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Pore Water Pressure and Moisture Content Studies under Experimental Pavements

Mesure de la Pression Interstitielle et de la Teneur en Eau sous des Revêtements Expérimentaux

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Summary

The paper describes a field experiment to study the seasonal variation of pore water pressure and moisture content at various depths: (a) under grass-covered soil, (b) under bare soil and (c) under impervious road pavements laid at different times of the year. A new type of field tensiometer for measuring pore pressures is described.

Under the grass there were very much larger seasonal changes both of pore water pressure and moisture content than under the bare soil and it is concluded that transpiration from the vegetation is the main cause of the summer drying which occurred at the site. Under the pavements, moisture conditions became virtually stabilized after a period of 2 to 3 years. A method which is outlined for estimating moisture content distributions from measured pore water pressures is shown to give close agreement with direct measurements of moisture content.

This approach combined with the assumption of a linear distribution of pore water pressure with depth provides a useful method for estimating the ultimate moisture content and strength of the subgrade.

Sommaire

Une expérimentation sur chantier a été entreprise pour étudier les variations saisonnières de la pression interstitielle et de la teneur en eau des sols, à diverses profondeurs, soit dans un terrain couvert d'herbes, soit dans un terrain dépourvu d'herbes, soit sous des chaussées construites en différentes saisons. Les auteurs décrivent un nouveau type de tensiomètre de chantier, qui a été utilisé pour la mesure de la pression interstitielle.

Dans le terrain herbeux, on a observé des variations saisonnières de pression interstitielle et de teneur en eau plus grandes que dans le terrain sans herbes; on en a conclu que la transpiration de la végétation était la cause principale du dessèchement constaté en été sur le chantier.

Sous les chaussées, la distribution de la teneur en eau s'est à peu près stabilisée après 2 à 3 ans. Une méthode, sommairement décrite, a été élaborée pour calculer la teneur en eau à partir des pressions interstitielles mesurées; elle a donné des résultats concordant d'une façon satisfaisante avec les mesures directes de teneur en eau.

Cette méthode, en supposant une répartition linéaire de la pression interstitielle avec la profondeur, fournit un moyen pratique d'évaluer la teneur en eau d'équilibre du sol de fondation, donc de sa force portante.

Introduction

The design of road and airfield pavements is complicated by the seasonal changes that occur in the moisture condition and strength of the surface soil, which provides the foundation for such shallow structures. Owing to the magnitude of these seasonal fluctuations, measurements of the strength of the soil made at a particular time before construction may bear little relation to the actual strength which the soil will have when the pavement goes into service.

For the past five years experiments have been in progress at the Road Research Laboratory, England, to study the seasonal changes of pore water pressure and moisture content which occur at various depths in unpaved soil and under pavements constructed at different times of the year. The ultimate moisture distributions measured under the pavements have been compared with estimates based on a method developed at the Laboratory, and have been described in detail elsewhere (CRONEY and COLEMAN, 1953). The measurements presented in this paper are confined to the first three years of the investigation.

Scope of the Investigations

The measurements in unpaved soil were made at depths down to 6 ft. (1·8 m) under natural grass vegetation of a type usually encountered during new road construction in Great Britain. To elucidate the effect of the vegetation on the moisture conditions in the soil, similar measurements were made under an area, on the same soil profile, which was kept completely free of all vegetation.

Concrete pavements were laid when the soil was approximately: (a) in its wettest and (b) in its driest condition, and the subsequent changes both in pore water pressure and moisture content were studied.

Owing to the limited width of roads, the influence which the moisture conditions in the verges has on the soil under the pavement is of special interest and a study of these 'edge' effects was included in the investigation.

Results

The negative pore water pressures (pressures less than 1 atmosphere) present in the soil above the water table were measured continuously by a new type of all-glass tensiometer developed for the purpose. Fig. 1 gives details of the instrument and of the method of installation.

A small glass reservoir sealed with a No. 5 porosity sintered glass plate (average pore size 2μ) is jointed to a glass capillary tube bent at its upper end to form a manometer. The instrument is filled with air-free water, some of which is subsequently displaced by the introduction of mercury into the open end of the manometer. When the porous plate is brought into contact with the soil the pore pressure of the latter is transmitted through the plate and can be deduced from the reading of the manometer. The volume of the reservoir and the diameter of the capillary tube are kept small to reduce temperature sensitivity and make the instrument rapid in operation. Tensiometers of this type will operate with comparatively little attention for several years if the negative pore pressures measured do not exceed 25 to 30 ft. (7·5 to 9 m) of water. Instruments with specially selected plates of maximum pore size less than 1μ have operated for limited periods at negative pore pressures of 60 ft. (18 m) of water. In the experiments described in this paper, however, it was usual to remove the tensiometers when negative pore pressures of about 28 ft. (8·5 m) were recorded.

To prevent damage to the instruments during service the glass measuring unit was enclosed in a brass outer case as shown in Fig. 1. The tensiometers were made in various lengths to record at depths up to 9 ft. (2·7 m).

Layout of the experiment and details of the soil conditions—A plan of the experimental area is shown in Fig. 2. The site is divided into seven areas (*A–G*) each 30 ft. (9 m) square. Area *A* is covered by the natural vegetation consisting of coarse grasses, clover and convolvulus, which is scythed twice during the growing season. Areas *B*, *E* and *G* are covered with concrete slabs which were constructed in summer, winter and autumn, respectively. Area *C* is kept entirely free of all

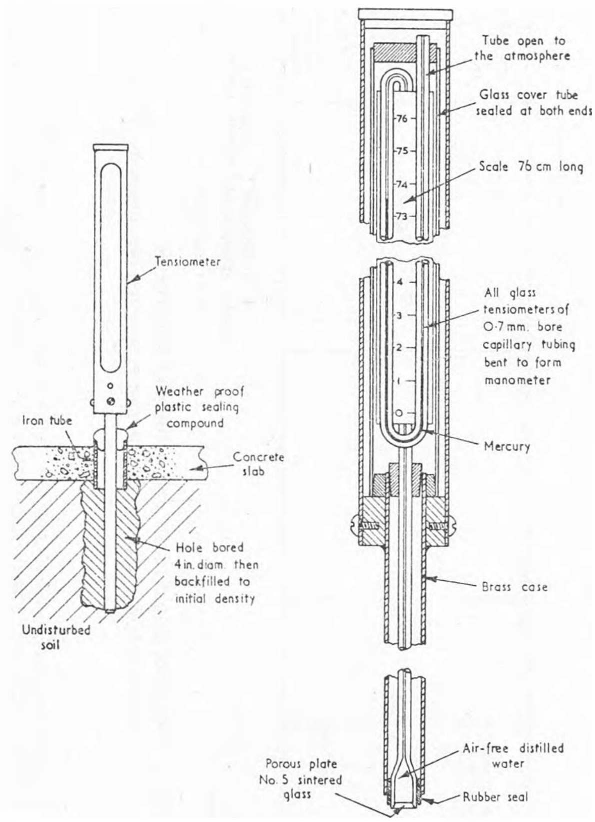

Fig. 1 Details of construction of tensiometers and methods of installation
Détails de la construction des tensiomètres et méthodes d'installation

vegetation. No measurements have been made in the remaining areas *D* and *F*.

The location of the tensiometers used to measure pore water pressures is indicated on the plan. (The number before the stroke is for identification purposes, the number following the stroke gives the recording depth in feet.)

Soil temperature measurements have been made at depths down to 6 ft. (1·8 m) under areas *A* and *B*. The location of the thermistors used for this purpose is marked on Fig. 2. The level of the water table is measured in the bore hole shown in area *A*.

The soil profile at the site consists of a stratum of sandy clay 2 ft. 6 in. (75 cm) thick overlaying a similar thickness of silty clay. Beneath this is a further stratum of sandy clay which merges at a depth of 8 ft. (2·4 m) into a sandy gravel. The water table for the greater part of the year is in this gravel layer. The variation of liquid and plastic limits with depth for the experimental plots is shown in Fig. 3.

Results

The pore water pressures measured under the centre of area *A* over the period June 1951 to January 1954 are shown in Fig. 4. The variation of the depth of the water table and the rainfall at the site are also given on this diagram. During the winter months (November to March) the pore water pressures at all depths are close to zero indicating that rainfall is percolating through the profile to the water table. Later in the spring the negative values of pore pressure increase rapidly, particularly near the surface, and it will be seen that during the summers of 1952 and 1953 it was necessary to remove some of the tensiometers. Even at a depth of 6 ft. (1·8 m) the seasonal drying is marked. In the late autumn, when the rainfall exceeds evaporation and transpiration, the water again begins to percolate through the profile and the negative values of pore water pressure begin to fall. The phase lag in the wetting of the profile with depth is apparent from the records.

Under the bare soil (area *C*), Fig. 5a, the summer increase in the negative pore water pressures is very much smaller at all depths than under the grass, showing that the greater part of the drying of the natural soil is due to transpiration from vegetation, and that surface evaporation plays a small part. There was evidence that the top few cm of the bare soil became very dry and hard, and this probably provided an almost impermeable layer limiting further evaporation.

The manner in which the construction of the concrete pavements stabilized the pore pressure conditions in the soil beneath is shown in Fig. 5b and in Figs. 6 a and b, which refer to areas *B*, *E* and *G*, respectively. After construction of the pavement on area *B*, in July 1951, the tensiometer readings fell rapidly indicating wetting of the soil. The fall, which was more rapid than was expected, was due to water leaking through a faulty construction joint. When this was sealed the tensiometer reading began to increase. Subsequent measurements have shown that the upward trend of the readings continued until the end of 1954 when the readings became stabilized except for small seasonal fluctuations which amounted to about ± 0·5 ft. (± 15 cm) of water at a depth of 1 ft. (30 cm).

The negative pore water pressures under the pavement on area *B* (constructed in the winter of 1952) show a similar steady increase with time. Under area *G*, where the pavement was constructed in the late autumn of 1952 (when the soil was in its seasonal driest condition), the negative pore pressures at depths below 3 ft. (90 cm) decreased slowly over a period of about 9 months. At the 1 and 2 ft. (30 and 60 cm) depths there was a small rise in the tensiometer readings. This was due to wetting of the surface soil which occurred between the stripping of the grass and the laying of the slab.

Since the end of 1953 the slow changes of pore water pressure which have occurred under all three concrete slabs have tended to produce a similar distribution of pore water pressure with depth under each pavement. The pore water pressure at the end of 1955 was approximately − 6 ft. (− 1·8 m) of water at a depth of 1 ft. (30 cm). The negative value of pore water pressure decreased with depth but the decrease was not linear, the pore pressures being less negative than would be expected, particularly at a depth of 3 to 4 ft. (0·9 to 1·2 m).

Discussion

Pore water pressure measurements—Under an infinite impermeable surfacing with a constant level of water table and constant temperature conditions in the soil, the distribution of pore water pressure with depth should be linear, the pore pressure x ft. above the water table being $- x$ ft. of water. At

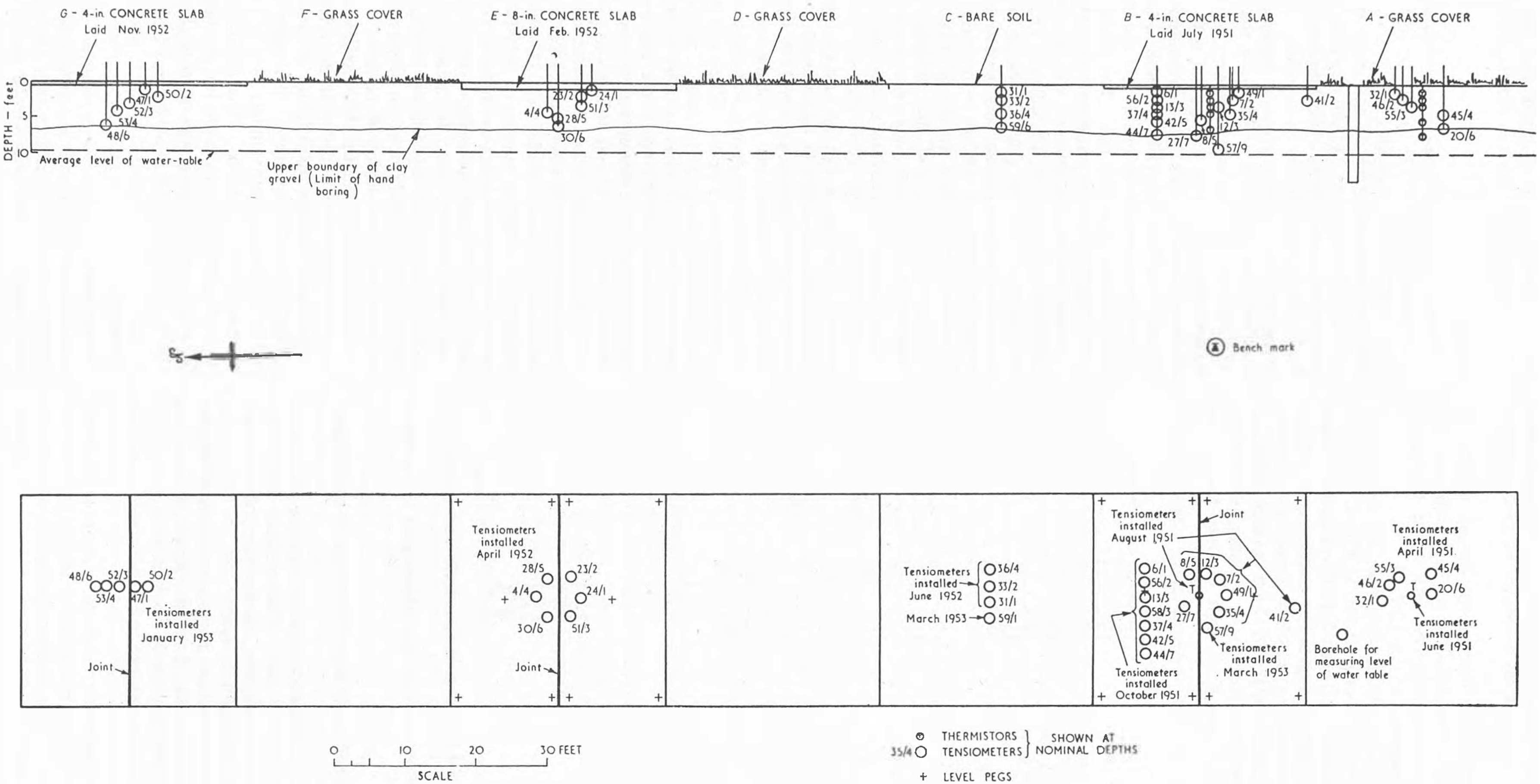

Fig. 2 Details of layout of site and position of instruments
Détails de l'aménagement du chantier et position des appareils

the present experimental site the water table was not at a constant depth but, as is shown in Fig. 2, fluctuated between depths of about 8 and 11 ft. (2·4 and 3·3 m). With the water table at its highest level the measured pore water pressure of − 6 ft. (− 1·8 m) of water at a depth of 1 ft. (30 cm) is lower than the theoretical estimated value of − 7 ft. (− 2·1 m). The reason for this appears to be 'edge' effects due to the finite area of the slabs, accentuated by the low permeability characteristics of the silty clay soil between depths of 2 ft. 6 in. and 5 ft. (0·7 and 1·5 m). Flow nets constructed on the basis of measured permeabilities of the soil give pore water pressure distributions very similar to those actually measured.

Temperature gradients measured by the thermistors, considered in conjunction with laboratory tests on vapour flow

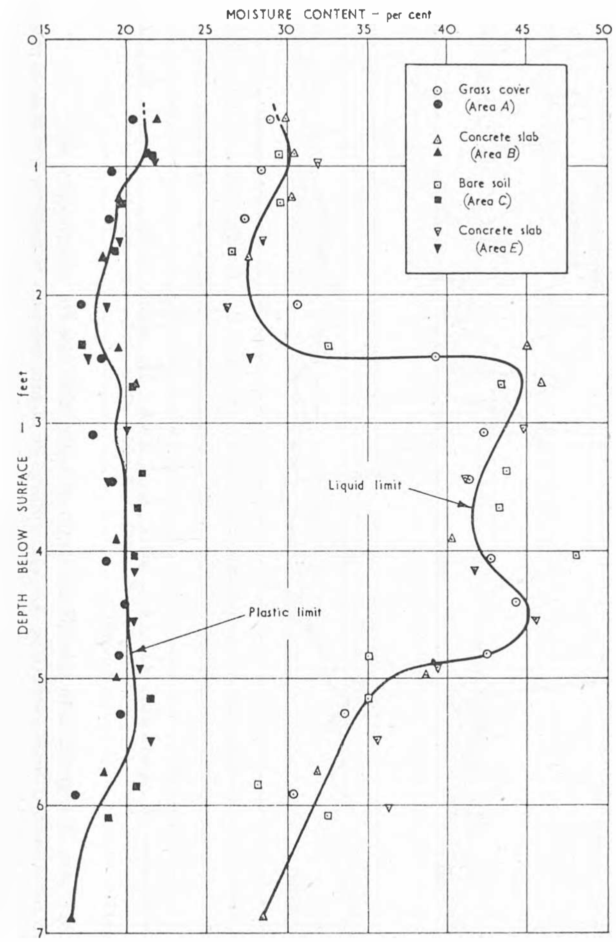

Fig. 3 Variations of liquid and plastic limits with depth at experimental site

Variation des limites de liquidité et de plasticité avec profondeur sur un chantier expérimental

through the soil, do not suggest that migration of water due to thermal effects has had any large influence on the distribution of pore water pressure under the concrete.

Tensiometers installed since the end of 1953 at various distances from the edge under slab *B* have shown that edge effects are very large at distances of about 1 ft. (30 cm) from the edge and that they are still appreciable at distances of 4 ft. (1·2 m). For example, at a distance of 1 ft. (30 cm) from the edge and at a depth of 1 ft. (30 cm), the seasonal variation of pore water pressure was between about − 30 and − 2 ft. (− 9 m and − 60 cm) of water; at a distance of 4 ft. (1·2 m) from the edge the corresponding variation was − 8 to − 4 ft. (− 2·4 m to − 1·2 m) of water. There is evidence that these edge effects are in part due to the roots of vegetation which spread under the pavement to take advantage of the comparative availability of the moisture.

Estimation of moisture contents from pore pressure measurements—A method of estimating the moisture content of soil from measurements of pore water pressure has been described in detail in another paper (Croney and Coleman, 1953). If the pore water pressure in a thin horizontal stratum of the soil is u, the suction due to surface tension and adsorptive forces is s, and the fraction of the overburden pressure P which affects the suction is α, then:

$$u = \alpha P + s \qquad \ldots . \ (1)$$

where αP is always positive and s is always negative.

α, the value of which lies between 0 and 1, can be measured directly in the laboratory by loading tests. For the soil profile under consideration, the sandy clay had an average of $\alpha = 0{\cdot}15$ and the silty clay an average value of 0·5. The overburden pressure P at any point in the soil profile is calculated from the average bulk density of the soil above, together with any surface load.

Equation 1 thus enables pore water pressures to be converted to suctions. For every soil in the undisturbed condition there is a relationship between suction and moisture content which can be studied by laboratory tests described in another paper (Croney, Coleman and Bridge, 1952). Using this relationship deduced values of suction can be converted to the moisture content scale.

By this method, the pore water pressure records given in Figs. 4, 5 and 6 can be redrawn to show the variation of moisture content. This has been done in Fig. 7 for the grassed area *A*.

Moisture content measurements—At regular intervals throughout the progress of the experiment, borings were made in the various areas so that the variation of moisture content with depth at different times of the year could be studied. Figs. 8 and 9 show, respectively, typical profiles under the grass cover and under the covered area *B*. A comparison is made between the actual measured moisture contents and those deduced from pore water pressure measurements using the method described above. The agreement is generally within ± 1 per cent of moisture content.

It has been noted that the pore water pressure distributions measured under the centre of the slabs were not linear with depth, as would be expected for an infinite pavement with a steady water table condition. Fig. 10 shows the estimated moisture content distributions for the three concrete slabs deduced both from the measured distribution of pore water pressure and from an assumed linear distribution based on the mean position of the water table (10 ft. (3 m) below ground level). The difference between the two distributions is small and for practical purposes the assumption of a linear distribution would not, at this site, lead to any serious design inaccuracy.

Conclusions

The experiments show that large seasonal changes of moisture content occur in grass-covered soil and that the strength of the soil at a given time is therefore unlikely to give a realistic indication of the ultimate strength under a pavement.

For the shallow water table conditions generally found in cohesive soils in Great Britain, the assumption of a linear distribution of pore water pressure with depth enables the ultimate moisture content under a pavement to be calculated from laboratory tests on the soil, with acceptable accuracy. This moisture content can be used in conjunction with the

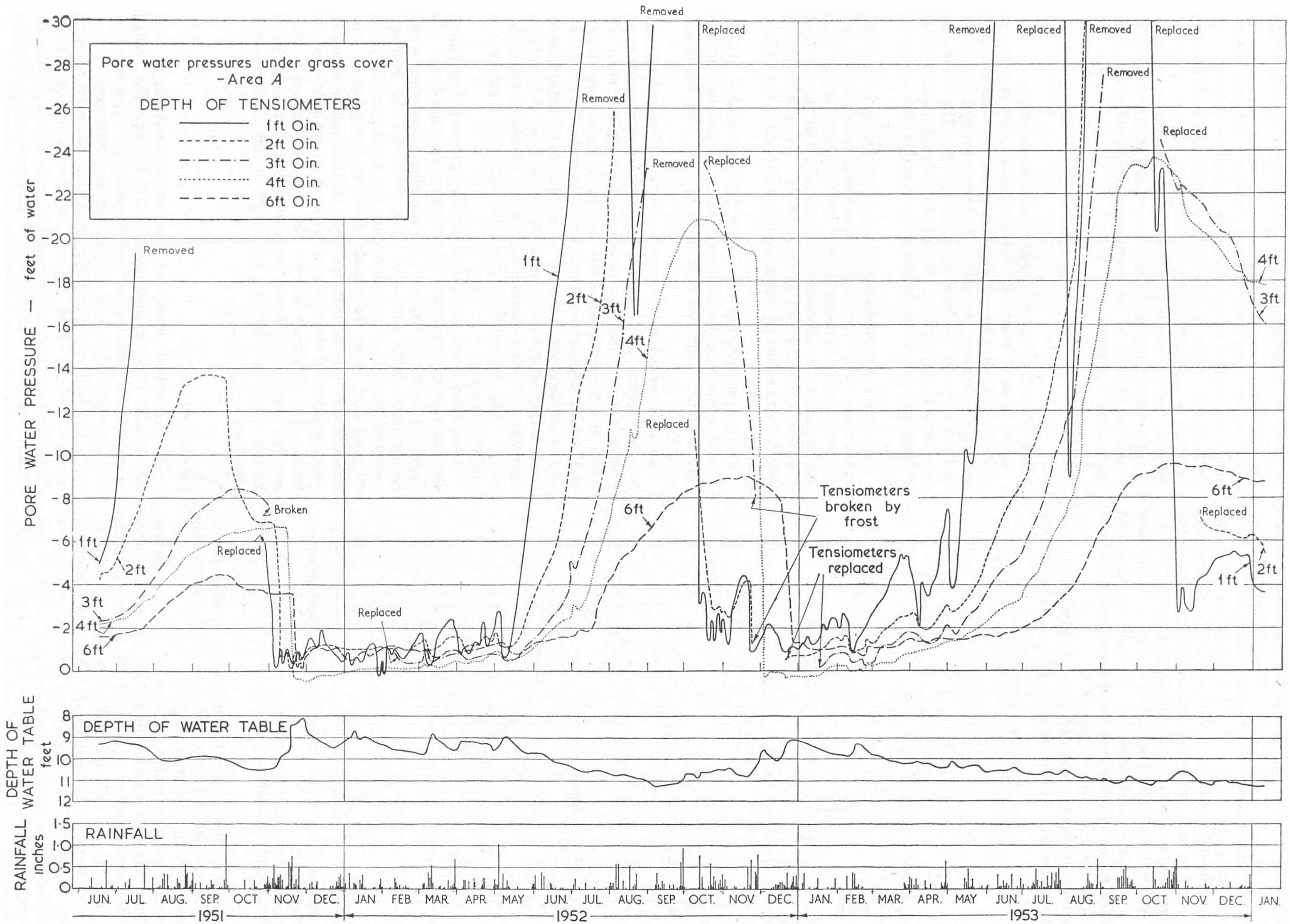

Fig. 4 Pore water pressures under grass cover (area *A*) together with rainfall and depth of water table data for experimental site
Pressions d'eau interstitielle sous un sol couvert d'herbe (superficie *A*) avec données de la précipitation atmosphérique et de la profondeur de la nappe d'eau du chantier expérimental

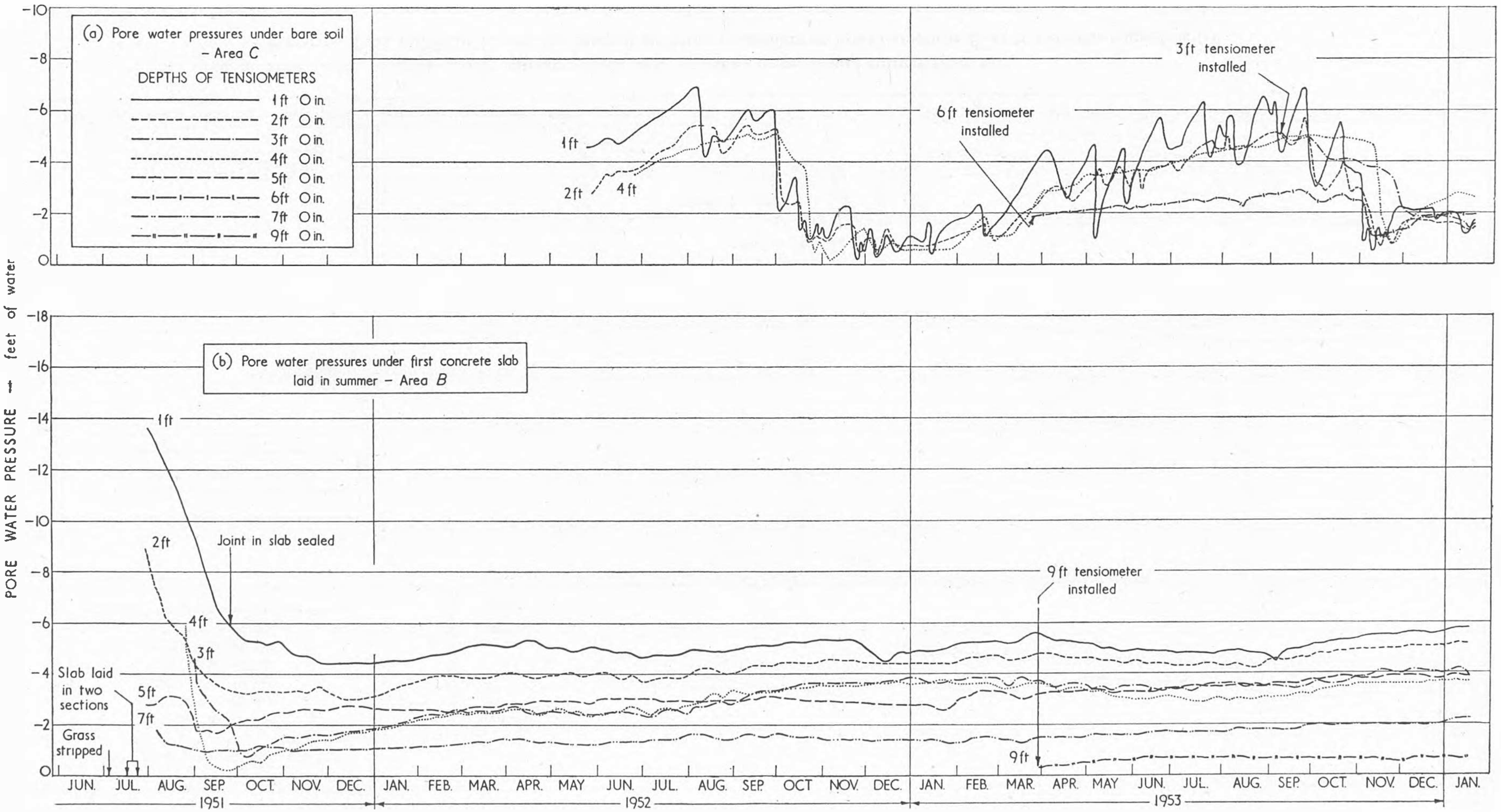

Fig. 5 Pore water pressures under bare soil (area *C*) and under concrete slab laid in early summer (area *B*)
Pressions d'eau interstitielle sous un sol dépourvu d'herbe (superficie *C*) et sous une plaque en béton construite au début de l'été (superficie *B*)

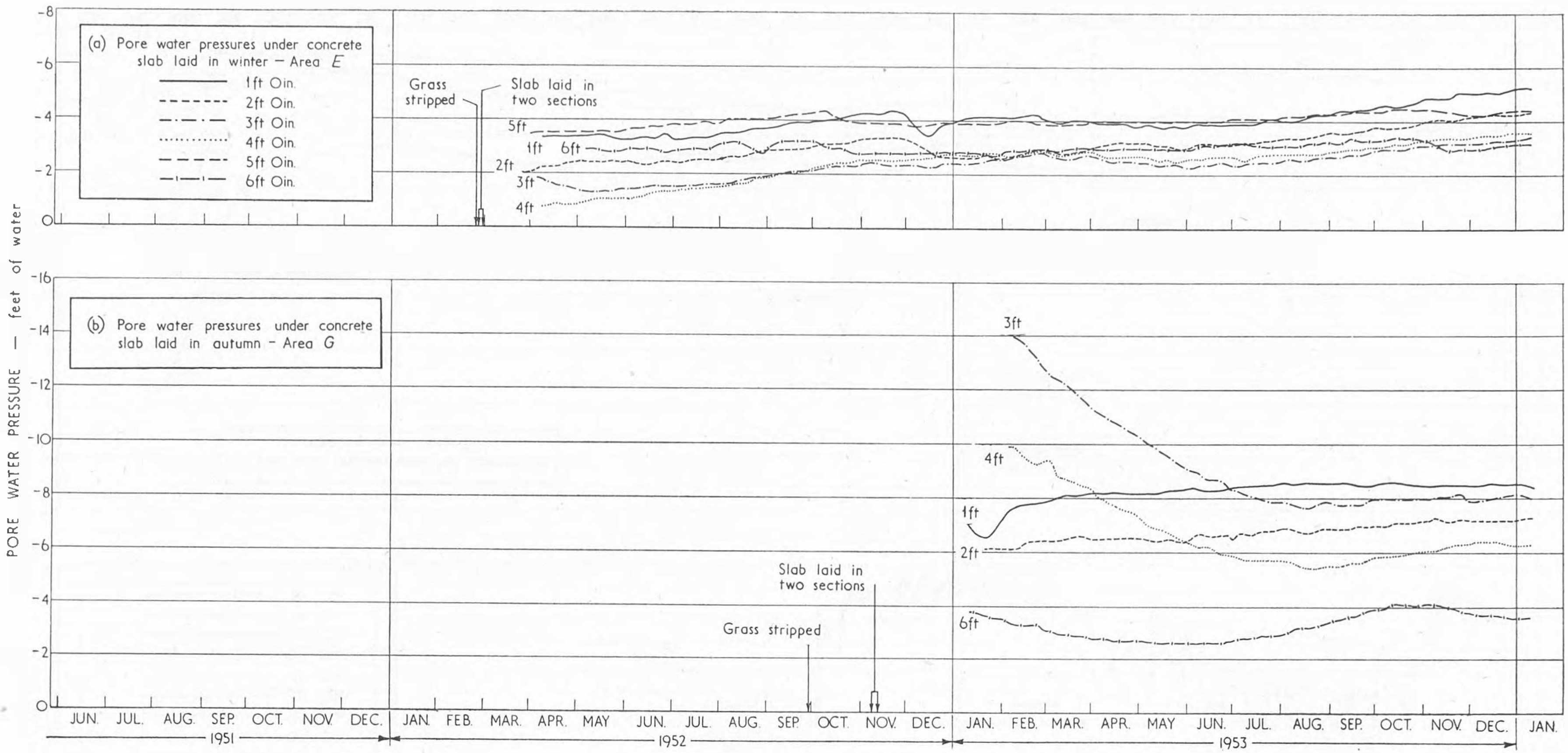

Fig. 6 Pore water pressures under concrete slabs laid in winter (area *E*) and autumn (area *G*)
Pressions d'eau interstitielle sous des plaques en béton construites en hiver (superficie *E*) et en automne (superficie *G*)

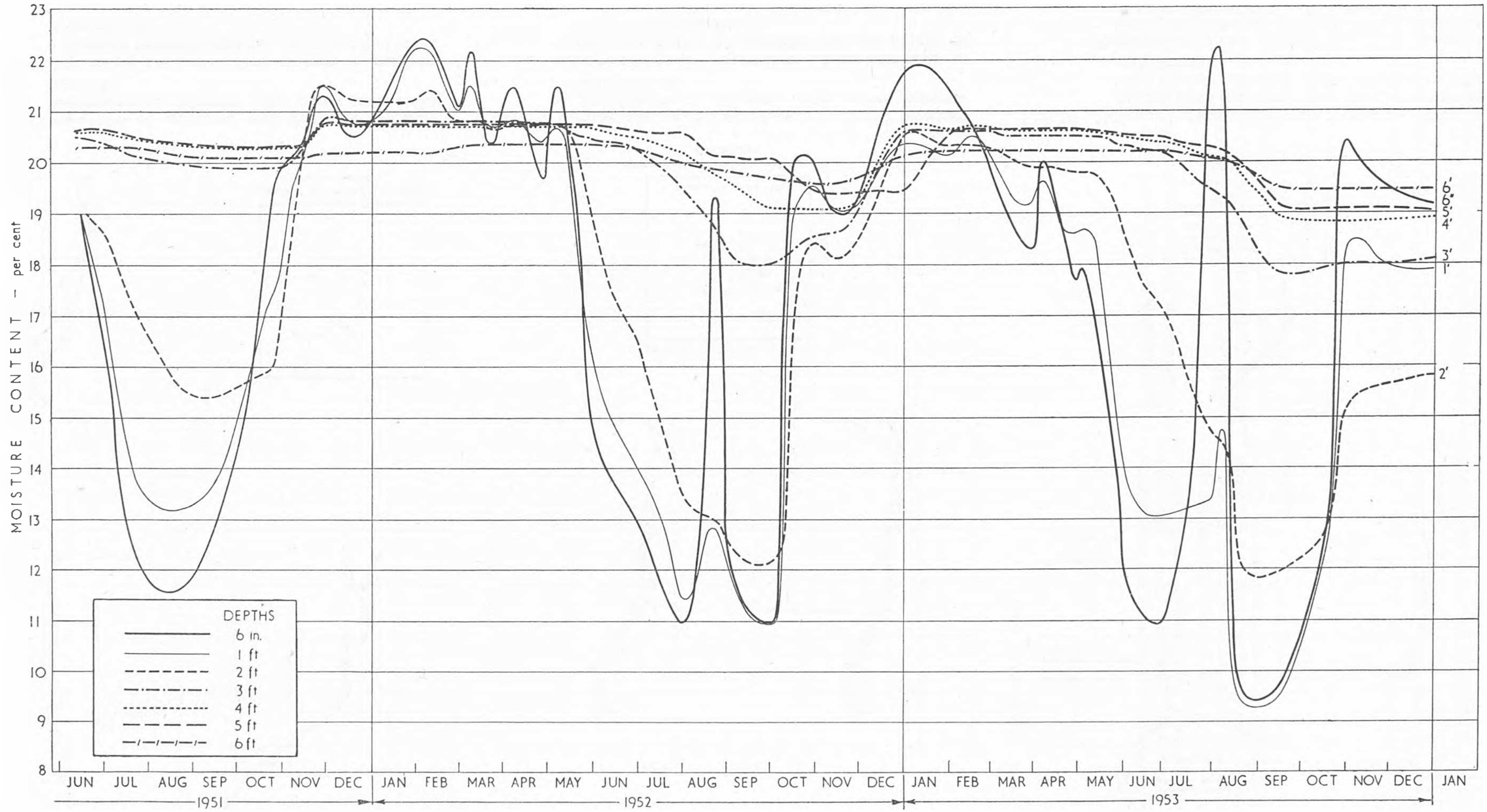

Fig. 7 Moisture contents at various depths under grass cover (area *A*). Curves deduced from measurements of pore water pressure and suction/moisture content data

Teneurs en eau à diverses profondeurs sous un sol couvert d'herbe (superficie *A*). Courbes déduites des mesures de la pression d'eau interstitielle et des données de suction/teneur en eau

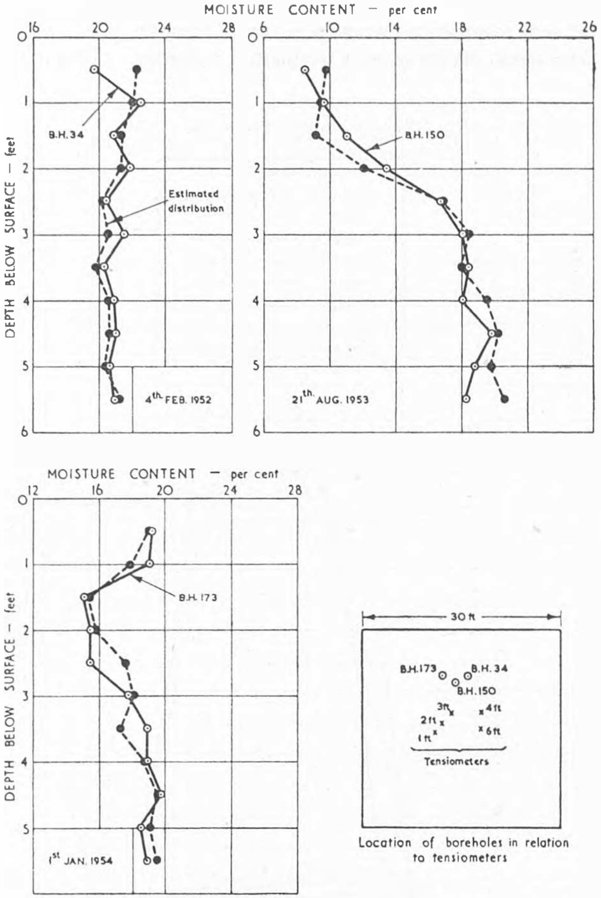

Fig. 8 Comparison of estimated and measured moisture distributions at different times under grass cover (area *A*)

Comparaison des répartitions estimées et mesurées à diverses périodes sous un sol couvert d'herbe (superficie *A*)

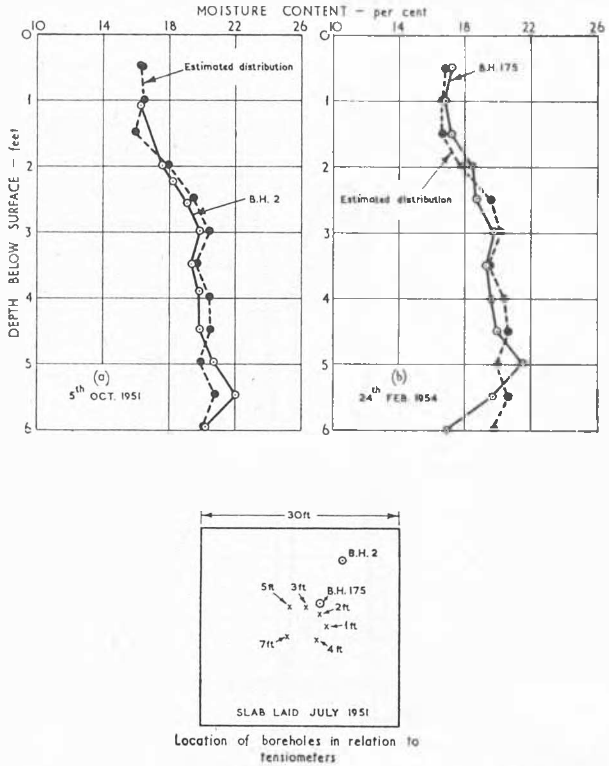

Fig. 9 Comparison of estimated and measured moisture distributions at different times under concrete slab (area *B*)

Comparaison des répartitions d'eau estimées et mesurées à diverses périodes sous une plaque en béton (superficie *B*)

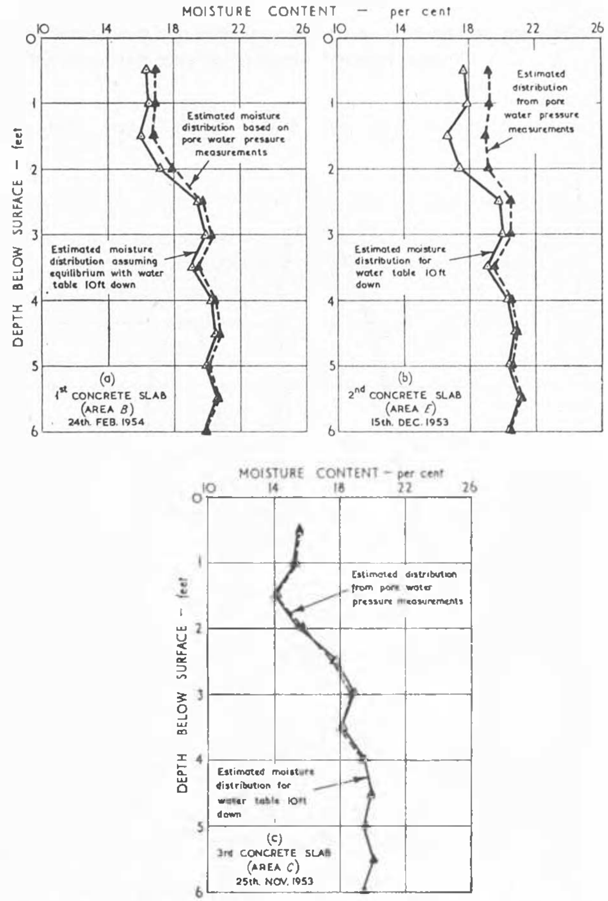

Fig. 10 Estimated distributions under concrete slabs, calculated from measured pore water pressures and from position of water table assuming moisture equilibrium

Répartitions d'eau estimées sous des plaques en béton, calculées des pressions d'eau interstitielle et de la position de la nappe d'eau, en supposant que l'eau est à l'état d'équilibre design method to be adopted (e.g. the California bearing ratio test for flexible pavements).

Several years may be necessary for the moisture conditions under a pavement to become stabilized. Comparatively small leaks in the pavement can have a profound effect on the soil moisture conditions beneath.

The moisture conditions in the verges may materially affect the soil under a road pavement for a distance of several feet in from the edge. Grass close to the pavement will help to minimize the increase of moisture content under the edges of the road in winter, but in a dry summer the desiccation of the soil by the roots of the vegetation may give rise to shrinkage problems on a heavy clay soil.

The work described in this paper was carried out as part of the programme of the Road Research Board of the Department of Scientific and Industrial Research (United Kingdom). The paper is presented by permission of the Director of Road Research. A complete account of the experiment at this site covering the period 1951–56 together with additional information from two other sites will be published in due course in a Road Research Laboratory Technical Paper.

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