Soil Moisture Suction Properties and their Bearing on the Moisture Distribution in Soils

Propriétés de succion des sols et leur influence sur la répartition de l'humidité dans les sols

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Summary

This paper first reviews the part played by soil moisture in determining the mechanical properties of soils. It is suggested that these properties may be more closely associated with the suction or reduced pressure at which the water is held in the soil structure, than with the actual moisture content measured on a weight basis. In the light of this discussion the effect which changes in the moisture condition of soil may have on the stability of shallow foundations is considered.

In the design of road and airfield pavements a method is required for estimating the changes which are likely to take place in the moisture condition of the soil foundation subsequent to the construction of the impervious pavement. In this connexion consideration is given to the fundamental factors which cause water to move in soil. It is shown that under an impermeable surfacing of infinite area an equilibrium distribution of moisture with depth will arise in the absence of temperature gradients. A method of calculating this distribution, in terms of moisture content, is developed.

Sommaire

Cet exposé rend compte, en premier lieu, du rôle joué par l'humidité du sol dans la détermination des propriétés mécaniques des sols. Les auteurs pensent que ces propriétés sont plus étroitement liées à la succion ou charge réduite à laquelle l'eau est soumise dans le sol, qu'à la teneur en eau mesurée en pourcents du poids sec du sol. C'est en tenant compte de cette idée qu'on a considéré l'effet que les modifications de l'état d'humidité du sol peuvent occasionner sur la stabilité des fondations de faible profondeur.

Dans l'étude de l'épaisseur et de la constitution des chaussées et des pistes d'envol, on a besoin d'une méthode pour calculer les modifications qui vraisemblablement pourraient se produire dans l'état d'humidité du sol de fondation, après la construction du revêtement imperméable. En conséquence les auteurs ont examiné les facteurs fondamentaux occasionnant le mouvement de l'eau dans le sol et ont démontré que, sous un revêtement imperméable d'une superficie infinie, l'état d'humidité du sol à chaque profondeur atteind une distribution équilibrée en l'absence de gradient de température. Une méthode a été développée dans laquelle cette répartition est calculée en fonction de la teneur en eau.

Introduction

The majority of soils are capable of attaining a considerable shear strength. In practice, however, the strength which a soil develops in the field depends critically on the prevailing moisture conditions, which in turn are largely a function of the climate.

The engineer responsible for the design of shallow foundations, such as those for roads and airfields, is particularly concerned with the effect which climate has on the properties of soils, since he normally deals with the surface strata which are most affected by weather conditions. What may be termed the moisture problem in soil mechanics can be broadly regarded as having two distinct aspects. First the engineer must know how the mechanical properties (principally strength and volume) of any soil will vary with the moisture condition. Secondly, to interpret this information usefully, he must be able to assess with some accuracy the moisture condition which the soil will have under the finished structure.

Although this paper is primarily concerned with the second of these aspects—the estimation of the moisture distribution beneath roads and runways—some consideration is first given to the part which moisture plays in determining the engineering properties of the soil.

The Influence of Moisture on the Engineering Properties of Soils

When an increasing load is applied to a soil, the load/deformation relationship can be analysed into three continuous sections. For very small loads the soil usually behaves elastically; as the load is increased compaction and/or consolidation occur during which processes a re-orientation of the particles with respect to one another takes place, resulting in deformation which is not recovered when the load is removed. The compaction or consolidation processes are in turn followed by shearing. The magnitude of the range of loads corresponding to each of the three sections of the load/deformation curve depends (a) on the conditions of test, e.g. the degree of confinement and rate of loading, and (b) on the initial condition of the soil, principally the state of disturbance and the moisture condition. If the magnitude of the load is restricted so that shear does not take place, repeated application of the load will, by compacting or consolidating the soil, eventually produce apparently elastic behaviour for that range and method of loading. By compacting the soil (particularly soil fill) prior to the laying of a road or airfield pavement, the range of stresses which the soil will accept without permanent deformation may be extended. It is important to realize, however, that the moisture condition of the soil does impose an upper limit on the stresses which the soil will accept without shearing.

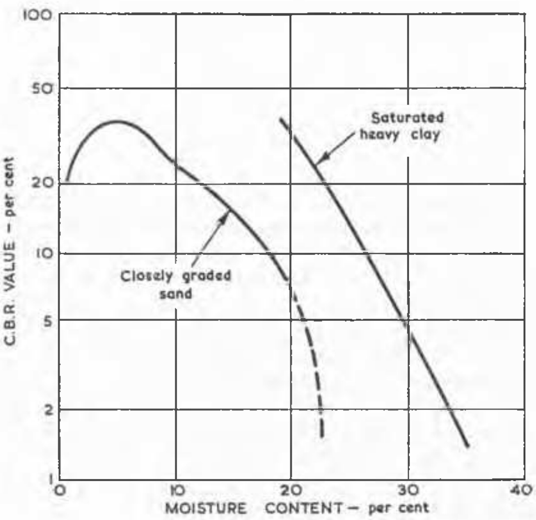


Fig. 1a Effect of Moisture Content on the Strength of Soils
Effet de la teneur en eau sur la résistance des sols

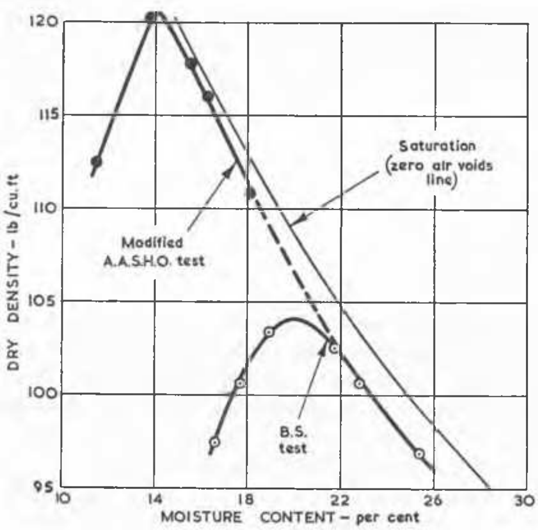


Fig. 1b Effect of Moisture Content on the Compaction of a Silty Clay Soil
Effet de la teneur en eau sur la compacité d'une argile limoneuse

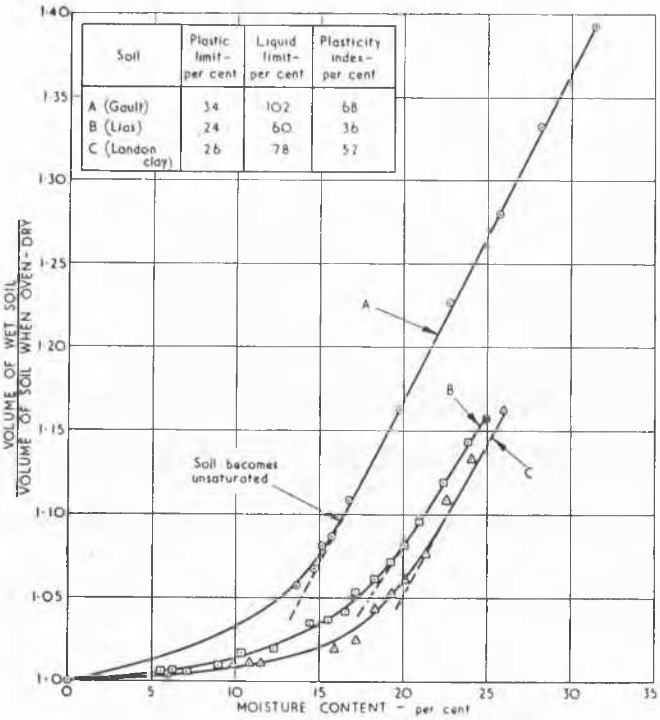


Fig. 2 Shrinkage Curves for three Heavy Clay Soils
Courbes de retrait de trois argiles lourdes

Figs. 1a and 1b show the form of the well-known relationships between strength and moisture content and between dry density (state of compaction) and moisture content. In Fig. 1a the strength is assessed in terms of the California bearing ratio (C.B.R.) test (*Davis*, 1951). The strength curves serve to emphasize that most soils, irrespective of their type, are capable of developing considerable strengths given favourable moisture conditions, and that in practice the performance of a soil depends largely on its climatic environment.

A change in moisture content can also affect the volume of soil. Heavy clay soils are normally saturated in the undisturbed condition in Great Britain, and when a decrease in moisture content occurs, the soil shrinks by an amount equal to the volume of water removed. Soils containing a large percentage of the more active clay minerals, such as montmorillonite, have a high field moisture content and consequently they will shrink uniformly over a much greater moisture range than less active clays. Fig. 2 shows the shrinkage measured when the moisture contents of three British clays were reduced from the approximate field value to zero. It will be seen that the Gault clay, perhaps the most troublesome clay found in Southern England, has the highest field moisture content and becomes unsaturated at a lower moisture content than either of the other soils. Silty clays, which are not normally saturated in the field, shrink to a much less marked extent.

Methods of Estimating the Moisture Distribution in Subgrades

General. It follows from the previous discussion that the moisture content at which a subgrade is prepared should approximate to the value which will be reached after moisture conditions have settled down subsequent to construction. Where this is not practicable, the effects of the changes which are likely to take place must, as far as possible, be allowed for in the design. In either case some method is required whereby the moisture conditions after construction can be estimated.

Since the problem is essentially one of moisture movements, it can only be approached from a consideration of the factors which cause water to move in the soil. Unfortunately, a difference in moisture content does not provide the potential causing water to migrate; transfer can take place from regions of low moisture content to regions of higher moisture content. Differences of hydrostatic pressure are the principal cause of movements of water in the liquid phase. The hydrostatic pressure at any point is determinded by the pressure imparted to the water by the overburden, and the suction by which the water is retained in the soil structure, termed the soil moisture suction.

Soil moisture suction. If the pressure of the water in the pores of a small sample of soil, removed (without disturbance or change of moisture content) from above the water-table, is measured when the sample is free from external stress, a value less than atmospheric pressure is obtained. The difference between the pressure of the water in the small *unloaded* sample and atmospheric pressure is defined as the moisture suction or, more briefly, as the suction of the soil. The reduction of pressure arises from the surface tension and adsorption forces by which the water is retained in the soil structure.

The relationship between soil moisture suction and pore water pressure. At any point beneath the surface of the ground, the soil is subjected to a vertical pressure due to the overburden together with any surface loading. The suction of any small element of the soil, *in situ*, is modified by the effect of the overburden. The modified suction being in fact the pore water pressure. If a is the fraction of the normal pressure which is effective in changing the suction, the resultant pore water pressure at the point is given by:

$$aP - s = u \quad \ldots \quad \ldots \quad (1)$$

where P is the total normal pressure
s is the moisture suction of the soil
u is the pore water pressure.

The value of P in this equation can be deduced from the total weight of wet soil above the point under consideration, together with any surface load. The pore water pressure, u, can be measured by tensiometer or any other convenient method. s is measured by a suction plate technique (*Croney*, *Coleman* and *Bridge*, 1952).

In a saturated clay all the normal pressure is carried by the soil water since the adsorbed water films surrounding the clay particles are continnous; a is therefore unity. In a material of rigid structure such as chalk, or in an incompressible soil, no part of the normal pressure is transmitted to the water and a is zero. In intermediate soils the value of a between 0 and 1 depends on the type of soil and on the moisture conditions; it can be deduced from loading and shrinkage tests (*Coleman* and *Croney*, 1952) or from direct measurements of pore water pressure and suction. Fig 3a shows measurements of pore water pressure and suction made at different depths in a silty clay. Field tensiometers were used to determine the pore water pressures, whilst the suctions were measured on small undisturbed samples using a rapid suction plate technique (*Croney*, *Coleman* and *Bridge*, 1952). Values of normal pressure were calculated from moisture content and dry density measurements and values of a were deduced using equation (1). The change of a with depth calculated in this manner, Fig. 3b, agrees satisfactorily with the results deduced independently from shrinkage tests (*Coleman* and *Croney*, 1952).

Pore water pressure and suction above and below a water-table. In uncovered soil the values of pore water pressure, and hence of suction, at different depths are determined principally by the rainfall, evaporation and transpiration from vegetation. Under a road or airfield pavement, the soil is less affected by

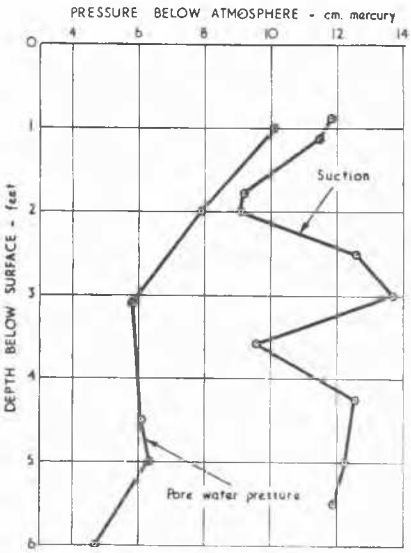


Fig. 3a Measured Pore Water Pressure and Soil Suction in a Silty Soil
Pression d'eau interstitielle et suction du sol mesurées dans un sol de silt

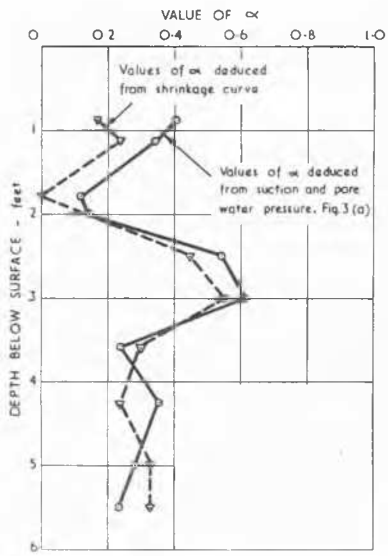


Fig. 3b Values of a at Various Depths Calculated (1) from Fig. 3a and (2) from Measured Shrinkage Curves
Valeurs de a à diverses profondeurs calculées (1) d'après la Fig. 3a et (2) mesurées d'après les courbes de retrait

rainfall and evaporation and it appears that in temperate climates the moisture conditions reached in subgrades can be estimated with useful accuracy from a knowledge of the soil properties, the position of the water-table and the loads imposed by the pavement.

If soil is covered by an impermeable surfacing of infinite extent the pore water pressure both above and below the water-table will, in the absence of temperature gradients, be determined by the position of the water-table. At the water-table the pore water pressure is zero, i.e. atmospheric; it decreases linearly with height above the water-table, the pressure x feet above the water-table being less than atmospheric pressure by an amount equivalent to a head of x feet of water. Below the water-table there is a similar linear increase of pore water pressure. For this idealized case, the corresponding suctions at every point above and below the water-table can be deduced from equation (1).

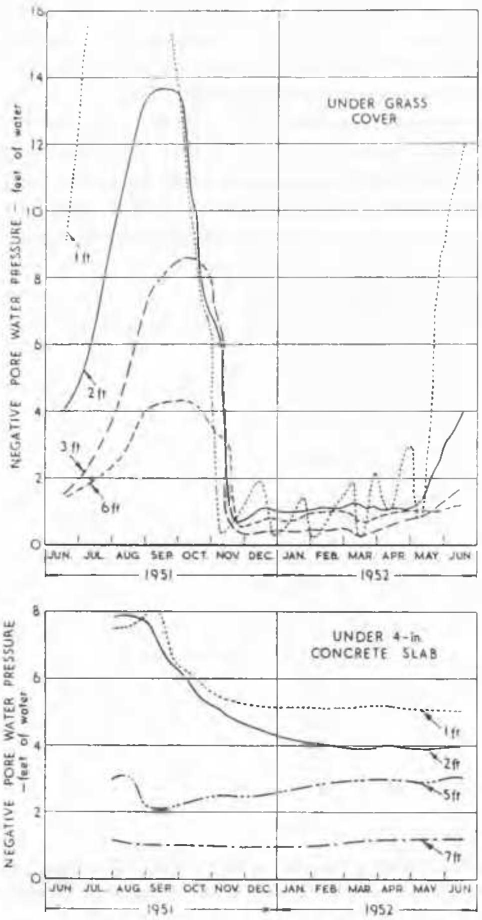


Fig. 4 Pore Water Pressures at Various Depths Beneath Grass and Adjacent Concrete Slab. Water-table at Depth of 9 ft.
Pressions d'eau interstitielle à différentes profondeurs sous l'herbe et la dalle adjacente en béton. Nappe d'eau à une profondeur de 2.7 m

Temperature gradients and "edge" effects to some extent prevent the attainment of a true equilibrium distribution of pore water pressure with depth beneath a finite area such as a road. This is particularly the case where the water-table is at a considerable depth or the moisture conditions prevailing in the uncovered soil are markedly different from the equilibrium value calculated for an infinite pavement. For the temperate climate of the British Isles it appears that moisture conditions close to the calculated equilibrium are attained and this approach should provide a useful basis for the design of roads and airfields. At the Road Research Laboratory, the seasonal change in pore water pressure at various depths is being measured under grass cover, and under the centre of a concrete slab 30 ft.square. The soil is a silty clay and the water-table is at a mean depth of about 9 ft. Fig. 4 shows that under the slab the pore water pressure does not vary greatly with season and is largely controlled by the water-table, but this is not the case under the grass cover. The pore water pressure in the top few feet of soil under the concrete is rather lower than would be expected from the position of the water-table. This may be due to the entry of water through joints which were not effectively sealed until the middle of September, 1951. Alternatively, it may be due to moisture transferred in the vapour phase as a result of temperature gradients. The measurements are being continued for a further year, and "edge" effects near the boundary of the concrete are being investigated.

If the equilibrium distribution of moisture content with depth is required, calculated values of suction can be converted to moisture content if the appropriate relationship between moisture content and suction is available.

The relationship between suction and moisture content. The suction of the moisture contained in a small sample of soil

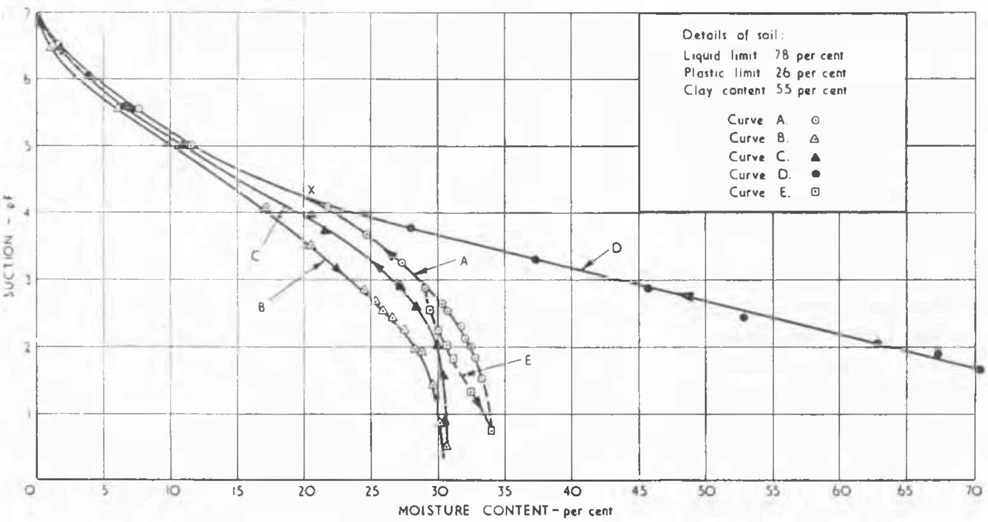
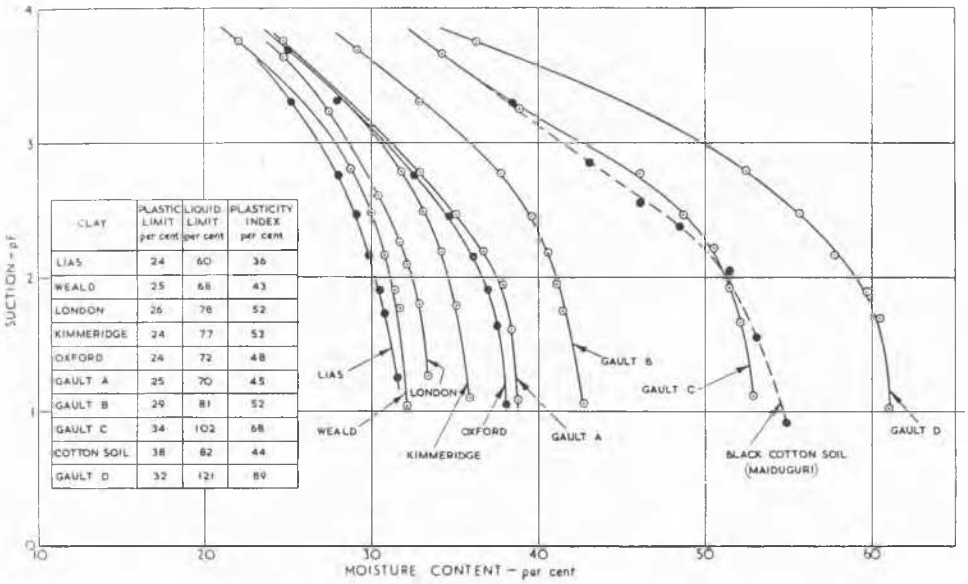


Fig. 5 Relationship between Suction and Moisture Content for a Heavy Clay Soil
Relation entre la suction et la teneur en eau d'une argile lourde

increases as the soil is dried. In contact with free water, the suction is zero but at air-dryness it may be many thousands of atmospheres. On the pF scale, introduced by *Schofield* (1935), the common logarithm of the suction expressed in centimetres of water is equivalent to the pF value of the soil water. (A suction of 1 cm of water equals pF 0; 10 cm pF 1; 100 cm pF 2, etc.) Methods of measuring the relationship between suction and moisture content and the general characteristics of the relationship for different types of soil are considered in detail in other papers (*Croney*, *Coleman* and *Bridge*, *Croney* 1952).

Fig. 5 shows the relationship between suction and moisture content for a heavy clay soil. Curve *A* was obtained on an undisturbed sample drying from approximately pF 0.5 to oven-dryness (pF 7). On re-wetting to pF 0.5 curve *B* was obtained, the difference in moisture content at pF 0.5 between curves *A* and *B* being due to re-packing of the particles caused by the intense consolidation pressures involved in drying. The second wetting curve *C* forms a closed hysteresis loop with curve *B*, the hysteresis arising partly from the resistance to shearing offered by the clay and partly from entrapped air. When the soil was dried from a slurried condition, curve *D*, joining curve *A* at *X*, was obtained. The suction corresponding to point *X* gives a measure of the consolidation pressure to which the natural soil had been subjected during its geological history.



CLAY	PLASTIC LIMIT per cent	LIQUID LIMIT per cent	PLASTICITY INDEX per cent
LIAS	24	60	36
WEALD	25	68	43
LONDON	26	78	52
KIMMERIDGE	24	77	53
OXFORD	24	72	48
GAULT A	25	70	45
GAULT B	29	81	52
GAULT C	34	102	68
COTTON SOIL	38	82	44
GAULT D	32	121	89

Fig. 6 Relationship between Suction and Moisture Content for Undisturbed Heavy Clay Soils Drying from pF 1 to pF 4
Relation entre la suction et la teneur en eau d'argiles lourdes intactes séchant à des températures variant de pF 1 à pF 4

Soils in the field, below the cover of the top soil, seldom develop suctions greater than pF 3 to pF 3.5 in the British Isles. The hysteresis loop between pF 0.5 and pF 3, formed by the curves *E* and *A* on Fig. 5, is therefore of particular interest. Drying curves for a number of undisturbed heavy clay soils covering the moisture range pF 1 to pF 4 are reproduced in Fig. 6.

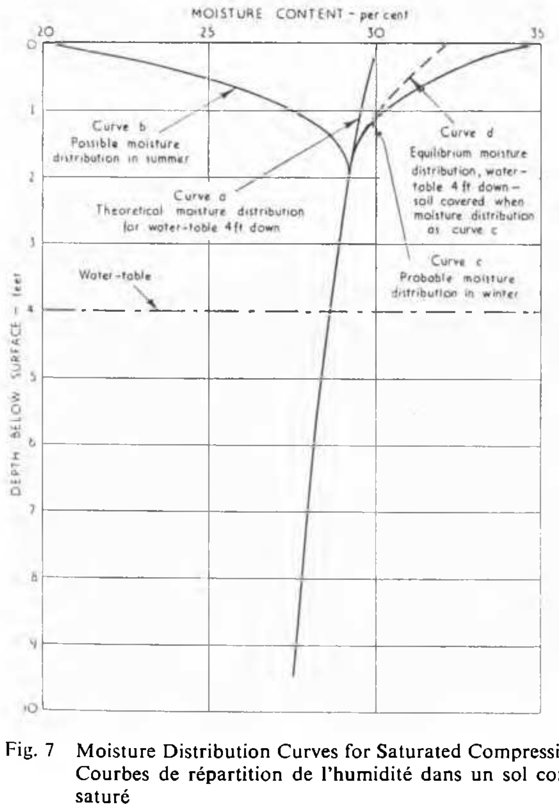


Fig. 7 Moisture Distribution Curves for Saturated Compressible Soil
Courbes de répartition de l'humidité dans un sol compressible saturé

Fig. 7, curve *a*, shows the theoretical equilibrium moisture distribution with depth calculated using equation (1) from curve *E* of Fig. 5, for a water-table at a depth of 4 ft. and no surface load. If curve *b* represented the moisture condition at the time of covering, the equilibrium distribution would be achieved as a result of the soil drawing water from the water-table. Were the soil covered in the condition represented by curve *c* some drainage would take place after covering but, as a result of the hysteresis in the suction/moisture content relationship, the final distribution, curve *d*, would represent a rather wetter condition than curve *a*.

Since the moisture content beneath a road or airfield pavement depends upon the suction, and hence upon the pore water pressure, the moisture content calculated for an infinite impermeable surfacing will only be realized if the corresponding equilibrium pore water pressure is achieved. The influence of climate, depth of water-table and temperature gradients on pore water pressure have already been discussed. Other factors which may disturb the moisture conditions under pavements are the roots of fast-growing vegetation (*Croney* and *Lewis*, 1948) and the freezing of the subgrade (*Croney*, 1949).

Discussion

In the application of soil mechanics to deep foundation problems, the interest is centred largely round the estimation of settlements, rather than on the actual distribution of moisture content. In saturated soils, the stress condition of the soil particles or effective pressure can be calculated from *Terzaghi*'s equation:—

$$\sigma = \sigma' + u \quad \ldots \quad (2)$$

where σ is the normal pressure [i.e. P in equation (1)]
and σ' is the effective pressure.

The effective pressure at any point in the soil above or below the water-table can be simulated by laboratory consolidation tests carried out with zero pore water pressure.

In the approach used in this paper the equilibrium of the stresses acting on soil water rather than those acting on the particles has been considered in deducing the equation (1), i.e.

$$aP = s + u$$

Inspection of equations (1) and (2) shows that in the saturated clay case where $a = 1$, effective pressure and suction are numerically equal, indicating that the same change in the condition of the soil can be effected by the application of a negative pressure to the soil water or a positive pressure to the soil mass. It is important to appreciate however that suction and effective pressure have an entirely different meaning in unsaturated soils to which *Terzaghi*'s equation cannot be applied.

In the regime above the water-table where pore water pressures are normally negative and the soil may contain air, the moisture distribution problem can only be approached, as in the present paper, by considering the combined effect on the soil water, of pressure applied to the soil and a reduction of pressure in the water itself.

Acknowledgment

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