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HIGHWAYS AND FOUNDATIONS IN BLACK COTTON SOILS

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HIGHWAYS AND FOUNDATIONS IN BLACK COTTON SOILS

Introduction

1. Black cotton soils are one of those clays with a high content of montmorillonite. These have a very high plasticity leading to high rates of expansion on wetting followed by shrinkage and considerable cracking on drying. The black cotton soils of Ethiopia have liquid limits ranging between 80 and 120 and plasticity indices of 40 to 80 (see figure 1). The activity of these clays is between 0.8 and 1.5. Thus by the Skempton classification the activity of these clays is considerable and, as one would expect, swelling potential is high.

2. More than 80 per cent of the potential areas of development are covered by black cotton soils. It is therefore apparent that most of the future development would take place on the black cotton soil: as much information should be made available on the engineering properties of these materials so that economies may be achieved in construction. The black cotton soil is predominant in the Shoa region and it extents to a radius of about 100 kms of Addis. Its importance in the construction of highways cannot be over estimated.

Engineering properties

3. The black cotton soil is a very fine clay and, as mentioned earlier, consists of montmorillonite which causes high swelling and shrinkage. 90 per cent of this clay is smaller than 0.15μ. This gives a very plastic clay which is very hard when dry but has almost no strength at high moisture content.

4. Information on consolidation is scanty but results of swelling tests show swelling deformations of 10 per cent under a pressure of approx. 1 kg/m^2. The relationship between shear strength moisture content is shown in figure 2. (Bekele, 1967). Little work has been done on the compressibility of these clays; the shrinkage limit of the black cotton soil is in general not known for the Addis Ababa area.

5. In order to obtain reliable design of building foundations the following characteristics of the black cotton soils must be known:

(i) Shrinkage limit

(ii) Linear shrinkage

(iii) Consolidation/swell characteristics, i.e. a consolidation test in which the sample is allowed to take in moisture under reducing load. This is approximately what happens during the rainy season.

(iv) Equilibrium moisture contents under covered and exposed areas, depth of cracks.

Bekele, WM, 1967. Some characteristics of Addis Ababa Soils Ethio-Swedish Institute of Building Technology.

6. Tests done elsewhere show that there is linear corralation between clay content (% < 2μ) with the plastic limit plasticity index, volumetric and linear shrinkage. Though these correlations may vary by location in Addis, assuming that these clays have the same geological origin, general correlations could be established both for design and for building regulations.

7. The following phenomena result from the properties outlined above:

(i) Shrinkage of the clay due to drying;

(ii) Swelling due to wetting;

(iii) Development of swelling pressures in clays which are confined and cannot expand;

(iv) Loss of support to structures due to shrinkage;

(v) Decrease in strength and bearing capacity resulting from swelling.

8. Several of these phenomena may occur at the same time depending on boundary conditions but the predominent factor is the equilibrium moisture content which is determined by loading, type of ground cover depth of ground water table, time of construction and suction properties of the soil.

9. The variation of suction with depth may be expressed as follows:

$$(hm)_z + Z = Z_w$$

$(hm)_z$ – suction at depth z in metres of water

Zw – depth of ground water below ground surface in metres.

10. Damage due to the phenomena listed above take the following forms:

(a) Appearance of uneveness along significant portions of roads or pavements without any sign of cracking;

(b) Longitudinal cracks parallel to road centre line;

(c) Localized deformation, especially near joints of bridges and culverts, followed by disintegration of road surface;

(d) Appearance of vertical cracks in walls, sometimes accompanied by tilting of walls or columns.

Foundations

11. The loads transmitted to foundation levels of small buildings are usually smaller than the swelling pressures. Buildings founded on such soils tend to be lifted when moisture content increases at foundation level.

12. Though it is a fact that swelling falls with high initial moisture content, bearing capacity also falls and the difficult choice has to be made of the moisture conten at which to construct in order to minimise swelling and shrinkage. The control of moisture content as a solution to this problem for small structures is not only impractical, but often expensive.

13. More successful solutions have been:

(i) the excavation of foundations to firmer strata (this is practical when these strata occur at shallow depths);

(ii) piling for greater depths;

(iii) permanent lowering of ground water table by the placing of more pervious material in the foundations and by judicious drainage.

14. Small diameter bored piles have been effective in many areas (Donaldson 1963).

15. A major problem with piles is the possibility of their failure in tension due to uplift forces.

16. The maximum uplift force T, could be calculated from:

$$T = \frac{\pi}{2} \cdot D. \left(2\, ch + k\, h^2 \gamma \tan \phi\right)$$

Where D - Diameter of pile
h - depth of expansive layer
k - co-efficient of earth pressure
γ - unit weight of soil
c - cohesion of soil
ϕ - angle of shearing resistance

The last two parameters c, ϕ, are assumed to be constant with depth.

Donaldson G.W. 1963 Piles in expansive soils, Vol.I. Proceedings Third African Regional Conference in Soil Mechanics and Foundation Engineering.

The maximum tensile force will be:

$$T_f = T-P$$

where P = structural loan on pile.

The amount of tensile reinforcement is determined by T_f (Collins 1953).

17. The problem of piles can be solved in a slightly different manner, in order to reduce the percentage of tensile steel, by making a short pile with sloping sides:

Consider the section of a pile shown (fig. 3b) such that the side slopes at an angle α defined by

$$\alpha = \tan^{-1} \frac{k \gamma\ L^2 \tan \phi}{T_f}$$

18. In such a situation, the weight of the uplifting mass of soil will act to withhold the file in position, this goes to reduce the tensile forces. Thus the application of such short piles would lead to a saving in steel.

19. It was noted above that the swelling/shrinkage potential was directly proportional to the clay (% 2μ) content. Where costs would allow, it would be advisable to provide the solution shown in fig.4.

20. The slope of the ground should be away from the building. Since black cotton clays have very low permeability a small slope 0.5 per cent would be adequate. If this drainage system is coupled with a wide roof overhang and storm drains, the foundations should be protected against extreme moisture content variations and thus against excessive swelling or shrinkage.

21. The foundation trench itself should be designed to drain off any water that may seep into it by giving it a slope in the appropriate direction and leading off the water by suitable underground drainage, preferably sand drains.

22. Because of the low permeability of black cotton soils local artesian pressures may develop at the contacts with bed rock. Thus it is not enough to determine this contact, the following additional information must be determined:

Collins L.E. (1953) Preliminary theory for the design of under reamed piles Trans. S.A. Institution of Civil Engineers Vol.3 No.11, November.

(1) Slope of the contact;

(2) Characteristics of the outcrop of the harder layer.

When these facts are known, the contact would be suitably drained and the common problem of the deformation of foundations placed on bedrock will be avoided, since in these cases, the foundation itself is not deforming but the intervening material.

11. The foundation of heavy structures on expansive soils do not require any special precaution except in the estimated of the effective bearing stresses resulting after loading. An estimate of moisture content from moisture/suction curves under external loads must however be made. For this purpose it would be necessary to use the curve corresponding to the suction under the load in question. The determination of the moisture/suction cruve for the appropriate load must be made in the laboratory as an essential test which would yield information for foundation design.

The pore pressure u, in an unsaturated soil

sample under all round pressure p is given by

$$u = \alpha p - s \qquad (5).$$

where s = suction

α = compressibility factor (Croney etal, 1958)

combining this with the Jennings equation,

$$\sigma' = p - \beta$$

where p = total stress in the soil

σ' = effective stress in the soil

u = pore water pressure

β = numerical factor usually less than unity,

one obtains

$$\sigma' = p - \beta(p - s)$$

Under heavy loading $\alpha = \beta = 1$ and effective out stress σ' under the given load p is approximately equal to the suction determined in the laboratory, under an all round pressure ..

Croney, D; Coleman J.D. and Black, W.P.M. (1958) Movement and distribution of water in soil in relation to highway design and performance HRB Special Report No. 40. Washington D. p.226-252.

12. Thus effective stresses at the foundation level could be determined and hence the effective bearing pressure at that level.

Consider the foundation shown (see fig. 5) above water table but which may be submerged during the rainy season.

Above water table the effective bearing capacity q is given by

$$q = CNc + p'Nq + \frac{1}{2}\gamma BN_{\gamma}$$

where c = cohesion

Nc, Nq, Nj are the Terzaghi Bearing capacity factors the net effective bearing capacity (allowable applied loads).

would be $q_L = q - p'$

For a submerged foundation the effective bearing capacity would be given by:

$$q' = CN_c + p'N_q + \frac{1}{2}\gamma B. N_{\gamma}$$

where $q = q' + u$

and q = total bearing capacity

q' = effective bearing capacity

u = pore pressure

and $q_L = q' - p'$ (ii)

<u>Highways and pavements</u>

13. In general the requirements for the performance of a flexible pavement on expansive clays are similar to those of other structures: economy, safety, tolerable deformation. In order to meet these requirements for flexible pavements the following soil properties must be known before design:

(a) the swell potential resulting from moisture changes after construction;

(b) the acceptable minimum density and optimum moisture content at a specified air voids ratio at placement of the clay subgrade;

(c) the strength characteristics of the clays;

(d) the equilibrium moisture profile after construction determined from that prior to construction and suction tests under the expected loads.

For expansive clays the critical factors are the shear strength and swell/shrinkage potential at extreme moisture conditions. The CBR method of pavement design takes all these factors into account and until theoretical tools become more refined, it remains the best method available for the design of pavements on swelling soils.

14. The CBR depends on the placement conditions of the clay in the field, i.e. on the range of moisture and density in the subgrade. The maintenance of a predictable range of moisture content and density, uniformly distributed, depends on the skill, experience and equipment available to the contractor. Thus the role of the building contractor in the final realization cannot be over estimated.

15. Placement moisture and density must ensure the following conditions in service:

(i) Minimum swelling limited to 2 per cent swell potential associated with a low rate of swelling.

(ii) Maintenance of required strength irrespective of moisture content;

(iii) A density high enough to minimise deformations resulting from traffic loading.

16. In order to ensure these performance conditions the subgrade must be placed at both optimum moisture and minimum swelling potential. The CBR for design is selected for the worst moisture conditions in the field after placement at equilibrium moisture content.

17. If the moisture/suction curve is known for the material at various loads the factor of safety of the pavement against bearing failure can be reliably estimated.

18. Swelling clays are found in such different climatic regions that no general rules can be established without a detailed recording of performance. It is on the performance data that design decisions and codes of practice will be based. Recorded data in this field are essential. For without this "post-mortem" on design, "hand book" designing methods may be too expensive by not fully reflecting local conditions and knowledge.

19. The drainage of roadways, especially near the hard shoulders is one of the essential means of ensuring that the moisture conditions assumed in the design are operative.

20. The author's experience of the M2, England, shows that filter drains coupled with perforated drainage pipes were adequate for the central reserve. The drain under the joint of pavement and hard shoulder cosisted of simple sand drains only with transverse collector drains connecting to man holes in the central reserve at appropriate distances. An effective drain must remove water from the soil without appreciable headloss at the same time it must not permit the migration of the soil into the drainage system and the consequent erosion and clogging of the drain. Thus it must be both loose enough to permit drainage and fine enough to hold the soil being drained in place. Such a drain is called a filter.

21. Based on the performance conditions outlined above, and on extensive experiments, Terzaghi established the criteria below:

$$D_c \leq D85 \text{ (soil)}$$

$$D_c = \tfrac{1}{2} D_{15} \text{ to } \tfrac{1}{5} D_{15} \text{ (soil)}$$

$$D_{15} \text{ (filter)} \doteq D_{85} \text{ (soil)}$$

$$D_{15} \text{ (filter)} \leq 4D_{15} \text{ (soil)}$$

Where D_o = maximum size of voids in filter. If the filter were a perforated pipe, wire scree or porous pipe, this fixes the maximum size of openings in terms of granular materials available.

22. The filter gradation curve should be smooth and parallel to, or less uniform than the soil being filtered. The range of gradations suitable for filter for a given soil are shown in the diagram, the best gradation should be on the coarser side (see fig.6).

23. If the soil being drained is gap graded, the portion coarser than the break is ignored; the gradation is recalculated using only the finer fraction. The design of the filter is then carried out as above.

Recording storage and use of geotechnical data

24. It is known that the general principles of soil mechanics have always had to be modified by the properties of local materials. Thus the body of local knowledge on specific behaviour of the soils is largely empirical. In view of this, an effort must be made to record the performance of structures accurately. This is the only way of knowing the behaviour of the materials in situ.

25. For example, the central recording and analysis of all geotechnical investigations in the country would yield valuable information on the detailed sub-surface structures in the municipal areas. This could easily explain anomalous behaviour of structures and, when enough information is available, may obviate the need to collect sub-surface information in certain cases. The information may be issued periodically as a geotechnical news letter to all interested members of the profession.

Terzaghi - Theoretical Soil Mechanics and
Peck; Soil Mechanics in Engineering Practice.

Kasiff. G. et al (1969). Pavements on Expansive Clays
Jerusalem Academic Press.

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(1) Bekele, WM 1967. Some characteristics of Addis Ababa Soils Ethio-Swedish Institute of Building Technology.

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(3) Collins L.E. (1953). Preliminary theory for the design of under reamed piles trans. S.A. Institution of Civil Engineers Vol.3 No.11, November.

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(5) Terzaghi - Theoretical Soil Mechanics and Peck Soil Mechanics in Engineering Practice.

(6) Kasiff. G. et al (1969). Pavements on Expansive Clays Jerusalem Academic Press.

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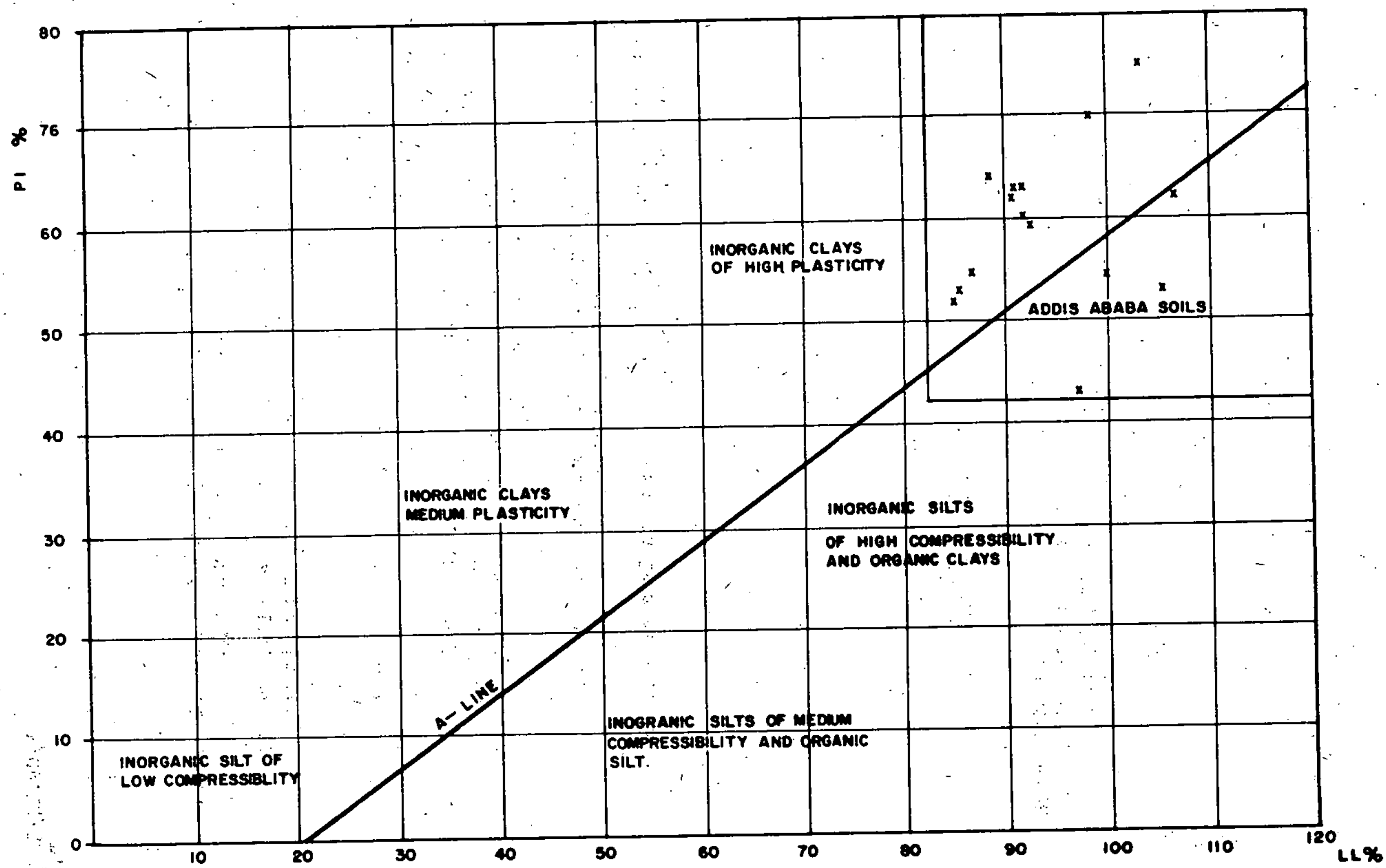

Fig I. PLASTICITY CHART SHOWING ADDIS BLACK SOILS

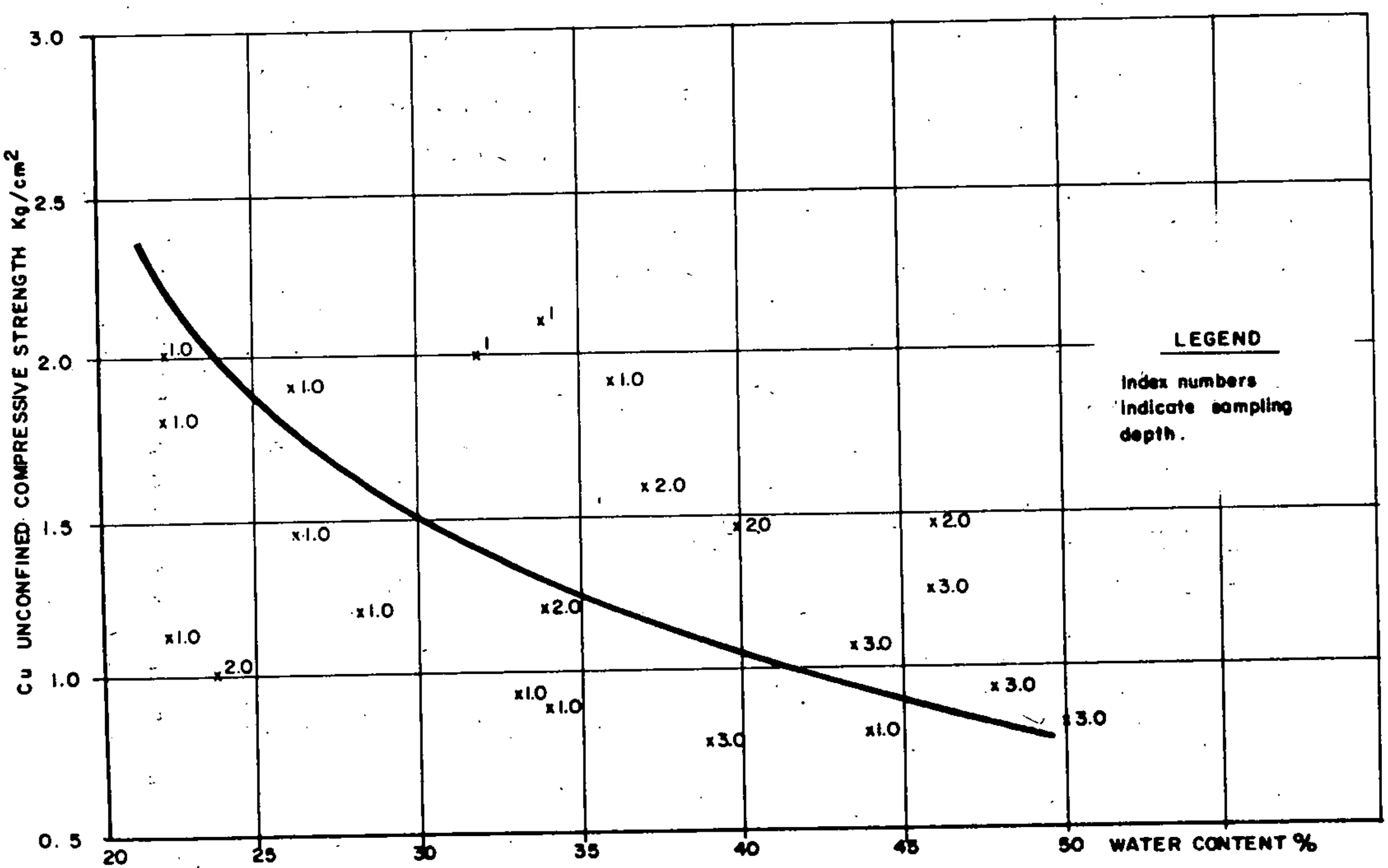

Fig. 2 CLAY—MOISTURE CONTENT FUNCTION: ADDIS ABABA RED CLAY

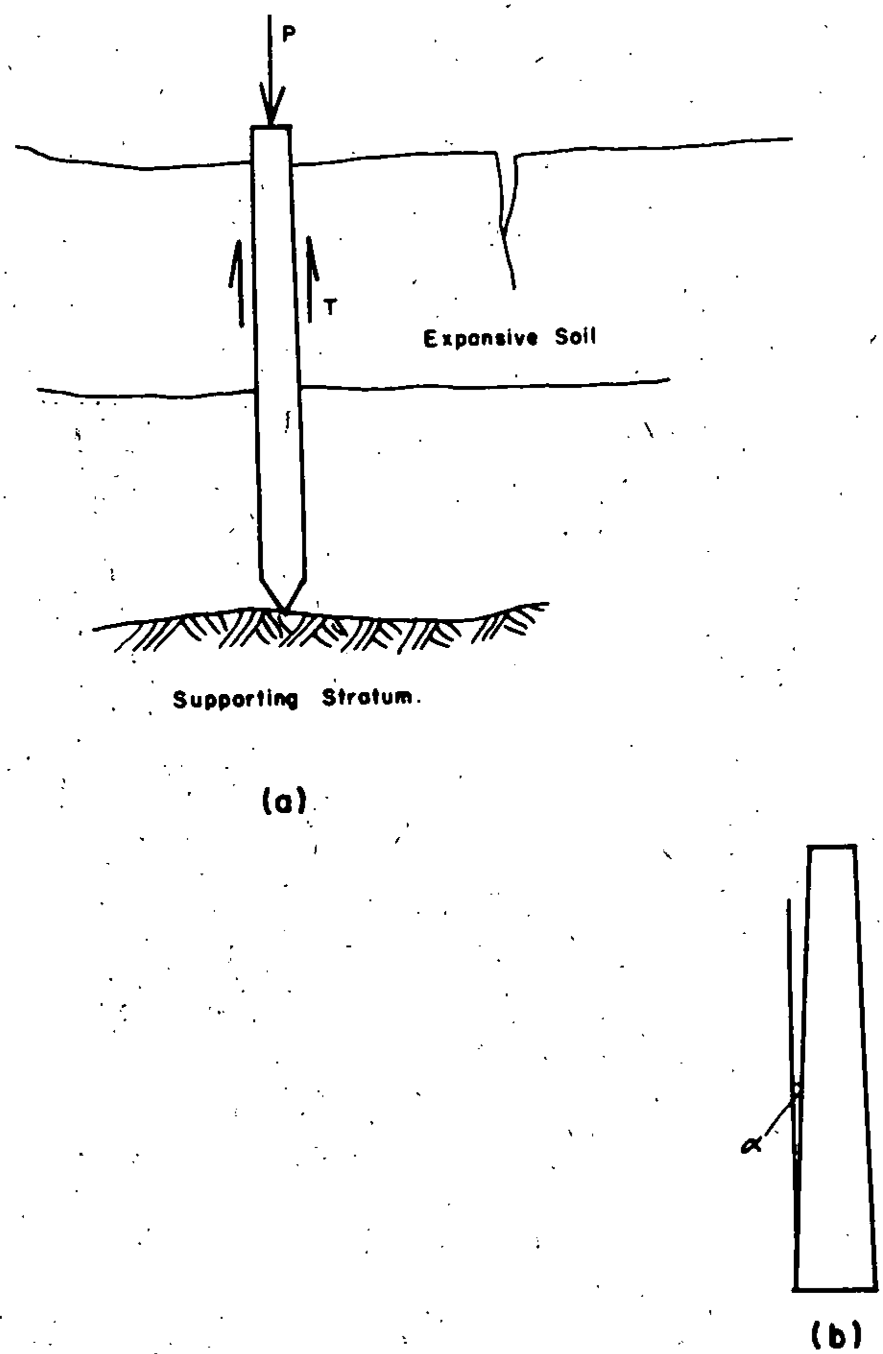

Fig 3 Bored Piles in Expansive Soils

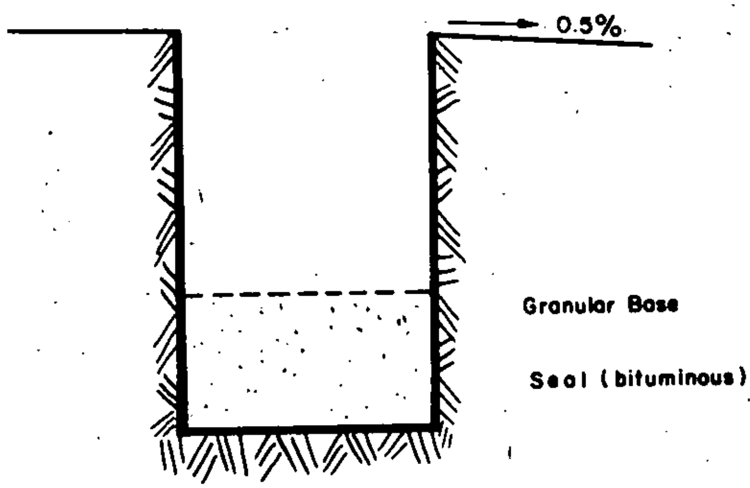

Fig. 4 Foundation Design for a light structure on Expansive Soil

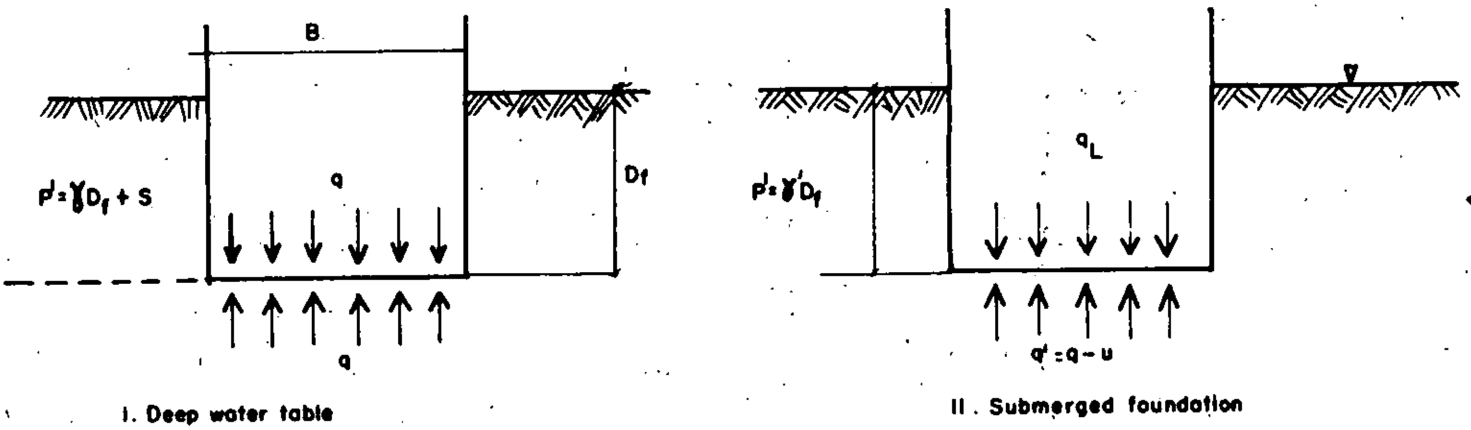

Fig. 5 Effective Bearing Stresses on Foundations

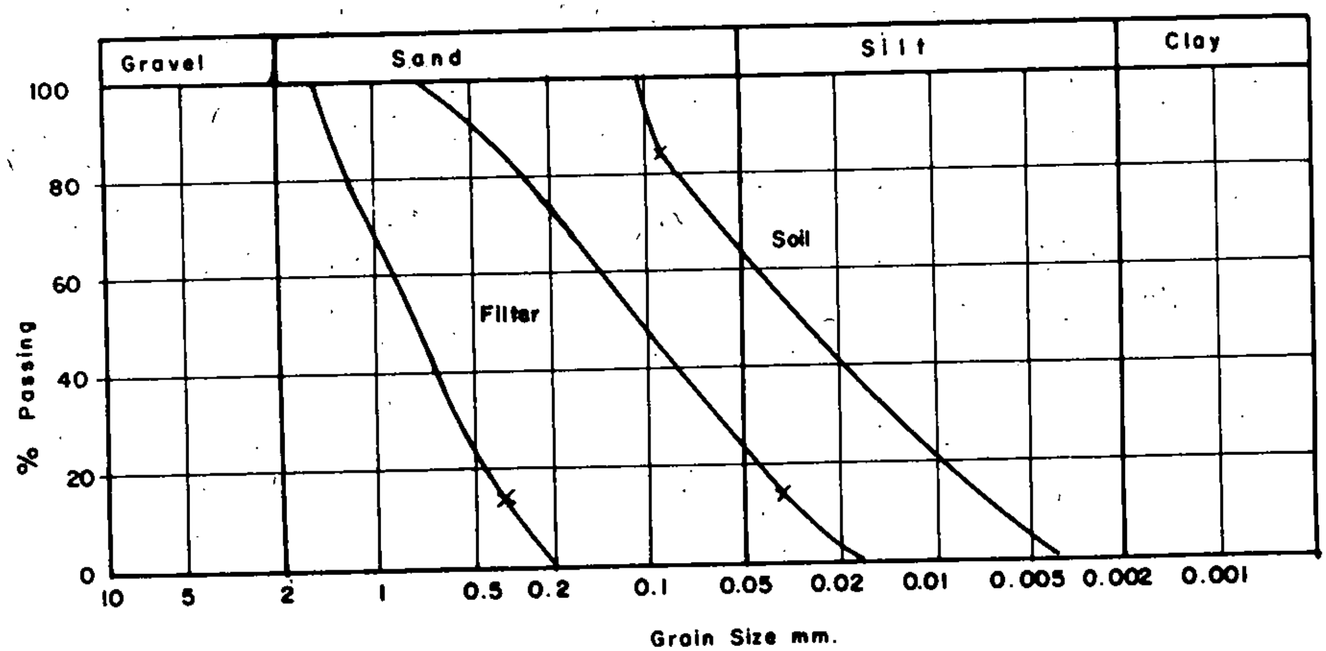

Fig. 6 Filter Design