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Transmission of Pressure States in Soils

Propagation des pressions dans les sols

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SUMMARY

Results are presented for a series of experiments carried out on different materials, with the purpose of establishing the laws of propagation of a pressure state in soils. This propagation, although occurring quite instantaneously in sandy materials, requires increasingly more time with the gradual transition to silty or clayey materials. The results are analyzed to determine the factors which govern the time required to reach equilibrium after the end of a sample has been subjected to a sudden increase in pressure. Interest is mainly focused on permeability.

SOMMAIRE

On expose les résultats d'une série d'expériences exécutées sur des matériaux de types différents afin d'établir les lois de propagation des pressions dans un sol. Cette propagation, presque instantanée dans les sables, exige des temps de plus en plus longs lorsqu'on considère des matériaux limoneux et argileux. L'analyse des résultats à pour but la recherche des facteurs dont depend le temps nécessaire pour établir l'équilibre des pressions, après un changement subit des pressions à une extrémité de l'échantillon.

A WATER-SATURATED SOIL can be considered a rigid body in regard to the propagation of a pressure state. In effect the very small compressibility, both of water and of solid grains, needs unnoticeable matter movements to transmit the applied pressures, and therefore propagation is practically instantaneous. Conversely, when air partially fills the space between grains or when solid particles, because of their constitution present a measurable compressibility, propagation of a pressure state requires a certain fluid movement, by which pressure variations are applied from outside. It is in fact essential that each interspace of the solid substance be reached by the amount of fluid corresponding to the volume decrease of air or solid substance required to establish a new pressure state. As the movement of a fluid is determined by its viscosity and by body permeability, the propagation of pressure states in soils depends upon these two factors.

PREVIOUS STUDIES

Mayer and Habib (1955), carrying out experiments on soil samples subjected to atmospheric pressure at one end and connected with a water-filled tank located 150 cm above the samples at the other end, studied the reduction of the pore water pressure in the time after a sudden interruption of the connection with the tank. According to Mayer and Habib the reduction is not instantaneous, but develops gradually, as if compressed air storage would expel water

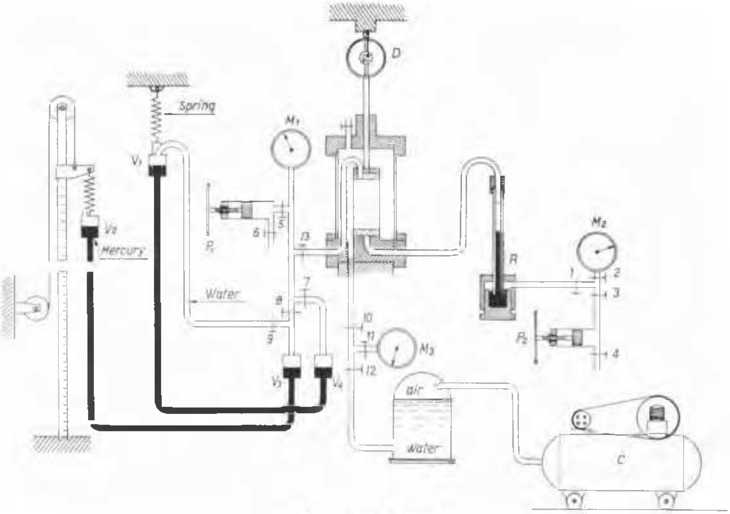

FIG. 1. Apparatus.

from the sample in a time comparable with that required by the saturation water to pass through the sample.

Mayer and Habib noted, moreover, that the pressurizing and unpressurizing mechanism of the air occluded in soils, despite saturation of long duration, in relation to the difference in water content; they recognized this mechanism as that expressed by Mariotte's law.

Limited information has been contributed by other authors on the phenomenon examined here, for example, in reports on the behaviour of the pore-pressure variations in earth dams caused by the reservoir filling or emptying (Paton and Semple, 1961). Some significant observations have been made by Gibson and Henkel (1954). Noting that it was not possible to obtain a complete drainage condition during an open triaxial test, they furnished a theoretical expression (subsequently confirmed by practical experience); by this expression it is possible to establish *a priori* how long a test must be continued in order that, in its course. pore pressures do not exceed a predetermined value. The time required for the condition to be verified gives results inversely proportional to the permeability coefficient. These authors also established the law by which the residual pressure decreases, in the course of time, after the triaxial test is ended and they assigned to the law the expression:

$$C_t \nabla^2 u = \partial u / \partial t$$

where C_t is a function of K.

EXPERIMENTS

Equipment

A normal triaxial apparatus was used (Fig. 1). The sample was enclosed in a watertight membrane and placed in a cell; its top face was connected with the water filled tank V_3 or V_4. The pressure on the sample face was kept unchanged during the test, by consequence of constant levels in the tanks V_1 and V_2, where, to keep constant pressures, any tendency of the level to decrease was exactly compensated by the decreasing length of springs to which the tanks were hung. Pressure, established by means of appropriate vertical shifting of tank V_2, and read on the manometer M_1, was transmitted instantaneously on the top face of the sample, by the sudden opening of cock 13. The underface of the sample was connected with the system RM_2. During the test the piston P_2 was moved, in order to keep the position of the mercury meniscus in the capillary tube R unchanged. Pressures on the manometer M_2 were read at short intervals. Pressure in the cell was maintained, by means of the compressor C, at a value at least 1 kg/sq.cm. higher than pressure applied to the top face of the sample. This pressure, shown by the manometer M_3, prevented the water from passing between the side surface of the sample and its membrane. The dynamometrical ring D measured and controlled the intergranular pressures of the material during the test.

Materials Tested

Experiments were carried out on materials of different permeabilities, selected so that the phenomenon could be explored on a rather wide permeability range.

TABLE 1. GRADATION AND PERMEABILITY OF SOIL MIXTURES

Sample	Sand (per cent)	Silt (per cent)	Clay (per cent)	Permeability coefficient, K (cm/sec.)
1	100	—	—	5.36×10^{-4}
2	90	10	—	5.08×10^{-4}
3	80	20	—	3.73×10^{-4}
4	70	30	—	3.63×10^{-4}
5	60	40	—	4.91×10^{-4}
6	50	50	—	6.58×10^{-4}
7	40	60	—	2.62×10^{-4}
8	30	70	—	1.35×10^{-4}
9	20	80	—	3.44×10^{-5}
10	10	90	—	7.24×10^{-6}
11	—	100	—	3.64×10^{-6}
12	—	90	10	4.60×10^{-4}
13	—	80	20	2.29×10^{-4}
14	—	70	30	2.93×10^{-5}
15	—	60	40	2.48×10^{-6}
16	—	50	50	1.07×10^{-6}

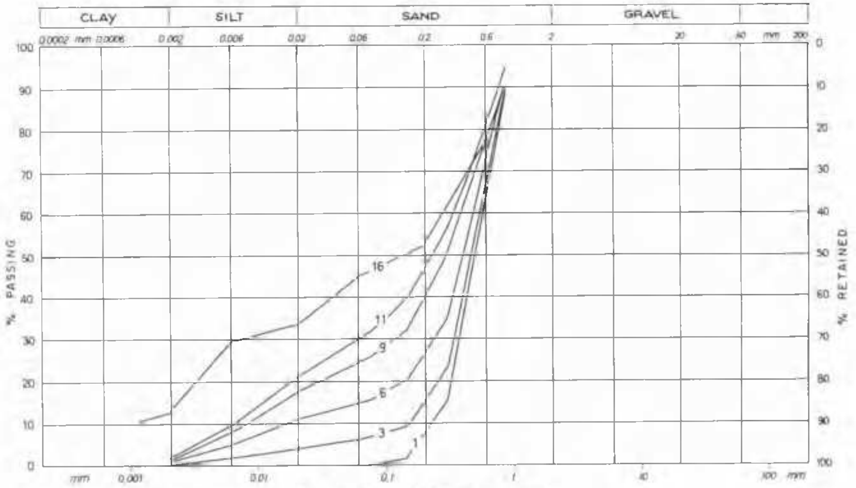

FIG. 2. Grading of tested materials.

Materials consisted of sand, and highly sandy or highly clayey silt mixes, in the proportions indicated in Table I. The grading curves of mixes were all contained in the range illustrated in Fig. 2. The samples were prepared by tamping the material with a compacting energy of 60 tons/cu.m., within cylindrical hollow moulds, 80 mm in diameter and 160 mm high, at a moisture approaching Proctor's optimum. The samples, wrapped in the watertight membrane, were then subjected to prolonged soaking in the consolidation cells.

Samples were next transferred to the triaxial apparatus and subjected to loading and unloading cycles: a first shift from zero to 2 kg/sq.cm. was followed by a reversion to the starting condition, then a new shift from zero to 2 kg/sq. cm., and others from 2 to 3.5 kg/sq.cm., from 3.5 to 1 kg/sq.cm., from 1 to 5 kg/sq.cm., from 5 to 1 kg/sq.cm. and finally from 1 kg/sq.cm. to zero, as indicated in Fig. 3. The various pressures were kept constant until equal values were reached on the two faces of the sample. When the cycle was completed the permeability of the material was measured under a pressure of 1 kg/sq.cm.

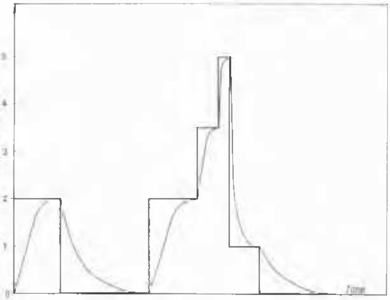

FIG. 3. Test cycle.

EXPOSITION AND DISCUSSION OF RESULTS

Test results have been graphically presented. Fig. 4 represents pressures at the sample base varying with the time. In the pressure unloading phase the following can be observed:

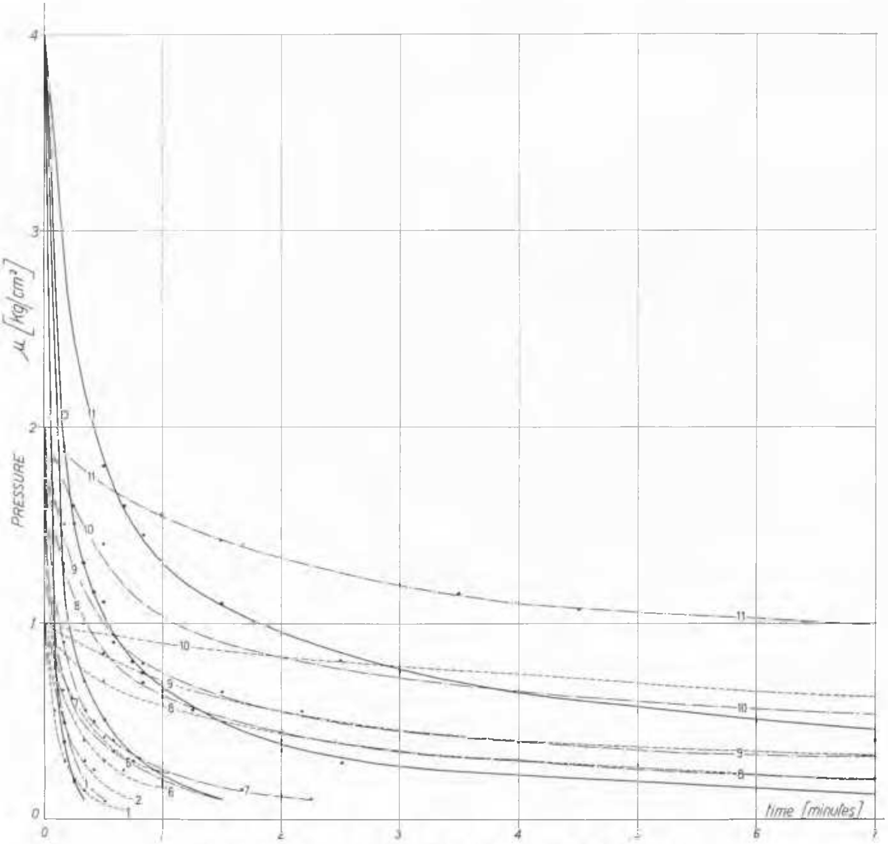

FIG. 4. Time *versus* pressures at the bottom face of the sample.

(1) Pressure states do not propagate instantaneously, but gradually in the course of time. (2) Propagation behaviour is dependent on the permeability of the tested material; the time required to establish a balance state of pore water pressures in the samples is greater with a decrease in the permeability. (3) The propagation speed varies directly with the difference Δu between the pressure applied on the top face of the sample and the previous water pressure.

The form of the curves in Fig. 4 is a typical one of exhaustion. However, if the data are transferred in the semi-logarithmic plane, as in Fig. 5, they are not straight lines but curves with asymptotic straight line behaviour. The position of these curves is determined by the ordinate log u_α and by the angular parameter α, and varies according to the laws indicated, in function of permeability, in the graphs of Figs. 6 and 7 in the range experimentally examined.

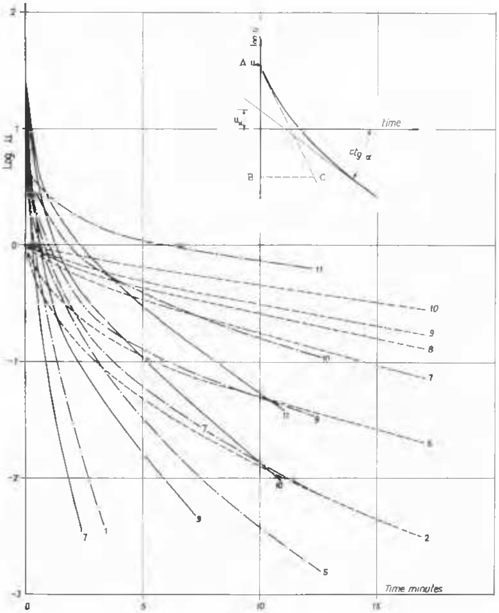

FIG. 5. Time *versus* pressures at the bottom face of the sample.

Each curve of Fig. 5 is also characterized by a more or less fast approach to the aforesaid asymptote.

The following expression, in interpolated form, has therefore been attained for the above-mentioned curves:

$$\log u = (\log u_\alpha - \alpha t) + e^{-\beta t} \log(u_0/u_\alpha)$$

where $\log u_\alpha - \alpha t$ is the asymptote of the curves of Fig. 5, $e^{-\beta t}\log(u_0/u_\alpha)$ is the difference between curves and the relative asymptote, u_0 being the initial water pressure in the sample; therefore β denotes an index of the speed of approach of the considered curve to the asymptote, and, by the notations of Fig. 5, results in

$$\beta = \frac{(\mathrm{AB}/\mathrm{BC}) - \alpha}{\log (u_0/u_\alpha)} .$$

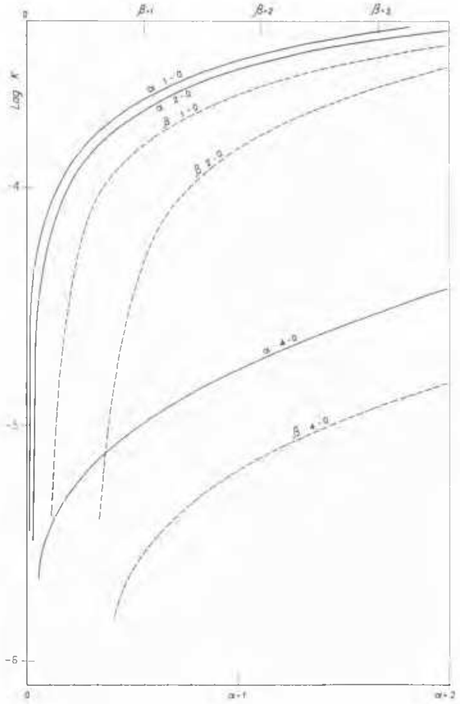

FIG. 6. α and β *versus* permeability of materials.

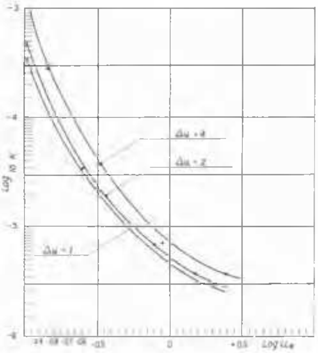

FIG. 7. u_α *versus* permeability of materials.

Quite analogous conclusions can be attained by considering the propagation of positive pressure jumps.

In this case, however, it is noted that, by equal Δu, the balance conditions are reached in a shorter time than that required to propagate a negative Δu. This results from the experimental data represented in Fig. 8, where the transmission time is compared directly with the permeability

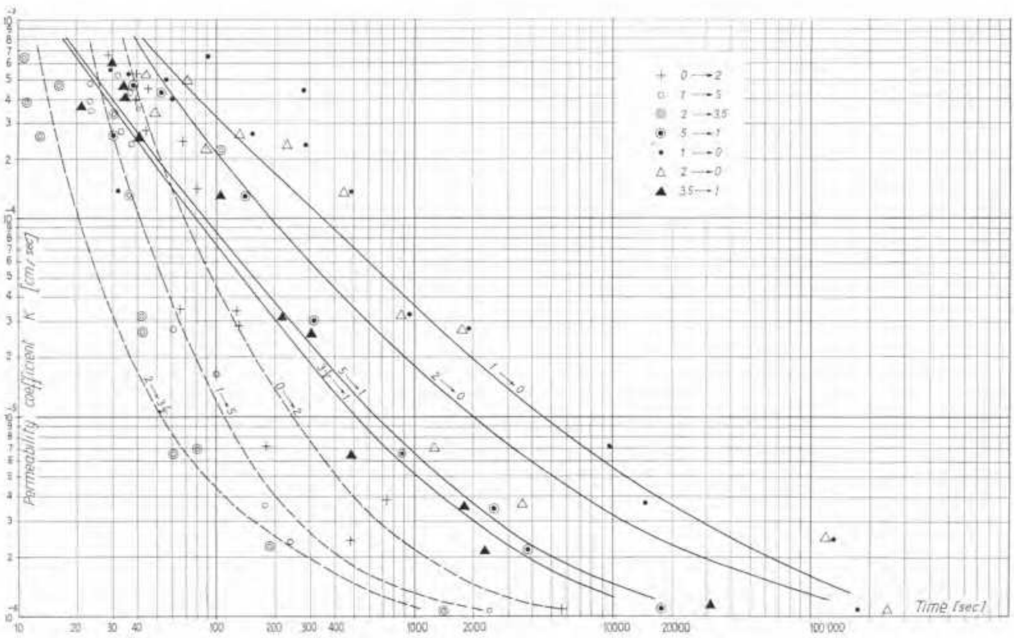

FIG. 8. Propagation times *versus* permeability.

coefficients of materials. Each curve of this figure refers to a particular Δu value. Also to be noted is the previously described dependence of the speed of pressure propagation on the permeability and on the amplitude of interval Δu. More conspicuously, it can be noted that positive Δu are more quickly transmitted than negative Δu of an equal amplitude.

But another factor, apart from K and Δu, influencing the transmission time in a remarkable way, issues from this representation. This is the value of the steady pressure u_0 in the sample prior to the pressure variation; for equal values of K and Δu, the transmission time is directly proportional to the u_0 values and *vice versa*.

It can be noticed, for example, that the curve representing the shift from 2 to 3.5 kg/sq.cm. is entirely on the left (that is, towards a shorter time) of the curve representing the passage from 1 to 5 kg/sq.cm. On account of what has been previously said relating to the dependence on Δu, the position of these curves in the diagram, without the u_0 influence, should be inverted. This new dependence is deemed to be ascribable to the fact that the amount of air held in the samples is unchanged during tests, only the water content of materials being varied.

The problem is therefore to be reconsidered in relation to the volume of air held in samples at the start of each test. It is obvious that as the u_0 values are higher, so the air-filled volumes are at the start, smaller. By consequence, for equal Δu, the values of permeating water will be smaller with higher values of u_0; therefore the time required to attain the balance decreases as u_0 is increasing.

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