

Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH
Kongressbericht

Band: 2 (1936)

Artikel: Experimental determination of the coefficient of permeability

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DOI: <https://doi.org/10.5169/seals-3364>

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VIII 7

Experimental Determination of the Coefficient of Permeability.

Experimentelle Bestimmungen des Durchlässigkeits- Koeffizienten.

Détermination expérimentale du coefficient de perméabilité.

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A knowledge of the coefficient of permeability is necessary in all calculations relating to the rate of settlement or to the percolation of water through the foundations of dams, etc. Generally speaking in the case of clay soils the coefficient of permeability is found by two methods due to Professor *Terzaghi*, namely the direct method in which use is made of a special arrangement known as the eudometer, and the indirect method so called because the coefficient K is deduced from observations of the curve of settlement, also by means of the eudometer.

The direct method consists in subjecting the soil when consolidated to a certain hydrostatic pressure which is produced by a column of water (approximately 50 cm high, with a cross section s). If H_1 is the initial height of the column and H_2 its height at the end of a time t , while $2H$ is the height of the sample in the eudometer and S the cross section of the eudometer, then the coefficient of permeability K_1 will be given by the formula:

$$K_1 = \frac{2sh}{S} \cdot \frac{1}{t} \cdot \log_e \frac{H_1}{H_2} \quad (1)$$

A correction is applied for temperature in order to refer the coefficient to 10^0 C.

The indirect method consists in observing the curve of consolidation and in separating that portion of the curve, close to the origin, which is in the shape of a parabola. If $\Delta\varepsilon$ is the variation in the void index, Δz the amount of settlement observed in the time t , a the coefficient of compressibility $= \frac{\Delta\varepsilon}{\Delta p}$, Δp the complementary pressure applied after the consolidation has taken place under a pressure p_0 , then the coefficient K_2 will be given by

$$K_2 = \frac{\Delta z^2}{4 \cdot \Delta p^2 \cdot a t} = \frac{\Delta z^2}{4 \cdot \Delta p \cdot \Delta\varepsilon \cdot t} \quad (2)$$

Certain difficulties are encountered in using the indirect method, some of which are easily overcome. For instance, some settlement is sometimes observed to take place instantaneously after the settlement curve has entered upon its

parabolic shape. It is easy to determine the apex of the parabola by the ordinary method. Another way is to plot the square of the amount of settlement as ordinates and the time as abscissae, obtaining in this way a straight line with a certain slope. On the other hand in certain cases the curve so obtained is not a parabola or a straight line on the scale of ordinates, and if so the method will not be approximately correct unless t is very small: even then it will be lacking in accuracy.

A comparison of the results obtained by the formulae 1 and 2 shows great differences between K_1 and K_2 when, as is often the case, H_2 has merely been observed after the end of a certain time t conditioned entirely by the possibility of carrying out a precise reading.

Causes of the Discrepancies Observed.

These result from two circumstances.

1) Formula 1 is based on Darcy's law which assumes a permanent régime throughout the thickness of the soil, but as a rule the measurement of H_2 is carried out before such a régime has become established. In fact the sudden increase in the pressure from 0 to H_1 is entirely transmitted to the water contained within the sample, but since the pressure inevitably remains zero at the upper portion it follows that after a very short time the hydraulic gradient between the water in the clay (at pressure H_1) and the external water (at zero pressure) is very steep. Consequently the hydraulic gradient tends slowly to decrease in accordance with the process indicated in Fig. 1.

At the beginning of the operation the velocity of the water is, therefore, greater than at the end, and the apparent permeability is greater.

Let q be the quantity of water which has passed through the surface of the clay in a time t . (This quantity is the same as that at the inside face and at the outside face, no swelling being observed). Let ε be the void index, H_1 the pressure applied (which will be assumed to remain constant during the operation); γ the density of the water; K the coefficient of permeability: $c = \frac{K}{\gamma a (1 + \varepsilon)}$ the coefficient of compressibility (equal to $\frac{d\varepsilon}{dp}$); and $2h$ the height of the sample.

The velocity of percolation $\frac{dq}{dt}$ is given by the following Fourier series:

$$\frac{dq}{dt} = \frac{K}{\gamma} \cdot \frac{H_1}{h} \left(\frac{1}{2} + \sum_1^{\infty} e^{-\frac{\pi^2 c n^2 t}{4 h^2}} \right).$$

This tends towards a limiting value for the permanent régime $\frac{K}{\gamma} \cdot \frac{H_1}{2h}$ which is given by Darcy's law for an infinite time value.

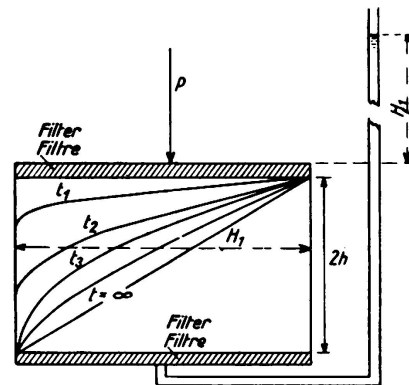


Fig. 1.

Distribution of hydraulic pressure in the interior of clay sample.

It is easy to see that in the case of clays having a coefficient of consolidation c which may frequently be of the order of 10^{-3} the régime is practically not established until about twenty-four hours after the beginning of the test.

Measurements carried out with no allowance for this consideration are, therefore, subject to an error which increases in importance with the amount of the hydraulic pressure for the values determined in accordance with formula 1 increases greatly with H_1 . What is said above justifies to some extent the method originally suggested by Professor *Terzaghi*. The hydraulic pressure was in fact 50 g/cm^2 and hence the differences are not very great by comparison with the coefficient obtained when t varies. In fact, to obtain a sufficiently accurate reading, having regard to the very small quantity of water percolating through the ground, the experiments have to be continued long enough for the régime to have become established by the time the reading is taken. On the other hand the error becomes very great when the hydraulic pressure is increased, as has been done by certain experimenters with a view to reducing the time required for the test. Figs. 2, 3 and 4 show how the coefficient K calculated from formula 1 varies as a function of time and as a function of the hydraulic pressure H_1 . These figures show that the period required to establish the régime is practically the same whatever the amount of the hydraulic pressure.

If it is desired to carry out the operation more rapidly which necessitates a much greater hydraulic pressure in order to obtain an accurate reading, use may be made of the integral given by Cauchy. This gives a result practically accurate, since $\frac{c\pi^2 t}{4h^2} < \frac{1}{10}$. With $c = 10^{-3}$, t may be less than 40 minutes. Starting from this integral it may be shown that the quantity of water which percolates through the ground is given by the formula

$$q = \frac{2SK_3H_1\sqrt{t}}{\gamma\sqrt{\pi c}}$$

$$\text{whence } K_3 = \frac{\pi q^2 \gamma}{4a S^2 H_1^2 t (1 + \epsilon)} \quad \text{because } c = \frac{K_3}{\gamma a (1 + \epsilon)} \quad (3)$$

This formula no longer contains the term $2h$ since this has been replaced by Cauchy's integral under conditions such that the thickness no longer affects matters. Since $q = S (H_1 - H_2)$ it may be deduced that

$$K_3 = \frac{\pi S^2 (H_1 - H_2)^2 \gamma}{4a S^2 H_1^2 (1 + \epsilon) t}$$

Other phenomena, however, appear to influence the result, and it has not been possible to effect a sufficiently large number of comparisons to enable a formula to be developed for calculating K_3 .

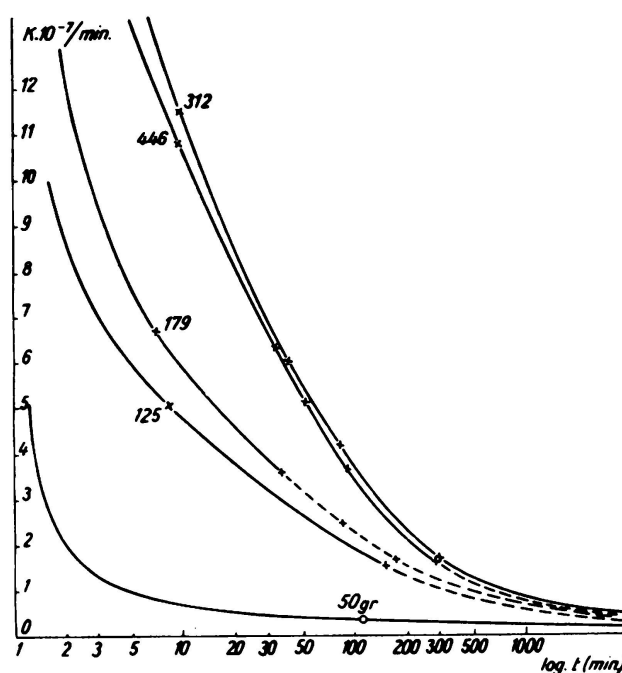
Nevertheless a number of facts appear to be established. The practical duration of the period required to establish the régime becomes longer as the coefficient of permeability becomes smaller. In practice the period is from one to two hours when K is of the order of $10^{-6} \text{ cm per min.}$ and may be a day when K is of the order of $10^{-7} \text{ cm per min.}$ The coefficient of permeability found at the beginning of the test is often ten times as great as the final value, and this is to

be expected in view of what is stated above. Some authorities consider that this may be attributed to the phenomenon of silting up of the pores.

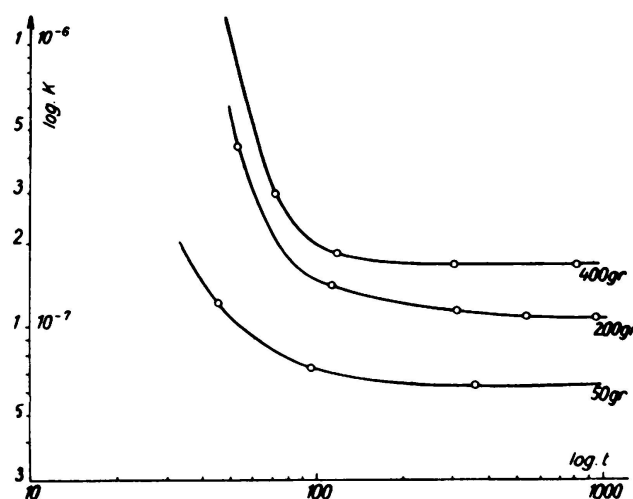
The author does not share this opinion, for if that were so it would not be found that the same results were obtained when the pressure was reduced to zero and the tests repeated after waiting for the hydraulic pressures to become equal. It would, indeed, appear unlikely that the phenomenon of silting was not permanent in its action.

2) The second reason for the discrepancy between the results obtained by using the two methods arises from the fact that the final coefficient of permeability sometimes varies very considerably with the hydraulic pressure, while the pressure of consolidation remains the same.

In a general way it may be stated that the coefficient of permeability increases with the hydraulic pressure, especially under low values of the latter. Anomalies are observed and the cause of these phenomena is still obscure. In carrying out tests with the eudometer the curves of consolidation (which serve the purpose of indirectly determining the value of K) are obtained by applying additional pressures equal to the pre-existing load in cases where this is less than 3 kg/cm^2 or equal to one half of that load when it exceeds this value. Hence the hydrodynamic pressure is considerably greater than 50 g/cm^2 which is the value commonly used for the direct determination of K , and in certain cases the coefficient of permeability as determined by the direct method may be too low. Seeing, however, that the coefficient obtained directly without waiting for the régime to be established is too high, the two errors may cancel out, and the result is frequently that the two coefficients obtained in the usual way coincide as between different laboratories. The explanation given above will enable the coefficients of permeability ob-



Soil following Darcy's law.



Soil not following Darcy's law.

Fig. 2 and 3.

Coefficients of permeability in relation to time, under various hydraulic pressures. The respective pressures applied are constant.

tained directly and indirectly to be compared more exactly. The results obtained to the present are very encouraging. Certain differences, however, appear to remain, even though in many cases they have been considerably reduced. The differences found between the coefficients rapidly determined and the coefficients as finally determined offer a means of better understanding the mechanism of the secondary phenomenon of consolidation. In making the compression test with the eudometer everything tends to diminish the coefficient of permeability, and as consolidation proceeds the hydraulic gradient becomes very much less steep, with the result that the coefficient of permeability becomes smaller.

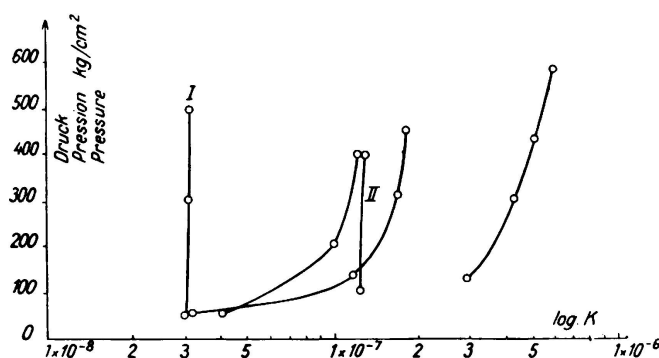


Fig. 4.

The real coefficients of permeability (for permanent condition) in relation to the hydrostatic pressure. The pressure applied is constant in each particular case. The soils No I and II follow Darcy's law, but not the others.

However, the fact that the curve of consolidation can practically be taken as a parabola — at least at the beginning of the process of consolidation — shows that during this period at least, the coefficient of permeability remains practically constant. This in turn shows that the coefficient of permeability does not increase continuously with the hydraulic pressure, but tends towards a constant value. This at least is what the author has been able to establish in a number of instances. There appears a need for further elucidation of questions relating to permeability, and steps are being taken to that end.

Conclusion.

The coefficient of permeability cannot be found with certainty until the permanent régime has been established. The length of time required for this régime to become established increases as the coefficient of permeability becomes smaller. In certain cases the coefficient of permeability increases with the hydraulic pressure.