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FOUNDATIONS FOR EARTH BUILDINGS IN THE TROPICS

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From a special study of the subject locally and an investigation in neighbouring countries, both aided by UNESCO, this article from the Building and Road Research Unit in Kumasi, Ghana, considers two aspects of foundations for low-cost earth houses, the soil and the sub-structure. The bearing capacity and propensity to settlement of different soils likely to be encountered are assessed. Practical recommendations are then given on the choice of soil and the appropriate preparations and on suitable and economic foundation sub-structures which have been found to perform well under various climatic conditions.

Basé sur une étude locale spéciale sur le sujet et une enquête dans les pays voisins, subventionnées en partie par l'UNESCO, cet article de l'Unité de Recherche sur les bâtiments et les routes de Kumasi (Ghana) considère deux aspects des fondations pour les maisons en terre à bon marché : le sol et l'infrastructure. La capacité porteuse et la tendance au tassement des différents sols que l'on est susceptible de rencontrer sont estimées, puis l'auteur donne des recommandations pratiques sur le choix du sol, les travaux préparatoires et les infrastructures de fondation appropriées et peu coûteuses dont le comportement a été trouvé satisfaisant dans diverses conditions climatiques.

For structures to perform satisfactorily they must have good foundations. By definition, a foundation is that part of the sub-structure in direct contact with and transmitting loads to the ground (ref 1). For the purpose of this paper the word foundation will denote two concepts, namely:

1. The soil or rock in-situ to which are transmitted the forces caused by the dead load of the structure and by all other loads applied to the latter.
2. The total ensemble of the structural parts of the sub-structure that serves as medium through which the weight of the superstructure and the forces due to the loads upon it are transmitted to the supporting soil or rock (ref 2).

The two concepts of a foundation will be respectively differentiated as foundation bed or soil and foundation sub-structure.

PRIMARY FUNCTION

The main function of a foundation as a whole is to spread the load from the superstructure so that the pressure transmitted to the ground is not such as to cause the ground to fail in shear, or to induce settlement of the ground that will cause distortion and structural failure or unacceptable architectural damage (ref 3). The type of foundation most appropriate for a given structure depends upon several factors, including the function of the structure and the loads it must carry, the sub-surface conditions, and the cost of foundation in comparison with the cost of the superstructure.

In recent years, a great deal of interest has been shown by many developing countries in the use of improved earth for low-cost and rural housing schemes. Some of these countries have requested information on earth buildings from the Building and Road Research Institute in Ghana. The bulk of this information has centred on how best to improve the durability of earth buildings, thereby improving their performance. Specifically, the requests and enquiries have mostly been on foundations for earth buildings.

These requests enabled us to focus attention on foundations of earth buildings during a case study of the performance of earth buildings at Ayidja, a village near the University of Science and Technology, Kumasi, and also during a study tour of Northern Nigeria, Cameroon and Senegal quite recently. The objective of this paper is to discuss aspects of the study pertaining to major defects of earth buildings arising from inadequate provision of good foundations and to indicate suitable types based on the results of this study as well as from observations from the study tour. The discussion will be confined to shallow and superficial foundations. Aspects of deep foundations are not relevant here.

MAJOR DEFECTS FROM POOR FOUNDATIONS

Provision of inadequate or no foundations for earth buildings has invariably led to rapid deterioration through erosion, underscouring and settlement cracks. The erosion and underscouring are caused by water, particularly swirling rain water. The base of the walls is eroded, the soil at the foot of the wall is gradually washed away until the building becomes unstable, (see figs 1 and 2). Settlement cracks occur in the building when the soil immediately in contact with that part of the sub-structure (foundation bed or soil) that serves as a medium through which the loads are transmitted becomes over-consolidated or compressed.

The rate and extent of erosion and underscouring depend on many factors, among which are the type of foundation soil, the siting of the structure, the topography of the area as well as the intensity and frequency of rainfall in the area. Naturally, where there is little or no rainfall the problem of erosion and underscouring of the base of the wall will be non-existent. However, erosion of a wall may occur in arid and semi-arid areas through sand laden winds. Under these conditions the erosion is sometimes termed abrasion. On the other hand, erosion and underscouring can be severe in hilly areas with poor drainage facilities, heavy rainfall and silty sandy soils (refs 4-6).

FOUNDATION SOILS

For convenience and clarity, the natural or artificial ground on which the sub-structure transmits the load is referred to in this paper as the foundation soil or foundation bed. That part of the sub-structure which transmits the load to the foundation soil is referred to as the foundation sub-structure.

Soil characteristics

The foundation soil consists of many types of geological materials ranging from rock through gravels and sands to peat. The suitability of these materials for foundation depends on their physical properties, which include moisture content, tendency to consolidate and bearing capacity. The best and most suitable foundation soil or bed is bedrock, which is sound, hard, undisturbed rock in its native location, of indefinitely great extent, not broken up by harmful seams and cracks and underlaid by no material except rock (ref 2). The bedrock may be igneous, sedimentary and metamorphic rocks. Typical bearing capacities for igneous and gneissic rocks in sound condition may be around 10 000kN/m^2 (100 ton/ft^2). For sedimentary rock like hard limestones and sandstones the bearing capacity is about 4000kN/m^2 (40 ton/ft^2).

The next foundation soil to be encountered is weathered rock, which is an intermediate stage between bedrock and soil. It may be residual above or alongside sound rock. It is likely to have seams filled with fragments of rock at different stages of disintegration. There are also boulders and cobbles which may be residual or may have been transported far from their original position relative to the parent bedrock. Bearing capacities of these are high but variable and may range from 2000-10 000kN/m^2 (20-100 ton/ft^2).

The most important foundation soil as far as earth buildings are concerned are the non-cohesive and cohesive soils. These are the types of soil which are frequently encountered during the construction of earth buildings. These may include laterites. The non-cohesive soils are compact gravel, compact well graded sands, compact gravel-sand mixtures, loose gravel, loose well-graded sands and gravel-sand mixtures as well as compact and loose uniformly-graded sands. The bearing capacities for the compact soils range from 300 to 600kN/m^2 (3-6 ton/ft^2) and for the loose non-cohesive soils 100-200kN/m^2 (1-2 ton/ft^2).

The cohesive soils include very stiff boulder clays and hard clays with shaly structure ; stiff clays and sandy clays ; firm clays as well as soft to very soft clays and silts. The bearing capacities for very stiff boulder clays and hard clays range from 300 to

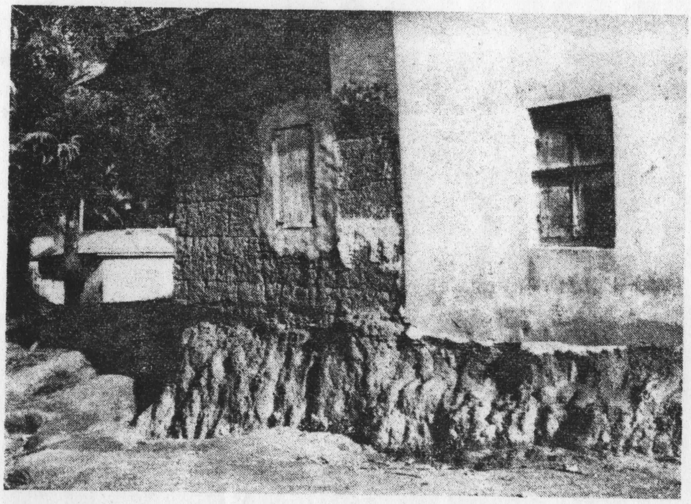

Fig. 1. Severe underscouring of an earth building

Fig. 2. Erosion at the base

600kN/m^2 (3-6 ton/ft^2). Firm clays and sandy clays have bearing capacities ranging from 75-200kN/m^2 (0.75-2 ton/ft^2) ; and the bearing capacities for soft to very soft clays and silts may vary from 0-75kN/m^2 (0-0.75 ton/ft^2). Peat and organic soils and fill as well as made-up ground may also be encountered during the construction of earth buildings.

The properties of the foundation soil or bed, the natural ground, determine to a large extent the size and strength of the foundation sub-structure to be designed. This important fact has often been ignored in the construction of earth buildings. The cost factor has always been paramount at the outset with the result that savings are achieved while the safety and durability of the structure are sacrificed. It is essential, therefore, to consider the foundation soil or the natural ground on which the building is to be founded.

Soil assessment and precautions

Sound bedrock is the best foundation soil with very high bearing capacity which is far in excess of what will be required for an earth building. When this type of natural ground is encountered there will be no question of absolute or differential settlements. Protection against erosion will, however, be required, taking into consideration the dip or slope of the bedrock. Its main *disadvantage* will be in regions where there are frequent earthquakes. Due to its rigidity, it will transmit effectively any seismic vibrations to the earth building. This may cause severe cracks or total collapse of the building.

Weathered rock may have more than the required bearing capacity for earth buildings and will make an excellent foundation bed. Generally, a residual soil is located directly above the parent rock from which it has been derived by physical and chemical disintegration and decomposition of the bedrock. As a rule, such a soil is recognised readily by gradual transition from relatively fine-grained material near the surface to soil containing angular rock fragments as the depth increases. When this type of foundation soil is encountered the top fine-grained soil, if shallow, should be removed and the remaining more granular soil compacted before the foundation sub-structure is laid. Absolute settlement is likely to be negligible for this soil. Care should be taken, however, to locate and remove pockets of relatively soft materials from the foundation trench so as to ensure near uniform settlement, if any.

The most frequently encountered foundation soils or beds are the non-cohesive and cohesive soils. The compact non-cohesive soils are suitable as far as bearing capacity and non-susceptibility to long term settlement are concerned. The loose non-cohesive soils, however, require some amount of compaction prior to founding the sub-structure. These soils have a tendency to long term settlement.

The very stiff to firm clays may possess adequate bearing capacity but this can be drastically reduced with an increase in their moisture content. Erosion and underscouring will be common with loose non-cohesive and cohesive soils. It has also been observed that for these soils, the finer the particle size, the further capillary action can bring the water level above the water table. Typical values of height of capillary rise are:

Clay — 200-400cm (80-160in) or greater
Silt — 70-150cm (28-60in)
Fine sand — 35-70cm (14-28in)
Medium sand — 12-35cm (5-14in)
Coarse sand — 2-5cm (0.8-2in).
There is a need, therefore, to consider the possibility of providing a capillary barrier for floors when these types of soils are encountered.

Peat and organic soils have a high proportion of fibrous or spongy vegetable matter formed by the decay of plants, mixed with varying proportions of fine sand, silt or clay. All these soils are highly compressible, and even lightly loaded foundations will be subject to considerable settlements over a long period if placed on them. For this reason these soils are to be avoided as foundation bed. Earth buildings should not be sited on them.

Made-up ground and fill should be treated as suspect because of the likelihood of extreme variability. Made ground and fill may be insanitary or may contain injurious chemicals. Industrial waste of town refuse may still be in a state of chemical activity, and waste often ignites and burns below ground, (ref 1). However, there are situations where the filling operation is adequately controlled by placing in thin layers and compacting selected suitable fill material. When the fill has been properly made it can be an adequate foundation bed as far as bearing capacity is concerned. But settlement is likely to occur and thus adequate precautions should be taken against both absolute and differential settlement.

Special attention should be given to the foundation bed when the soils are known to be expansive. Foundation movements on swelling soils such as montmorillonitic clays are associated with changes in moisture content which must therefore be stabilised as far as possible. The seasonal swelling and shrinkage of heavy clay soils in the tropics can be aggravated by plant transpiration, which dries out the soil faster than it would otherwise dry by evaporation and drainage. The success of buildings on expansive soils has been shown by experience to depend more on the type of construction employed than on the foundation. Structures should always be flexible enough to accommodate the movement that is bound to occur. Masonry structures, for example, should use soft rather than hard mortars, small rather than large blocks or other building units, and separated structural units to tolerate movements with minimal cracking (refs 8 and 9). More elaborate and precise methods of designing foundations on expansive soils are available but the cost involved does not justify the adoption of these methods for earth buildings. Alternatively, if it is at all possible, the site should be avoided for a new area.

THE SUB-STRUCTURE

Simplicity in design

The function of the foundation sub-structure is to transmit all the dead, superimposed and wind loads from the building to the soil on which it sits in such a manner that settlement, and in particular differential settlement, is limited so that failure of the underlying soil is avoided. In order to perform this function effectively, the foundation sub-structure must provide in its design and construction adequate strength and stability. In fulfilling these functions the foundation soil and sub-structure and the superstructure should be considered as one unit and the tolerable total and differential settlement must be related to the type and use of the structure and its relationship to the surrounding.

In general, foundation design must take into account the effects of construction on adjacent property, and the effects on the environment of such factors as vibrations from pile-driving, and pumping and discharge of ground water. Thus, the designer of the foundation sub-structure must ensure that the foundation meets basic considerations of safety, dependability, functional utility and economy.

In comparison with the cost of the superstructure of earth buildings, foundation cost is the decisive factor which determines whether or not to provide for a foundation sub-structure. The whole idea behind the use of earth for building is to reduce cost, so that thorough site investigation and soil testing before designing a foundation for such a building may not seem economic. Perhaps a large project may justify the cost of such site investigation.

Equally, it is not good engineering to construct earth buildings without any foundation. Under favourable conditions earth walls have been built on the natural ground surface without any foundation sub-structure, but under these conditions the building may not perform satisfactorily for long. As most earth buildings are houses, only simple rudimentary foundation sub-structures need to be designed to minimise absolute and differential settlements, erosion and underscouring.

Foundation types and techniques

There are many types of shallow foundation sub-structures but the most suitable one for earth buildings on account of cost and ease of construction is the strip footing. For earth walls, continuous footings are commonly used, with the foundation wall resting on the footing and extending upwards to support the walls. Figure 3 shows a typical continuous footing and foundation wall.

In designing a footing three factors should be borne in mind — the depth of the footing, its size, and the material to be used. The size and depth of the footings depend on the type of material used in making them, the weight they must support and the load the foundation soil will support as well as the climate of the area. The depth of the footing should be placed below the frost line in temperate areas and below the depth of seasonal moisture changes in the tropics. The size of the footing will depend on the bearing capacity of the foundation soil and the bearing pressure of the structure. It is obvious that the foundation must be safe and durable. Therefore concrete, stone, brick and concrete blocks are most suitable and durable materials. Stabilised soils may be used in arid and semi-arid areas.

From observations, concrete footings are found to be most popular, and most expensive. To obtain a good concrete foundation it is necessary that — after the trench is dug to get rid of the top soil — the foundation soil is rammed or compacted before the concrete is poured. Sometimes reinforcing steel may be required in areas prone to earthquakes, hurricanes, or excessive swelling and shrinkage of the foundation soil. Figure 4 illustrates a reinforced concrete footing.

Figures 3 and 5 show masonry footings which have been observed to perform well and can be constructed with either bricks, concrete blocks or rubble stone laid in mortar. It is very necessary to level the bottom of the trench when using bricks, concrete blocks or any regularly shaped materials so as to ensure a level bottom. For rubble stone footings the trench need not be level but the final course should be level. Masonry footings are harder to lay, require more time to complete and are not easily reinforced with steel. For these reasons they are not normally recommended for areas of hurricanes and high wind.

Foundation walls

The foundation walls, which rest on the footings and support the walls of the house, must be strong, have a flat surface on which to start the earth wall, must be straight and must be level. Concrete, bricks and concrete blocks are also suitable foundation wall materials. Well stabilised soil or laterite, either in the form of rammed-in-place earth or blocks, have been found to perform well in arid and semi-arid areas.

The thickness of the foundation wall should be the same as that of the wall of the earth building. Its height should be sufficient so that rain splashes will not reach the earth blocks and cause them to erode or wash out. This height depends on the amount of rainfall and width of roof overhang.

From observations, in Northern Nigeria and Senegal it is necessary that the foundation wall should extend 22.5 cm (9 inches) above ground surface in dry regions where the annual rainfall is less than 25 cm (10 inches). Where the rainfall is between 25-75 cm (10-30 inches) a year the height of the wall must be 30 cm (12 inches), and 45 cm (18 inches) where rainfall is as high as 75-125 cm (30-50 inches) or more. Wide roof overhang and good drainage facilities help to minimise erosion and underscouring.

Another form of footing which combines the foundation wall with the footing is that made with rubble (see fig 3). The foundation is

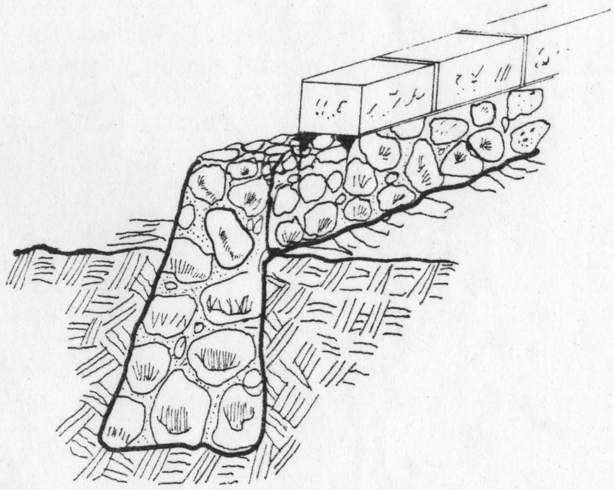

Fig. 3. A typical masonry footing with foundation wall (after ref 10)

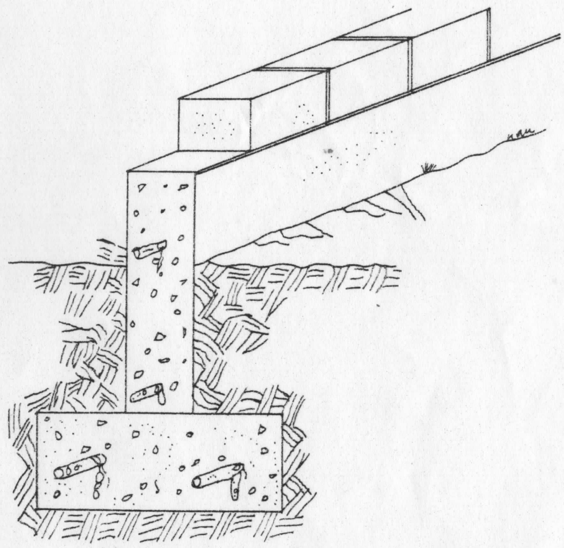

Fig. 4. A reinforced footing (after ref 10)

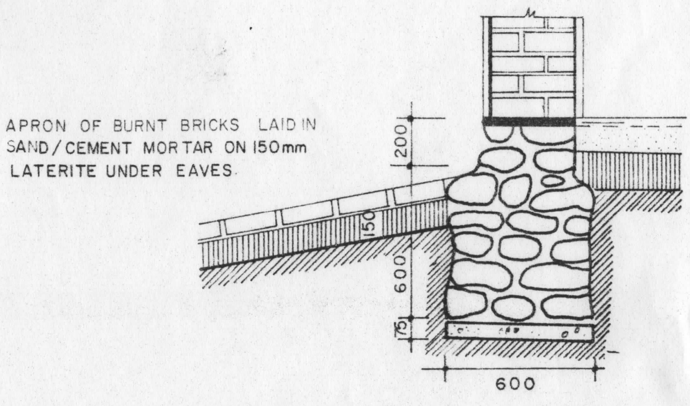

Fig. 5. Stone foundation suitable for adobe or sun-dried and burnt brick walls, with termite shield and damp-proof membrane (after ref 11)

built in one solid piece and tapers up to the width of the earth wall. This type of foundation is economical, especially where there are stones at the site. However, much patience is required in its construction.

Materials and methods

Figures 6-15 show different combinations of foundation materials that can be used in designing the footing. For a dry climate where the rainfall is low figure 6 illustrates a suitable shallow footing ; figures 7-9 show other varieties which perform well in dry areas. In figure 7, protection from moisture is provided by heavily coating the bottom of the trench and both sides of the bricks with tar. Figures 13 to 15 illustrate types of concrete footing which have been observed to be suitable for areas of heavy rainfall. Finally, figure 10 shows a footing of soil cement with the base of the trench lined with a thin layer of concrete.

There are many combinations of footings that can be designed but the choice of any one of these will depend on the availability of material, on the foundation soil type and on the prevailing climatic conditions of the area.

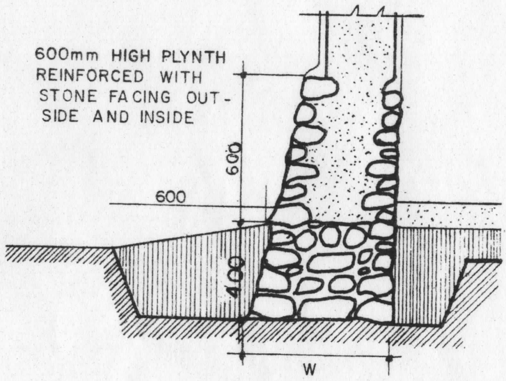

Fig. 8. Stone foundation suitable for Attakpame or wattle and daub (after ref 11)

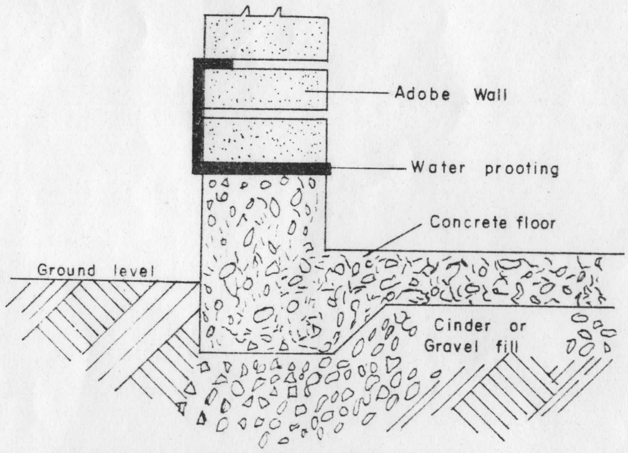

Fig. 6. Shallow footing for a dry climate (after ref 9)

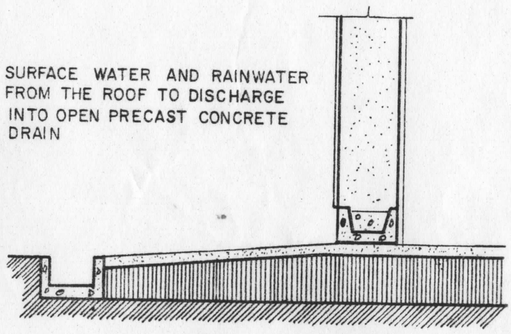

Fig. 9. Attakpame wall with precast U-beam base (after ref 11)

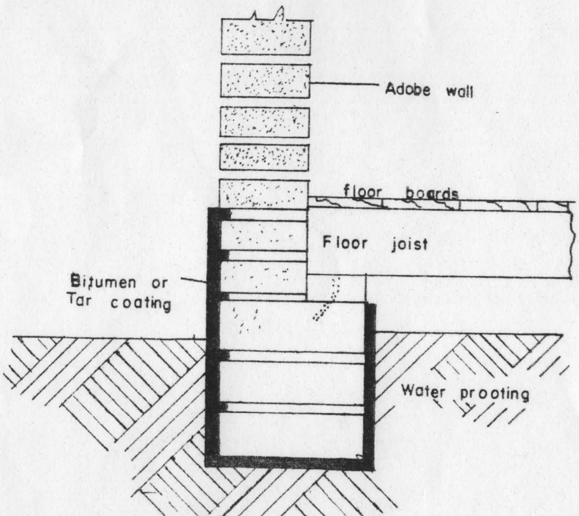

Fig. 7. Adobe foundation for a dry climate (after ref 9)

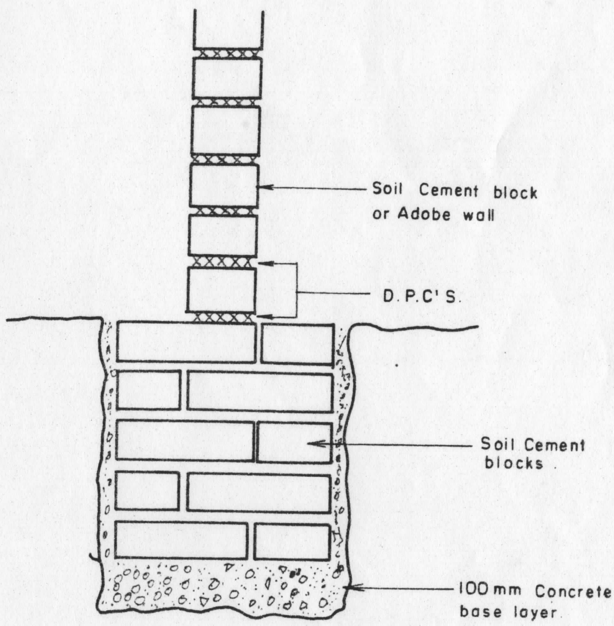

Fig. 10. Soil-cement block foundation (after ref 9)

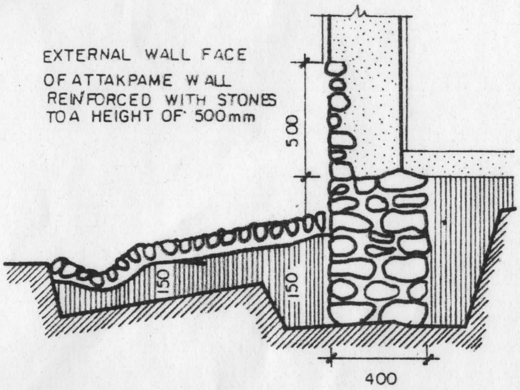

Fig. 11. Stone foundation suitable for attakpame or sun-dried brick or adobe ; with apron of stones set in sand/clay/bitumen mortar on top of 150 mm thick well-rammed laterite below eaves overhang (after ref 11)

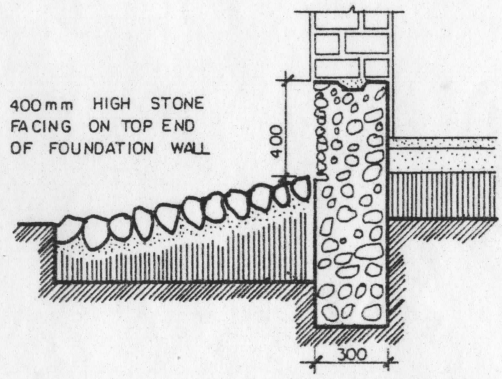

Fig. 14. Concrete strip foundation, with apron under eaves overhang of stone set in soil/sand/bitumen to falls, suitable for heavy rainfall areas (after ref 11)

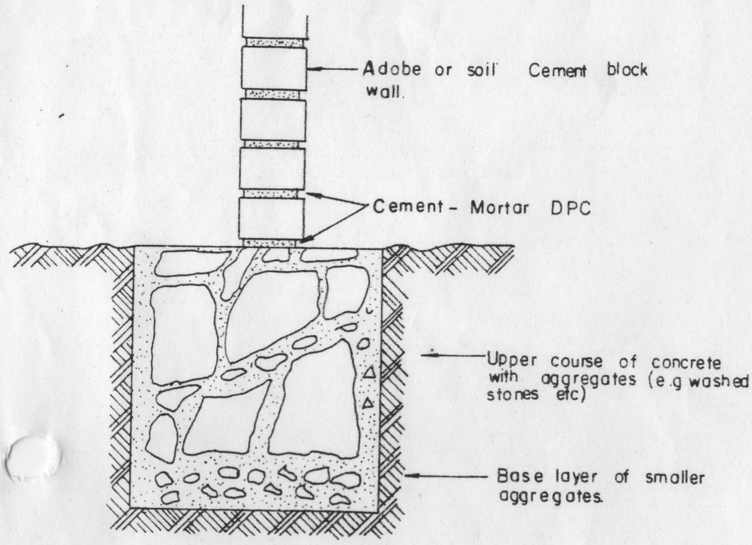

Fig. 12. A Cyclopean concrete foundation (after ref 9)

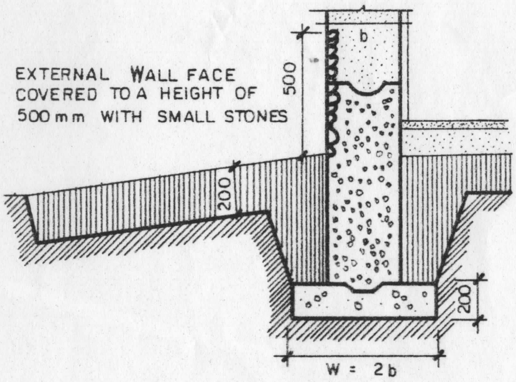

Fig. 15. Reinforced concrete strip foundation suitable for attakpame, sun-dried brick, adobe or burnt-brick walls in areas where both heavy rainfall and earthquakes occur (after ref 11)

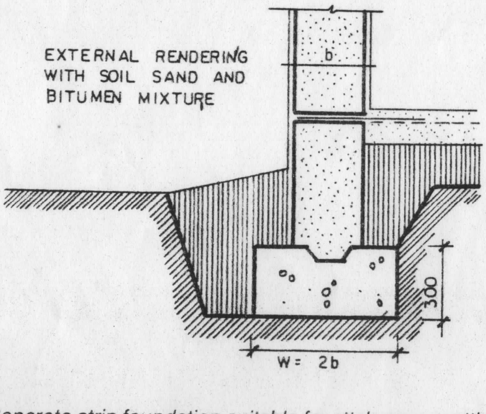

Fig. 13. Concrete strip foundation suitable for attakpame, wattle and daub, sun-dried brick, or adobe walls in heavy rainfall areas (after ref 11)

CONCLUSIONS

On the basis of this study and from observations from elsewhere the following recommendations may be made :

1. Earth buildings must be built on foundation soils with good bearing capacities and with little or no tendency to consolidate excessively and over a long time. For these reasons bedrock, weathered rock, non-cohesive soils and lateritic gravels and sandy soils are recommended as suitable foundation soils. The comparative cost of the superstructure of the earth building and the cost of getting these types of foundation soils must be borne in mind.

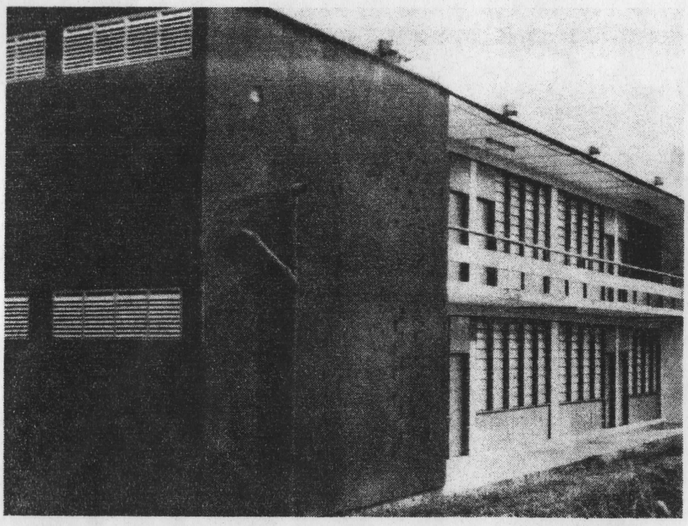

Fig. 16. The principles applied to a modern structure ; the improved earth building for an administration block at the Faculty of Architecture, UST, Ghana

2. Since peat and organic soils are highly compressible and will consolidate over a long period, and since shallow and superficial foundations are the only economically acceptable foundation types for earth buildings, earth buildings should not be founded on peat and organic soils, especially where these are deep seated and extend to the surface of the ground.
3. Earth buildings should only be sited on well-compacted fill or made-up ground where the fill material is suitable and chemically inert.
4. Foundation sub-structures should be constructed with concrete, bricks, concrete blocks and stones. Stabilised soil blocks may be used in arid and semi-arid regions. In areas where rainfall is moderate to heavy, aprons, long eaves overhang and good drainage facilities are additional recommendations for earth buildings. When these measures are taken, the durability of earth buildings will be improved and the performance life of the building may be prolonged.

ACKNOWLEDGEMENTS

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