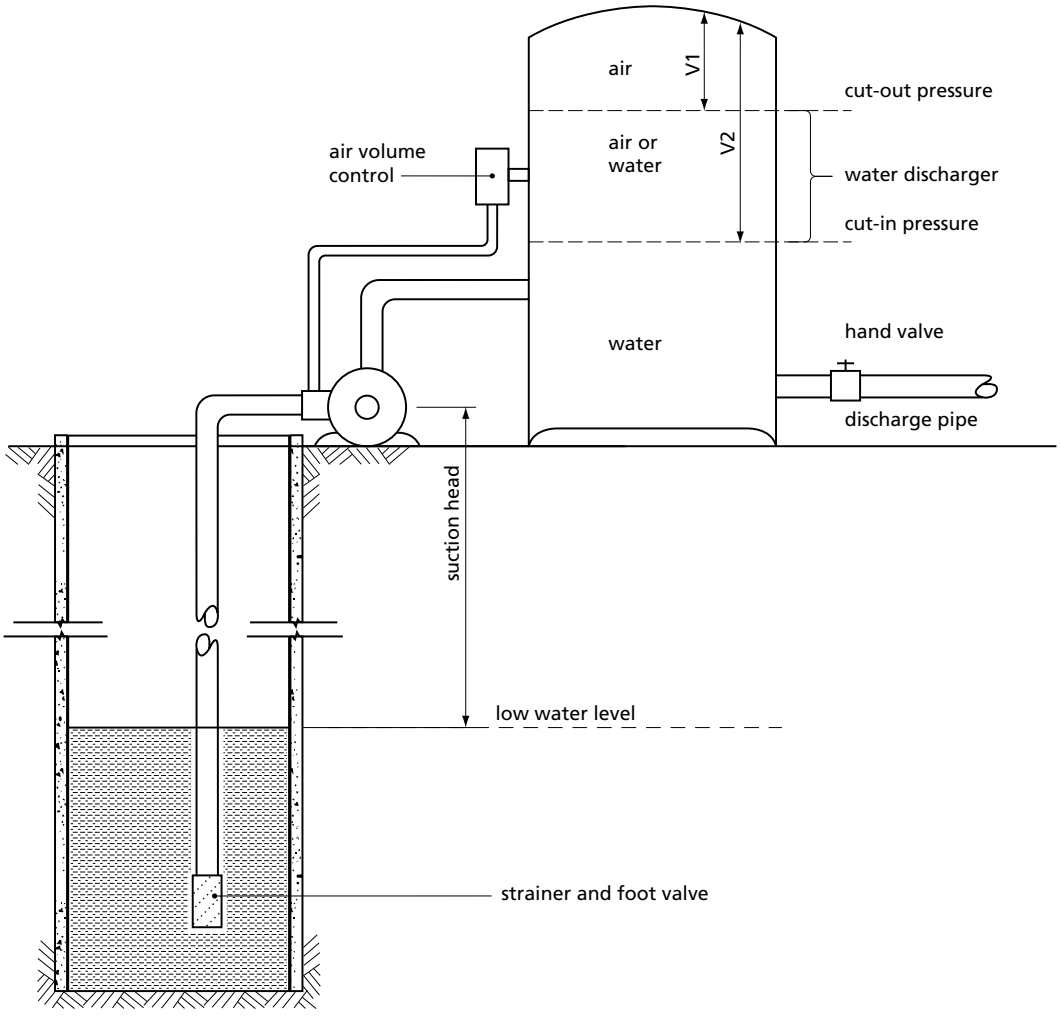


Figure 19.19 **Hydropneumatic water system**

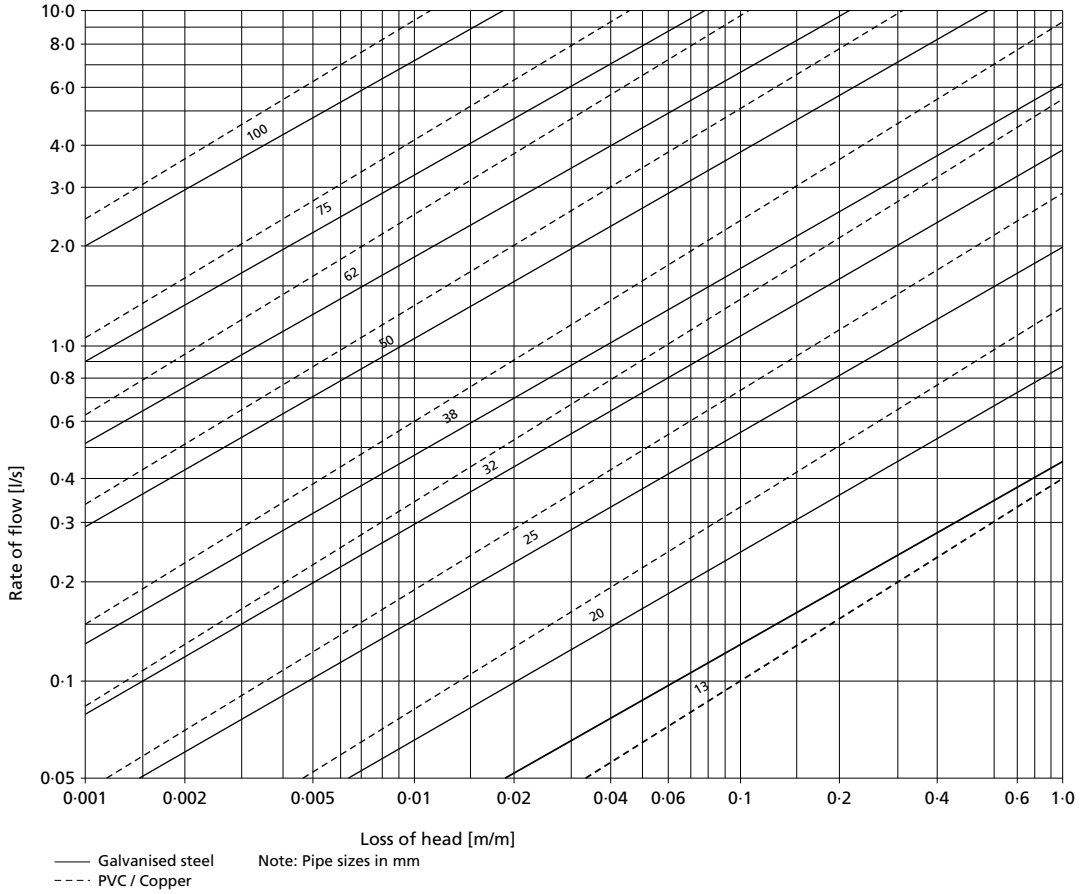


Figure 19.20 **Friction losses in pipes**

generates less friction than a pipe with a rough surface, such as concrete.

The length is directly proportional to the friction head in pipes. Figure 19.20 gives the loss of head for both smooth and rough pipes of several sizes and for a range of flow rates.

Other losses can occur when water flow in a pipe is interrupted by passing through fittings, or from one pipe size to another, where there will be a friction loss. This results from turbulence in the flow, which uses up energy, with the result that more energy must be used to produce a higher pressure at the start of the pipelines. As friction loss is proportional to the square of the velocity of flow, it can be ignored at low velocities, such as in drainage pipes.

However, friction loss can be significant in high-pressure irrigation lines or water-supply systems, especially if there are a large number of fittings. It is common practice to add 10 percent to the friction loss of the pipes to allow for all the various fittings.

Water-system problem

Example:
It is necessary to design the water system for domestic and stock watering for a family of five people who keep 3 zebu cows and 10 goats. The water will be pumped from a dug well that is 3 metres below and 5 metres away from where the pump will be located. The pump will need to discharge into the storage tank at a minimum of 300 kPa of pressure. The discharge from the tank between cut-out and cut-in pressure should be approximately one-twelfth of daily water consumption, so that the pump will operate no more than 12 times per day.

Water will be discharged from the tank at a distance of 50 metres to a single tap, and the head loss at a flow of 1 litre/second should not exceed 10 percent of the average pressure. The pump dealer has advised that the pumps are approximately 75 percent efficient in terms of power demand, and the electric motors are 85 percent efficient.

Determine the following:

1. Total daily water consumption (maximum flow 1 litre/second)
2. A suitable type and capacity of pump
3. A suction pipe sized to have a friction head of 8 percent or less of the suction head
4. An adequate tank size
5. A suitable discharge pipe size
6. A motor size capable of driving the pump.

1. From Table 19.1, a single water tap supply indicates 10–20 litres/day per person. Choose 20 litres.
   From Table 19.2, local cattle require 20 litres/day and goats require 3 litres/day.

   5 people × 20 = 100 litres
   3 cows × 20 = 60 litres
   10 goats × 3 = 30 litres

   Total daily needs are 190 litres at 1 litre/second maximum flow

2. The lift from well to pump is low (3 metres) and the water demand is low. Choose a shallow-well jet pump with a 1.2 litres/second capacity. The extra capacity will allow for some loss of capacity caused by wear over the life of the pump.

3. Calculate the loss of head per metre of suction pipe.

   3 m × 0.08 = 0.24 m/8 m of pipe = 0.03 m/m. From Figure 19.20, the intersection of 1.2 litres/second and 0.03 m/m head loss is 38 mm plastic pipe. Choose a 38 mm PVC suction line.

4. Tank size: 190/12 = 16 litres discharge/cycle. Choose a pressure range of 200–300 kPa; atmospheric pressure equals 100 kPa.

   $P_1V_1/T_1 = P_2V_2/T_2$, but assume $T_1 = T_2$

   $V_2 = V_1 + 16$ as P_1 drops to P_2
   $400 \times V_1 = 300 \times (V_1 + 16)$
   $100 \times V_1 = 4\,800$
   $V_1 = 48$ litres
   $V_2 = V_1 + 16 = 48 + 16 = 64$ litres
   V_2 = should be around half of the tank size
   Approximate tank size = 2 × 64 = 128 litres.

5. Average pressure at the tank is (200 + 300) / 2 = 250 kPa (1 metre of head = 9.8 kPa), therefore 250 kPa = 25.5 metres of head 25.5 × 10 percent = 2.55. Which gives:

   2.55/50 m/m = 0.5 m/m allowable loss at 1 litre/second flow.

   From Figure 19.20, 20 mm PVC pipe is small but 25 mm PVC pipe is satisfactory.

6. Power to lift water from the well and overcome all head at a flow rate of 1 litre/second is as follows:

   Total head = 3 + 0.24 + (300 / 9.8) + 2.55
   = 36.4 metres of head

   1 litre water = 1 kilogram mass and gravitational force = l kg × 9.8 m/s^2
   Force required = 1 kg × 9.8 m/s^2 = 9.8 N
   Work done = 9.8 N × 36.4 m = 357 Nm

   As this amount of work is done each second,

   power = work/second = 357 Nm/s or watts (W)
   356 / 0.75 pump efficiency = 475 W input required by pump
   475 / 0.85 motor efficiency = 560 W input to motor
   560 / 220 V = 2.5 amp running current, which gives:

   2.5 × 2 = 5 amp starting current.

Summary of requirements

1. Total daily water consumption: 190 litres at 1 litre/second.
2. Jet pump with minimum capacity of 1.2 litres/second at 36 metres total head.
3. 38 mm suction pipe (PVC).
4. Tank size: approximately 128 litres.
5. 25 mm discharge pipe (PVC).
6. Motor of 560 W minimum input.

Water system design features

1. Even if the home water system consists of only one tap near the house, a complementary drainage system is essential. A pit 1 metre square and 0.5 metres deep, filled with stones or gravel, should be constructed under the tap to carry off leakage and spillage without creating a muddy area.
2. Perhaps the second step in the development of a rural home water system is the installation of a solar water heater. This can be as simple as a black 208-litre oil drum installed on the roof, either refilled periodically from the tap or connected permanently by a branch pipe from the water supply line. A combination of a check valve in the supply line to the water heater and a pressure safety valve at the tank is advisable. Although the check valve will prevent warm water from draining back into the cold-water line when pressure is low, a safety valve is absolutely essential when the check valve is used to prevent excessive pressure build-up from hot water.
3. If an extensive home water system is planned, complete with toilet, shower and sinks, it is prudent to plan a good drainage system at the same time. Soakaways are necessary for disposing of shower and sink water, unless the water must be saved for irrigation or stock watering, in which case a collection tank should be constructed. It is best to treat waste from a toilet in a septic tank, with the effluent allowed

to soak away into a pit or drainage field. These systems will be discussed later.

4. Pipe materials for cold water may be either plastic (PVC or high-density polythene) or galvanized steel. Although steel is more expensive and difficult to work with, it is not easily damaged. Galvanized pipe has a relatively short life when exposed to acid water, but lasts very well when the water is neutral or slightly alkaline.
5. Pipe of 20–25 millimetres in diameter should be used as a main supply line, but 13 mm will be adequate for branches to sinks, shower and water closet. Each branch should have a shut off valve to facilitate repair work.
6. Tropical areas are normally an ideal place in which to make use of solar water heating. Two square metres of properly positioned collector should heat 20 litres or more to 45–50 °C on most sunny days. Solar heaters are discussed in greater detail in Chapter 20.

WATER TREATMENT

The preferred way to obtain pure water is a safe water source that is well protected from pollution. A good example would be a tube well 20–30 metres uphill from any pollution, and equipped with a pump, a tight-fitting cap and a well designed apron. Unfortunately, good sources of water are not always available, and some treatment will be advisable. Four methods are discussed briefly.

Boiling

A 208-litre oil drum may be cleaned and then mounted horizontally over a brick fire box, as shown in Figure 19.21. A tap should be fitted at the bottom of one end and the tank should be set at a height to allow enough clearance to place a bucket under the tap. The tank should not be filled completely and the filler plug should never be installed tightly. Water should be boiled for 15–20 minutes and 1–2 litres should be drawn from the tap during the boiling process. Once cooled, the 200 litres should provide enough drinking water for several days.

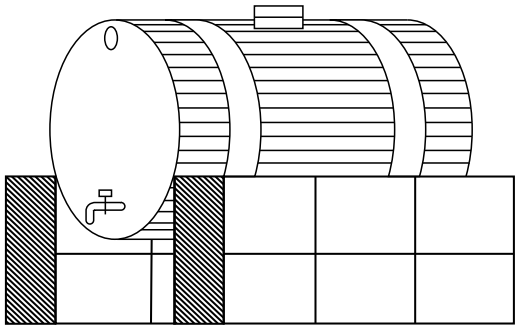


Figure 19.21 **Water boiler**

There are a number of filter designs that will clarify water and remove some bacteria. They all require periodic cleaning, the difficulty of which depends on the size and type of filter.

A medium-sized upward-flow sand filter can be effective in reducing suspended solids, and is easy to clean and maintain. The filter containers can be made either from either 208-litre drums, or from 175–200-litre concrete tanks made by using a hessian bag filled with sand or sawdust as a form and applying mortar over it. If good quality mortar is used, small tanks will not need reinforcing.

A filter cross-section is shown in Figure 19.22. Successive layers, first of stones then gravel, coarse sand and fine sand, are placed in the tank until it is around half full. A layer of charcoal, crushed to approximately 5 mm in size, is desirable, as it will trap bacteria, which is helpful in removing disease-carrying micro-organisms from the water. The charcoal bed is enclosed with thin cloth and weighted down by a top layer of sand.

Water poured into the top tank flows through the tube to the bottom, where it percolates up through the gravel, sand and charcoal and out through the hose to a water jar. Before being used, some water should be passed through the filter to make sure that the filter is working properly. The drain plug at the bottom should be large so that, when it is removed, water will flow back through the sand rapidly and flush away all accumulated sediment. Experience will indicate when back-flushing is necessary.

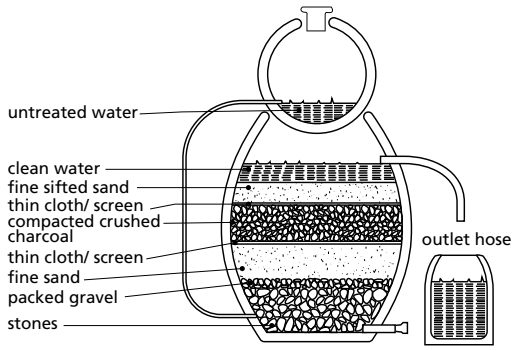


Figure 19.22 **Upward-flow water filter for filtering up to 40 litres per day**

Chlorination

Proper attention to detail is needed to make a satisfactory job of chlorination. However, proper chlorination can make drinking water much safer. After adding the correct amount of chlorine material, thoroughly mix it into the water and allow it to stand for at least 30 minutes.

Treatment levels are given in parts per million (ppm): 1 mg/m^3 equals 1 ppm. Water that is clear and not suspected of dangerous contamination can be treated with 5 ppm of active chlorine. If the water is a

TABLE 19.7
Sources of chlorine for water treatment

Compound	Active chlorine percentage by weight	Quantity of chlorine to add to 100 litres to obtain the following concentration (grams)			
		5 ppm	10 ppm	15 ppm	50 ppm
HTH $Ca(OCl)_1$	70	8	15	23	80
Chlorinated lime	25	20	40	60	200
Sodium hypochlorite (NaOCl)	14	38	75	113	380
Sodium hypochlorite	10	48	95	143	480
Laundry bleach	5.25	95	190	285	950

little cloudy, 10 ppm is safer. Sources of chlorine vary considerably in terms of the amount of active chlorine available. Table 19.7 gives information about several materials.

While these quantities may be reduced proportionally for smaller quantities of water, measurements become more critical for amounts under 100 litres, and it is advisable to ask a pharmacist to weigh out several packages of treatment material in quantities appropriate for the quantity of water to be treated each time.

The 50 ppm column in Table 7 is the level at which to treat a new or repaired well or cistern. This dosage is left to stand for 24 hours before flushing out.

Water treatment by solar disinfection (SODIS)

This is by far the cheapest and most effective means of water treatment in tropical rural areas. It involves placing water in a transparent bottle, painted black on one side, and exposing it to tropical sunlight for several hours. It is more environmentally friendly than boiling because boiling involves the use of energy from burning wood.

SODIS (or SOlar DISinfection) is a treatment method used to eliminate the pathogenic micro-organisms that cause waterborne diseases. It is ideal for disinfecting the small quantities of water used for consumption and depends on solar energy alone.

The treatment process is a simple technology using solar radiation to inactivate and destroy the pathogenic micro-organisms present in the water. The best use of solar energy is the combined application of two treatment processes. First, boiling water to kill micro-organisms; second, using the UV radiation from the sun to kill micro-organisms. In combination, they are sufficient to sterilize the water.

Basically the treatment consists of filling transparent plastic (PET) or glass bottles with water and exposing them to full sunlight for approximately five hours. To absorb more heat and raise the water temperature, the bottle is painted black on one side and placed on a black surface, in the sun, with the clear side facing the sun. The recommended exposure time is 5 hours under bright sunlight or a 50 percent cloudy sky, or two consecutive days under a 100 percent overcast sky.

OPEN CHANNEL FLOW

A knowledge of the principles of open channel flow is necessary when designing ditches to carry water into grade-level storage and channels to carry away storm water without causing erosion. The same principles apply to the design of irrigation canals, road splashes and drifts. The most common problems are:

1. Estimating the flow in a channel when the cross-section, gradient, depth, etc. are known or can be measured. This is useful in planning irrigation canals, ditches, and natural watercourses.
2. Estimating the depth of flow at which a given channel will carry a given rate of flow. This can be useful in estimating how high a river flood crest will rise, or how deep the flow will be in an irrigation channel or over a drift.
3. Designing a channel to carry a given rate of flow. This is useful in designing channels to carry storm runoff away from buildings or other structures.
4. Designing a channel to carry an estimated maximum flow, when the velocity must not exceed a given maximum value. This is a problem of designing stormwater diversion drains or other unlined channels when the velocity must be low enough to avoid scouring of the channel. A suitable cross-section and gradient must be chosen.

The quantity of water flowing in an open drainage channel is the product of the cross-section area of the channel and the speed of flow.

$$Q = A \times V$$

where:
Q = flow in cubic metres per second (m^3/s)
A = cross-section area of the channel (m^2)
V = average velocity of flow (m/s)

If the velocity is measured at any cross-section in a channel, the water will be found to flow more slowly along the sides and bottom. This is caused by frictional resistance, and is more pronounced in vegetated channels than in paved channels. However, in practice a theoretical average velocity is used.

The equation of continuity shows that, for a constant discharge Q, the velocity must change inversely with the section area of the channel.

$$Q = A_1 \times V_1 = A_2 \times V_2 = A_3 \times V_3$$

There are two types of flow in a channel, which may give the same discharge but at different velocities and depths. A rapid, shallow flow is called a *supercritical* or shooting flow. A deeper, slower flow is called a *subcritical* flow. An example of each type of flow is found on a dam spillway. The thin layer rushing down the spillway surface is supercritical flow. After hitting the standing wave at the bottom, the water moves away much more slowly in a subcritical flow. In general, supercritical flow should be avoided, as erosion will occur in all channels that are not lined with concrete.

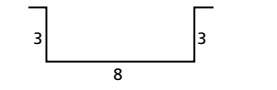
The velocity of flow in a channel is determined by the gradient, the shape and size of the cross-section and the roughness of the surfaces. Obviously, the velocity will be greater in steep, smooth channels. Not so obvious is the fact that two channels with the same cross-section area, but with different shapes, can have different velocities. This results from the different amounts of surface contact and frictional resistance.

The effect of cross-section shape is measured by the hydraulic radius of the channel (R). It is found by the equation:

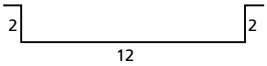
$$R = A / P$$

where:
R = hydraulic radius (metres)
A = cross-section area (m²)
P = wetted perimeter (metres)

The wetted perimeter is the length of the cross-section in contact with the water. Figure 19.23 illustrates the effect of shape on the hydraulic radius. While both channels have an area of 24, the upper channel has a larger hydraulic radius.



R = 24/14



R = 24/16

Figure 19.23 **Channels of equal area but with different hydraulic radii**

When other factors are equal, the channel with the larger hydraulic radius will have the higher channel velocity.

The two most common shapes for earth channels are shown in Figure 19.24. The trapezoidal shape has a tendency to gradually change to the parabolic shape over a period of time.

The variables that affect the velocity of flow are related, as shown, in the empirical equation called the Manning formula for open channel flow.

$$V = \frac{1}{n} \times R^{2/3} \times S^{1/2}$$

where:
V = velocity (m/s)
R = hydraulic radius (m)
S = gradient (m/m)
n = Manning's roughness coefficient

$$R = A/P$$

where:
A = cross-sectional area (m²)
P = wetted perimeter (m)

TABLE 19.8
Value of Manning's roughness coefficient (*n*)

(a)	*Channels free from vegetation*	(*n*)
	Uniform cross-section, regular alignment, free from pebbles and vegetation, in fine sedimentary soils	0.016
	Uniform cross-section, regular alignment, few pebbles, little vegetation, in clay loam	0.020
	Irregular alignment, ripples on bottom, in gravelly soil or shale, with jagged banks or vegetation	0.025
	Irregular section and alignment, scattered rocks and loose gravel on bottom, or considerable weed on sloping banks, or in gravelly material up to 150 mm diameter	0.030
(b)	*Vegetated channels*	
	Short grass (50–150 mm)	0.030–0.060
	Medium grass (150–250 mm)	0.030–0.085
	Long grass (250–600 mm)	0.040–0.150
(c)	*Natural stream channels*	
	Clean and straight	0.025–0.030
	Winding, with pools and shoals	0.033–0.040
	Very weedy, winding, and overgrown	0.075–0.150

Extracted from *Field Engineering for Agriculture Development* by Hudson.

With the Manning formula, any three variables can be used to find the fourth variable. When, for example, R, S and n can be measured or estimated, it is possible to calculate velocity.

While open-channel problems may vary in detail, the principle is usually the same. The designer has some fixed quantities, such as a given discharge to be carried, and some variables, such as gradient and velocity, which have restricted ranges. These can be used to determine a size and shape. Usually there is no single solution but a range of satisfactory alternatives.

TABLE 19.9
Maximum channel velocities in metres per second (cover after two seasons)

	Vegetative cover		
Soil	**Bare**	**Medium grass**	**Long grass**
Light, silty sand	0.3	0.75	1.5
Coarse sand	0.75	1.25	1.7
Firm clay loam	1.0	1.7	2.3
Coarse gravel	1.5	1.8	-
Shale, hardpan	1.8	2.1	-
Rock	2.5	-	-

TABLE 19.10
Design velocities for grass waterways (m/s)

	Slope		
Soil	**0–5%**	**5–l0%**	**10%**
Erosion-resistant veils	2.0	1.75	1.50
Erosion-prone soils	1.75	1.50	1.25

Source: Department of Conservation, Government of Zimbabwe

Example:
An earth- or grass-lined channel should be designed with a flow velocity fast enough to avoid sediment deposits. but not so fast that erosion will occur. Table 19.9 suggests maximum velocities for various channel soils and vegetative covers.

For convenience, Figure 19.25 may be used to solve open channel flow problems. For example, assume a channel is to be designed for a firm clay–loam soil with a medium grass cover (200 mm) to be established. The maximum expected flow is 2.0 m³/s and the gradient is approximately 0.025 m/m. Choose a channel shape and determine a satisfactory size from Table 19.8; read a value for roughness coefficient (n) of 0.030–0.085; choose 0.04.

From Table 19.10, read 1.7 m/s acceptable velocity.

From Figure 19.25, read 0.30 metres hydraulic radius.

Choose a parabolic shape arbitrarily.

$A = Q/V = 2 / 1.7 = 1.18$ m²
$P = A/R = 1.18 / 0.30 = 3.93$ m
$P = t + (8d^2 / 3t)$, (assume a value for t of 3.75 metres)
$d^2 = (P - t) \times 3t / 8$
$d^2 = (3.93 - 3.75) \times 3 \times 3.75 / 8 = 0.25$
$d = 0.5$ m
$A = (2 / 3)\ td$
$A = (2 / 3) \times 3.75 \times 0.5 = 1.25$ m²

which is close to the previous $A = 1.18$ m²

In summary, a parabolic-shape channel 3.75 metres wide and 0.5 metres deep will be satisfactory.

RURAL SANITATION

When dealing with the problems of poor sanitation in the rural areas of developing countries, it might be tempting to assume that improved technology is the answer, e.g. the assumption that new latrines will provide the required 'technological fix'. However, technology alone does not solve everything, for it has been found that newly built latrines may not be fully utilized and, when used, may not reduce significantly the diseases caused by poor sanitation.

Good sanitation depends on people and how they organize hygiene-related activities. It depends on a large 'package' of hygiene measures, and latrines are

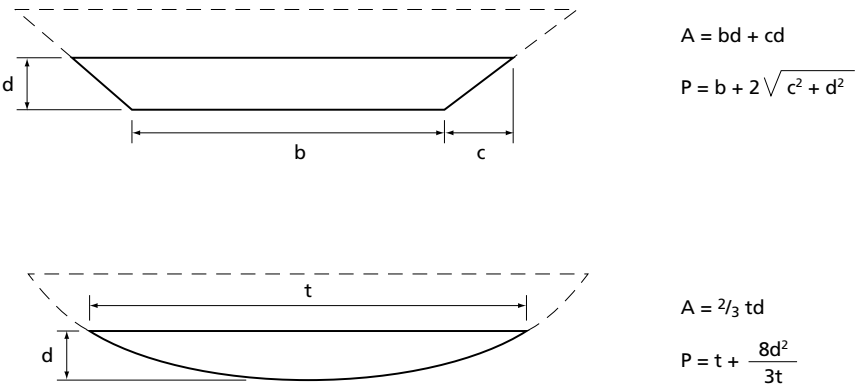


Figure 19.24 **Basic dimensions of common channel sections**

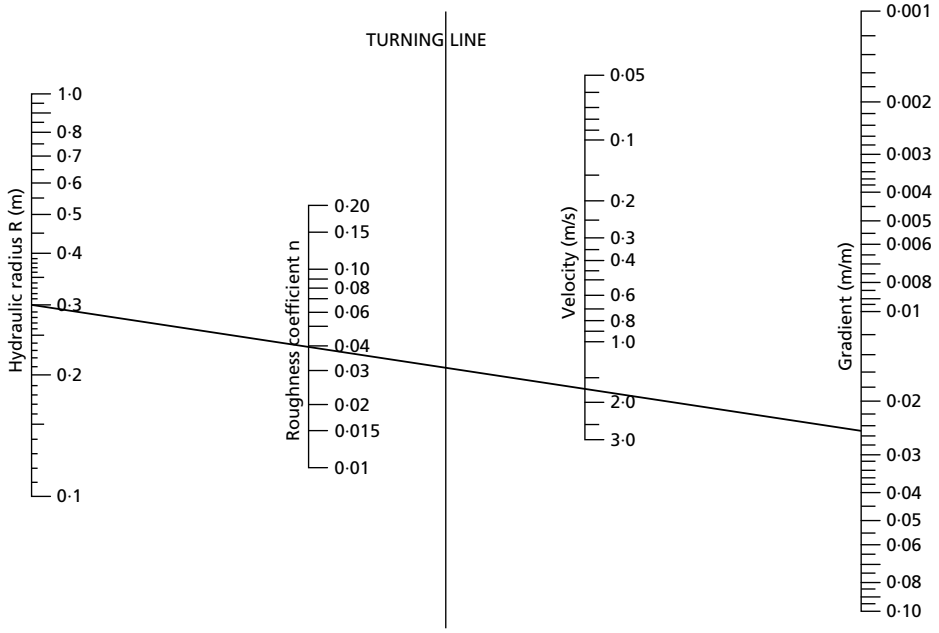


Figure 19.25 **Nomograph for Manning's formula**

only a part of this package. Technology does have a part to play, and many rural communities need basic technical assistance. While latrines may not always be a practical solution, if they are, they must be designed carefully to suit local cultural patterns.

Wastewater treatment and sanitation

A rainbow of water

It is common practice in in the field of water and sanitation to refer to different types of water as different colours:

- Green water refers to the direct use of rainwater by plants after it has been stored in the soil's unsaturated zone.
- Blue water refers to the combination of surface water and renewable groundwater. Blue water is the water that can be managed by engineering interventions and that can be allocated, reallocated and measured by traditional monitoring.
- White water is either the part of the rainfall that feeds back directly to the atmosphere through evaporation from bare soil, or rainfall that is intercepted for human use, such as from roof catchments. Together, white and green water form the vertical component of the water cycle, as opposed to blue water, which is horizontal.
- Black water is wastewater from the toilet.
- Grey water is wastewater from washing, bathing, washing of clothes and from the kitchen, which can be reused in agriculture or industry. It can also be processed into drinking water, often after mixing with blue water.
- Ultraviolet water represents 'virtual water', which is invisible but detectable. It is the amount of water used in the production of water-consuming products, in its widest sense. Grains, produced under proper conditions, use approximately 1–2 m^3 of (often green) water per kilogram. The trade in grain is a trade in 'virtual' water.

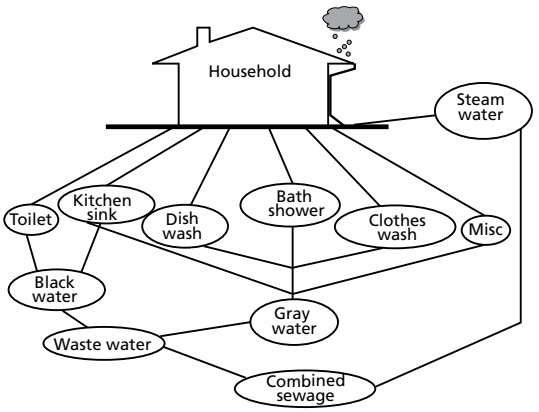


Figure 19.26 **Sources of household wastewater (International Environmental Technology Centre of the United Nations Environment Programme [UNEP–IETC], 2000)**

Wastewater can be divided into grey water and black water. Grey water consists of the wastewater from washing/bathing, washing of clothes and from the kitchen, while wastewater from the toilet is called black water. Storm water also contains solids and pollutants

that have been picked up from the surfaces it flows over, and therefore also requires treatment. Storm water collection is important from the standpoint of flood control. If wastewater is combined with storm water it is called combined sewage.

The main aim of wastewater treatment is to reduce the Biological Oxygen Demand (BOD) and Suspended Solids (SS) to acceptable levels. Normally BOD is reduced to less than 20 mg/litre, and SS to less than 30 mg/litre. SS is removed by filtration and sedimentation. BOD is mainly reduced by aerating the water. However, anaerobic treatment may also be used to recover energy. If the wastewater is discharged into bodies of water that are sensitive to nutrients, the nutrients should also be removed. Pathogenic and faecal indicator micro-organisms need to be reduced to acceptable levels to ensure that they will not pose any threat to human health.

Different treatment techniques can be adopted, depending on land availability and on the quantity and characteristics of the wastewater. Treatment plants, which are used for treating sewage, usually employ biological processes. The process is dependent on natural micro-organisms that utilize oxygen and organic contaminants in wastewater to generate CO_2, sludge and treated water.

The following guidelines should be followed for rural treatment systems:

1. Do not mix different kinds of waste. Collect solid wastes, wastewater and storm water separately, but have an integrated plan to deal with them.
2. Promote a low-cost, decentralized wastewater treatment system.
3. Develop norms based on existing standards for reuse of treated water for non-potable applications.
4. Water under or near a pit or septic tank can become polluted. To prevent this, septic tanks should be located 15–20 metres away from the nearest water supply point, and 3 metres from the nearest house.
5. Kitchen waste should be separated from animal and toilet waste to ensure hygiene.

Classification of wastewater treatment methods

Wastewater can be treated on-site or off-site. The common on-site treatments are:

- pit latrines and pour-flush latrines;
- composting toilets;
- septic tanks and Imhoff tanks.

Common off-site treatment systems include:

- activated sludge treatment;
- trickling filtration;
- constructed wetlands;
- simple anaerobic systems;
- upflow anaerobic sludge blanket (UASB);
- lagoons or ponds;
- decentralised wastewater treatment systems (DEWATS).

Pit latrines

Many latrine designs can be built in areas where more sophisticated sanitary systems are not possible. The simplest design is the pit latrine, with certain characteristics that are common to the many variations of this design. A latrine should always be dug at least 30 metres downhill from a well, if the well is the source of the family water supply. However, in areas where the water table is very high, the distance should be increased to 200 metres or more. The latrine should also be at least 10 metres from the nearest house or kitchen.

While a pit a little less than 1 metre in diameter is sufficient, an oval pit measuring 0.7 metres by 1.5 metres will provide more convenient space for the person digging. The depth is at least partially dependent on the stability of the soil, and therefore on how deep the hole can be dug without danger of a cave-in. While a depth of 4–5 metres is normal in stable soil, an increase to 7 metres will reduce the problem of flies. In areas with a high water table, the depth may have to be decreased because, in order to avoid pollution, the bottom of the pit should be no less than 1 metre above the highest groundwater level. A pit with a diameter of 90 cm that is 5 metres deep will last for around five years if used by a family of six people.

The desired depth and the character of the soil will determine whether a stabilizing liner is necessary. Most latrines should have a block or brick liner for at least the top 1 metre. To install a stabilizing liner, a hole is dug a little less than 1 metre deep and approximately 1 metre in diameter, and lined with concrete blocks or bricks. After curing for a few days, the balance of the pit can be dug out, taking care not to make the diameter too large, allowing the blocks to sink. If the soil is sandy, a complete liner may be necessary. Bamboo is one possibility for lining the remainder of the pit sides.

A simple floor to cover the pit can be made of bamboo or timber. However, cast concrete provides a much more durable and sanitary slab. See Figure 19.28 and the accompanying paragraphs for the design and construction of a two-piece cast concrete slab that includes footpads and a slope toward the hole. The type of structure built above the slab to give privacy is largely a matter of personal preference. Bamboo, offcuts, concrete blocks or corrugated steel are all possibilities for wall construction. Corrugated iron sheets or thatch may be used for roofing.

A desirable feature to include is a vent pipe. A vent will not only reduce odours but, if screened at the top, it will catch numerous flies. The vent hole can be cast in the slab so that the vent is just outside the toilet hut. For optimum effectiveness, the vent should be located on the side facing the prevailing sunshine, should be as large in diameter as possible, should be

painted black and should have a screen over the top. This combination of design features tends to produce a significant air current that carries off odours and traps flies. Figure 9.27 shows a latrine of this type.

The vent pipe can be made at low cost using hollowed bamboo, but alternative materials, such as masonry, cement/sisal, reeds/mud, PVC or galvanised iron, can also be used. A piece of glass fitted at the base of the vent pipe will provide light to attract flies away from the squatting hole and will trap them in the vent pipe.

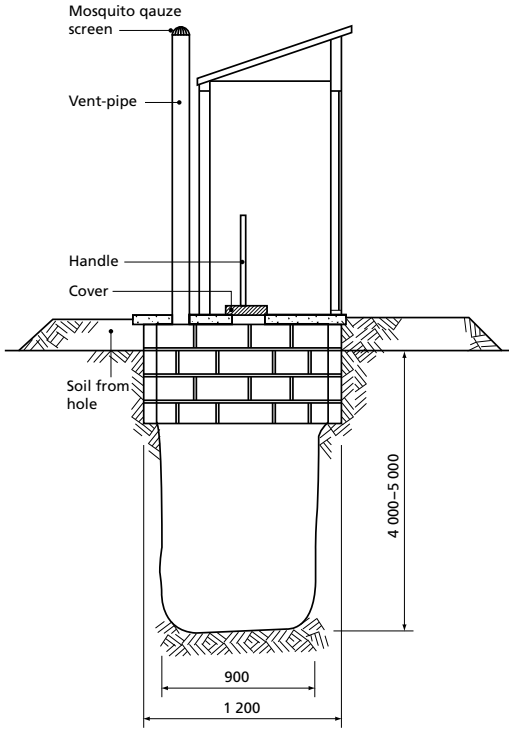


Figure 19.27 **Pit latrine with vent pipe**

Latrine slab

The latrine slab can be cast to provide a perfectly satisfactory two-piece slab that is easy to handle. First, a small mould is constructed to cast the footpads, which should be approximately 10 cm by 30 cm by 2 cm, with rounded corners. The footpads are cast a few days prior to casting the slab and are stored in a bucket of water to cure. The form for the slab is then built using four boards measuring 7 cm by 120 cm and any convenient thickness. A round block 5 cm thick and 10–12 cm in diameter, and a rectangular block measuring 10 cm by 20 cm by 5 cm, are needed for the hole. If a vent pipe is to be installed, another 7 cm thick round block will be needed, with a diameter to match that of the pipe.

Two screeds are required: one straight and the other curved enough to be 1–2 cm lower in the middle. Three pieces of polythene are cut to the lengths required to serve as separators between the two halves of the slab (See Figure 19.28, section B–B). Six pieces of 8 mm reinforcing rod, cut to fit tightly into the form, are also needed. Find a flat surface (a floor or levelled earth), spread a piece of polythene and position the form and the wood blocks on it. Mix a 1:3 cement-to-sand concrete (or 1:2:2 cement–sand–small gravel), using just enough water to obtain a workable mixture.

The polythene separators are then positioned, and a uniform 2.5 cm layer of concrete is placed on either side. The reinforcing bars are then fitted, as shown in Figure 19.28, section A–A. Next, the form is filled, and the concrete is compacted and levelled with the straight screed. Then, using the curved screed in the middle one-third of the form, work out from the centre of the concrete in both directions to give the sloping surface. Smooth lightly with a steel trowel. Place the dampened footpads in place, working them into the surface slightly. Use any excess concrete to cast a pad to be laid just outside the privy entrance.

After all signs of free water have disappeared from the surface, finish the concrete with a steel trowel. Cover and keep damp for several days. Handle with care. A number of variations and refinements in latrine use and design may be considered.

Placing a thick pad of grass in the bottom of a newly dug latrine and then adding some vegetable waste regularly will turn the latrine into a compost pit, with a substantial reduction in odour. When the pit is full, it is necessary to dig a new latrine hole and move the slab and hut. The full hole is covered and left for at least six months, after which the compost may be removed and used as fertilizer.

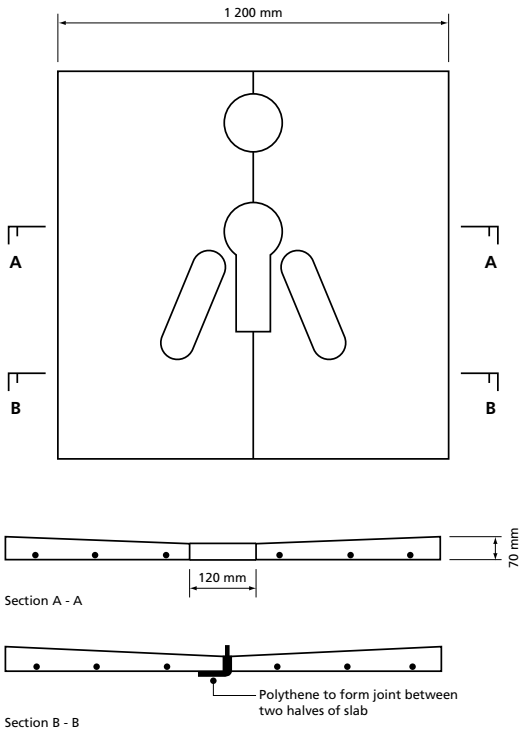


Figure 19.28 **Concrete slab cast in two pieces**

Aqua privies

Aqua privies are usually equipped with either a water-trap hole or a discharge below water level. Either of these alternatives will reduce odours considerably. However, some water must be added daily for complete decomposition of the waste, and a soakaway pit is essential to dispose of the effluent that is discharged (see Figure 19.29).

One way to ensure that extra water is added each day is to combine a bath house with the privy. Figure 19.30 shows the plans for such a combination. In the illustration, a separate soakaway is shown for the bath, as it is combined with a pit latrine. However, if it were combined with an aqua privy, the water would be directed into the privy tank.

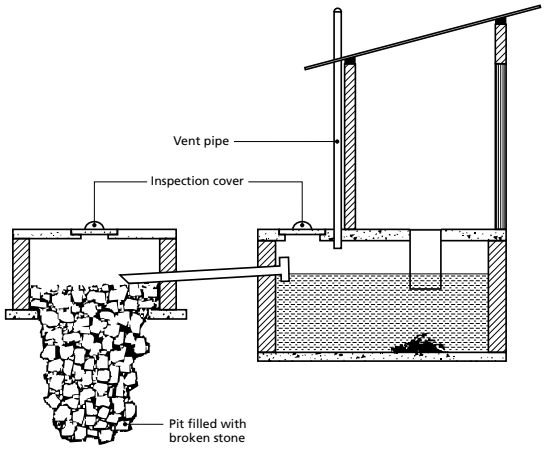


Figure 19.29 **Aqua privy with soakaway pit**

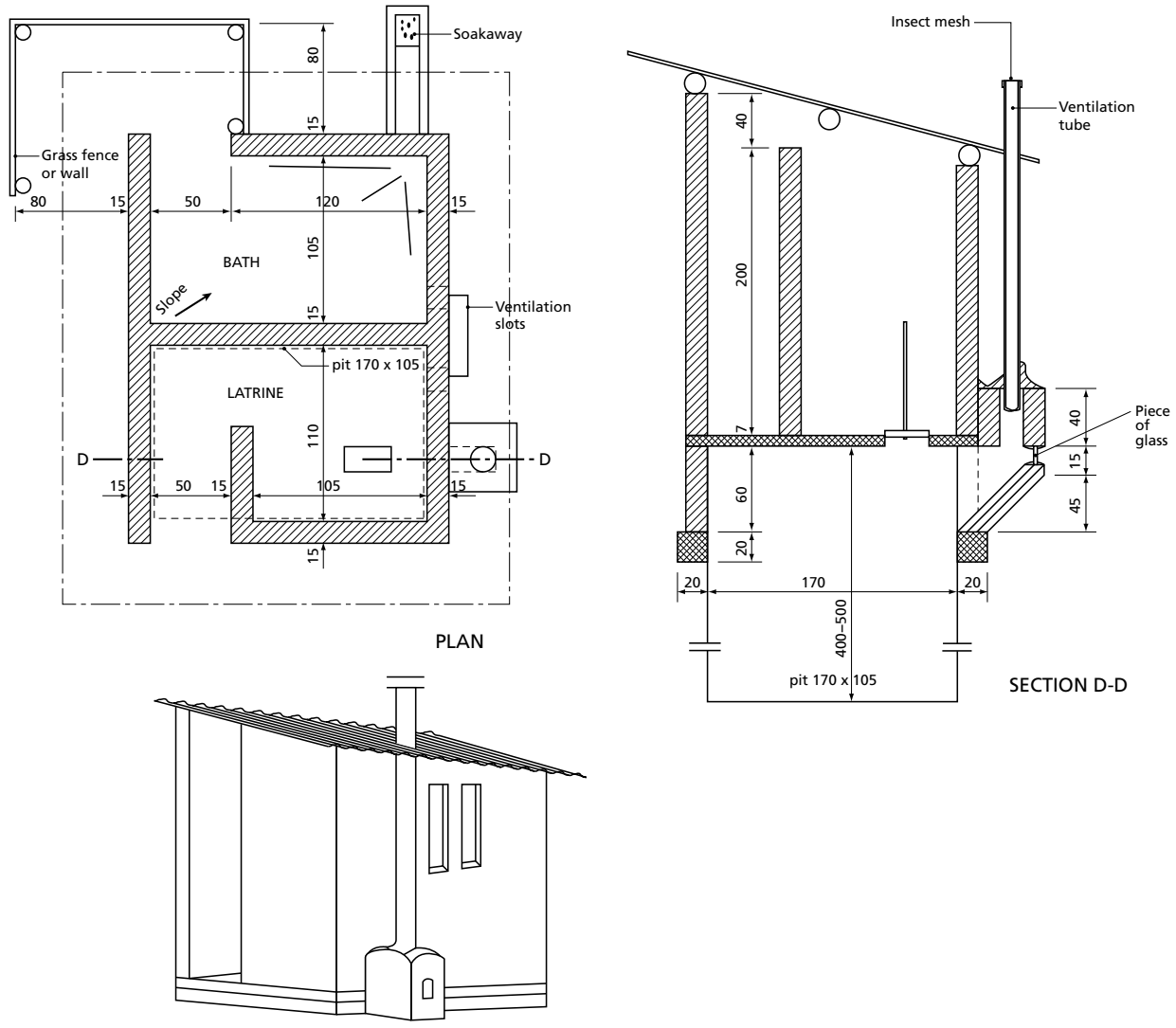


Figure 19.30 **Bath house and latrine (all dimensions in centimetres)**

A bath house is an inexpensive but convenient additional facility for a family, either with or without piped water.

A farm home with an adequate and continuous water supply can be equipped with a water closet toilet. A water closet system uses a much larger quantity of water than the other systems mentioned, and requires the installation of a septic tank, plus a large soakaway or drainage field, to handle the considerable amount of effluent.

Septic tanks

The septic tank is a large concrete or concrete-block tank, the base of which is at least 150 cm below the inlet and outlet level. The raw sewage flows into the tank through an open tee, and the effluent leaves the tank through a similar tee. The tank is divided by a wooden baffle that extends from 50 cm above the bottom to 25 cm above the sewage level. A heavy scum forms on the surface and all digestive action is by anaerobic bacteria, i.e. bacteria that live and multiply without the presence of air. Figure 19.31 shows a cross-section of a septic tank.

Soakaway trenches

The effluent from a properly operating septic tank will be almost free of solids, and further biological activity in the soakaway trench, or pit, will be aerobic in nature, i.e. some air needs to be present. Therefore, trenches with a depth of approximately 50 cm are preferred over deep pits. Before a tank and soakaway system are installed, it is important to check with the local authorities concerning design specifications. If there are no specific rules, the information given in Table 19.11 may be used. Percolation time is found by digging a hole 30 cm square and 60 cm deep. Fill the hole with water and let it drain completely. Refill the hole and then measure the seconds per millimetre rate at which the water level falls.

The outlet from the septic tank should be approximately 50 cm below ground level. However, sometimes this is made difficult by site gradients and the need to install the tank low enough to ensure that the sewerage lines will drain into it. Although the soakaway field is usually close to the tank, it may need to be located some distance away because of site conditions. The soakaway trench should be approximately 100 cm wide and 50 cm deep and with very little slope. A layer of gravel or broken stone is placed in the bottom of the trench, and then 100 mm clay tile or 100 mm perforated PVC pipe is laid in the trench.

The maximum slope of the soakaway lines is 1:200. If lines have to be installed at different levels because of

TABLE 19.11
Septic tank and soakaway trench sizes

Number of people regularly in the home	Tank interior dimensions (centimetres below drain level)	Soakaway trench (metres)* with percolation rates (seconds per millimetre)			
	Length × width × depth	10–30	30–60	60–100	100–140
2–4	200 × 100 × 150	10	30	60	100
6	250 × 125 × 150	15	45	90	150
8	250 × 125 × 150	20	60	120	200
10	250 × 150 × 150	25	75	150	250

*Trenches should be 100 cm wide and 50 cm deep

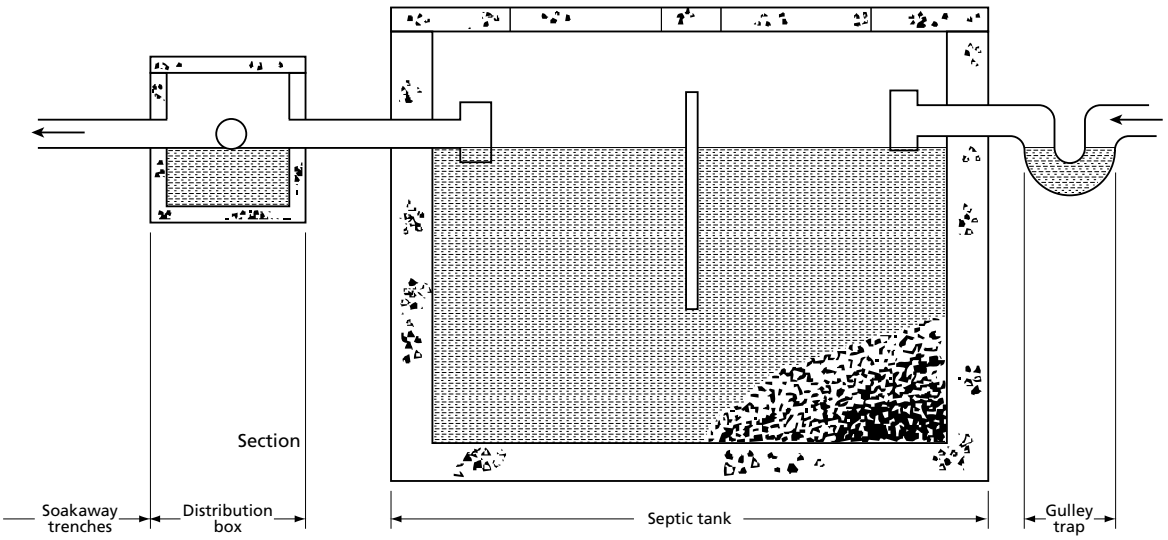


Figure 19.31 **Septic tank and distribution box**

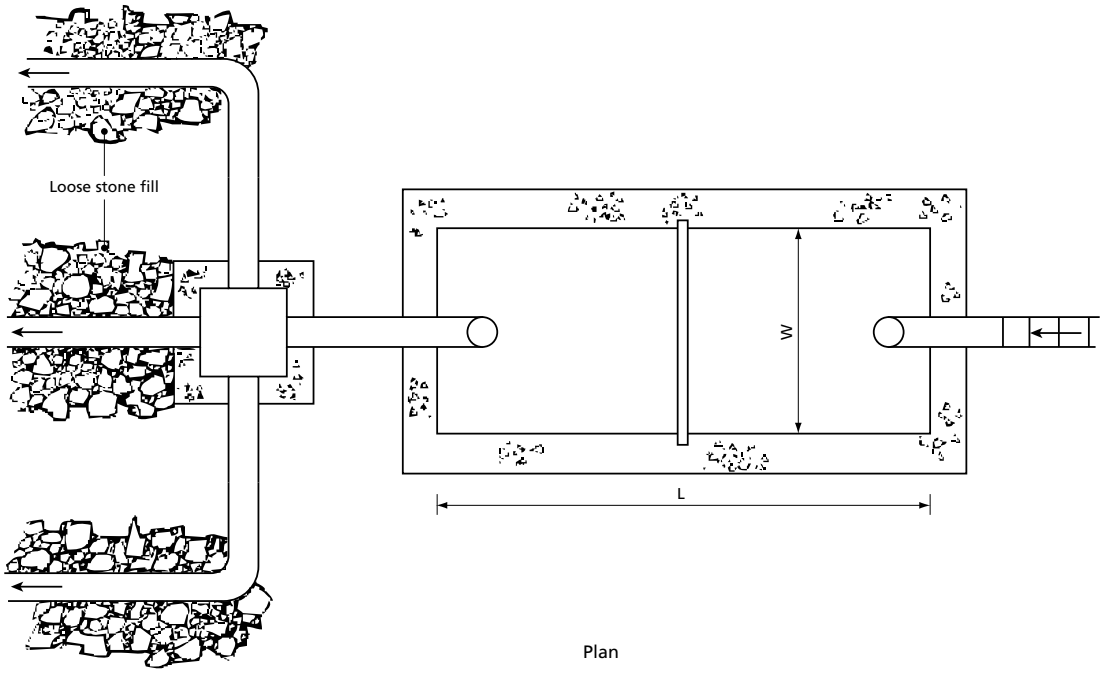


Figure 19.32 **Tank and soakaway field**

a sloping site, leakproof pipe or tile should be used to carry the effluent from one level to the other, but the seepage lines themselves should always be nearly level. Gravel or stone is added until the lines are covered. Hay, grass or newspapers can be laid over the stones before backfilling, to prevent the soil from filling the open spaces between the stones (see Figure 19.32). Although both aqua privies and septic tanks need to be cleaned out periodically, if they are built large enough, the period between clean-outs can be as much as two to three years, depending on how heavily the system is used.

WASTE MANAGEMENT

Waste management may be defined as the practice and procedure, or the administration, of activities that provide for the collection, separation, storage, transportation, transfer, processing, treatment and disposal of waste. In rural areas, the majority of waste takes the form of crop residues, animal manure and human excreta, which must be managed effectively to minimise their effects on people and the environment. However, most rural areas in tropical Africa often face the added burden of poverty, geographic isolation, limited local government resources, and financial and other constraints, making it difficult to manage the waste generated.

In the rural areas, the majority of the waste is produced from agriculture, and such wastes vary in quantity and quality. Wastes from on-farm processing are low-strength, high-volume liquid wastes, while those from livestock operations tend to be high-strength, low-volume wastes. As liquid and solid waste result from on-farm processing and livestock production, both liquid- and solid-waste management strategies must be implemented. The waste from crop residues tends to be much easier to manage than waste from livestock facilities.

The discussion of waste management will focus mainly on agricultural waste, particularly livestock waste, as livestock production is the main agricultural activity in rural areas. The discussion will cover sources, collection, storage, transportation, treatment and utilization of the waste.

Sources of waste

In rural areas, waste comes primarily from agriculture (crop and livestock production) and non-agricultural activities. Agricultural wastes consist of on-farm processing wastes, liquid and solid animal wastes, used packaging materials, agricultural chemicals, crop and field residues, greenhouse and nursery wastes, dead livestock and obsolescent vehicles, equipment, and buildings. Non-agricultural sources include waste from industry, clinical waste and other waste generated by human activity.

Agricultural wastes

On-farm processing

On-farm processing waste is generally low in nitrogen, high in biological oxygen demand (BOD) and suspended solids, and undergoes rapid decomposition. Fresh waste has a pH close to neutral, which decreases in storage. Waste from on-farm processing includes waste generated from washing and blanching raw materials, cleaning processing equipment and cooling the finished product. Such processing facilities include those for processing fruit and vegetables, meat and poultry and dairy

products. In many cases, these operations are not very large compared with those in urban and periurban areas.

Livestock production
A large quantity of manure is produced each year from livestock facilities. While part of the total livestock waste production remains in the pastureland and rangelands, large volumes accumulate in feedlots and buildings, and must be collected, transported and disposed of economically. Livestock manure includes fresh excreta (solid and liquid), bedding material, the material remaining after liquid drainage and water evaporation, and material resulting from aerobic or anaerobic storage. Among livestock production operations, beef cattle, poultry, pigs and dairy cattle generate the largest volumes of manure.

The characteristics of livestock wastes depend on the digestibility and composition of the feed. The characteristics of the manure of various animals may be found in numerous sources in the literature, such as the handbooks of the American Society of Agricultural and Biological Engineers (ASABE). Livestock faeces consist mainly of undigested feed, mostly cellulose fibre, which has escaped bacterial action.

Undigested proteins are excreted in the faeces, and the excess nitrogen from the digested protein is excreted in the urine as uric acid (in the case of poultry) and urea (in the case of animals). Faeces also contain residues from the digestive fluids, waste mineral matter, worn-out cells from the intestinal linings, mucus, bacteria and foreign matter, such as dirt, that has been consumed along with the food.

Chemical wastes
Chemical wastes come mainly from fertilizers and pesticides. Continuous fertilizer application often results in excessive amounts of nutrients in the soil, particularly nitrogen and phosphorus compounds. Excessive amounts of these nutrients can end up in surface waters, resulting in overfertilization and acceleration of the eutrophication process in aquatic systems, particularly by phosphorus.

Chemicals used to control crop pests (pesticides) may also remain in the soil, enter water streams or percolate and contaminate underground water. This results in pollution of the environment, disturbing ecosystems, as some fauna may be killed (unintentionally) by these chemicals. Pesticides are categorized according to their use as insecticides, herbicides, fungicides, rodenticides, fumigants, etc.

Crop and field residues
Crop residues are useful wastes because they are:

- good sources of plant nutrients;
- the primary source of organic material added to the soil;
- important components for the stability of agricultural ecosystems.

The potential uses of crop residues include livestock feed, bedding for animals, composting, biogas generation, mushroom culture and raw material for industry.

Non-agricultural wastes

Packaging materials
The requirements of consumers and supermarkets have forced the food industry to package products in a wide range of different packaging materials. There is also a health requirement to keep products safe and hygienic for consumers. Some of these packaging materials are biodegradable and can be recycled by composting, while others are not and may be burnt or disposed of in landfills. A proper and suitable solid waste management system should be in place to cater for this waste, otherwise it results in pollution of the environment and destroys the aesthetic value of the locality. The methods used to dispose of such waste include recycling and burning.

Special wastes
Special wastes are those that need special handling, treatment and disposal because of their hazardous potential or large volumes. Although these wastes should not enter the solid waste stream, they frequently do, particularly in developing countries. Special wastes include hazardous waste in the household waste stream (e.g. oil-based paints, wood preservatives, household cleaners, used motor oil and batteries), tyres, used oils, and construction and demolition debris. Such wastes are often hard to dispose of safely in rural areas. Burning in a pit is an option that is frequently employed.

Household waste
Household waste should be collected, treated and disposed of to ensure that it does not endanger the environment. In scattered households, liquid human waste is managed through the use of pit latrines. Liquid wastes from the kitchen and laundry are best disposed off in soak pits, as described in earlier in this chapter.

For large farms and agro-industries, such as sugar mills, household waste management problems can be immense. Up to 10 000 workers and their dependants may be living close to these establishments. In this case, household wastes are collected and treated in line with practices in the municipality. This may involve manual or vehicle collection of wastes, transportation, disposal at landfills or incineration. Liquid wastes are collected by sewage systems and treated in municipal waste systems.

Waste collection

Waste collection refers to the initial capture and gathering of the waste from the point of origin or deposition at a collection point. Different collection systems exist, depending on the source and type of waste concerned.

Dairy: The collection methods for dairy waste vary depending on the management of the dairy operation. Dairy animals may be partially, totally or seasonally confined. Manure accumulates in confinement areas and in the areas where the dairy animals are concentrated before and after milking. The curbs at the edge of the paved lots and reception pits where the runoff exits the lots can be used to collect the manure. The runoff from rain and flushing may then be controlled by diversions and sediment basins. The manure and associated bedding accumulated in roofed confinement areas can be collected and stored as a solid.

Beef: Beef cattle can be confined on unpaved lots (see Figure 19.33), or on partially paved or totally paved lots. As most of the waste is deposited around watering and feeding facilities, it is advisable to pave these areas to make scraping of manure easy.

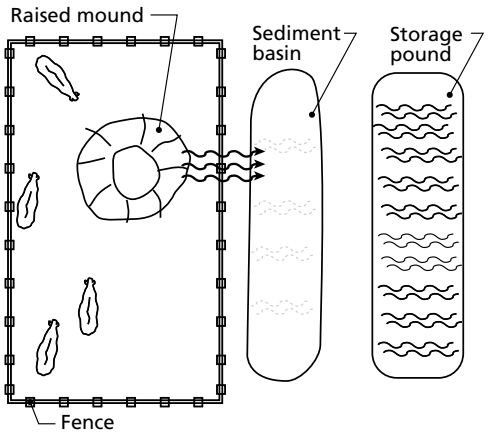


Figure 19.33 **Waste collection from an unpaved beef feedlot**

Pigs: Pig manure can be collected by scraping (solid or slurry manure) or flushing (liquid manure).

Poultry: The manure from broiler and turkey operations is allowed to accumulate on the floor, where it is mixed with the litter. Near the waterers or drinkers, the manure-litter pack forms a 'cake' that is generally removed between flocks. The rest of the litter pack generally has low moisture content and may be removed once a year, or more frequently, depending on the litter condition and management practice. For laying hens, manure accumulates under the cages and is removed by scraping between the flocks, or more frequently, depending on the manure condition and indoor air quality.

Waste storage

Storage is the temporary containment of waste. The storage period should be determined by the utilization schedule. The waste management system should identify the storage period; the required storage volume; the type, estimated size, location and installation cost of the storage facility; the management cost of the storage process; and the impact of storage on the consistency of the waste.

Dairy & Beef: Milking-house waste and contaminated runoff must be stored as a liquid or slurry in a waste storage pond or structural tank. For beef cattle, manure can be stored as a bedded pack in the confinement area, if bedding is added in sufficient quantities. In areas of high rainfall, dry-stacking facilities should be roofed.

Pigs: Pig manure can be stored as a solid, a slurry or a liquid. If stored as a solid, it should be protected from precipitation. Above- or below-ground tanks or an earthen waste storage pond can be used to store slurries or liquid waste.

Poultry: Litter from broiler, turkey and laying-hen operations is stored on the floor of the housing facility. When it is removed, it can be transported directly to the field for land application. If the spreading is to be delayed for an extended period of time, the litter should be stored in a roofed facility. If it is wet, it should be stored in a structural tank or an earthen storage pond.

Transportation of waste

Transportation of waste involves the transfer of waste from the collection point to the storage facility and onwards to the treatment facility, and finally to the utilization site. Livestock waste may be transferred as a solid, a liquid or a slurry, depending on the total solids concentration or consistency of the waste.

Livestock waste from dairy, beef and pig units can be in liquid or slurry form and can be transferred through open channels or pipes, or in portable liquid tanks. Solid and semi-solid waste can be transferred by mechanical conveyers or by sweeping down curbed concrete alleys using hand-held equipment. Semi-solid waste can be transferred in large pipes by gravity, or using piston pumps where warranted.

For poultry, liquid waste can be transferred in pipes or tank wagons, while dried litter can be scraped, loaded and hauled as a solid, using wheelbarrows, animal-drawn carts, trailers, etc. If the poultry houses are a long way from the fields where the litter is to be applied, it may be transported in a truck.

Waste treatment

Treatment is any function designed to reduce the pollution potential of the waste, including physical, biological and chemical treatment. Designing a waste treatment plant involves:

- an analysis of the characteristics of the waste before treatment;
- determination of the desired characteristics of the waste following treatment;
- selection of the type, estimated size, location and installation cost of the treatment facility;
- determination of the management cost of the treatment process.

Dried livestock manure may also be composted. Composting stabilizes the manure into a relatively odourless mass that is easier to market, and also helps to kill disease organisms, so that the manure can be reused as bedding or supplemental feed to livestock. Dead livestock, such as pigs and poultry, may also be composted.

Both livestock and municipal waste are usually treated in their liquid form using lagoons (anaerobic and aerobic). An anaerobic lagoon is commonly used for treating liquid livestock waste. For pigs, an aerobic lagoon or oxidation ditch, where methane gas would be produced, may also be used. Methane may then be harvested and used for household cooking.

Lagoons

Lagoons are earthen basins or ponds constructed for the biological treatment and long-term storage of livestock waste. The waste in the lagoon is diluted with water from rainfall, building wash water, or wastewater from livestock drinking systems. While in the lagoon, the manure is stabilized by bacterial action before eventually being applied on the land as fertilizer.

The waste-stabilizing bacteria involved are: (i) anaerobic bacteria (inhibited by oxygen); (ii) aerobic bacteria (requiring oxygen), or (iii) facultative bacteria (maintained with or without oxygen). Anaerobic lagoons are much smaller than aerobic ones, and decompose more organic matter per unit volume than aerobic lagoons. Therefore, most livestock facilities use anaerobic lagoons to treat livestock waste.

Anaerobic lagoon

The surface area of an anaerobic lagoon should be small, and it should be as deep as possible to promote anaerobic conditions and decrease the land area required. An anaerobic lagoon is loaded in such a way that surface re-aeration and photosynthetic activity cannot maintain aerobic conditions. The rate of accumulation of the solids depends on the solids loading rate, the characteristics of the raw waste and the rate of solids stabilization. The biodegradable fraction of the solids undergoes anaerobic decomposition. Considerabe quantities of gas may be generated, with a resultant decrease in the biological oxygen demand (BOD) and chemical oxygen demand (COD) of the lagoon contents.

TABLE 19.12
Advantages and disadvantages of anaerobic lagoons

Advantages	Disadvantages
• Manure can be handled with water-flushing systems, sewer lines, pumps and irrigation equipment. • The high degree of stabilization reduces odours during land application. • High nitrogen reduction minimizes the land area required for liquid effluent disposal. • Long-term storage is provided at low cost.	• Public perception that a lagoon is an open container of manure. • Offensive odours if improperly designed and maintained. • Limited nitrogen availability if manure is used as a fertilizer.

Anaerobic lagoon design

The design of anaerobic lagoons involves sizing the lagoon to ensure that sufficient volume is available for the treatment and storage of manure or effluent before pumping out. Usually, the storage period is one year (365 days).

The total volume of the lagoon is determined by the sum of the:

- minimum design volume;
- manure storage volume between periods of disposal;
- dilution volume (not less than 50 percent of the minimum design volume);
- sludge accumulation volume between periods of sludge removal.

Figure 19.34 and Figure 19.35 give illustrations of these volumes for both single-stage systems (using only one cell for waste treatment) and multi-stage systems (using two or more cells connected together for waste treatment). In multi-stage lagoons, the effluent produced in the first cell is transferred to the secondary cells, where further biological treatment occurs, resulting in effluent with far less odour than in the preceding cells.

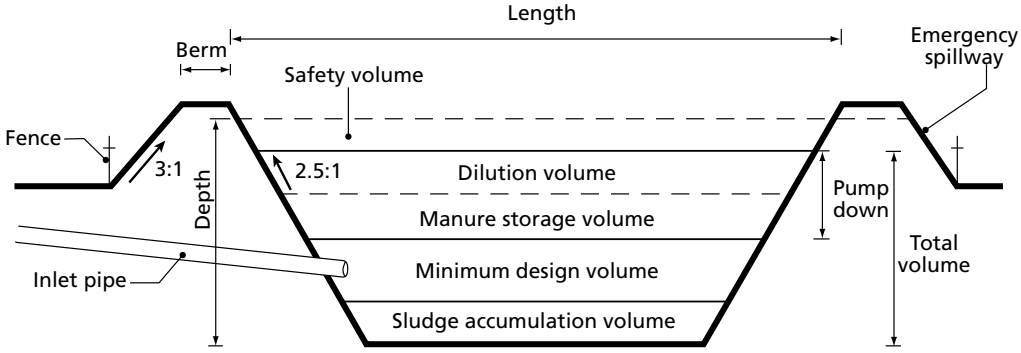


Figure 19.34 **Schematic of a single-stage anaerobic lagoon**

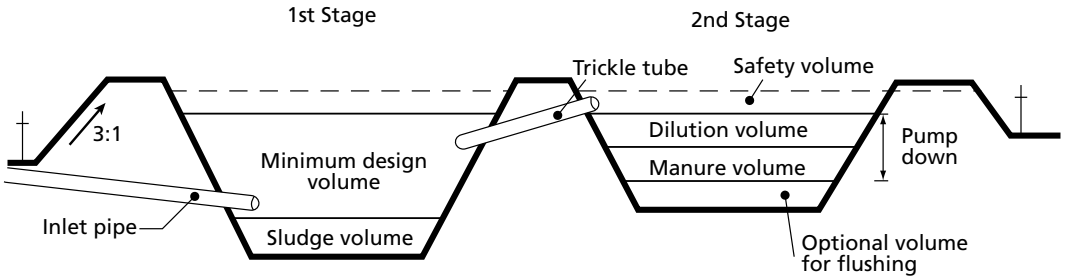


Figure 19.35 **Schematic of a two-stage anaerobic lagoon**

Minimum design volume: This is the volume required to ensure sufficient bacterial degradation of volatile solids. The liquid level should never drop below the minimum design volume, otherwise decomposition will be incomplete and odour problems may occur. The minimum design volume is determined from the maximum loading rate of volatile solids (set by the local authorities) and the production of volatile solids on the farm.

Manure storage volume: This is the amount of manure the lagoon will receive during the projected storage period. If solids are partially removed from the liquid manure before it enters the lagoon, the total lagoon design volume can be reduced by up to 25 percent. Solids can be removed from the manure by a settling tank or a mechanical separator, and then applied to the land or composted before land application.

Dilution volume: This includes all extra water, such as building wash water, spillage from animal watering systems, feedlot runoff or direct precipitation. Usually, it should not be less than 50 percent of the minimum design volume.

Sludge accumulation volume: This accounts for the manure solids that cannot be liquefied by bacteria and gradually accumulate at the bottom of the lagoon as sludge. Fractions of total solids that are assumed to stay as sludge are 50 percent volatile solids plus all the fixed solids. To maintain the minimum design volume for manure treatment, the volume of sludge accumulation over the time between sludge removals must be considered.

When a lagoon is located below the source of liquid manure, it is possible to drain the manure into the lagoon by gravity, using PVC pipes 15–25 cm in diameter with clean-outs and rigid joints. The inlet to the lagoon can be either above or below the liquid surface in the lagoon. The inlet should project at least 600 cm into the lagoon, should be supported every 240 cm, and should discharge into at least 90–150 cm depth of liquid. The last section of pipe, which extends below the liquid surface, should be laid with a slope of 1:48. Figure 19.36 and Figure 19.37 show the above- and below-surface lagoon inlets.

In a multi-stage lagoon system, an overflow pipe transports the supernatant liquid from one cell to the next. The typical pipe is a 15 cm diameter pipe (trickle tube) through the first cell's berm, tilted 30 cm on an uphill slope (Figure 19.38). The pipe should be as far as possible from the main inlet, to ensure that no untreated raw manure is transported.

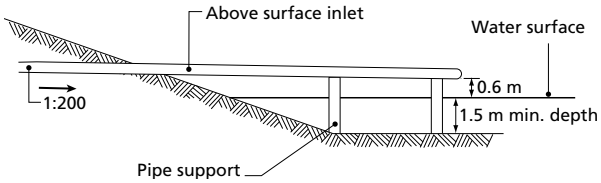


Figure 19.36 **An above-surface lagoon inlet**

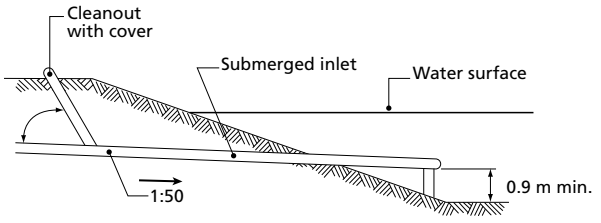


Figure 19.37 **A below-surface lagoon inlet**

Designing an earth embankment

The top width of the berm (Figure 19.39) around the lagoon should be at least 240 cm. When building the berm, allow an extra 10 percent height for settling. If possible, the berm should be capped with topsoil and seeded with grass. The outside slope of the lagoon berm should have a minimum slope of 3:1 (the horizontal run as a ratio of the vertical rise). The slope should be 5:1 if the area is to be mowed by tractor.

Lagoon sealing

The main reason for sealing the lagoon is to prevent seepage, which can pollute underground water and affect treatment performance by causing fluctuations in the water depth. Sealing methods can be grouped into three categories:

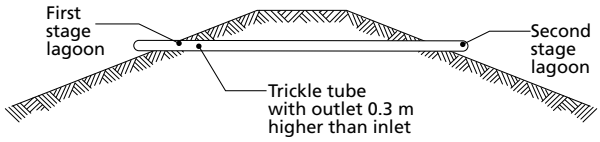


Figure 19.38 **Suggested overflow of a two-stage lagoon**

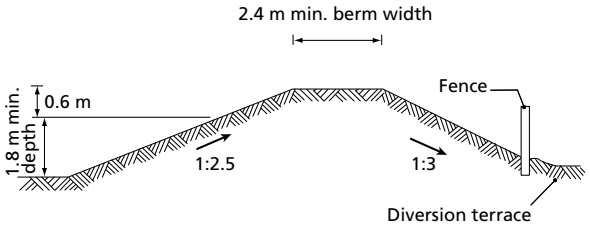


Figure 19.39 **Suggested design of a lagoon berm**

- synthetic and rubber liners;
- compacted earth or soil cement liners;
- natural and chemical treatment liners.

Choosing the appropriate lining for a specific site is a critical factor in lagoon design and seepage control. Seepage rates range from 0.003 cm/day for synthetic membranes to approximately 10 cm/day for soil cement liners. Detailed information about liners is available from manufacturers.

Locating the lagoon

The following factors should be considered when selecting the site for a lagoon:

- It should be located at a safe distance from residential areas, as the odours generated can be a nuisance.
- The site should be at least 120 metres from water wells or watercourses.
- Lagoons should be hidden from public view by landscaping or buildings because sight and smell are intimately interlinked in public perceptions.
- Lagoons should be built on low-permeability soils to minimize the seepage of effluent that could contaminate underground water. If necessary, plastic liners or a layer of compacted clay may be used to seal the lagoons.

REVIEW QUESTIONS

1. Outline six sources of water in a rural setting.
2. What are the likely contiminants of water sources in a rural setting?
3. Describe four methods you would use to determine the optimum size of a water storage tank for rainwater harvesting.
4. Outline four methods of treating water that you would use in a rural setting.
5. Briefly describe two types of well casing.
6. Name and describe two types of handpump and two types of power driven pump.
7. Describe the merits and demerits of using the earth (ground) as a water storage medium.
8. Briefly describe two types of pit latrines that may be used in a rural setting.
9. Discuss the required conditions necessary for composting process to take place effectively.
10. Consider a livestock production facility near you, gather the necessary information, and design a single stage lagoon for it.
11. Discuss the various animal waste utilization means around your area.
12. Discuss and critique the existing animal waste management strategy of a particular livestock operation near you. Formulate an improved waste management plan for the operation.
13. Outline and discuss the major waste sources in your locality and how such waste is handled to reduce its pollution effects.

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Chapter 20
Rural energy

INTRODUCTION

Rural development and transformation can only take place if there is an adequate supply of energy for crop and animal production, processing of agricultural produce, transport, education and domestic use, among other things. For expanded modern production, reliable and adequate sources of energy need to be developed.

Energy is the capacity to perform work. Energy comes in different forms or types. The energy forms are equivalent – any form of energy can be transformed to another form without changes in magnitude, i.e. energy is neither created nor destroyed. This ability of energy to transform from one form to another defines the basis on which we interact with energy in our daily activities.

Energy is a scalar physical quantity conventionally measured in joules (J). One kilojoule (1 000 J) is the amount of energy required to raise the temperature of one litre of water by ¼ °C. The rate at which a process uses energy defines its power rating. Power is the rate of doing work (i.e. the rate at which energy in one form is transformed to another form) and is measured in watts (W/s).

Energy can be categorized into two main groups, i.e. kinetic energy and potential energy. Kinetic energy is energy in motion and includes: electrical, gravitational, spring, magnetic, mechanical, light and heat energies. Potential energy is stored energy and includes forms such as nuclear energy and chemical energies.

Energy is an important ingredient in the life of a human being. Apart from the human body needing energy in various forms around the clock, civilization is defined by how much we are able to convert the energy from one form to another to suit our needs. Thus we have improvised ways to produce energy in forms that suit our needs.

Trends in our world have shown that there is a strong correlation between the per capita energy consumption and level of development in a country. For example, countries that have high electrical energy consumption per capita are generally more developed than countries with low per capita consumption. It is therefore important in the development and design of rural structures that energy requirements be taken into consideration.

ENERGY SOURCES

In order to generate energy, sources must be identified from which it can be produced efficiently. There are several natural sources that can provide energy in various forms of which some have been used extensively while others are used as alternatives.

Chemical form of energy has been obtained extensively from wood, coal, natural gas and hydrogen. These sources are extensively used in the production of heat energy for everyday use or for transformation into the electrical form of energy.

Gravitational form of energy has been harnessed from waterfalls (hydropower). This has seen the development of huge hydropower plants. The current technology has even enabled development of microplants.

Heat form of energy has been sourced from geothermal plants and burning of fuels. Kinetic form of energy in contrast to chemical form of energy cannot be stored and must be used immediately or be transformed into a form suitable for storage. The sources of this energy to humankind are wind and ocean waves. Nuclear energy is sourced from fission of uranium. The light form of energy has been sourced from solar, which is actually the mother of all forms of energy.

The energy resources are usually categorized as renewable and non-renewable. Renewable energy resources are those that can be replenished quickly, e.g. solar power, biomass, geothermal, hydroelectric, wind power and fast-reaction nuclear power. Non-renewable energy resources include fossil fuels and uranium, which are used to fuel slow-reaction nuclear power. Projections of how long a non-renewable energy resource will last depend on many changeable factors. The availability of non-renewable energy will depend on the growth rate of consumption and economic recovery of remaining resources.

Fossil energy resources are currently the most affordable and easier to store and transport than renewable sources. For renewable energy sources to become more widely used, many difficulties will have to be overcome, mostly relating to economic production and distribution. However, it should be noted that renewable choices may just be the best choice in some situations, especially in rural settings.

Rural energy choices

The sustainability of any particular energy resource is an important consideration in determining where to invest in energy technology and infrastructure. All energy resources, whether renewable or non-renewable, must be used efficiently and sustainably in order to safeguard the future use.

In a rural setting, the best energy sources will depend on answering a variety of questions including: What is to be the intended use of the energy, how it is to be used, where it is being used and what energy sources are available. One should also consider the convenience of use and reliability of the source, costs, safety, health and the environment.

For sustainable development the energy resource used should be:

- Appropriate for local needs and resources.
- Cost-effective.
- As far as possible, generate income in the rural setting.
- Minimize negative impact on the productive capacity of the land.
- Must take into account the fact that in future there will be need for expansion and therefore emission standards must be adhered to and thus need to consider the environmental impact of the choice.
- Must provide a secure supply of energy that will not be interrupted by international crisis.

Rural energy supply routes

There are several mature energy supply routes that can be adopted for use in a rural setting. Deciding on a given route requires an understanding of resources at one's disposal and their relative costs and benefits. Technologies that have been found appropriate for rural areas include the electricity supply via the national grid, electricity generation via diesel generators, biomass energy, solar energy, biogas, and small and minihydro and hybrid systems.

BIOMASS ENERGY

Biomass refers to all organic matter produced by plants through the process of photosynthesis. Biomass is available everywhere. Biomass provides food, construction materials, fibers and energy. To provide energy, biomass is burned or fermented in order to make use of the chemical energy stored within it. Biomass is basically solar energy stored in chemical bonds of organic matter. It is therefore an inexhaustible fuel source if harnessed properly.

During combustion, oxygen from the atmosphere combines with the carbon in biomass to produce CO_2 and water that may be allowed to escape to the atmosphere to start a new cycle. Use of biomass as a source of energy is therefore a friendly way of managing municipal, agricultural and industrial waste.

The amount of heat produced in the combustion is directly propositional to moisture content of the biomass used. Moisture content also influences thermo chemical processes. The energy content, lower calorific value (LCV), of nearly all kinds of anhydrous biomass feed stocks when combusted fall in the range 15–19 MJ/kg. The values for most woody materials are 18–19 MJ/kg, while for most agricultural residues, the heating values are in the region of 15–17 MJ/kg.

Conversion process

There are four basic technologies that are used to convert biomass into energy: direct combustion, thermo-chemical conversion processes, physicochemical and biochemical processes.

Biomass is used directly in combustion as in wood stoves and furnaces. The heat produced in this process can be used for cooking, space heating or production of electricity, which may be centralized or decentralized. Through thermochemical processes (pyrolysis and gasification), biomass can be processed into intermediate products, such as charcoal and producer gas, before final use. Physicochemical processes as used in production of vegetable oil and its eventual conversion to biodiesel, which can then be used for generation of electricity or as source of energy for transport vehicles. Biochemical conversion involves use of micro-organisms. For example, enzymes of bacteria are used in production of biogas discussed in the section, "biogas".

In rural areas of the tropics, biomass still remains the dominant source of energy. Most used sources of biomass include wood fuel, charcoal, crop residue, vegetable oil and animal waste. These are used to provide energy for cooking meals, firing kilns, lighting (as in oil lamps) and electricity cogeneration in rural-based agricultural factories.

Major advantage of biomass in comparison to solar or wind energy as a renewable source of energy is that the stored bioenergy can be used on demand. Therefore, it can be used to smoothen the fluctuation in their supplies.

However, unsustainable use of biomass can lead to environmental degradation. Also, cost of technical use of biomass is higher than that of fossil fuels. The low concentration of energy in biomass is a disadvantage when compared to fossil fuels because these are easily transported and stored given that they occupy less space. However, burning of biomass results in lesser emissions of pollutants, such as sulfur, nitrogen oxides, and carbon dioxide, to the surroundings.

ELECTRICITY

Electrical form of energy is currently the most important form of energy. Electrical energy is not found alone as a source of energy in nature. Electricity, therefore, must be produced from some other energy source, e.g. petroleum. Electricity is used extensively all over the world because it is easy to transport over wires from where it is produced to destination of use including industries, farms and homes. However, electricity must be used as soon as it has been produced because it is kinetic energy and thus cannot be stored.

Generation of electrical energy is a big industry all over the world. Electricity has been conventionally generated from sources such as hydropower, heat, geothermal and nuclear. The generation in this case involves building of huge power plants. The generated electricity from these sources is fed into the national grid.

Mechanization of agriculture demands that high density energy sources such as electrical energy be used. This is necessitated by the fact that most of production structures, machines and appliances can efficiently be run with electricity. Therefore, availability of electrical energy supply in a rural setting promotes agricultural mechanization.

For energy audit purposes a basic understanding of units of measurement of electricity might be necessary. The most important electrical energy parameters that should be understood by the user include: voltage, current and resistance.

Voltage (measured in volts) is the rate at which energy is drawn from a source of electricity. The movement of energy produces a flow of electricity in a circuit. Current (measured in amperes) is the flow of electricity through an electrical circuit. This flow is dependent on the supply voltage and the load connected to it; the bigger the load the lower the current. Resistance (measured in ohms) is a measure of the load in the electrical circuit. A material that is a good conductor of electricity offers low resistance to the electrical current flow, whereas that which is a poor conductor hinders flow of the current.

The mathematical relationships between these three parameters are given as: Current = Voltage/Resistance; Voltage = Current × Resistance; and Resistance = Voltage/Current. The electrical power is expressed as: Power (watts) = Voltage (volts) × Current (amperes). When one kilowatt flows for an hour, one kilowatt-hour (kWh) of energy is transferred. Power usage is commonly billed in kWh.

Rural electrification

Most rural areas are off the national grid. Therefore, governments all over the world, especially in developing countries put up policies to facilitate rural electrification, while ensuring that this supply is of high quality, affordable and sustainable.

To supply electricity to the rural settings off-grid, the technology that has been used most is the use of isolated diesel power stations. However, current trend has seen adaptation of renewable energy technologies because of their suitability and environmental friendliness.

Decentralized rural electrification involves installation of standalone systems, e.g. photovoltaic (PV), wind and biogas or minigrids that use mixed sources e.g. renewable/diesel ministations. The advantage of such systems are that they allow for optimal of use of natural resources. They reduce energy distribution losses as energy is supplied directly. Also standardization and modularization of the technology has provided high degree of flexibility. It is thus easy to install, maintain and scale up the systems without advanced training.

On grid electricity

The electricity can be sourced from the national grid, where this is available. The grid is usually extended to the rural areas through rural electrification programs. Depending on the needs of the customers, electricity is usually delivered to the farmsteads by single phase or three phase secondary distributions.

During the design and construction phase of a rural structure, it is important that such structures be made electricity ready. This usually involves electrical wiring of the premises with the help of a licensed electrician, as is usually demanded by the utility supplier.

The factors taken into consideration during the construction of rural structures that may require on-grid electricity are discussed in Chapter 8. Figure 8.85 shows a typical electrical distribution system.

Electricity from diesel generators

A diesel generator is a combination of a diesel engine and an alternator used to produce electrical energy. They can be used in areas far from grid or as a back-up to grid supply in the event that power fails. As a backup to grid supply, the system is usually fitted with automatic changeover switches.

A generator must be capable of delivering the power required for the hours per year anticipated by the user to allow reliable operation and prevent damage. The manufactures must give a generator a rating based on internationally agreed definitions. These standard rating definitions are designed to allow correct machine selection and valid comparisons between manufacturers to prevent them from misinforming the customers about the performance of their machines, and to guide designers.

Though the ratings are an important factor on whether a particular generator size is good for a particular use, choice is usually based on the maximum load that has to be connected and the acceptable maximum voltage drop. If the generator is required to start motors, then it will have to be at least three times the largest motor, which is normally started first. This means that it will be unlikely to operate at anywhere near its ratings.

Generators must be installed correctly to ensure that they function correctly and reliably and at low maintenance costs. Usually, the manufacturers will provide detailed installation guidelines covering important factors such as: sizing and selection, electrical factors, cooling, ventilation, fuel storage, noise, exhaust and starting systems.

Advantage of diesel generators is that they can be improvised to use other sources of fuels such as biodiesel and biogas. This promotes a combination of different but complementary energy systems. Some disadvantages of diesel generators include: high operation and maintenance costs, the geographical difficulties of delivering the fuel to rural areas and environmental pollution.

FOSSIL FUELS

Fossil fuels are formed by natural resources, such as anaerobic decomposition of buried dead organisms.

Fossil fuels include peat, lignite, coal, petroleum, shale oil and natural gas. Fossil fuels are non-renewable resources because they take millions of years to form.

The fossil fuels burn to release energy. This energy can then be converted to mechanical-kinetic-thermal energy in many systems, such as steam plants, internal combustion engines, gas turbines and rockets. The heat energy produced can also be used directly.

Compared to competing energy sources, such as solar energy and wind energy, energy from fossil fuels is currently still cheaper. However, because of non-renewability of the fossil fuels, prices are expected to rise in the future as supplies diminish. Also, the renewable energy processing technologies will improve. This is expected to lead to increased use of alternative energy sources.

Fossil fuels are currently very important in agricultural production. Almost all field machineries are powered by petroleum products such as diesel and petrol. Petroleum products such as kerosene and natural gas, are also used intensively in lighting and cooking.

The disadvantages of the use of fossil fuel include:

- Probable contributor to global warming through greenhouse gas emissions
- Pollutes air through emission of nitrogen oxides, sulfur dioxide, volatile organic compounds and heavy metals
- Cause of acid rain because emission of sulfuric, carbonic and nitric acids
- Offshore oil drilling poses danger to aquatic life
- Oil refineries pollute air and water
- Fossil fuels prices are influenced by world politics of oil regions

HYDROELECTRIC POWER

In the generation of hydroelectric power, a weir creates a potential difference (head) between the water before and after the weir. This potential difference can be utilized by a power plant. The water flows through a turbine, which transforms the potential energy into mechanical energy. An electric generator converts this into electricity. A transformer converts the generator voltage to the grid voltage. The power output, P, is expressed as:

$$P = \eta_G \, \eta_T \, \rho_w \, gHQ$$

where η_G is the efficiency of the generator, η_T the efficiency of the turbine, ρ_w the density of the water (kg/m^3), g the gravitation constant (m/s^2), H the head (m) and Q is the flow rate (m^3/s).

Small hydro and micro hydropower

In mountainous areas where there are many rivers and streams, the power of flowing water can be harnessed and used to generate electricity. The hydropower from this source can be particularly beneficial in rural areas, where electricity from other sources may be unavailable or very expensive.

Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. Small hydro has a generation capacity of up to 10 MW. Small hydro can be further subdivided into mini hydro, usually defined as less than 1 000 kW, and micro hydro, which is less than 100 kW.

Small hydroplants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydroprojects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electricity distribution network. As small hydroprojects usually have minimal reservoirs and involve negligible civil construction work, they are regarded as having a relatively low negative environmental impact compared with large hydro projects.

Micro hydro systems consisting of a propeller turbine, a generator, wires and switches can be built in mountain streams or rivers and used to generate electricity for individual households. Such very small-scale systems could supply power to remote mountain communities more cheaply and reliably than either diesel generators or high-voltage grids. In addition to using hydroelectricity in their homes, people living in remote rural communities can use it to power a wide range of small-scale agricultural and industrial activities, from which they can derive income.

The advantage of hydropower is that it is an inexhaustible energy source that has minimal environmental impact and can be used for electricity supply throughout the world. The disadvantages are that microscale types depend on availability of fast flowing streams or rivers that may not be available everywhere and that hydroelectric power may interfere with mobility of fish and impact negatively on the plants.

COGENERATION FROM AGRICULTURAL INDUSTRY

Cogeneration is the simultaneous production of heat and electricity from one fuel source. Power plants and heat engines, in general, waste more than half the available energy that can be put into useful use. This helps in reducing the amount of fuel used resulting in less pollution.

Cogeneration can be employed in rurally set agricultural factories. For example, sugar factories do have excess biomass that can be used for this purpose. With adaptation of relevant technologies these factories can generate electricity for their use and the excess can be used to power surrounding villages and towns or sold to utility companies.

SOLAR ENERGY

The use of solar energy dates back to before recorded history and has been, and is being, used by all farmers in the production of their crops. Agriculture is essentially an energy conversion process in which solar energy is converted through photosynthesis into food for

humans and feed for animals. Solar energy can also be captured and used for a variety of functions on the farm and in rural areas in general. The purpose of this section is to describe the nature of solar energy, and to relate it to some applications.

Solar flux

The energy reaching the earth from the sun is referred to as solar flux. The energy approaching the earth's atmosphere perpendicular to the surface is 1.27 kW/m². As it has to travel through the earth's atmosphere, only about l kW/m² reaches the earth under optimum conditions and, for practical purposes, a value of 0.9 kW/m² is often used for latitudes where the altitude (angle of the sun's rays to the earth) is close to 90 degrees.

Factors that affect the actual amount of energy available in a particular area include:

1. *Latitude and season*: As the axis of rotation of the earth is inclined 23.5°, the angle at which the sun strikes the earth is continually changing throughout the year. Between latitudes 23.5° north and 23.5° south, the sun will be perpendicular for two days each year and its noon altitude never drops below 43°. However, farther north or south, the sun never reaches 90° and, in winter, the angle may be very low (only 16.5° in winter at latitude 50° north or south).
2. *Weather:* The frequency of cloudy days is an important factor in the amount of radiation received over a period of time. Although the belts around the earth between latitudes 20° and 30°, north and south, receive nearly 90 percent of the total solar radiation, there are huge regional variations. Consequently, for design work it is imperative to have solar information for the local area, including seasonal variations.

Application of solar energy

Increasing the use of solar energy depends largely on the cost of alternative sources of energy and improved designs of solar energy equipment. Although solar energy is free, the equipment used to capture it is not. This means that applications that can be used throughout the year, and those that are simple enough to be low in cost, are likely to be the most practical.

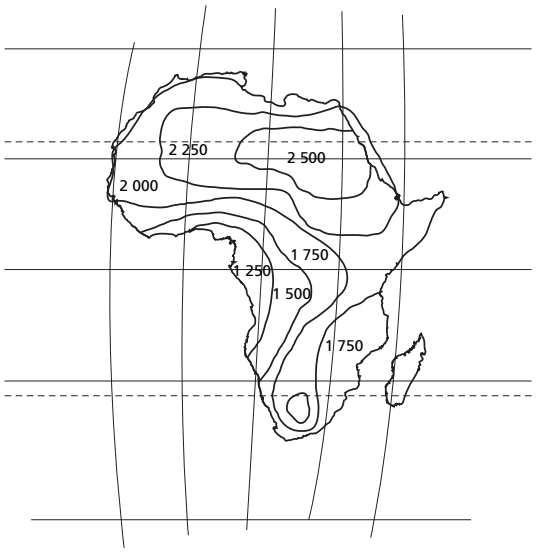


Figure 20.1 **Mean annual solar radiation on a horizontal surface kWh/m²**

Some possible applications in rural areas are:

1. Open-sided buildings facing north, to warm and dry the interior (most practical in latitudes south of 25° S).
2. Crop-drying in thin layers in the sun.
3. Food-drying in small solar dehydrators.
4. Water-heating (see Figure 20.4).
5. Solar cooking.
6. Forced-air drying of grain by blowing air through a long plastic duct before it enters the drying bin.
7. Electricity generation using photovoltaic plates.

TABLE 20.1
Mean daily solar radiation on a horizontal surface (kWh/m²)

Place	Latitude (°)	Elevation (m)	January	April	July	October	Annual
Kenya							
Kericho	0	2 070	6.14	5.16	4.95	5.19	5.46
Mombasa	4	55	6.53	6.66	4.45	6.28	5.84
Nairobi	1	1 890	6.34	5.31	3.72	5.47	5.24
Tanzania							
Arusha	3.5	700	7.24	5.74	4.81	6.49	6.04
Dar es Salaam	7	55	5.42	3.89	4.27	5.22	4.86
Mbeya	9	2 400	4.46	4.58	6.13	5.93	5.23
Zambia							
Bulawayo*	20	1 358	9.01	7.00	5.81	8.40	9.04

* Maximum daily values

Solar collectors

There are several types of solar collectors, including:

1. parabolic focusing collectors that concentrate the sun's energy for high-temperature applications;
2. parabolic cylinders for medium temperatures;
3. flat-plate collectors for relatively low-temperature applications. This type is the simplest and least expensive and has the most applications for rural areas.

A flat-plate collector can be as simple as a water tank painted black, or it can be considerably more complex, e.g. a collector surface painted black, with one or more transparent layers that allow the sun's rays to enter while reducing the reradiation of heat, all mounted in a sealed frame with insulation on the back (see Figure 20.2). In most cases, the heat collected is removed using either air or water. Which of these is used depends on the purpose of the collector; for drying products, air would be used; for heating water, water would be used.

Collector plates may be made of metal with water tubes bonded to the plate. Copper has high conductivity and is easily soldered to the plate. Aluminium also has good conductivity but is difficult to bond to the plate. Manufactured aluminium plates have the water lines pressed into the surface. Glass, glass-reinforced plastic and plastic films may be used to cover the collector.

Glass allows more than 90 percent of the solar energy to pass, fibreglass allows about 80 percent, if kept clean, and polythene film, around 90 percent. However, polythene loses a great deal of heat through reradiation. Glass has the longest life; fibreglass can be expected to last 10 years, and polythene only 1–2 years.

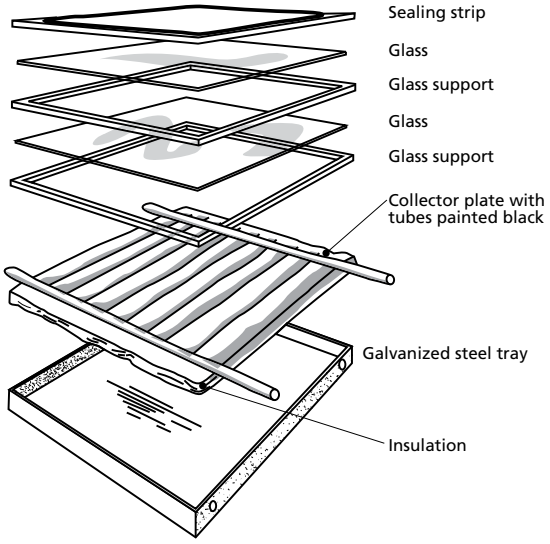


Figure 20.2 **Exploded view of typical flat-plate collector (by courtesy of Cooperative Extension Service, Cornell University)**

The efficiency of collectors varies greatly. The parabolic units mentioned earlier may reach an efficiency of 50–75 percent. Flat-plate units operate in the range of 25–50 percent, depending on the design and mounting position. Some simple designs may be even less efficient. In many cases, an inexpensive, simple design is the most practical. Low efficiency can often be offset by increasing the size of the collector. It is important to remember that no matter which type of collector is used or how efficient it is, it can never collect more energy than the product of the local flux rate and the collector area. In fact, it could be said that the size (area) of a collector is its most important characteristic.

Orientation of flat-plate collectors

Collectors of any type are more effective if they are moved continually to ensure that they remain perpendicular to the sun's rays. However, controls to accomplish this are expensive and impractical for rural operations. Instead, an effort is made to locate the collector in the best average position. This requires an understanding of two angles: azimuth and altitude (see Figure 20.3).

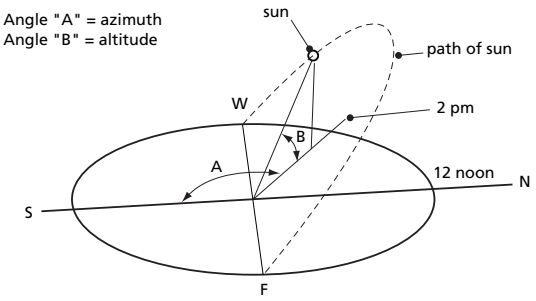


Figure 20.3 **Azimuth and altitude (southern hemisphere)**

The *azimuth* is the horizontal angle of the sun in relation to the true south meridian. It will be measured in an easterly direction in the morning and in a westerly direction in the afternoon. The *altitude* is the vertical angle the sun makes with the horizontal plane at the earth's surface. At the equator, the sun's altitude will be to the north from March to September, and to the south from September to March. Further south, the sun has a north altitude for an increasing length of time; until south of latitude 23.5° S the altitude is always to the north.

As the sun's altitude is so high in the low latitudes, it is fairly effective to place a collector horizontally. However, some angling of the collector will improve the average performance. The following angles from the horizontal are suggested:

Year-round operation:	the latitude angle
Summer operation only:	latitude minus 10°
Winter operation only:	latitude plus 10°

For example, a collector to be installed in Lusaka, latitude 15° S, for all-year use should be tipped 15° to the north and face within 10° east or west of north.

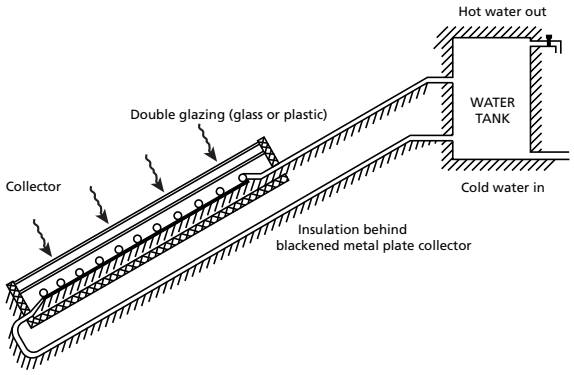


Figure 20.4 **Solar water heater**

Photovoltaic cells

A photovoltaic (PV) solar cell is an electronic device that converts sunlight directly into electricity at an atomic level. The concept used in the PV cell is the photoelectric effect shown by some materials that causes them to absorb photons of light and release electrons. These free electrons are captured to create electricity. A cross-section of a basic PV cell is shown in the Figure 20.5.

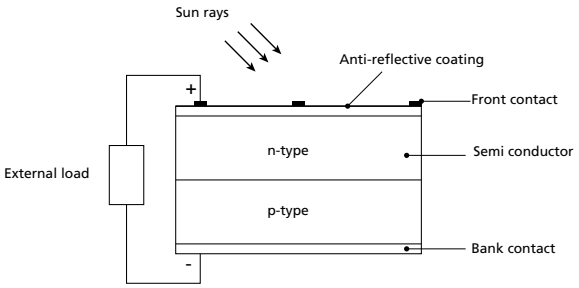


Figure 20.5 **A cross-section of a basic PV cell (solar cell)**

The semiconductor in a PV cell is usually made of silicon. A small amount of impurities, dopants, is introduced to the silicon to produce desired electrical properties. In a solar cell, phosphorus and boron dopants are used. The elements establish an N-type side and a P-type side.

The negative type side is doped with phosphorus. This results in the silicon having an excess of electrons. The positive type side is doped with boron, resulting in holes that carry a positive charge in the silicon. A junction is the result when N-type side and P-type side are combined to form an electric field. The junction creates a barrier, which only allows electrons to flow to the N-side.

When light energy strikes a PV cell in the form of photons, some of the photons are absorbed near the junction and in the process free the electrons and holes in the silicon and supply them with enough energy that enables them to cross the junction. The electrons can then be picked up on the metal contacts on the surface of the solar cell. This forms an electrical current, in an external circuit, which can be used to power an external load, e.g. a lamp.

The amount of current formed in a PV cell is dependent on the intensity of the light incident on the cell and the wavelength of the incident ray. A PV cell usually absorbs a combination of direct solar radiation and diffuse light bounced off the surrounding surfaces. To maximize amount of radiation absorbed, the solar cells are usually coated with anti-reflective material.

Individual PV cells produce low voltage. Therefore, the cells are usually electrically connected in series, parallel or series-parallel combinations to build up a PV system. Parallel connections are usually limited because the associated increase in the current results in higher transmission losses.

Solar cells connected in a series configuration form a module. Usually, modules are designed for operation with 12-V lead-acid rechargeable batteries where a series connection of 32–40 solar cells is optimal. Modules can then be electrically connected in parallel-series configurations to form arrays (see Figure 20.6). The cells or modules connected in series must have the same current rating to produce an additive voltage output. Similarly, modules must have the same voltage rating when connected in parallel to produce larger currents.

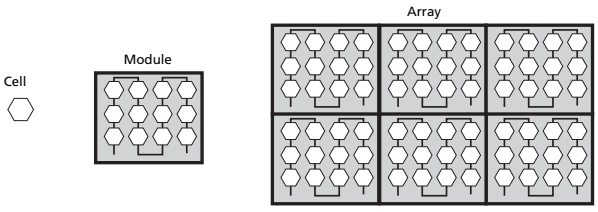


Figure 20.6 **Solar panel configurations**

PV systems have an important use in rural areas where they provide power for such applications as pumping water, lighting, vaccine refrigeration and electrified livestock fencing. They are also becoming increasingly important in rural areas for telecommunications – especially for charging mobile phones.

A basic PV installation consists of four main components: the *solar panel*, the *batteries*, the *regulator* and the *load* (see Figure 20.7). The panels are responsible for collecting the energy of the sun and for generating

the electricity. The battery stores electrical energy for later use. The regulator ensures that the panel and battery are working together in an optimal fashion. The load refers to any device that requires electrical power, and is the sum of the consumption of all electrical equipment connected to the system.

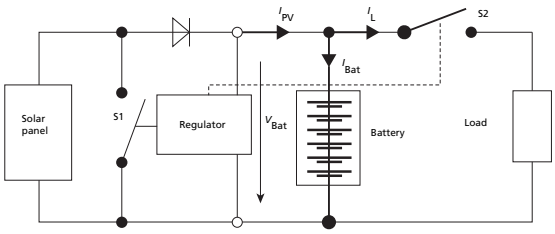


Figure 20.7 **PV battery system with parallel charge**

The electricity generated by the panel is direct current (DC) and may require a *DC/AC inverter* if some of the equipment contributing to the load requires alternating current (AC). Every electrical system should also incorporate various safety devices in case something goes wrong. These devices include proper wiring, circuit breakers, surge protectors, fuses, ground rods and lightning arresters. Figure 20.8 shows the schematics of a basic installation in a house.

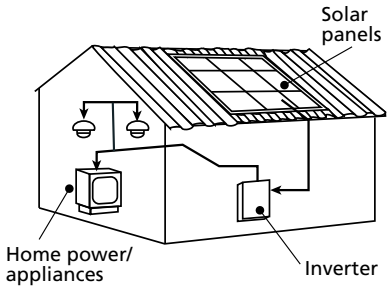


Figure 20.8 **Stand alone PV system**

Apart from the advantage of being a renewable source of energy, use of PV systems have other benefits. The fact that they are modular, allows them to be used at any scale, micro or large and the system easily can be expanded. Once installed, PV systems require minimal maintenance because there are no moving parts that wear off frequently. No fuel is required by this system, thus transportation costs are eliminated. The PV systems are also quiet during operations.

The major disadvantage of a PV system is the relatively high capital required to install the system, though this is fast coming down because of improvement in technologies and large-scale production of PV panels. Other disadvantages include the inefficient utilization of incident solar rays, the need to maintain a system of batteries and the intermittent supply because of the influence of cloudy conditions.

BIOGAS

Biogas is the gas produced through the biological breakdown of organic matter in the absence of oxygen. Biogas originates from biogenic material, and is a type of biofuel.

One type of biogas is produced by anaerobic digestion, or fermentation of biodegradable materials, such as biomass, manure, sewage, municipal waste, green waste and energy crops. This type of biogas comprises primarily methane and carbon dioxide. The other principal type of biogas is wood gas created by the gasification of wood or other biomass. This type of biogas comprises primarily nitrogen, hydrogen and carbon monoxide, with trace amounts of methane.

The gases methane, hydrogen and carbon monoxide can be combusted or oxidized with oxygen. Air contains 21 percent oxygen. This energy release allows biogas to be used as a fuel. Biogas can be used as a low-cost fuel in rural setting for any heating purpose, including cooking. It can also be used in modern waste-management facilities, where it can be used to run any type of heat engine and to generate either mechanical or electrical power. As biogas is a renewable fuel, it qualifies for renewable energy subsidies in some parts of the world.

Biogas is used in several countries around the world on a small or large scale. In countries such as China and India, waste from factories is used to generate biogas. Apart from the disadvantage that the initial cost of a biogas plant is high, the use of biogas has several advantages, including:

1. Use in place of fuelwood to reduce deforestation.
2. Utilization for lighting.
3. If produced in large quantities, it can be used to drive engines.
4. It provides a cheap way of managing waste.
5. Digested slurry is a high-quality fertilizer.

At the very basic level of production, biogas generation involves slurrying together the waste stream in a homestead and allowing it to ferment to produce methane gas. After the gas has been completely extracted, the remainder can be used as fertilizer. On an industrial scale, apart from employing the natural fermentation method, biogas can be produced using advanced waste processing systems, such as mechanical biological treatment.

Designing a small-scale biogas system is not complicated and can easily be implemented at rural level. For large-scale production involving the use of huge amounts of waste from factories and sewerage systems, more expertise is required.

Biogas digesters

Biogas systems recover the recyclable elements of household waste and process the biodegradable fraction in anaerobic digesters. There are three digester designs in common use: Chinese, Indian and Sri Lankan digesters.

The Indian biogas digester has an expandable gas cylinder or dome. As shown in Figure 20.9, the waste is collected and fed into the digester from drains on either side. The digester walls are constructed using bricks and cement. The cylindrical dome is made of sheet metal and moves freely up and down as biogas is produced and drawn from it for use.

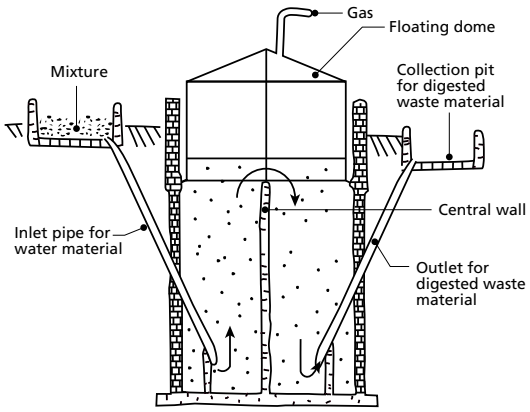


Figure 20.9 **Indian biogas digester** (adapted from Munasinghe, 2007)

In the Chinese design, the biodigester and the composter are a single permanent structure constructed using cement and bricks (see Figure 20.10). The biogas is collected in the upper chamber and the waste decomposes in the lower chamber. It has some similarities with the Indian digester in that it has two drains to feed in waste and to collect the composted waste.

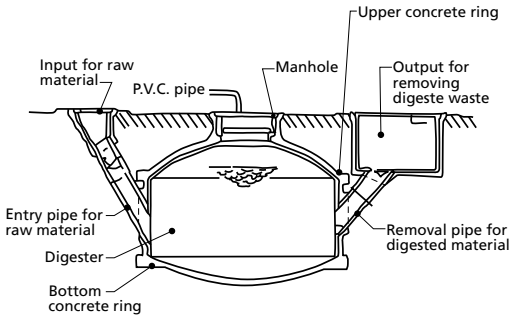


Figure 20.10 **Chinese biogas digester** (adapted from Munasinghe, 2007)

In the Sri Lankan design, the cylinder is constructed using brick and cement, while the chambers used to collect the biogas are made of low-cost 45-gallon barrels, which can be bought from a normal market. These barrels are kept separately and connected with air pipes. The raw material is added and waste is collected by removing the cap on the top (see Figure 20.11).

One of the special advantages of the Sri Lankan biodigester is that there is no need to add the raw material daily, as it can use straw, hay and other agricultural wastes. Therefore, when filled, biogas can be obtained for about 5–6 months.

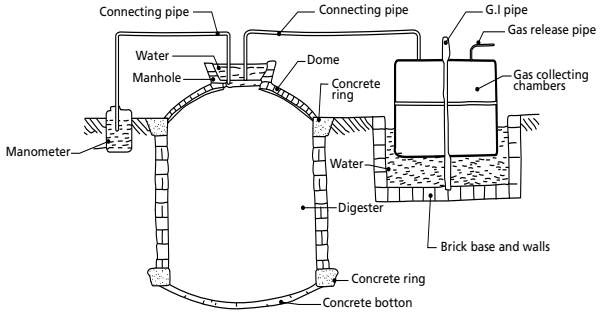


Figure 20.11 **Sri Lankan digester** (adapted from Munasinghe, 2007)

In both the Indian and Chinese digesters, the waste needs to be fed in daily and therefore the best option is to connect the digester to the cattle shed or pigsty. In both cases, toilets that are used on a daily basis can also be used to produce biogas. This gives additional sanitation advantages.

Table 20.2 provides information concerning the amount of waste required and the output.

TABLE 20.2
Amount of waste needed and output

The capacity of a digester (square metre)	Raw material (cow dung) kg (per day)	For cooking (number of people)	The number of lamps that can be supported
1	25	3–4	2
2	50	4–7	3
3	75	7–10	6
4	100	10–12	8

Source: Munasinghe, 2007.

The use of biogas systems will require thorough feasibility study of a given setting. As it is a chemical process, maintaining optimal production could be a hard task to the rural dweller. It should also be noted that already fabricated digesters are available in the market. Because these are optimally designed by experts, who are also ready to install them, buying a prefabricated system may be a quicker and sustainable solution.

WIND POWER

Wind is air moving from an area of high pressure to an area of low pressure. These pressure differences are as a result of solar radiation on the surface of earth. Moving wind contains energy in the form of kinetic energy. Wind therefore, is an indirect form of solar energy. While the maximum solar irradiance is about 1 kW/m^2, wind can have high power density. For example, a violent storm has energy content as high as 10 kW/m^2. Hurricanes go as high as 25 kW/m^2, while a gentle breeze of 5 m/s has a power density of only 0.075 kW/m^2.

Rural dwellers in the tropical climates have benefited from wind energy for centuries using it mostly in grain cleaning. However, current technology allows more to be done with the wind. Wind power derived from wind energy can be converted into a usable form of energy, such as electricity, using wind turbines.

At the end of 2010, the worldwide capacity of wind-powered generators was 194.4 gigawatts (GW). Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production, or 40 times current electricity demand. This would require large amounts of land to be used for wind turbines, particularly in areas with the best wind resources.

Wind energy, as a power source, is attractive as an alternative to fossil fuels, because it is plentiful, renewable, widely distributed, clean and produces no greenhouse gas emissions. However, wind power is non-dispatchable, therefore, for economic operation all of the available output must be used as and when it is available – otherwise battery storage systems have to be used to store it.

Power content of wind

Moving air molecules have mass and speed and therefore have kinetic energy. This energy can be extracted by the blades or rotor of a wind turbine. The power content of wind, P_w (W) that the wind contains is calculated by differentiating its kinetic energy content with respect to time and thus can be expressed by:

$$P_w = \frac{1}{2}\dot{m}v^2 \tag{20.1}$$

where $\dot{m}$ is the mass flow rate of air in kg/s and v is the speed of the wind in m/s. The mass flow rate is mathematically given by:

$$\dot{m} = \rho A v \tag{20.2}$$

where ρ is the density of air in kg/m^{3}and A is the cross section area in m^2. The density of air, ρ, varies with the air pressure and temperature. It changes proportionally to the air pressure at constant temperature. For example at 100 kPa, -10 °C, the density of air is 1.324 kg/m^3 while at 100 kPa, 30 °C the density is 1.149 kg/m^3.

If the elevation, z and temperature, T of a site is known then the density of air can be calculated by

$$\rho = \frac{353.049}{T}\exp\left(-0.034\frac{z}{T}\right) \tag{20.3}$$

From equation 20.3 it can be seen that the density of air decreases with increase in elevation and temperature of a site. For most practical applications, air density is taken as 1.225 kg/m^3.

Substituting for $\dot{m}$ into equ. 20.1, the total wind power is given by:

$$P_w = \frac{1}{2}\rho A v^3 \tag{20.4}$$

From equ. 20.4, it is seen that for a given cross-sectional area, A, the wind power depends on air density and cubic power of the wind speed.

Wind turbine power

To effectively use wind power, a wind turbine should take as much power from the wind as possible. The ratio of the power used by the turbine P_T to the power content P_w of the wind is called the power coefficient.

The maximum power coefficient attainable is referred to as the Betz power coefficient ($C_{p,\ betz}$) and is about 0.593. Real wind turbines do not reach this theoretical optimum; however, good systems have power coefficients between 0.4 and 0.5. The ratio of the used power P_T of the turbine to the ideal usable power P_{ideal} defines the efficiency, η, for the power utilization of the wind:

$$\eta = \frac{P_T}{P_{ideal}} = \frac{P_T}{P_w c_{P,Betz}} = \frac{P_T}{\frac{1}{2}\rho A v^3 c_{P,Betz}} = \frac{c_P}{c_{P,Betz}} \tag{20.5}$$

For sizing purposes, an overall efficiency, η_T, is used to calculate power generated by a particular wind turbine of a given cross-sectional area, A_T and wind velocity V.

$$P_T = \frac{1}{2}\eta_T \rho A_T v^3 \tag{20.6}$$

Analysis of wind regime

Because the cubic relationship between air velocity and its power content, even a small variation in wind speed may result in significant change in the amount of power produced. For example, an increase of wind speed by 5 percent will enhance the productivity of the turbine by 15.7 percent. Therefore it is important that the site with appropriate wind regime be chosen.

This can only be achieved by thorough analysis of wind regime in an area.

Wind measurement

Wind direction is reported by the direction from which it originates. For example, a northerly wind blows from the north to the south. Weather vanes pivot to indicate the direction of the wind. Wind speed is measured by anemometers, most commonly using rotating cups or propellers. When a high measurement frequency is needed (such as in research applications), wind can be measured by the propagation speed of ultrasound signals or by the effect of ventilation on the resistance of a heated wire. Sustained wind speeds are reported globally at a 10 metres height and are averaged over a 10 minute time frame. Where measurements are not immediate, the *Beaufort scale* (Table 8.1) is often applied to give the wind force. This scale allows an approximate estimation of wind speed without complicated measurement systems.

Wind speed and height

Wind flow above the ground is slowed by frictional resistance offered by the earth surface. The resistance to flow is caused by the ground itself, the vegetation and buildings, and other structures. The rate at which the velocity increases with height depends on the roughness of the terrain. The roughness of terrain is usually represented by roughness class or roughness height.

For the estimation of the wind potential, wind speed measurements at other heights are necessary. However, if the type of ground cover is known, the wind speed at other heights can be calculated.

The wind speed v_{h2} at height h_2 can be calculated directly with the *roughness length*, z_0 of the ground cover and the wind speed v_{h1} at height h_1 with the help of the following equation:

$$v_{h_2} = v_{h_1} \frac{ln\left(\frac{h_2 - d}{z_o}\right)}{ln\left(\frac{h_1 - d}{z_o}\right)} \tag{20.7}$$

Obstacles can cause a displacement of the boundary layer from the ground. This displacement can be considered by the parameter d. For widely scattered obstacles, parameter d is zero. In other cases, d can be estimated as 70 percent of the obstacle height.

The *roughness length*, z_0 describes the height at which the wind is slowed to zero. In other words, surfaces with a large roughness length have a large effect on the wind. Roughness length ranges from 0.0002 at open sea to 2 at inner cities.

Mean wind speed

The mean wind speed is often used to give the site quality. However, mean wind speed only partly describes the potential of a site because of the stochastic nature of wind. In simplicity, the average wind speed at a site can be expressed as:

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{20.8}$$

However, for wind power calculations, because wind power is not linearly dependent on wind speed, equ. 20.8 can result into errors. This can be rectified by weighting the velocity of its power content when computing the average. Thus, the average wind should be expressed as:

$$v_m = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^3\right)^{\frac{1}{3}} \tag{20.9}$$

Wind speed distribution

The wind is stochastic in nature. The speed of wind in an area will vary from time to time and even on a year-to-year basis. Hence, before a decision is made as to whether a wind energy technology should be adopted, it is important that the wind behaviour in a given location be thoroughly understood. This enables the designer to decide on viability of a project and in the selection of appropriate turbine characteristics.

The average wind speed in an area gives the designer a preliminary indication on the wind energy potential of the site. However, detailed planning requires that the distribution also be considered. A wind speed frequency distribution gives much better information about the wind conditions of a certain site than the mean wind speed. Statistical models have been used successfully to define distribution of wind regime over a period of time.

The most commonly used models are the Weibull and Rayleigh distribution. These models facilitate the determination of factors, such as the percentage of time the wind regime is within a useful velocity range; the most frequent wind velocity; velocity contributing maximum energy to the regime and duration of extreme wind speed.

The Weibull model closely mirrors the actual distribution of hourly wind speeds at many locations. The *Weibull distribution* of wind speed, v with shape parameter, k and scale parameter, c is given by:

$$f_{Weibull}(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{20.10}$$

The cumulative distribution of the velocity function (equ. 20.10) gives the fraction of time that the wind velocity is equal or lower than v. Thus the cumulative distribution $F(v)$ is the integral of equ. 20.10 and is given by:

$$f_{Weibull} = 1 - \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \quad (20.11)$$

The shape and scale parameters depend on the site. Substituting $c = 2V_m / \sqrt{\pi}$ in the Weibull distribution and using $k = 2$ results in the *Rayleigh distribution*.

Wind turbine topologies

Wind turbines are broadly classified into two categories based on their axis of rotation: the horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).

Horizontal axis wind turbines

Horizontal axis wind turbines (HAWT) have their axis of rotation horizontal to the ground. Today, almost all wind power plants use rotors with horizontal axes. Systems with vertical axes are only used for very special applications.

The advantages of horizontal axis turbine are:

1. The rotor solidity is lower than VAWT, thus cost is lower compared.
2. The average height of rotor swept area can be high above ground. This tends to increase productivity on a per kW basis.
3. Low cut-in wind speed and easy furling.
4. Relatively high power coefficient.

The disadvantages of horizontal axis turbines include:

1. The generator and gearbox of these turbines are to be placed over the tower, which makes its design more complex and expensive.
2. The need for the tail or yaw drive to orient the turbine towards wind.

Depending on the number of blades, horizontal axis wind turbines are further classified as single bladed, two bladed, three bladed and multibladed. Single-bladed turbines are cheaper because savings on blade materials. The drag losses are also less for these turbines.

Single-bladed designs are not very popular because problems in balancing and visual acceptability. Two-bladed rotors also have these drawbacks, but to a lesser extent. Most of the present commercial turbines used for electricity generation have three blades. Three-bladed rotors have an optically smoother operation and hence visually integrate better into the landscape. The mechanical strain is also lower for three-bladed rotors. The advantages of three-bladed rotors compensate for the disadvantage of the higher material demand so that today mainly three-bladed rotors are built.

Rotors with more number of blades (6, 8, 12, 18 or even more) are also available. The ratio between the actual blade areas to the swept area of a rotor is termed as the solidity. Hence, multibladed rotors are also called high-solidity rotors. These rotors can start easily as more rotor area interacts with the wind initially. Some low-solidity designs may require external starting.

Though frictional losses are high in multibladed turbines, some applications such as water pumping require a high starting torque. For such systems, the torque required for starting goes up to 3-4 times the running torque. Starting torque increases with the solidity. Hence to develop high starting torque, water pumping wind mills are made with multibladed rotors.

Vertical axis wind turbines

The axis of rotation of vertical axis wind turbines (VAWT) is vertical to the ground and almost perpendicular to the ground and to the wind direction. These systems are mostly used for special applications. The major designs in the market include the: Darrieus rotor, Savonius rotor and Musgrove rotor.

The advantages of VAWT include:

1. Their structure and their assembly are relatively simple.
2. The electric generator and the gear as well as all electronic components can be placed on the ground. This simplifies the maintenance compared to rotors with horizontal axes.
3. Rotors with vertical axes need not be oriented into the wind; therefore, they are perfectly suited for regions with very fast changes of wind direction, i.e. no need for yaw system.
4. The blades have a constant chord or twist. Thus, the blades can be manufactured easily.

The disadvantages of VAWT are:

1. The poorer efficiency.
2. Higher material demand of the systems.

Generation of electrical energy from wind turbines

Electricity generation is the most important application of wind energy today. The major components of a wind turbine generator shown in Figure 20.12 include the: tower, rotor, high speed and low speed shaft, gear box, generator, sensors and yaw drive, power regulation and controlling units, and safety systems.

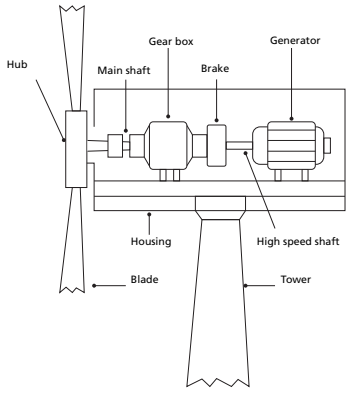


Figure 20.12 **Components of a wind turbine generator**

The tower supports the rotor and nacelle of a wind turbine at the desired height. The major types of towers used in modern turbines are lattice tower, tubular steel tower and guyed tower. The box has gear trains that are used to manipulate the speed of the rotor according to the requirement of the generator.

The rotor brake should stop the wind turbine below a predefined starting wind speed (*cut-in wind speed)* typically, 2.5–4.5 m/s. At the rated speed (nominal wind speed) typically 10–16 m/s, the wind turbine generates the rated power. The nominal wind speed is usually higher than the design wind speed typically 6–10 m/s.

Above the nominal wind speed, the power of the wind turbine must be limited. If the wind speed becomes too high, the wind power plant can be overloaded and damaged. Therefore, wind turbine must be stopped. The rotor brakes stop the wind turbine and the rotor is turned out of the wind if possible.

The generator is one of the most important components of a wind energy conversion system. The generator must be well suited to work under fluctuating conditions because the wind speed keeps on varying from time to time. Different types of generators are being used with wind machines. Small wind turbines are equipped with DC generators of a few watts to kilowatts in capacity. Bigger systems use single or three phase AC generators.

Wind turbine siting

A siting study needs to be undertaken to determine where to locate a wind turbine. The major objective of a siting study is to locate a wind turbine such that cost of energy is maximized while minimizing such things as noise and visual compacts. The scope of a siting study can have a very wide range, which could include everything from wind prospecting for suitable turbine sites over a wide geographical area to considering the placement of a single wind turbine on a site or of multiple wind turbines in a wind farm (this is generally called micrositing).

Several steps are involved in the successful planning and development of a wind turbine installation site. These include:

1. preliminary site identification;
2. detailed technical and economical analysis;
3. environment, social and legal appraisal;
4. micrositing and construction.

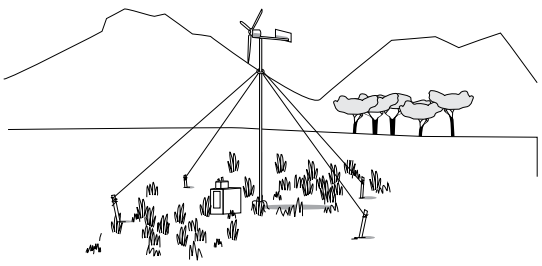


Figure 20.13 **A wind turbine installation in a remote setting**

Figure 20.13 shows a typical wind turbine installation in a remote setting. Before such an installation is made, the steps above must be followed.

In the first step, one identifies a suitable location having reasonably high-wind velocity. A candidate site must usually have a minimum annual average wind speed of 5 m/s. Wind data from local weather stations, airports or published documents such as wind maps may be used for this purpose.

In the second step, more rigorous analysis is required. The nature of the wind spectra available at the sites must be thoroughly understood for the detailed technical analysis. For this, wind speed has to be measured at the hub height of the proposed turbine. Anemometers installed on guyed masts are used for wind measurement.

In step three, environmental issues are analysed and documented. The major concerns are visual effects, avian interaction, noise emission and ecological factors. Local survey and consultation with the local planning authority would be helpful in determining the environmental acceptability of the project. It should also be ensured that the proposed project is acceptable to the local residents.

Once the proposal for the project is approved by the competent authority, then it is possible to proceed further with the micrositing. Micrositing involves laying out the turbine and its accessories at optimum locations at the selected site. In the case of a wind farm project, the turbines are placed in rows with the direction of incoming wind perpendicular to them.

HYBRID POWER SYSTEMS

A hybrid system is a combination of different but complementary energy supply systems based on conventional and renewable energies. Hybrid systems capture the best features of each energy resource. They can be integrated in minigrid, which is usually connected to diesel-based plants. If carefully designed, these systems can provide high-quality electrical power that can be used to meet power needs in rural settings or as a backup to grid supply. Where applicable, the excess power can be sold to the national grid.

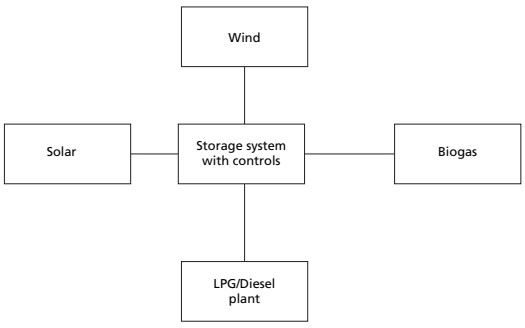


Figure 20.14 **A typical hybrid system arrangement**

Figure 20.14 shows a typical hybrid system arrangement. The system combines two or more energy sources from renewable energy technologies, such as biogas, small hydro, PV panels and wind, with conventional technologies, such as diesel/Liquefied petroleum gas (LPG) generators. The subsystems are electrically and electronically connected. The controls are done via electronics and electricity stored in batteries.

The supplementation of the diesel-based plants with renewable sources of energy is environmentally friendly. It significantly minimizes delivery and transport problems with regard to diesel and drastically reduces maintenance cost and emissions from such plants.

The choice of a right combination of renewable energy options to be used in a hybrid system is reached after doing a thorough feasibility study that takes into consideration the economic, technical and socio-cultural factors.

ENERGY EFFICIENT RURAL BUILDINGS

Planning buildings for energy efficiency reduces maintenance costs required to achieve optimal operational conditions during its productive use. Energy efficiency is achieved by proper selection and placement of materials, proper siting and sizing of a building so that it is responsive to local conditions.

Another way of ensuring that buildings are energy efficient is through landscaping, given that the surroundings of structures have been found to influence the internal climate. For example, buildings surrounded by trees/scrubs are always cooler, during hot seasons, compared to those in open spaces making them more comfortable if there is no air-conditioning service or if there is air-conditioning, energy use in such buildings will be lower. Landscaping strategies will depend on climatic conditions of a site. Some of the techniques that promote energy conservation include:

- Siting buildings to take advantage of natural landforms that can then act as windbreaks.
- Tree planting for the purpose of providing shade and thus reducing cooling costs.
- Planting or building windbreaks to slow winds near buildings thus preventing heat loss.
- Sheltering walls with plants, e.g. vines to create a windbreak directly against a wall.
- Building green roofs that cool buildings with extra thermal mass and evapotranspiration.
- Reducing the heat island effect with permeable paving and minimizing paved areas.

ENERGY AUDITS

This is the assessment of current energy use and developing a cost-effective plan to upgrade or add energy efficient equipment. Energy audits help review efficiency as regards use of electric energy and fossil fuels and may help in deciding whether renewable energy technologies are appropriate for a particular establishment.

For a small establishment, such as a residential house, one can perform a personal energy audit. This will require that one understands: energy transformation units, rate of energy transformation and power rating of appliances in use before conducting the audit. Auditing would then simply mean going around the house to list the appliances in use and their power consumption. One can then analyse the data to establish if the appliances are efficient enough in terms of energy usage.

Inefficient appliances may require repair or may be totally replaced with new more efficient technologies. The audit may also help one decide on what energy needs may be met by use of renewable sources of energy. For example, it may be appropriate to use a solar water heater instead of an electrical water heater.

However, sometimes an energy audit of an enterprise may be required by government or by a bank especially if a grant or loan is to be given. In such a scenario, an energy audit is usually done with the help of a hired energy auditor who is usually an engineer or technically oriented person. The steps involved in energy auditing include:

- An initial interview to gather information about the operation and explain the audit process.
- A site visit to collect information about energy use.
- Data analysis by the expert.
- Audit report analyzing current energy use and recommendations for improvement.
- Review of audit recommendations and discussion of opportunities for implementation.

The energy audit usually ends with a final report that gives detailed information about efficient energy needs of the establishment. It should give recommendations on energy savings at the enterprise level that can be achieved. This should be reported in units understood by the end user. The energy savings recommendations should be made for each major activity, including a comparison with the baseline condition for estimated cost of equipment replacement or upgrade, estimated savings in energy cost, including appropriate assumptions and documentation, and estimated payback period for implementing each recommendation. Various standards have been developed to assist in energy auditing. A good reference on this is the American Society of Agricultural and Biological Engineers, Standard 612 for Performing On-farm Energy Audits.

ENERGY ECONOMICS

In the process of deciding on which energy system to invest in, it is important to consider the economic efficiency of the system. In most cases, economic efficiency has been the primary decision factor. Therefore, the solution with the best economic benefits is usually chosen before consideration of technical and environmental aspects.

There are classical economic calculations that can be put into use. The aim of these calculations is to find the

one system out of the various possible energy solutions that provides the desired type of energy at the lowest cost. The result of economic calculations is the cost for one unit of energy.

For example, for electricity-generating systems the costs are related to a kilowatt-hour of electricity. For estimating a specific final cost, all the costs, such as installation of the power plant, operations and maintenance costs as well as disposal costs, are divided by the total number of kilowatt-hours generated during the plant's lifetime. If the aim is to compare cost over the life span of the plant, then inflation must be taken into consideration.

REVIEW QUESTIONS

1. Explain the forms of energy.
2. Differentiate between renewable and non-renewable energy sources.
3. Outline the uses of solar energy in a rural setting.
4. What factors would you consider before deciding on an energy source?
5. Discuss the role of renewable energies in the future.
6. What is an energy audit?
7. How would you design a rural building to ensure that energy is efficiently used?
8. How can proper landscaping result into energy savings in a rural setting?
9. If a building uses ten bulbs drawing 240 V and 0.25 A for eight hours per day, how many kWh will have been used in 30 days?
10. Explain the working principle of a PV cell.
11. Explain how you would size up a biogas and wind energy system for a family of five.
12. What are hybrid energy systems and what are their advantages?

FURTHER READING

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Appendix I
SI base units

1 THE SEVEN BASE UNITS IN THE INTERNATIONAL SYSTEM OF UNITS (SI)

Quantity	Name of base SI Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

2 SOME DERIVED SI UNITS WITH THEIR SYMBOL/DERIVATION

Quantity	Common symbol	Unit	Symbol	Derivation
Term		**Term**		
Length	a, b, c	metre	m	SI base unit
Area	A	square metre	m^2	
Volume	V	cubic metre	m^3	
Mass	m	kilogram	kg	SI base unit
Density	ρ (rho)	kilogram per cubic metre	kg/m^3	
Force	F	newton	N	$1\ N = 1\ kgm/s^2$
Weight force	W	newton	N	9.80665 N = 1 kgf
Time	t	second	s	SI base unit
Velocity	v	metre per second	m/s	
Acceleration	a	metre per second per second	m/s^2	
Frequency (cycles per second)	f	hertz	Hz	1 Hz = 1 c/s
Bending moment (torque)	M	newton metre	Nm	
Pressure	P, F	newton per square metre	Pa (N/m^2)	$1\ MN/m^2 = 1\ N/mm^2$
Stress	σ (sigma)	newton per square metre	Pa (N/m^2)	
Work, energy	W	joule	J	1 J = 1 Nm
Power	P	watt	W	1 W = 1 J/s
Quantity of heat	Q	joule	J	
Thermodynamic temperature	T	kelvin	K	SI base unit
Specific heat capacity	c	joule per kilogram degree kelvin	J/ kg × K	
Thermal conductivity	k	watt per metre degree kelvin	W/m × K	
Coefficient of heat	U	watt per square metre kelvin	w/ m^2 × K	

3 MULTIPLES AND SUB MULTIPLES OF SI–UNITS COMMONLY USED IN CONSTRUCTION THEORY

Factor	Prefix	Symbol
10^{6}	mega	M
10^{3}	kilo	k
(10^{2}	hecto	h)
(10	deca	da)
(10^{-1}	deci	d)
(10^{-2}	centi	c)
10^{-3}	milli	m
10^{-6}	micro	u

Prefix in brackets should be avoided.

Appendix II
Conversion tables

- Practical values for use in everyday calculations
- Note, the conversion factors marked * are exact

1 LENGTH

Metre	Inch	Foot	Yard
1*	39.3701	3.2808	1.0936
0.0254*	1*	0.0833	0.0278
0.3048*	12	1*	0.3333
0.9144*	36	3	1*

1km = 0.6214 miles

2 AREA

m^2	cm^2	mm^2	in^2	ft^2	yd^2	acre	ha
1*	10 000	10^6*	1 550.0031	10.7639	1.196	0.2471×10^{-3}	0.1×10^{-3}
0.1×10^{-3}	1*	100*	0.155	1.0764×10^{-3}	11.96×10^{3}	24.71×10^{-9}	0.1×10^{-6}*
10^{-6}*	0.01*	1*	1.55×10^{-3}	10.7639×10^{-6}	1.196×10^{6}	0.2471×10^{-9}	0.1×10^{-9}*
0.64516×10^{-3}	6.4516*	645.16*	1*	6.9444×10^{-3}	0.7716×10^{-3}	0.1594×10^{-6}	64.516×10^{-9}
0.09290304*	929.0304	92903.044	144*	1*	0.1111	22.9568×10^{-6}	9.2903×10^{-6}
0.83612736*	8361.2736	0.8361×10^{6}	1296*	9*	1*	0.2066×10^{-3}	83.6136×10^{-6}
4046.8561	40.4685×10^{6}	4.0469×10^{9}	6272640*	43560*	4840*	1*	0.4047
10000	100×10^{6}	10^{9}	15.5×10	107639.1	11959.9	2.4711	1*

3 VOLUME

m^3	cm^3	in^3	ft^3	yd^3
1*	10^6	61023.744	35.3147	1.3080
10^{-6}	1*	0.0610	35.3146×10^{-5}	1.3080×10^{-6}
16.387×10^{-6}	16.387064*	1*	0.5787×10^{-3}	21.4334×10^{-6}
0.0283	28316.847	1728*	1*	0.0320
0.7646	764554.86	46656*	27*	1*

4 MASS

kg	g	pound	oz
1*	1000*	2.2046	35.274
0.001*	1*	2.205×10^{-3}	0.0353
0.45359237*	453.5924	1*	16*
0.0283	28.3495	0.0625*	1*

5 DENSITY

kg/m³	lb/ ft³	lb/in³
1*	0.0624	3.6106×10^{-5}
16.0185	1*	5.787×10^{-4}
27679.906	1728*	1*

6 FORCE

N	kgf (=kp)	Lbf
1*	0.102	0.2248
9.80665*	1*	0.2246
4.4482	0.4536	1*

7 PRESSURE AND STRESS

Pa = N/m²	mm Hg (0°C)	UK ton–force/in² (tonf/in²)	Pound force/in² (LBF/in² (= psi))
1*	7.5006×10^{-3}	64.7488×10^{-9}	0.145×10^{-3}
133.322	1*	115841.53	0.0193
15.4443×10^{6}	8.6325×10^{-6}	1*	2239.4237
6894.76	51.7283	446.543×10^{-6}	1*

8 VELOCITY

m/s	km/h	ft/s	mile/h
1*	3.6*	3.2808	2.2369
0.2778	1*	0.9113	0.6214
0.3048*	1.0973	1*	0.6818
0.447	1.609344*	1.4667	1*

9 TEMPERATURE

°C	°F	°K
°C	(1.8 × °C) + 32*	°C + 273.15*
(°F – 32)1.8*	°F*	(°F – 32) / 1.8 + 273.15*
°K – 273.15*	(1.8(°K – 273.15)) + 32'	°K*

10 ENERGY

J, Nm, Ws	kWh	kcal	ft 1bf	therm
1*	0–2778 × 10^{6}	0.2388×10^{-3}	0.7376	9.4781×10^{-9}
3.6 × 106*	1*	859.845	2.6552×10^{6}	0.341
4.1868×10^{3}	1.163×10^{-3}	1*	3.088×10^{3}	39.6832×10^{-6}
1.3558	0.3766×10^{-6}	0.3238×10^{-3}	1*	12.8506×10^{-9}
105.505×10^{6}	29.3071	25 199.56	77.8168×10^{6}	1*

11 POWER

W, Nm/s, J/S	hp	ft lbf/s	Btu/h
1*	1.341×10^{-3}	0.7376	3.4121
745.7	1*	550*	2544.4328
1.3558	1.81820×10^{-3}	1*	4.6262
0.2931	0.393×10^{-3}	0.2162	1*

Appendix III
Greek alphabet

Capital	Lower case	Name	Capital	Lower case	Name
A	α	alpha	N	ν	nu
B	β	beta	Ξ	ε	xi
Γ	γ	gamma	O	o	omicron
Δ	δ	delta	Π	π	pi
E	ε	epsilon	P	ρ	rho
Z	ζ	zeta	Σ	σ (at end of word) c	sigma
H	η	eta	T	τ	tau
Θ	θ	theta	Y	υ	upsilon
I	i	iota	Φ	ϕ	phi
K	κ	kappa	X	x	chi
Λ	λ	lambda	Ψ	ψ	psi
M	μ	mu	Ω	ω	omega

Appendix IV
List of symbols

a, b, c, d, = length, width depth etc
a = acceleration
A = cross sectional area
C = compression force
(suffix) $_c$ = compression
d = diameter
δ = deflection (delta)
D = diameter, dead load
e = eccentricity, distance
E = modulus of elasticity
ε = direct strain (epsilon)
θ = angle, rotation (theta)
f, σ = stress (tension or compression) (sigma)
F, P, R = force, reaction
g = acceleration due to gravity
h = distance, lever arm
H = height, depth, horizontal force
I = second moment of area, moment of inertia, imposed load
k = constant
l, L = length, span
ΔL = change in length
λ = slenderness ratio (lambda)
m = mass, metre
M = moment, bending moment
μ = coefficient of friction (mu)
N = newton
N_x A_x = neutral axis
P = pressure, stress
Q = shearing force
r = radius, distance, radius of gyration
t = thickness
(suffix) $_t$ = tension
T = tension force
τ = shear stress (tau)
V = volume
w = specific weight, intensity of loading
(suffix) $_w$ = working or allowable value
W = weight force, load
X = horizontal axis
Y = vertical axis
X-X, Y-Y = reference
Z = section modulus
> = greater than
< = less than
Σ = summation (capital sigma)
ρ = density (rho)

Appendix V
Design tables and charts

1 REQUIREMENTS FOR BATCHING ORDINARY CONCRETE MIXES OF VARIOUS GRADES AND OF MEDIUM WORKABILITY

Grade	Water: cement ratio	Maximum size of aggregate (mm)	Cement: aggregate ratio[6]	Sand to total aggregate (%)	Batching by weight (kg dry materials per m³, litre per m³ concrete)				Batching by volume, naturally moist materials (litre per m³ concrete)				Litre per bag cement (50 kg)			Yield (m³)
					Cement	Sand	Stones	Maximum[1] water	Cement[2]	Sand[3]	Stones[4]	Maximum[5] water	Sand[3]	Stones[4]	Maximum[5] water	
C7	0.95	40	10.8	35	185	700	1 300	175	135	510	830	114	135	225	30	0.27
C7	0.95	20	9.4	40	205	770	1 160	194	155	560	740	131	135	180	32	0.24
C10	0.85	40	9.2	35	215	690	1 290	182	150	500	820	121	115	190	28	0.23
C10	0.85	20	8.1	40	235	760	1 140	199	175	550	730	137	115	155	29	0.21
C10	0.85	14	7.6	45	245	840	1 020	208	185	610	650	144	125	135	29	0.20
C15	0.75	40	7.8	35	250	680	1 270	187	185	490	810	128	100	160	25	0.20
C15	0.75	20	6.7	40	280	750	1 130	210	210	540	720	149	95	130	26	0.18
C15	0.75	14	6.4	45	290	840	1 020	217	215	600	650	154	105	110	26	0.17
C20	0.66	40	6.7	30	285	570	1 340	188	210	410	850	132	75	150	23	0.18
C20	0.66	20	5.7	35	325	650	1 200	214	240	470	770	157	70	120	24	0.15
C20	0.66	14	5.4	40	335	720	1 090	221	250	520	690	162	80	105	24	0.15
C25[7]	0.58	40	5.7	30	330	560	1 320	191	245	410	840	137	60	125	20	0.15
C25[7]	0.58	20	4.9	35	375	640	1 190	217	275	470	760	161	60	100	21	0.13
C25[7]	0.58	14	4.6	40	390	720	1 080	226	190	520	690	168	65	90	21	0.13
C30[7 8]	0.51	40	5.1	30	365	560	1 300	186	270	400	830	132	55	115	18	0.14
C30[7 8]	0.51	20	4.4	35	410	630	1 170	209	305	460	750	153	55	90	18	0.12
C30[7 8]	0.51	14	4.0	40	440	700	1 060	224	325	510	670	168	60	75	19	0.11
C35[7 8]	0.45	20	4.0	35	445	620	1 160	200	330	450	740	146	50	85	16	0.11

See footnotes at bottom of Appendix V: 2

2 REQUIREMENTS FOR BATCHING ORDINARY CONCRETE MIXES OF VARIOUS GRADES AND OF HIGH WORKABILITY

Grade	Water: cement ratio	Maximum size of aggregate (mm)	Cement: aggregate ratio[6]	Sand to total aggregate (%)	Batching by weight (kg dry materials per m³, litre per m³ concrete)				Batching by volume, naturally moist materials (litre per m³ concrete)				Litre per bag cement (50 kg)			Yield (m³)
					Cement	Sand	Stones	Maximum[1] water	Cement[2]	Sand[3]	Stones[4]	Maximum[5] water	Sand[3]	Stones[4]	Maximum[5] water	
C7	0.95	40	9.4	40	210	790	1 180	199	155	570	750	136	135	180	32	0.24
C7	0.95	20	8.2	45	235	870	1 060	223	175	630	680	159	135	145	34	0.21
C10	0.85	40	8.2	40	235	770	1 160	199	175	560	740	137	120	155	29	0.21
C10	0.85	20	7.3	45	255	840	1020	216	190	610	650	152	120	130	30	0.20
C10	0.85	14	7.0	50	265	930	930	225	195	670	590	161	125	110	30	0.19
C15	0.75	40	7.0	40	270	760	1 130	202	200	550	720	141	100	135	26	0.19
C15	0.75	20	6.1	45	305	830	1 020	228	225	610	650	165	100	105	27	0.16
C15	0.75	14	5.8	50	310	900	900	232	230	650	570	168	105		27	0.16
C20	0.66	40	6.1	35	305	650	1 210	201	225	470	770	143	75	125	23	0.16
C20	0.66	20	5.3	40	345	730	1100	227	255	530	700	168	75	100	24	0.14
C20	0.66	14	5.1	45	350	800	980	231	260	580	620	171	85	90	24	0.14
C27[7]	0.58	40	5.2	35	355	650	1 200	205	265	470	760	149	65	110	21	0.14
C27[7]	0.58	20	4.5	40	400	720	1 080	232	295	520	690	175	65	85	21	0.13
C27[7]	0.58	14	4.3	45	405	780	960	234	300	570	610	175	70	75	21	0.12
C30[7 8]	0.51	40	4.7	35	385	630	1 180	196	285	460	750	140	60	95	18	0.13
C30[7 8]	0.51	20	4.1	40	430	710	1 060	219	320	510	617	163	60	80	19	0.12
C30[7 8]	0.51	14	3.8	45	455	780	950	232	335	560	610	174	60	65	19	0.11
C35[7 8]	0.45	20	3.7	40	470	700	1 040	211	350	500	670	155	55	70	16	0.11

[1] Including moisture content in aggregate. Use less water if acceptable workability can be achieved.

[2] Bulk density 1 350kg/m³ i.e. 37 litre per bag of 50 kg.

[3] Moisture content 5% and bulk density 1 450kg/m³ (Sand with natural moisture will form a ball in the hand when squeezed, but the ball has a tendency to fall apart)

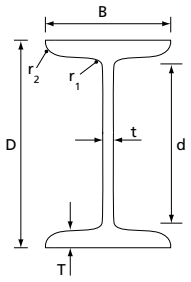
[4] Moisture content 2% and bulk density 1 600kg/m³.

[5] Excluding moisture according to [3] and [4] in aggregate. Use less water if acceptable workability can be achieved.

[6] Solid density of aggregate 2 600–2 700 kg/ m³

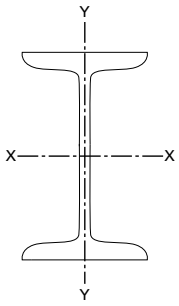
[7] Concrete of grade C25 and higher should preferably be batched by weight and the moisture content of the aggregate should be checked in order to achieve the intended grade. Batching requirements are nevertheless given for batching by volume and may be used when only in small quantities are required.

[8] Concrete of grade C30 and higher should be mixed in a mechanical mixer in order to achieve the intended grade.



3 DIMENSIONS AND PROPERTIES OF STEEL I-BEAMS

Nominal size	Mass Per metre	Depth of section (D)	Width of section (B)	Thickness		Radius		Depth between fillets d	Area of section
				Web (t)	Flange (T)	Root (r_1)	Toe (r_2)		
mm	kg	mm	mm	mm	mm	mm	mm	mm	cm²
254 × 203	81.85	254.0	203.2	10.2	19.9	19.6	9.7	166.0	104.4
254 × 114	37.20	254.0	114.3	7.6	12.8	12.4	6.1	199.2	47.4
203 × 152	52.09	203.2	152.4	8.9	16.5	15.5	7.6	133.2	66.4
203 × 102	25.33	203.2	101.6	5.8	10.4	9.4	3.2	161.0	32.3
178 × 102	21.54	177.8	101.6	5.3	9.0	9.4	3.2	138.2	27.4
152 × 127	37.20	152.4	127.0	10.4	13.2	13.5	6.6	94.3	47.5
152 × 89	17.09	152.4	88.9	4.9	8.3	7.9	2.4	117.7	21.8
152 × 76	17.86	152.4	76.2	5.8	9.6	9.4	4.6	111.9	22.8
127 × 114	29.76	127.0	114.3	10.2	11.5	9.9	4.8	79.4	37.3
127 × 114	26.79	127.0	114.3	7.4	11.4	9.9	5.0	79.5	34.1
127 × 76	16.37	127.0	76.2	5.6	9.6	9.4	4.6	86.5	21.0
127 × 76	13.36	127.0	76.2	4.5	7.6	7.9	2.4	94.2	17.0
114 × 114	26.79	114.3	114.3	9.5	10.7	14.2	3.2	60.8	34.4
102 × 102	23.07	101.6	101.6	9.5	10.3	11.1	3.2	55.1	29.4
102 × 64	9.65	101.6	63.5	4.1	6.6	6.9	2.4	73.2	12.3
102 × 44	7.44	101.6	44.4	4.3	6.1	6.9	3.3	74.7	9.5
89 × 89	19.35	88.9	88.9	9.5	9.9	11.1	3.2	44.1	24.9
76 × 76	14.67	76.2	80.0	8.9	8.4	9.4	4.6	38.0	19.1
76 × 76	12.65	76.2	76.2	5.1	8.4	9.4	4.6	37.9	16.3

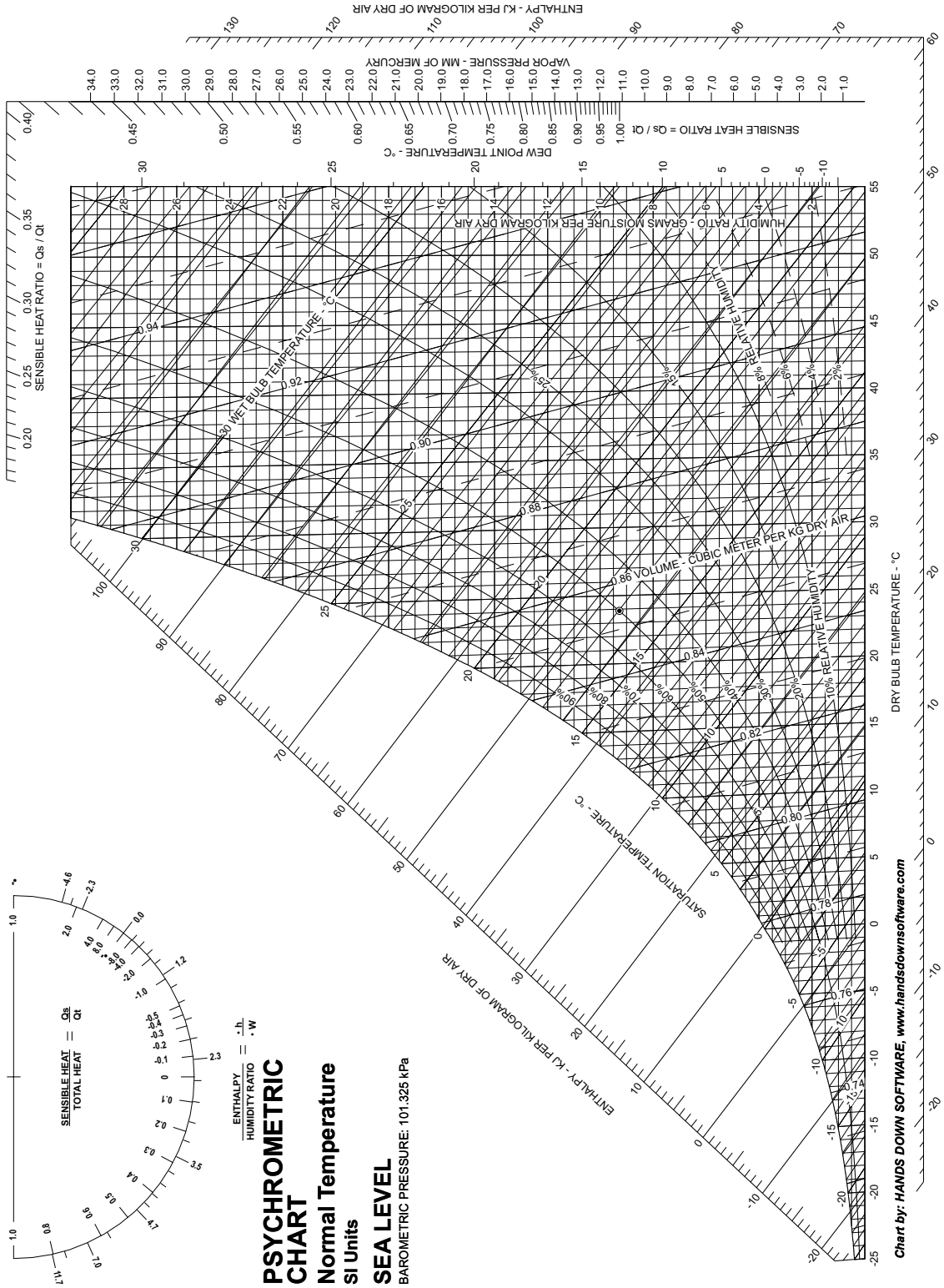


3 JOISTS, DIMENSION AND PROPERTIES *(continued)*

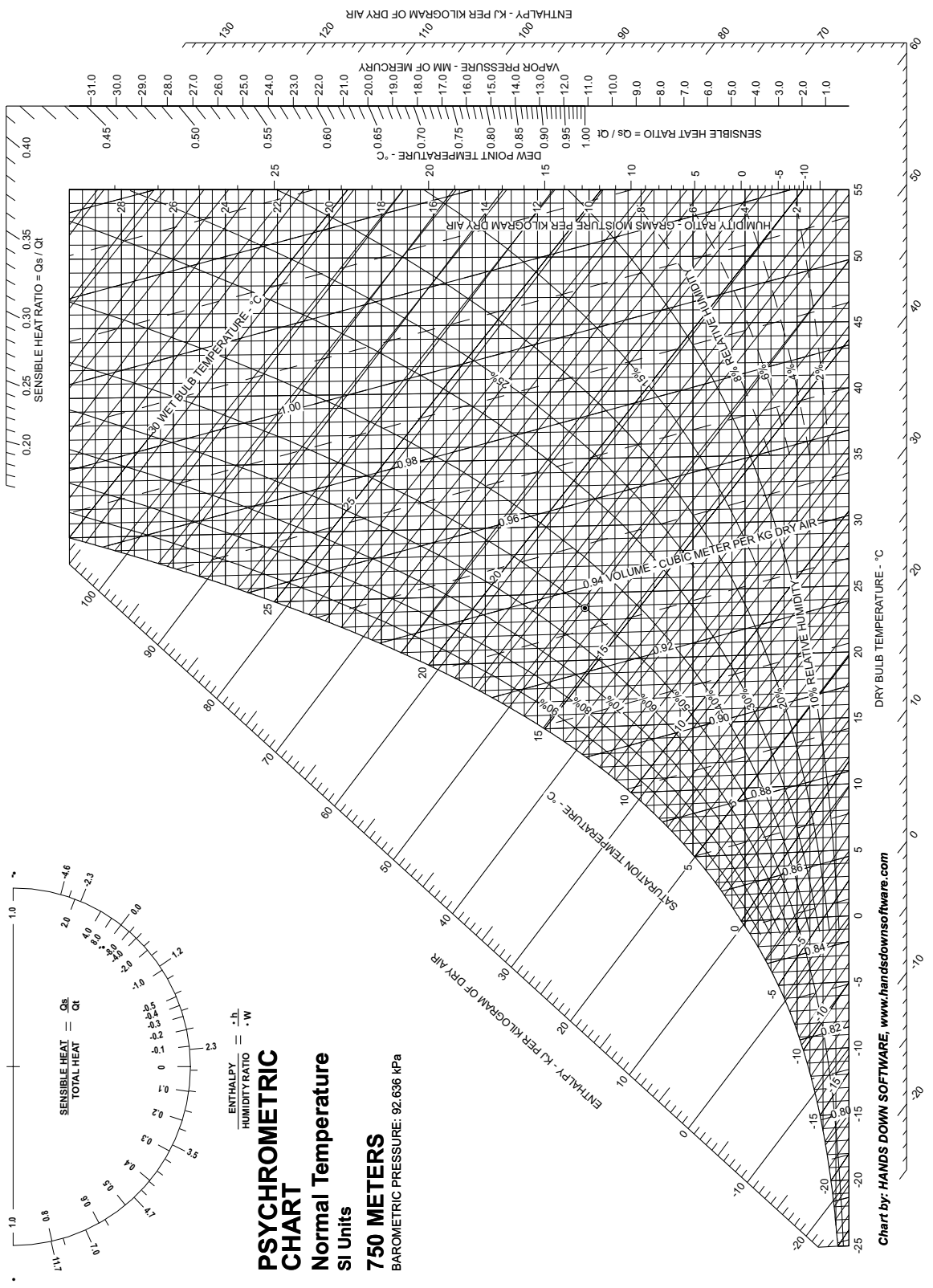
Minimal size	Moment of inertia			Radius of gyration		Elastic modulus		Ratio
	Axis x–x		Axis	Axis	Axis	Axis	Axis	D/T
	Gross	Net	y–y	x–x	y–y	x–x	y–y	
mm	cm^4	cm^4	cm^4	cm	cm	cm^3	cm^4	
254 × 203	12 016	10 527	2 278	10.7	4.67	946.1	224.3	12.8
254 × 114	5 092	4 243	270.1	10.4	2.39	401.0	47.19	19.8
203 × 152	4 789	4 177	813.2	8.48	3.51	471.4	106.7	12.3
203 × 102	2 294	2 024	162.6	8.43	2.25	225.8	32.02	19.6
178 × 102	1 519	1 339	139.2	7.44	2.25	170.9	27.41	19.7
152 × 127	1 818	1 627	378.8	6.20	2.82	238.7	59.65	11.5
152 × 89	881.1	762.6	85.98	6.36	1.99	115.6	19.34	18.4
152 × 76	873.7	736.2	60.77	6.20	1.63	114.7	15.90	15.9
127 × 114	979.0	800.9	241.9	5.12	2.55	154.2	42.32	11.0
127 × 114	944.8	834.6	235.4	5.26	2.63	148.8	41.19	11.2
127 × 76	569.4	476.1	60.35	5.21	1.70	89.66	15.90	13.3
127 × 76	475.9	400.0	50.18	5.29	1.72	74.94	13.17	16.7
114 × 114	735.4	651.2	223.1	4.62	2.54	128.6	39.00	10.7
102 × 102	486.1	425.1	154.4	4.06	2.29	95.72	30.32	9.9
102 × 64	217.6	182.2	25.30	4.21	1.43	42.84	7.97	15.4
102 × 44	152.3	126.9	7.91	4.01	0.91	30.02	3.44	16.7
89 × 89	306.7	263.7	101.1	3.51	2.01	69.04	22.78	9.0
76 × 76	171.9	144.1	60.77	3.00	1.78	45.06	15.24	9.1
76 × 76	158.6	130.7	52.03	3.12	1.78	41.62	13.60	9.1

In calculating the net moment of inertia, one hole is deducted from each flange.

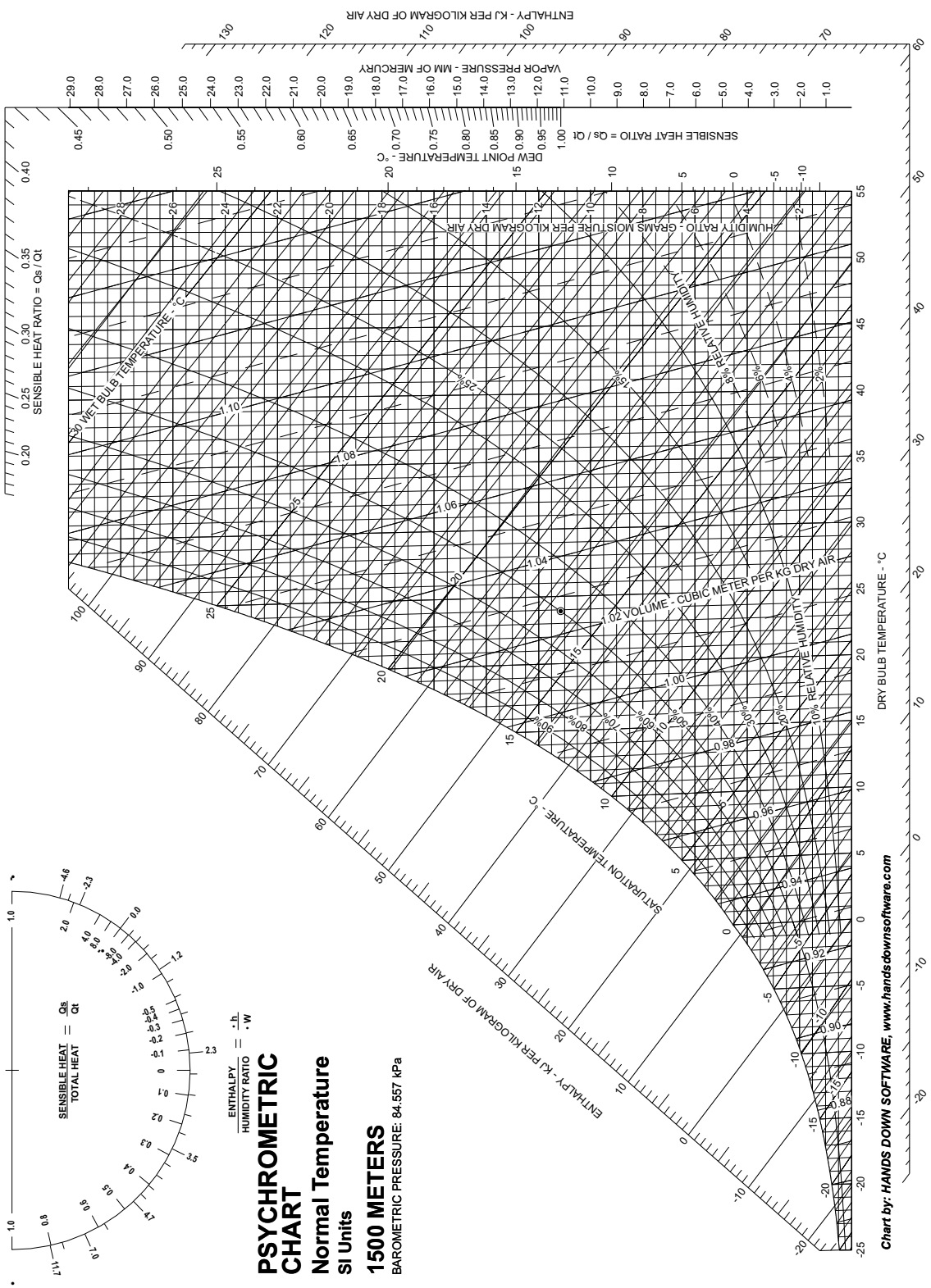
4 PSYCHROMETRIC CHART SEA LEVEL



5 PSYCHROMETRIC CHART 750M ABOVE SEA LEVEL



6 PSYCHROMETRIC CHART 1 500M ABOVE SEA LEVEL



7 TYPICAL PROPERTIES OF COHESIONLESS MATERIAL

Material	Angle of shearing resistance θ (deg)	Specific mass (kg/m³)*
Gravel	35–45	16–20
Sand		
– loose	25–35	17–19
– compact	30–40	18–21
Organic topsoil	15–30	13–18
Broken brick	35–45	1 1–16
Ashes and clinker	35–45	6–10
Maize corn	30	7–8
Rice	30–45	5–6
Millet	30–45	6–7
Soya	30	7–8.5
Potatoes	35	7
Fertilizer (general)	35	10

*Multiplied by 10^2

8 TYPICAL SPECIFIC MASS OF MATERIALS

Material	Specific mass (kg/m³)*
Concrete	
– unreinforced	23
– reinforced	24
– lightweight	7–15
Masonry	
– granite	26
– limestone	20–26
– sandstone	21–25
– slate	25–28
Brickwork	12–20
Timber	
– softwoods	4–7
– hardwoods	6–12
Steel	77

*Multiplied by 10^2

9 TYPICAL ALLOWABLE BEARING CAPACITIES

Material	Allowable bearing capacity (kN/m²)
Plain concrete	2 000–6 000
Masonry or brickwork	1 500–5 000
Compact sands and gravels	300–600
Loose sands and gravels	150–400
Solid non-fissured rocks	600–3 000
Hard clays and soft rocks	300–600
Stiff clays and sandy clays	150–300
Firm clays and sandy days	75–150
Soft clays and silts	0–75
Fill and made ground	Variable

Note: the values for soils apply where the foundation is 1m or more wide and at a depth of at least 0.6m. The allowable bearing capacity is about one-third of the ultimate bearing capacity

10 TYPICAL STRENGTH PROPERTIES AND ALLOWABLE STRESSES (N/mm²)

Mild-steel Sections	
Young's modulus (E)	206 000
Tension or compression stress in bending	155–165
Axial tension	155 (depends on slenderness ratio)
Bearing	190
Shear	115
Mild-steel rivets and bolts	
Axial tension	
– rivets	100
– bolts	120
Shear	
– rivets	90–100
– bolts	80
Bearing	
– (double shear) rivets	265–315
– bolts	200

Timber (green > 18% moisture)

	Softwoods	Hardwoods
	(values in thousands)	
Young's modulus (E)	4–12	5–19
Bending or tension parallel to grain	3–1 1	4–27
Compression parallel to grain	2 ½ –8 ½	4–27
Compression perpendicular to grain	¾–1½	1½ –5½
Shear parallel to grain	½ –1¼	¾–3 ½

Extracts from B.S. 499 and C.P. 112 are reproduced by permission of the British Standards Institution. Complete copies of the standard can be obtained from them at Linford Wood, Milton Keynes, MK146LE, England.

Appendix VI
Number of pens and stalls required in breeding pig units of various sizes

Choose values at the upper part of the intervals given where management, housing and production performance is of good standard and the production intensity is high

Num-ber of pigs in the herd	Combined pen Piglets to 12 weeks in farrowing pen	Piglets transferred from to weaner pens at 2 farrowing weeks after weaning				Places in service/ gestation pens weaning at		Boar gilt pens pens 4–6 gilts	Two-stage pens for 10–12 growers	Finishing pens for 8–10 finishers	One-stage finishing pens for 8–11 finishers
		Farrowing pens: weaning at		Pens for 7–11 weaners weaning at							
		6 wks	8 wks	6 wks	8 wks	6 wks	8 wks				
2	1	–	–	–	–	2	2	0	1	1	2
4	2	–	–	–	–	3	3	0	2	2	4
6	3	–	–	–	–	5	4	0	3	3	6
8	4	–	–	–	–	6	5	0	3	3	6
10	5	–	–	–	–	7	6	1	4	4	7–8
15	8	–	–	–	–	9–11	8–11	1	5	6	9–11
20	10	–	–	–	–	12–15	11–14	1	7	8	12–15
25	13	–	–	–	–	15–19	14–18	2	8–9	9–10	15–19
30	14–16	9–10	11–12	7–8	4–5	18–24	16–20	2	10–12	11–13	20–25
40	18–22	12–14	14–16	9–11	5–7	25–30	22–28	2	12–14	13–16	25–30
50	23–28	15–17	18–20	12–14	6–9	30–36	28–35	3	14–16	15–19	30–35
60	27–33	18–21	21–24	14–16	8–11	35–45	33–42	4	16–20	20–25	35–45
80	38–44	25–28	28–32	18–22	10–14	45–60	44–55	5	23–26	27–34	50–60
100	45–55	31–34	35–38	23–27	13–18	60–75	55–70	6	–	–	60–70
120	60–70	37–41	42–46	27–32	16–22	75–90	60–85	7	–	–	70–90
150	80–90	47–51	53–57	35–41	22–27	90–100	75–95	8	–	–	90–110
200	110–120	62–68	70–76	55–65	28–36	110–140	100–130	9	–	–	130–150

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Rural structures in the tropics

DESIGN AND DEVELOPMENT

This book is an effort by FAO to compile an up-to-date, comprehensive text on rural structures and services in the tropics, focusing on structures for small- to medium-scale farms and, to some extent, village-scale agricultural infrastructure. The earlier edition, entitled *Farm structures in tropical climates. A textbook for structural engineering and design*, published in 1986, has been used for over two decades as a standard textbook for teaching undergraduate and postgraduate courses on rural structures and services in universities throughout sub-Saharan Africa.

This second edition will help to improve teaching – at all educational levels – on the subject of rural buildings in developing countries of the tropics and it will assist professionals currently engaged in providing technical advice on rural structures and services, from either agricultural extension departments or non-governmental rural development organizations. This book will also provide technical guidance in the context of disaster recovery and rehabilitation, for rebuilding the sound rural structures and related services that are key to development and economic sustainability.

While this book is intended primarily for teaching university- and college-level agricultural engineering students about rural structures and services, resources might be made available to produce textbooks based on this material for teaching at other educational levels. Although parts of the background material relate specifically to East and Southeast Africa, the book's principles apply to the whole of tropical Africa, Latin America and South Asia because, while building traditions may vary, the available materials are similar.

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