The permeability of natural soft clays. Part I: Methods of laboratory measurement

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The methods of measuring the permeability of clays in the laboratory are investigated. Constant head tests in the triaxial are best suited for testing large specimen under field stress conditions provided the cell is modified to eliminate leakage. Using this type of test, the validity of Darcy's law is confirmed.

Falling head tests in the oedometer are very simple to perform and subject to minimal sources of errors. However, small size specimens may not be totally representative.

Indirect evaluations of the permeability from consolidation tests are shown to be unreliable particularly in structured natural clays: evaluation of k from c_v measurements in step-loaded tests gives much too low values, constant rate of strain tests strongly overestimate k in the vicinity of σ_p' and give nonrepresentative e vs. lg k relations; controlled gradient tests tend to underestimate k at all void ratios.

Keywords: permeability, clays, laboratory tests, test equipment, consolidation tests.

Les méthodes de mesure en laboratoire de la perméabilité des argiles sont analysées. Les essais à charge constante dans le triaxial sont les mieux adaptés à l'étude de grands échantillons sous les conditions de contraintes règnant sur le terrain sous réserve que la cellule soit modifiée pour éliminer les fuites. A l'aide de ce type d'essai la validité de la loi de Darcy est confirmée.

Les essais à charge variable dans l'oedomètre sont très simples à réaliser et sont sujets à des sources d'erreurs minimes. Cependant, les échantillons de petites dimensions peuvent ne pas être parfaitement représentatifs.

Les évaluations indirectes de la perméabilité à partir d'essais de consolidation s'avèrent non fiables particulièrement dans les argiles naturelles structurées: l'évaluation de k à partir de mesures de c_v dans les essais à chargement par paliers donne des valeurs beaucoup trop faibles; les essais à vitesse de deformation controlée surestiment énormément k à proximité de σ_p' et donnent des relations e vs lg k non représentatives; les essais à gradient constant ont tendance à sous estimer k à toutes les valeurs d'indice des vides.

Mots-clés: perméabilité, argiles, essais de laboratoire, équipement, essais de consolidation.

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1. Introduction

The measurement of the permeability of natural soft clays is a problem of growing importance in geotechnical engineering. The permeability is a dominant parameter in the design of waste disposal facilities involving burial in natural clay deposits or the use of clay liners in surficial or underground reservoirs. Following work by Raymond (1966), Mesri and Rokhsar (1974), and Tavenas *et al.* (1979), it has been realized that the consolidation analysis of clay foundations is better achieved by means of numerical methods using the permeability and the compressibility of the clay as independent input parameters than by resorting to the Terzaghi solution based on the compounded coefficient of consolidation c_v. The permeability is also a key element in the analysis of groundwater regimes in slopes or in the design of water retaining structures.

In spite of this importance, the permeability of natural clays has not been investigated as intensively as their mechanical behaviour and some important aspects are still in a rather confused state of knowledge. For example the validity of Darcy's law is not clearly established, some authors suggesting the possibility of nonlinear gradient–velocity relationships (Hansbo 1960) or the existence of threshold gradients below which no flow would occur (Miller and Low 1963), whereas others (Olsen 1965; Mitchell 1976) confirm the validity of the linear relationship

$$[1] \quad v = ki$$

The parameters determining the magnitude of k, the law of variation of k with the void ratio, or the importance of permeability anisotropy of natural clays are not clearly established yet. Even the merits of the various laboratory or field measuring techniques could be better defined (Olson and Daniel 1981).

Under these circumstances, and as part of a continuing research on the properties of natural soft clays and on the behaviour of clay foundations, it was decided to develop a large research program on the permeability of natural soft clays at Laval University. As a first step, the laboratory methods of permeability measurement were investigated with the aims of checking the validity of Darcy's law, comparing the various methods of direct and indirect evaluation of k, and establishing the best practical method. The results are presented in this paper.

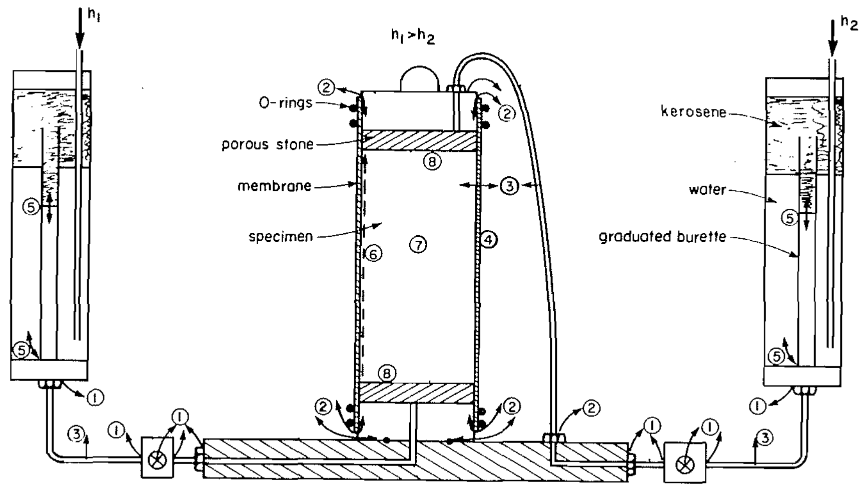

FIG. 1. Sources of errors in a triaxial permeability test installation. 1. Leakage in external fitting. 2. Leakage in fitting within the cell. 3. Osmosis and diffusion through membrane and lines. 4. Saturation of membrane. 5. Leakage and diffusion within the back-pressure burette (negligible). 6. Preferred flow between membrane and specimen. 7. Lack of saturation of the specimen and porous stone. 8. Consolidation/swelling of the specimen.

Using the conclusion of this first study, a wide variety of natural clays from Quebec, the USA, and Sweden were investigated in terms of initial permeability, permeability anisotropy and permeability–void ratio relationships. The results are presented in Part II (see following paper). Finally the *in-situ* testing techniques are presently under investigation.

2. Permeability tests in the triaxial cell

2.1. General

Permeability tests in the triaxial cell present many advantages. Cells of any dimension can be built easily to accommodate varying sizes of specimen, thus reducing the problem of specimen representativity. The possibility to test the clay under effective stresses and back pressures equivalent to the *in-situ* condition is a distinct advantage. Both falling head and constant head tests may be performed, the latter being generally preferred, particularly since it is easy to measure both the inflow and outflow of permeant and thus to check the accuracy of the permeability measurement. The triaxial cell thus appears as the ideal tool for investigating the permeability of natural clays.

2.2. Equipment

Due to the very low permeability of clays, the measurement of k implies the observation of very small flows over extended periods of time. The identification and, if possible, the elimination of errors on the observed flow are key requirements for the accurate evaluation of the permeability of clays.

In a standard triaxial test installation, the sources of error are varied and numerous. Figure 1 schematically presents a setup for a constant head test in a common triaxial cell; the phenomena adversely affecting the accuracy of throughflow measurements are identified.

The mechanical leakage in the external fittings (*1* in Fig. 1) is the most important source of error. It is also easiest to eliminate by attaching the back-pressure burettes directly to the cell base and by enclosing all fittings in the back-pressure chamber, as suggested by Leroueil (1977). Figure 2 shows the principle of the cells used in the present study to carry out constant head tests on specimens with diameters of 50, 100, and 200 mm. Figure 3 shows the benefits obtained from the use of such a "leak-free" cell base: a leakage of approximately 1 cm^3/week in a standard system of independent burettes and base connected by tubings, fittings, and valves was practically eliminated by using the "leak-free" cell base.

The leakage in fittings within the cell is usually much less important. It may be further reduced by careful construction and tightening of all fittings and by using a viscous cell fluid. The osmosis and diffusion through the membrane and tubings within the cell cannot be totally eliminated. However, comparative studies by Leroueil (1977) have shown that the use of silicone oil as a cell fluid reduces the leakage by osmosis and diffusion through a common rubber membrane of 0.3 mm thickness and 150 cm^2 perimetral area to less than 0.05 cm^3/week. In the present study silicone oil was used systematically as a cell fluid and the specimens were enclosed in a system of two membranes separated by a "saran wrap" foil and a film of silicone grease. In this manner the leakage by osmosis and diffusion was further reduced to negligible values, as indicated by the results shown in Fig. 3.

Experience has shown that the rubber membrane needs to be water saturated before mounting, otherwise

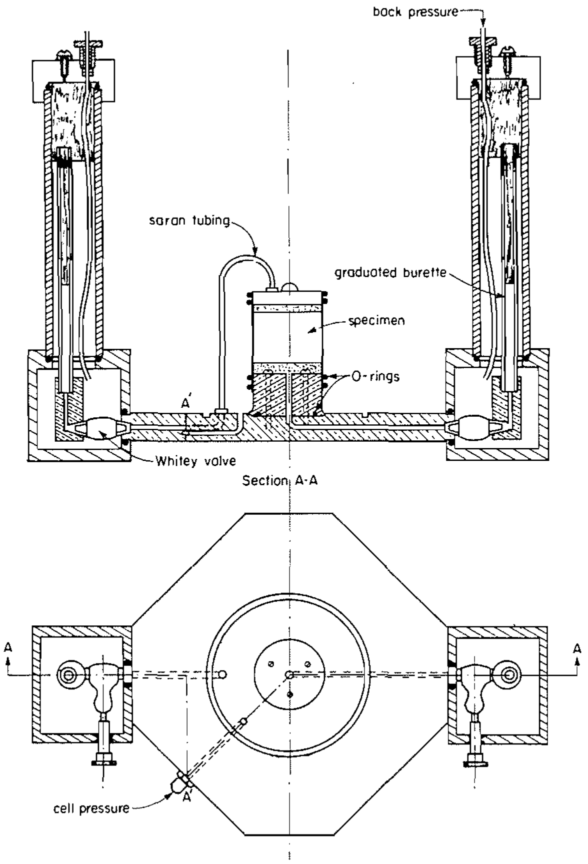

FIG. 2. "Leak-free" triaxial cell for permeability tests.

the volume of water required to saturate the membrane would produce an error in the flow observation over a duration of 1 or 2 weeks for large specimen.

Even when using a rubber membrane fitting exactly with the specimen diameter, preferred flow may occur between the specimen and the membrane. Such flow may be avoided by applying a sufficiently high effective lateral stress. The magnitude of this stress must be defined experimentally for the given size of specimen and characteristics of rubber membranes. In the test conditions of the present study, the effective lateral stress required to avoid preferred flow was found to be in the order of 25 kPa. The existence of such necessary minimum σ_3' imposes a limitation on the minimum depth at which samples may be reliably tested under *in-situ* effective stress conditions.

Finally, in order to ensure proper saturation, the porous stones were first boiled and all specimens were mounted under water in a large tank fitted to the cell base. This method, which is now standard for mounting all triaxial test specimens at Laval University, has proved satisfactory and no problem of specimen decomposition in water has ever been observed in unfissured intact clays.

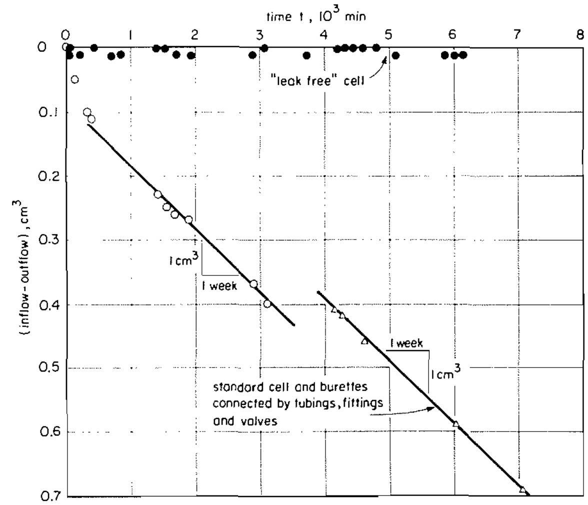

FIG. 3. Observed leakage in a conventional and a "leak-free" triaxial cell during permeability tests.

2.3. *Effect of consolidation/swelling of the clay*

During permeability tests in the triaxial cell the volume changes of the specimen cannot be avoided and thus contribute to an error on the observed flow. These volume changes may be due to two different phenomena.

After consolidation of the specimen under the *in-situ* effective stresses and pore pressure, the gradient i necessary to produce the flow is produced by applying a pore pressure difference, i.e., an effective stress difference between the ends of the specimen. Corresponding volume changes are produced in a primary consolidation process, i.e., over a limited period of time. The sign and magnitude of these volume changes depend on the initial state of the specimen and on the method of applying i. If the specimen is initially overconsolidated, the volume changes will be small and relatively rapid due to the stiffness of the overconsolidated clay. If the gradient $i = (\Delta u)/H\gamma_w$ is applied by increasing or decreasing the back pressure by Δu at one end of the specimen of height H, the effective stresses acting in the specimen will be decreased or increased and swelling or consolidation will be generated in the entire specimen. In order to minimize the volume changes it thus appears preferable to apply i by increasing the back-pressure by $(\Delta u)/2$ at one end and decreasing it by $(\Delta u/2)$ at the other end so as to have compensating consolidation and swelling developing at the same time within the specimen. If, on the other hand, the specimen is initially normally consolidated, the application of a decreased back pressure would generate large consolidation volume changes in that part of the specimen and create an unacceptable error. In this case the gradient should preferably be produced by increasing the back pressure by Δu at one end of the specimen so as to produce swelling in the now slightly overconsolidated clay. If the

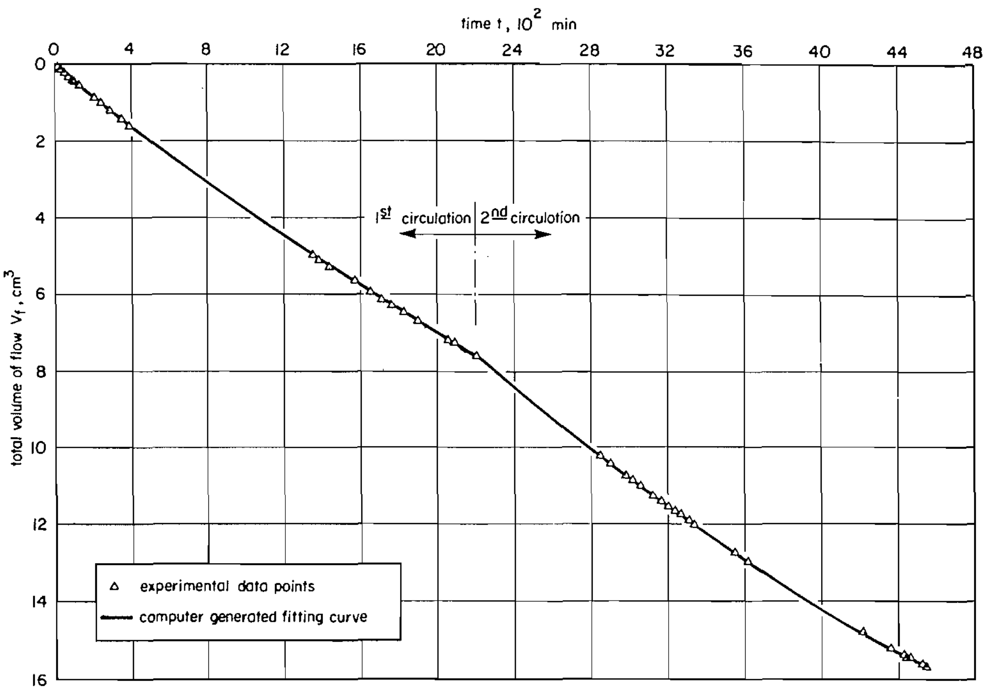

FIG. 4. Flow–time relationships during a constant head triaxial permeability test.

gradient, i.e., the pore pressures, vary during the test, volume changes will necessarily occur and affect the accuracy of the permeability measurement unless the gradient variations are slow and the flow is large as compared with the induced volume changes.

Another cause of volume changes is the development of secondary consolidation/swelling with time in the specimen. This time dependent process cannot be eliminated and will necessarily create an error on the measured flow. This shows in the accurate measurement of inflow and outflow as a difference increasing with time. This difference must be sufficiently small as compared with the total flow under usual gradients so as to have a negligible effect on the accuracy of k. However, as we shall see later, it becomes relatively so large under very small gradients as to restrict the possibility of checking the validity of Darcy's law.

In order to minimize the errors due to the volume changes of the specimen it has been found appropriate to wait for a few days after the application of the gradient before making the flow and k measurements. The length of the waiting period was found in the order of 2 days for the 50 mm specimen to 1 week for the 200 mm specimen.

2.4. Head variations due to the burettes

The triaxial equipment shown in Fig. 2 was intended for use in constant head tests in which a back pressure differential would be applied between the top and bottom burettes and the inflow and outflow would be measured. The back pressures $u + \Delta u/2$ and $u - \Delta u/2$ are maintained by means of mercury pots equipped with precision screws to allow an accurate positioning of the mercury surfaces, checked by means of a cathetometer. However, due to the different densities of the water and the colored kerosene the weight of the liquid column in each burette varies with the displacement of the water–kerosene interface. Since the two interfaces travel in opposite directions this effect is compounded and produces a non-negligible variation of the applied head.

Figure 4 presents the flow–time relationship observed in a typical "constant head" test in a cell equipped with 10 cm^3 burettes. The distinctly curved shape of the V_f vs. t relationships in two successive burette circulations reflects the variations of the applied gradient from high initial values (i = 7.45) when the water–kerosene interfaces are high in the inflow and low in the outflow burette, to lower final values (i = 5.08) when the interface positions have been inversed. In order to account for this phenomenon, the flow–time observations were interpreted by means of a computer program which first fitted a curve to the data points (cf. Fig. 4) and then interpreted this curve over equal time intervals to compute the flow velocity and the average gradient over each interval; the gradient is computed from the average position of the interfaces in the burettes during the time interval.

The head variation in the burettes also causes a change in effective stress within the specimen and thus associated volume changes. If the head variation is rapid and the flow limited, the error due to the associated volume changes may become prohibitive. This is evidenced in Fig. 5 which shows the results of 7 successive measurements on a 200 mm specimen.

In the test series A, 100 cm^3 burettes were used in tests with a mean gradient of 12.5. The large capacity of the burettes resulted in a relatively slow pore pressure change of 2.3 kPa over a period of 72 h. The associated volume changes of the specimen were too small to affect the flow measurement and the observed velocity–gradient relationship fits well with Darcy's law once the permanent regime has been established in tests A2, A3. In the test series B, 10 cm^3 burettes were used in tests with various mean gradients. Under the highest mean gradient of 12.5, the small capacity of the burette and the high flow velocity resulted in a rapid variation of the pore pressure, amounting to 1.2 kPa in 6 h. Under such circumstances the volume changes of the specimen became relatively large as compared with the flow and the observed velocity–gradient relationship deviates strongly from Darcy's law and the results of test series A. Under reduced gradients the duration of the pore pressure change is increased, up to 3 days at the lowest gradient of 1.4. The rate of volume changes is correspondingly decreased and it becomes relatively small as compared with the observed rate of flow. As shown in Fig. 5, the deviations of the v vs. i relationship from Darcy's law are less and less important with reducing gradients and it becomes negligible at the lowest gradient of 1.4.

2.5. *Verification of Darcy's law*

The triaxial equipment shown in Fig. 2 was used to check the validity of Darcy's law on a 200 mm diameter, 200 mm high specimen of undisturbed Louiseville clay. The specimen, retrieved from 14 m depth using the Laval University over-coring tube sampler (La Rochelle *et al.* 1981), consists of a homogeneous clay characterized by $w = 65\%$, $w_L = 62\%$, $w_p = 25\%$, clay fraction $= 85\%$, $\sigma_p' = 280$ kPa. It was consolidated under $\sigma_v' = 84$ kPa, $\sigma_h' = 42$ kPa, using a back pressure of 130 kPa.

The gradients of 1.5, 6.5, and 12.5 were imposed in successive tests on the same specimen by applying $+(\Delta u)/2$ at the base of the specimen and $-(\Delta u/2)$ at the top, the values of Δu being 3, 13, and 25 kPa respectively. The various factors discussed earlier were accounted for. Burettes of 100 cm^3 were used and at least two full burette circulations were allowed before making the actual test. The flow–time observations were interpreted using the method described earlier to account for the head variation due to the burettes. The difference between the observed inflow and outflow was less than 3% of the total inflow, and the gradient – flow velocity relationships were developed from the mean of inflow and outflow in each test.

Figure 6 presents the gradient – flow velocity relations obtained in the three tests on the Louiseville ϕ 200 mm specimen. The v vs. i relationships in each test

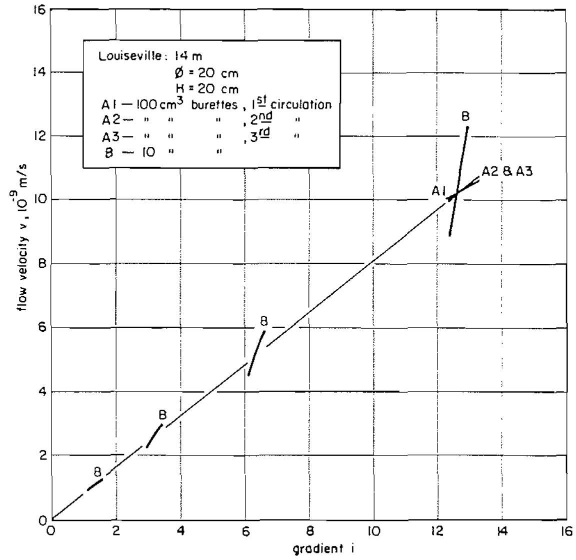

FIG. 5. Flow velocity – gradient relationships in seven triaxial permeability tests with different rates of head variation.

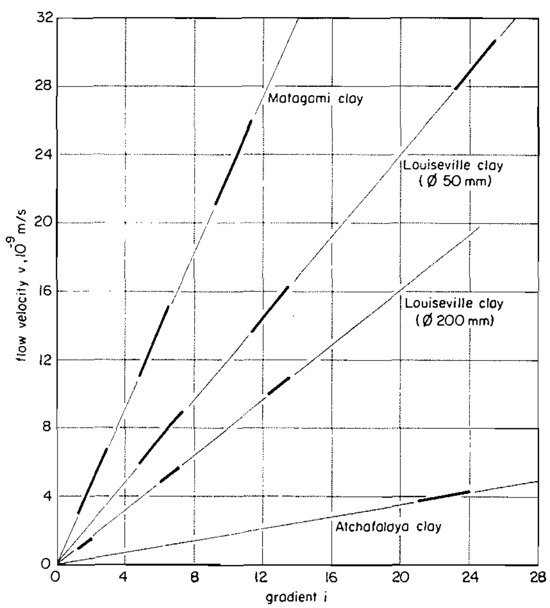

FIG. 6. Flow velocity – gradient relationship from triaxial permeability tests under various gradients on four different clays.

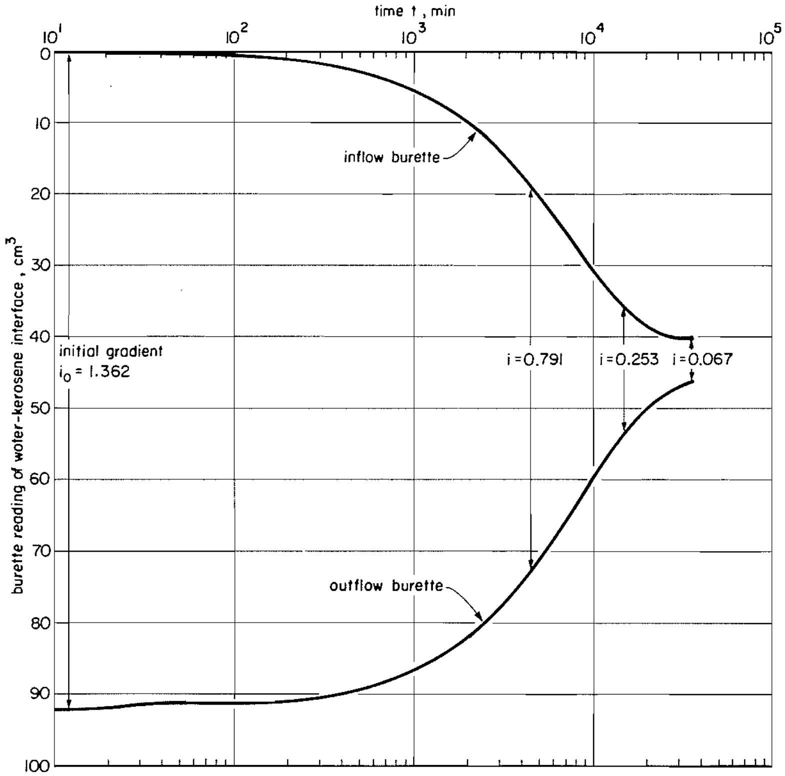

FIG. 7. Results of a triaxial permeability test using the difference in water level in the in- and outflow burettes to produce a falling head.

and the combined results all agree very well and fall on a straight line going through the origin. These results confirm the validity of Darcy's law $v = ki$ with $k = 8.1 \times 10^{-10}$ m/s, at least within the accuracy of the test installation and interpretation. Figure 6 suggests that, if any threshold gradient were to exist, it would have to be very small, say less than 0.2.

Similar tests were carried out on specimens of different sizes and origins. Results for a ϕ 50 mm specimen of Louiseville clay and for ϕ 200 mm specimens of Matagami varved clay and of Atchafalaya (USA) clay are also shown in Fig. 6. In all cases the v vs. i relationships fall on straight lines passing through the origin, thus confirming the validity of Darcy's law.

In order to further check the eventual existence of a threshold gradient a permeability test was performed in the triaxial on a 200 mm diameter specimen of Matagami varved clay. The same back pressure was applied to both burettes so that the only gradient was produced by the different weights of the water columns in the inflow and outflow burettes. The test was thus a variable head test since the initially high water–kerosene interface in the inflow burette moved downward with progressing percolation while the initially low interface moved upward in the outflow burette. The results are shown in Fig. 7 in terms of the variations with lg t of the interface positions in the inflow and outflow burettes. In the later stages of the tests two important phenomena may be noticed. First the elevation of the interface in the inflow burette becomes nearly constant while that in the outflow burette still rises; this indicates that secondary consolidation produces volume changes in the specimen which override the permeation process. In addition, the difference in elevation of the two interfaces, which directly represents the gradient, continues to diminish while the minimum gradient observed at the end of the test was less than 0.07. These results suggest that any threshold gradient would have to be less than this value, but that the unavoidable occurrence of secondary consolidation/swelling within the specimen makes it impossible to truly check the validity of Darcy's law under very low gradients. This later conclusion would appear to be general to any test in any natural clay. On the other hand, the experimental evidence available (Figs. 6 and 7) is sufficient to conclude that for all practical purposes, Darcy's law can be considered as valid in soft clays. This conclusion is supported by field observations of pore pressures in clay foundations which indicate that dissipation of excess pore pressures still develops under gradients less than 0.1.

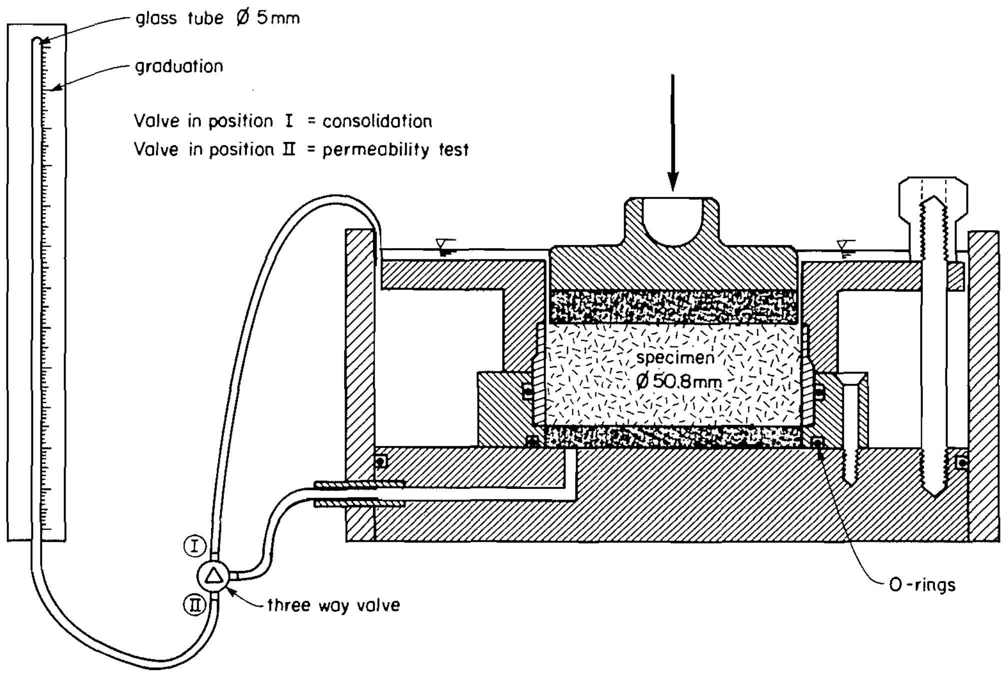

FIG. 8. Oedometer cell adapted for falling head permeability tests.

3. Falling head permeability tests in the oedometer

3.1. General

The conventional oedometer test equipment and procedure may be easily adapted to perform falling head permeability tests. Besides the simplicity of the equipment and procedure, the great merit of such tests lies in the possibility of measuring not only the permeability under the initial site conditions σ_{vo}' e_o, but also, and rapidly, the law of variation of k with the void ratio under increasing effective vertical stresses.

3.2. Equipment

The conventional oedometer cell must be modified as shown on Fig. 8 to make a tight connection between the bottom of the specimen and the cell base. The specimen has a diameter of 50.8 mm and a height of 19 mm. The bottom porous stone is connected by a flexible tube to a three-way Whitey valve which allows connections with either the free water in the cell for normal, double drainage, consolidation tests, or the base of a 1 m high vertical glass tube, 5 mm in diameter, and graduated in millimetres for the falling head permeability test.

In this type of cell no back pressure may be applied. In order to avoid saturation problems, the specimens are mounted into the cell under water. This procedure was found satisfactory and comparative tests with an oedometer equipment allowing the use of a back pressure showed no difference in either consolidation or permeability behaviour in the type of clays tested in the present study.

The problem of leakage and its eventual influence on the accuracy of permeability was investigated. The volume of leakage in the equipment shown in Fig. 8 was found to be in the order of 0.007 cm^3/day, which corresponds to an error of less than 0.5% on the measured flow in a typical 24 h duration permeability test.

3.3. Effect of consolidation/swelling

At the end of any 24 h duration consolidation stage of the conventional step-loaded oedometer test, the permeability test is started by connecting the base of the specimen to the glass tube filled with water. An initial head in the order of 100 cm is thus applied between the base and the top of the 19 mm high specimen. The corresponding pore pressure difference of 10 kPa may produce various types of effective stress changes depending on the condition of the specimen.

If the height of the specimen is allowed to change during the test, the applied pore pressure u_b produces first a reduction of the effective stress $\Delta\sigma_v' = u_b$ at the base of the specimen, decreasing to 0 at the top (Fig. 9*b*). During the test u_b decreases and σ_v' increases, ultimately back to its original value. The entire specimen will swell particularly in the early stage of the test, but the magnitude of the corresponding volume change will be small since the swelling will develop in the overconsolidated state in all cases. As for the gradient distribution it will be nearly constant over the height of the specimen. Thus the only significant source of error

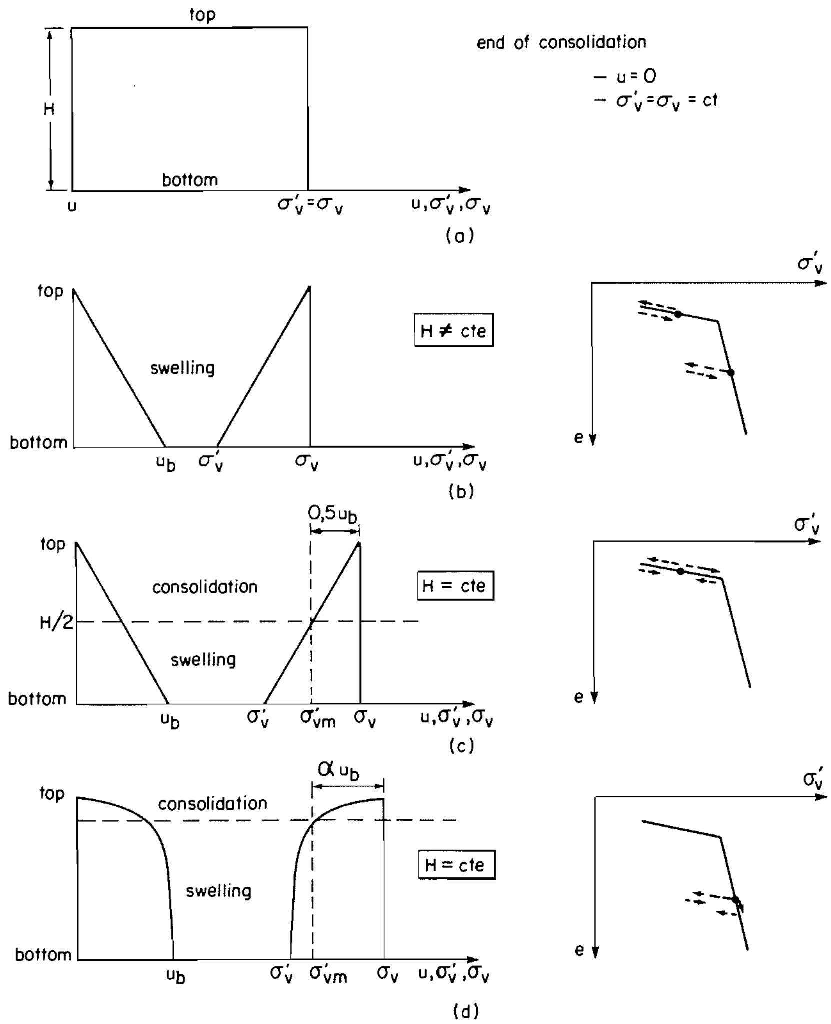

FIG. 9. Stress conditions and volume change behaviour during falling head tests in the oedometer.

will be associated with the flow required by the swelling of the specimen.

On the other hand, the purpose of permeability tests in the oedometer being usually to define the void ratio – permeability relationships of the clay, it is a common practice to maintain the height (H) of the specimen perfectly constant during the permeability test by means of a suitable clamping device fitted to the oedometer loading frame. In this case the mean void ratio e_m of the specimen is maintained constant. Since the void ratio is uniquely related to the effective stress, this implies that the mean effective stress σ_{vm}' in the specimen must be a constant. In order to maintain e_m and σ_{vm}' constant when the gradient is applied, the reduction in σ_v' and the swelling near the base of the specimen must be compensated by an increase in σ_v' and associated consolidation near the top of the specimen.

If the specimen is overconsolidated, its moduli in compression and swelling are roughly equal. The conditions $e_m = C^{st}$ and $\sigma_{vm}' = C^{st}$ would then be satisfied by an increase of the total stress acting on the specimen $\Delta\sigma_v = 0.5u_b$ so that the effective stress distribution within the specimen would be such as in Fig. 9*c*. The lower half of the specimen would swell while the upper half would be consolidated by an equal amount. This could create some error on the flow measurement but the gradient would still be uniformly distributed. If the specimen is in a normally consolidated state, the different moduli in normally consolidated compression and overconsolidated swelling will create a more complex stress condition as shown in Fig. 9*d*. In addition to the internal water content redistribution, the gradient becomes unevenly distributed over the height of the specimen, possibly creating an additional error in the measurement of k. In developing Fig. 9*c*,*d*, no secondary consolidation was taken into account; it would produce a total and effective stress relaxation, the effects of which are difficult to evaluate. Thus, the method of maintaining the specimen height constant results in complex effects of consolidation/swelling that might adversely affect the interpretation of the permeability test.

However, the errors on the flow measurements resulting from the consolidation/swelling process in oedometer tests seem to be much more limited than in triaxial tests. In the present research the specimen height was systematically maintained constant and the head–time relationships showed no deviation from the theoretical linear lg h vs. t relation corresponding to Darcy's law. Comparative tests with and without maintaining the specimen height constant also showed negligible effects. This may be associated with the small magnitude of possible void ratio variations as compared with the total flow involved in 24 h permeability tests: for the type of clays tested, the maximum error on the observed flow would be less than 2% and generally in the order of 0.5%. Under these conditions it would seem preferable to leave the specimen free to swell, not necessarily because of the better quality of the test results (the two procedures give results of equivalent quality), but because it is simpler.

3.4. Test procedure and interpretation

Having mounted the specimen in a modified oedometer cell such as shown in Fig. 8, the conventional oedometer test is started applying the load in stages with a 1.5 increment ratio and a 24 h stage duration. At the end of consolidation under an effective vertical stress equal to or near σ_{vo}', the first falling head permeability test is carried out. In order to avoid a preferred flow along the walls of the oedometer ring, the initial head h_o in this test should be less than $0.5\sigma_{vo}'$. The falling head test is continued for 24 h, observing the variations with time of the water level in the permeability tube. The consolidation test is then resumed. Further permeability tests may be carried out after all or any selected subsequent loading stages to define the relationship between permeability and void ratio. In each test, the initial head should preferably be less than half the effective consolidation stress σ_v'.

Darcy's law for a falling head test may be expressed in the form

$$[2] \quad k = 2.3026 \frac{aH}{A} \frac{1}{t_2 - t_1} \lg \frac{h_1}{h_2}$$

where a is the cross-sectional area of the permeability tube, A, the cross-sectional area of the specimen, H the height of the specimen, and t_1 and t_2 the times at which the water levels h_1 and h_2 have been measured in the permeability tube. The test results may thus be plotted in the form of lg h vs. t relationships as shown in Fig. 10.

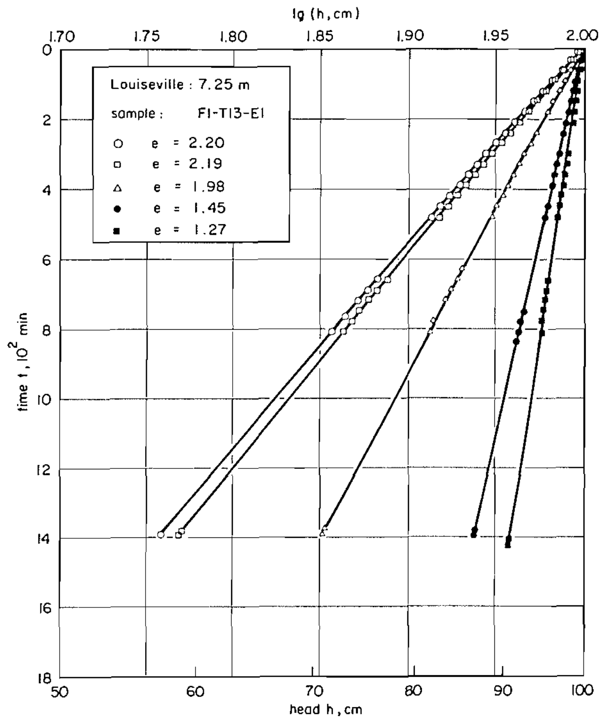

FIG. 10. Typical logarithm of head–time relationships in falling head tests in the oedometer.

The excellent linearity of the experimental data is evidence of both the validity of Darcy's law under gradients of 30–50 and the quality of the test results. The permeability of the Louiseville clay may be easily computed at the various void ratios from the data in Fig. 10. The complete results of the oedometer/permeability test are then developed in terms of e vs. lg σ_v' and e vs. lg k relationships as shown in Fig. 11.

4. Indirect evaluation of *k* from consolidation tests

4.1. General

It is well established that the rate of consolidation of a clay specimen under an applied stress is partly governed by its permeability. Since consolidation tests are routinely performed in geotechnical engineering it was logical to consider using the observation of rates of consolidation as a mean of indirectly evaluating the permeability of natural clays in their initial condition e_o, σ_{vo}' or under decreasing void ratios. Three types of consolidation tests are commonly performed and may be used for permeability evaluation: the conventional step-loaded test, the constant rate of strain test (CRS), and the controlled gradient test (CGT).

Unfortunately the Terzaghi theory used to interpret rates of consolidation in terms of permeability makes use of a series of assumptions which do not properly fit the actual behaviour of natural clays. As a result the

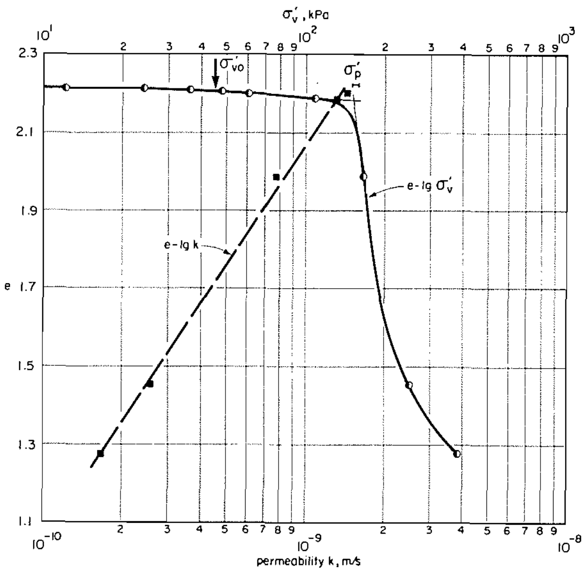

FIG. 11. The e vs. lg σ_v' and e vs. lg k relationships from a typical OEDK test on Louiseville clay.

indirect evaluation of k may be associated with significant errors.

4.2. k *from* c_v *measured in step-loaded oedometer tests*

The closed-form solution of Terzaghi's one-dimensional consolidation theory presumably applies very well to the consolidation process in an oedometer specimen during any load step. It is, however, important to recall that Terzaghi's theory and closed-form solution are based on the following assumptions: (1) strains are small and one dimensional; (2) the soil is saturated; (3) the soil grains and the pore fluid are incompressible; (4) the soil is homogeneous; (5) the soil's compressibility and permeability are constant during the consolidation process; (6) flow is one dimensional and according to Darcy's law; (7) there is a linear relationship between effective stresses and strains; (8) the soil presents no creep or secondary deformations.

The equation of one-dimensional consolidation developed on these bases is written

$$[3] \quad \frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2}$$

in which c_v is the coefficient of consolidation, assumed constant and equal to:

$$[4] \quad c_v = \frac{k(1+e)\sigma'}{0.434\gamma_w C_c} = \frac{kM}{\gamma_w}$$

with k = permeability, M = modulus of deformability, e = void ratio, and C_c = compression index of the clay. The solution of [3] is written in the form of $U = f(T)$ where the time factor $T = c_v t/H^2$, H being the length of the drainage path, and using assumption (7), the degree

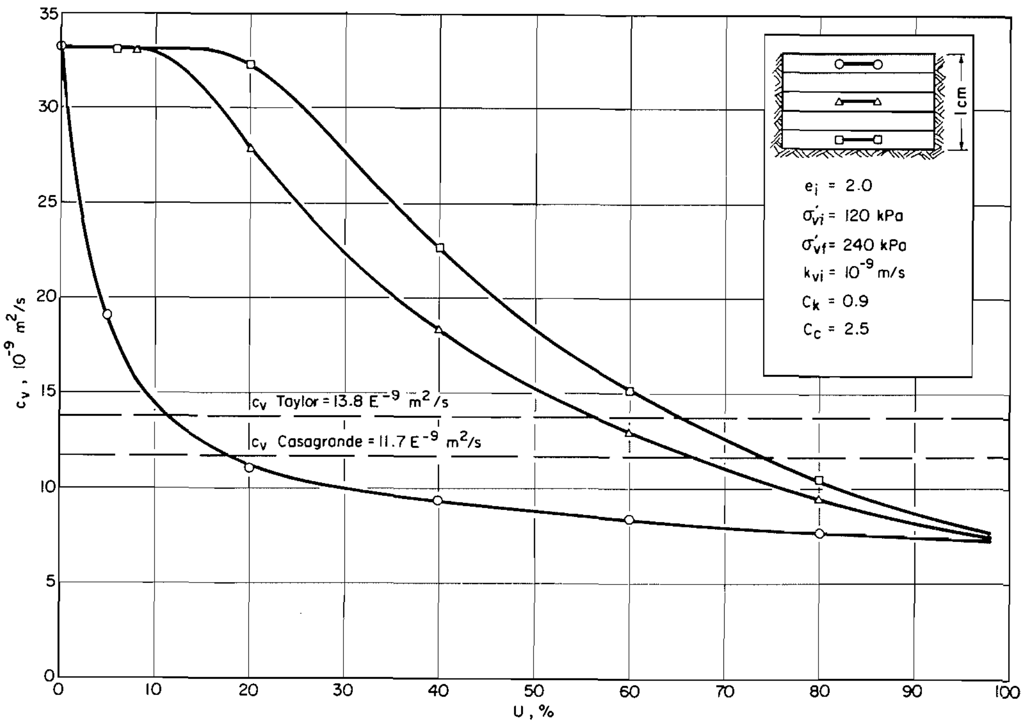

FIG. 12. Variations of c_v during consolidation in an oedometer specimen of Louiseville clay.

of consolidation U is considered equal to the ratio of the settlement at time t to the final settlement. Since the various assumptions are seldom, if ever, satisfied, empirical procedures need to be developed to interpret the time–settlement observations in terms of degree of consolidation, thus allowing the definition of T and consequently of c_v: the methods proposed by Casagrande and Fadum (1944) and Taylor (1948) serve this purpose and are routinely used. Once c_v has been measured the permeability k may be obtained from [4] if the other clay characteristics are known.

The problems associated with the application of Terzaghi's solution to natural clays have been pointed out by Tavenas *et al.* (1979). The most serious weakness lies in the assumption of constant k, M, and c_v during consolidation. Indeed, in their normally consolidated state, clays exhibit significant variations of their compressibility M, permeability k, and thus of their coefficient of consolidation c_v as the void ratio is reduced during consolidation. The CONMULT numerical solution of [3], which accounts for the variations of k and M during consolidation, was used to illustrate the deviations from Terzaghi's solution in a typical load step ($\sigma_v' > \sigma_p'$) on the Louiseville clay. As shown in Fig. 12, the coefficient of consolidation during this load step in the normally consolidated range is reduced from $33 \times 10^{-9}\ m^2/s$ at the beginning to $7.5 \times 10^{-9}\ m^2/s$ at the end of consolidation. The reduction in c_v is much faster near the drainage boundary than in the middle of the specimen so that a nonhomogeneous condition is created in the specimen. This results in a deformation of the pore pressure isochrones as well as in a modification of the settlement–time relationship. The values of c_v obtained from this modified settlement–time relationship by either Taylor's or Casagrande's method are intermediate to the actual maximum and minimum values of c_v as shown in Fig. 12; Taylor's c_v is higher since the method of interpretation is based mainly on the early part of the settlement–time relationship, when c_v is higher. The differences between the two interpretations of c_v would be even greater if the variation of C_c with σ_v' (cf. Fig. 11) had been taken into account. The "intermediate" values of c_v interpreted from test results are further difficult to transform into permeability values using [4] since it is difficult to properly define the corresponding values of the other variables M or σ' and e.

The use of Terzaghi's one-dimensional consolidation solution to interpret the results of step-loaded oedometer tests in terms of c_v and k thus appears highly questionable.

4.3. k *from CGT and CRS consolidation tests*

In its most general form the differential equation of one-dimensional consolidation may be written:

$$[5] \quad -\frac{k}{\gamma_w}\frac{\partial^2 u}{\partial z^2} = \frac{\partial \epsilon_v}{\partial t}$$

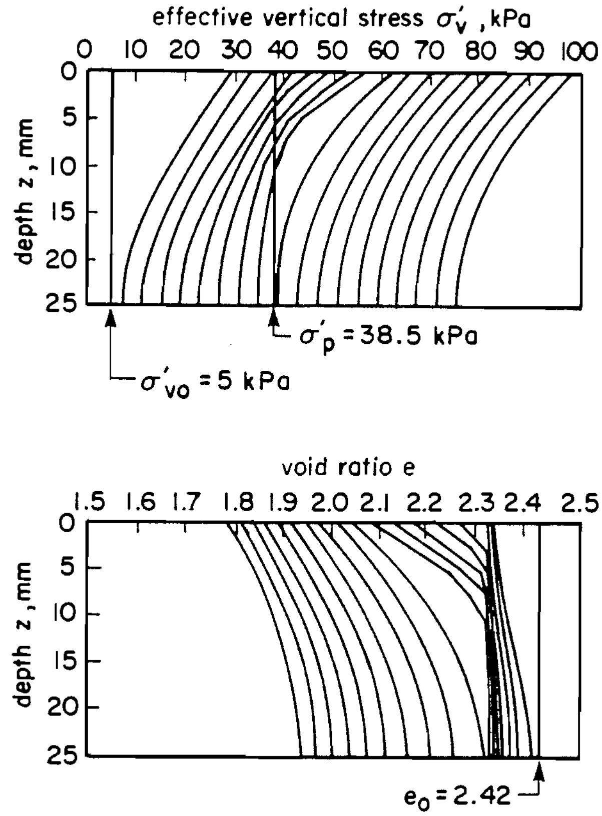

FIG. 13. Variation of σ_v' and e in an oedometer specimen during a constant gradient test (from Magnan and Deroy 1981).

or, assuming a linear relationship between the volumetric strain ϵ_v and the effective stress $\sigma' = \sigma - u$:

$$[6] \quad \frac{kM}{\gamma_w}\frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} - \frac{\partial \sigma}{\partial t}$$

In the controlled gradient test the pore pressure at the base of the specimen u_b is maintained constant. Assuming that k, M, as well as the shape of the pore pressure isochrone are all constant during the test, Lowe *et al.* (1969) have shown that [6], in which $(\partial u/\partial t) = 0$, leads to a parabolic pore pressure distribution with depth z in the specimen of height H:

$$[7] \quad u = -u_b\frac{z^2}{H^2} + \frac{2z}{H}u_b$$

The permeability of the clay may be directly obtained from [7] and the application of Darcy's law at the upper face of the specimen. At that location the flow of pore water is equal to the volumetric strain of the specimen and the velocity is thus:

$$v = \partial H/\partial t$$

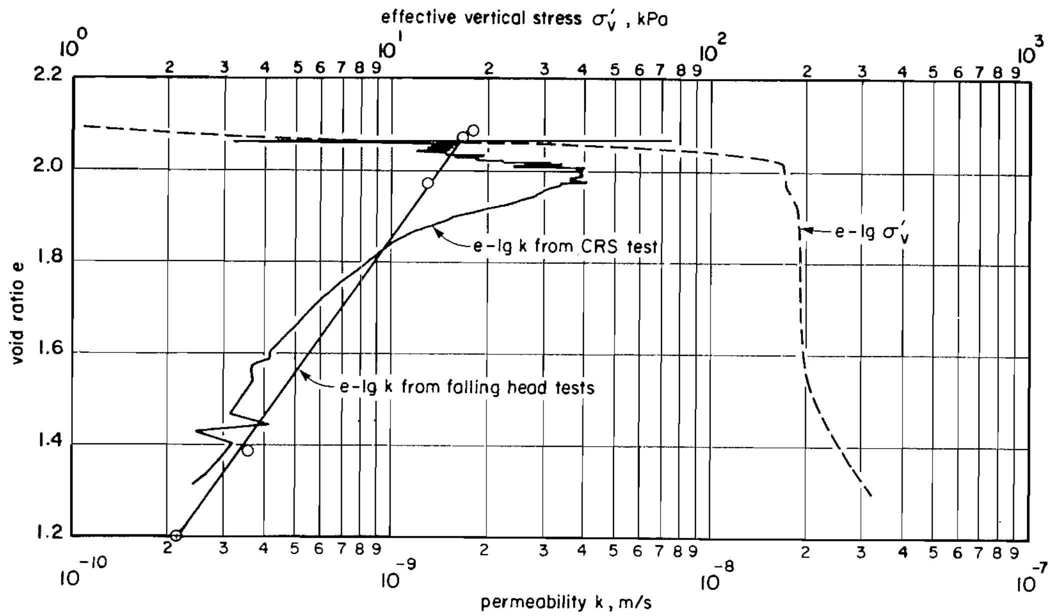

FIG. 14. The e vs. lg σ_v' and e vs. lg k relationships from a CRS test and from falling head tests on Louiseville clay.

The gradient is obtained by deriving [7] with respect to z at z = 0, leading to:

$$i = \frac{1}{\gamma_w}\frac{\partial u}{\partial z} = \frac{2u_b}{\gamma_w H}$$

Darcy's law then leads to:

$$[8] \quad k = \frac{\partial H}{\partial t}\frac{H\gamma_w}{2u_b}$$

Thus the observations of the variation of the specimen height with time produces the variables $\partial H/\partial t$ and H necessary to obtain k from [8] and the corresponding void ratio from $\Delta e = (1 + e_o)\,[(\Delta H)/H]$. The CGT would directly produce the e vs. k relationship as one of its results.

In the constant rate of strain test the mean rate of strain is constant. Smith and Wahls (1969) have resolved [5] assuming a constant permeability and a linear time – void ratio relationship. In the particular case, most commonly considered, where the void ratio is assumed constant with depth at any time, [5] leads to a pore pressure distribution and to an expression of k that are identical to those obtained for the CGT test, eqs. [7] and [8]. Since $\partial H/\partial t$ is imposed and constant, the pore pressure u_b in a CRS test may be used in [8] to obtain k as a function of H or rather the void ratio e.

As in the step-loaded consolidation test, the assumptions necessary to arrive at [7] in the CGT or CRS test are not properly representative of the behaviour of a natural clay and the quality of that equation and the ensuing evaluation of the void ratio – permeability relationship are questionable. Using the results obtained by Tavenas *et al.* (1979), Leroueil *et al.* (1980) have suggested that the change in compressibility of a natural clay, when it becomes normally consolidated during a CGT or CRS test, produces a deformation of the pore pressure isochrone and a significant increase of the exit gradient beyond the theoretical value of $i = (2u_b/\gamma_w H)$. Using an adapted version of CONMULT, Magnan and Deroy (1981) have illustrated the effect of changing compressibility at σ_p', resulting in increased exit gradients (Fig. 13). Thus, computing the permeability at that stage of the test on the basis of [8] would result in an overestimation of k. Figure 13 also shows that a strongly nonuniform void ratio distribution is created, the void ratio near the drainage boundary at the point where k is computed being much less than the average void ratio with which the computed k value is usually correlated. These two phenomena combine to produce an interpreted void ratio – permeability relationship that strongly differs from the actual one.

The detrimental effect of the questionable interpretation of CGT or CRS tests is best illustrated by the example in Fig. 14. The e vs. lg k relationship obtained from a CRS test on a specimen of Louiseville clay is quite at variance with the results of falling head tests for void ratios in the range of 1.8–2.1. The computed permeability supposedly increases from 1.5×10^{-9} to 4×10^{-9} m/s for effective vertical stresses increasing from σ_{vo}' to σ_p'; it then decreases rapidly to 0.8×10^{-9} m/s at a void ratio of 1.8 or for $\sigma_v' = \sigma_p' + 10$ kPa. For lesser void ratios the decrease of k is attenuated but the computed values are consistently less

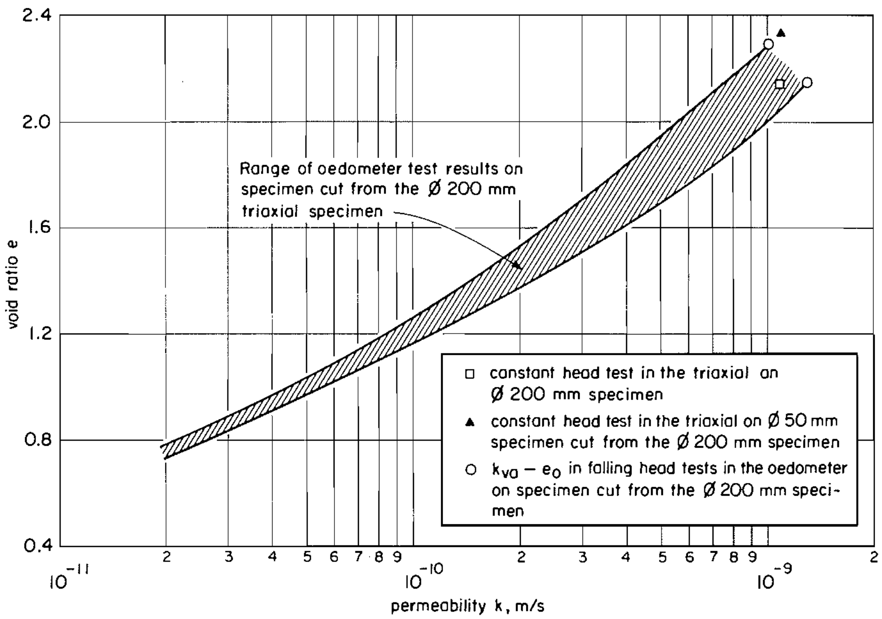

FIG. 15. The e vs. lg k relationships from oedometer and triaxial permeability tests on Batiscan clay.

than the results of direct measurement which correspond to a linear e vs. lg k relationship. The strong overestimation of k for void ratios in excess of 1.8 results from the wrong evaluation of k in the vicinity of σ_p'; the underestimation of the e vs. lg k relationship at small void ratios may be associated with the use of the mean void ratio instead of the void ratio at the upper boundary where k is measured. In any case, the permeability – void ratio relationship computed from the CRS test is nonrepresentative of the actual behaviour of the Louiseville clay due to the errors in the method of interpreting the test results.

The adverse effect of the method of interpretation on the computed e vs. lg k relationship is less in CGT than in CRS tests. This is due to the fact that, in CGT tests, a small value of u_b is usually imposed limiting the range of possible exit gradients and thus the error on k; in addition k is computed from an average strain rate which incorporates the effect of nonhomogeneous strain conditions created at σ_p'. On the contrary, in CRS tests, the pore pressure at the base u_b may be large, allowing large variation of the exit gradient at σ_p', and the permeability is computed from the local pore pressure u_b which is measured at the opposite end of the specimen and which is very sensitive to the peculiar behaviour developing near σ_p'.

5. Discussion

5.1. Direct measurements in the triaxial and the oedometer

The first important result of the present study was to confirm the validity of Darcy's law in natural clays submitted to gradients of 0.1–50. As a result the common falling head tests in the oedometer, using high gradients, are perfectly acceptable. Another consequence of practical interest is that high gradients may be used in any type of permeability tests in order to maximize the flow to measure and minimize the detrimental effects of leakage and consolidation/swelling of the specimen.

The problem of sample representativity or scale effects was investigated by means of constant head tests in the triaxial on ϕ 200 × 200 mm and ϕ 50 × 50 mm specimens and of falling head tests in the oedometer. Figure 15 presents a typical result for the Batiscan clay. The vertical permeability at the initial void ratio e_o in the various sizes of specimen varies between 1×10^{-9} m/s and 1.3×10^{-9} m/s, the value of k observed on the large triaxial specimen being in the middle of the range of values measured on the smaller oedometer specimen. Similar tests were carried out on natural clays from 13 different sites in Canada and elsewhere. Figure 16 presents the comparison between k_{vo} measured on large and small triaxial specimens and on oedometer specimens, all small specimens being cut from the large triaxial specimen. The agreement is generally good, with all data in the ranges of:

$$0.63k_{vo\,oed} < k_{vo\,\phi200} < 1.56k_{vo\,oed}$$
$$0.65k_{vo\,oed} < k_{vo\,\phi50} < 1.20k_{vo\,oed}$$

The difference in k_{vo} is representative of the small scale variability of natural clays. Following observations by

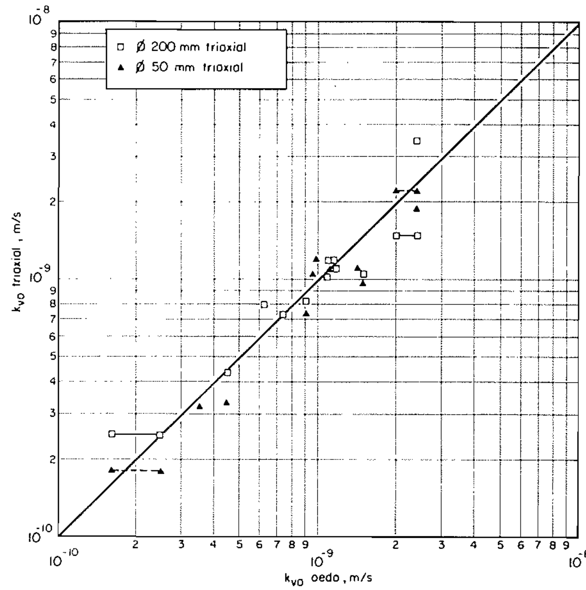

FIG. 16. Comparison of permeabilities measured in large triaxial and small oedometer tests.

Leroueil (1977), it has been a repeated experience that the void ratio of a reputedly homogeneous natural clay may vary by ±5–8% within a 200 mm diameter, 200 mm high specimen, this variation being at random. Then, the larger specimen in the triaxial would exhibit void ratio and permeability characteristics where these small scale variations have been averaged out, while they could affect the results of oedometer tests. From this point of view, it would appear preferable to perform permeability tests on large specimens in the triaxial. On the other hand the performance of several oedometer tests provides a range of void ratio – permeability data from which representative e vs. lg k relationship may be easily selected. In view of the greater simplicity of the oedometer test equipment and procedure, of the need for specimen of small, routine size, and of the reduced cost of this test as compared with the more sophisticated triaxial test on large specimens, it appears more practical and equally satisfactory to measure the permeability characteristics of natural clays by means of falling head tests in the oedometer.

5.2. *Quality of* k *evaluations from various methods*

From the preceding analyses it can be inferred that the indirect evaluation of k from consolidation tests should produce questionable results. In order to evaluate the magnitude of the possible errors on k, comparative permeability evaluations were made on a series of natural clays using the following methods of test or interpretation: direct measurement by falling head tests in the oedometer (OEDK), interpretations of c_v in step-loaded oedometer tests using Taylor's method (OEDc_vT) or Casagrande's method (OEDc_vC), and interpretation of constant rate of strain tests (CRS) and of controlled gradient tests (CGT). Figure 17 presents a typical comparison of the e vs. lg k relationships obtained from the various methods on the Louiseville clay.

The direct measurement in OEDK produces a linear e vs. lg k relationship and a magnitude of $k_{vo} \simeq 1.8 \times 10^{-9}$ m/s which was confirmed by repeated OEDK as

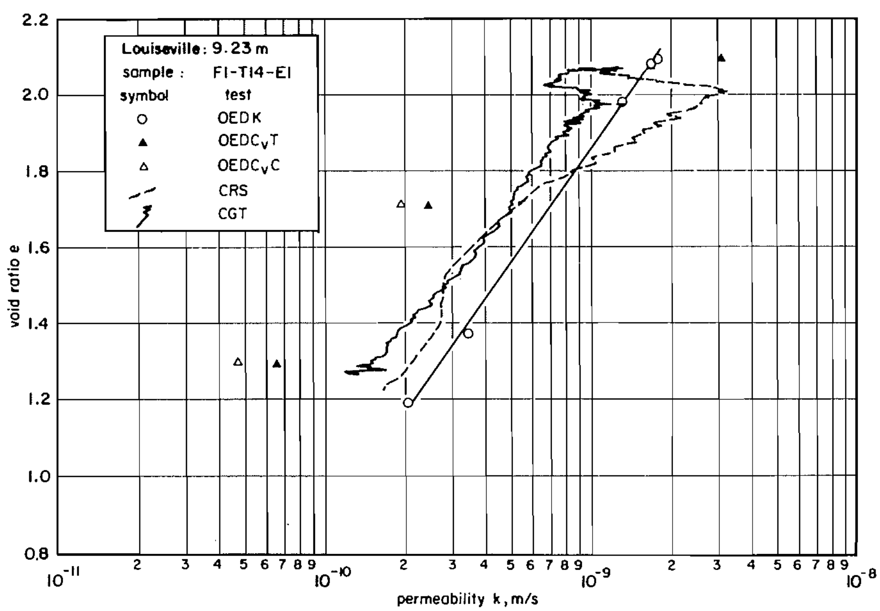

FIG. 17. Comparison of e vs. lg k relationships from OEDc_v, OEDK, CRS, and CGT tests on Louiseville clay.

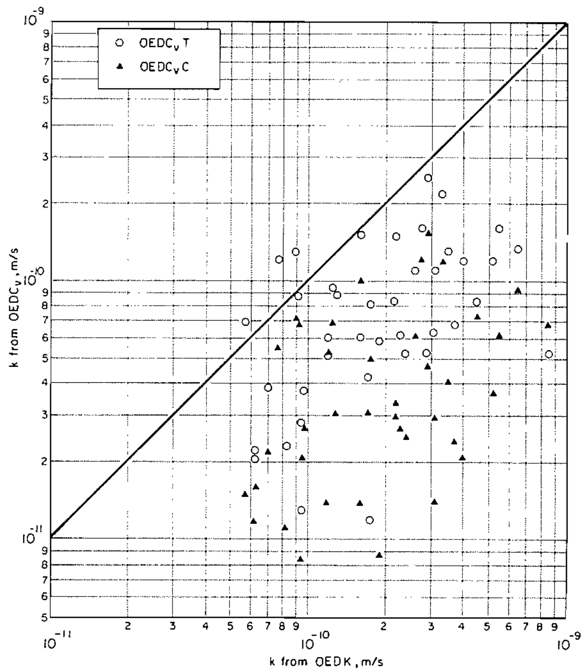

FIG. 18. Comparison of permeabilities measured in OEDK and computed from OEDc_v on Champlain clay specimens.

well as large scale triaxial tests. This e vs. lg k relationship may be used as a reference. As already noted (Fig. 14) the e vs. lg k relationship interpreted from CRS tests is strongly at variance with this reference, k being overestimated by a factor of 2 at σ_p', and underestimated by 20–40% at reduced void ratios. The CGT test also produces a different e vs. lg k relationship, the irregularities of which are less marked than in the CRS test; k seems to be systematically underestimated, as a result of the abusive use of a mean void ratio instead of the proper void ratio at the upper drainage boundary of the specimen. In a recent comparative study of 30 tests on Champlain clays, Samson *et al.* (1981) have observed similar deviations and they report a ratio of the measured permeability to that computed from CRS and CGT varying from 1.20 to 1.65. Finally the interpretation of c_v measurements in consolidation stages of step-loaded oedometric tests leads to strongly erroneous values of k as compared with the results of OEDK performed on the same specimen as part of the same test. This is further evidenced in Fig. 18 which shows comparisons of k from falling head tests in the oedometer with k computed from c_v determined using Taylor's or Casagrande's method in the same oedometer test. In all but three cases k from OEDc_v is underestimated; Taylor's method gives k values which are closer to the actual permeability than those obtained from Casagrande's method; finally the scatter is so large as to preclude the development of empirical corrections.

In view of these results and of similar observations on the wide variety of clays tested in Part II of this research, the indirect methods of evaluating k from consolidation tests must be disqualified as a means of defining the permeability characteristics of natural clays.

6. Conclusion

The investigation on the equipment and methods of measuring the permeability characteristics of natural clays presented in this paper has led to the following conclusions.

(1) Darcy's law is valid in natural soft clays for gradients ranging from 0.1 to 50. It is probably also valid at very small gradients but the verification is made impossible by the development of primary and secondary volume changes in the clay specimens and other sources of error during the permeability test.

(2) Reliable methods and equipment have been developed to measure k on intact specimens. Constant head tests in the triaxial require the use of "leak-free" equipment and the measurement of both in and outflow to account for the unavoidable volume changes of the specimen during the test. The advantage of the triaxial test is to permit testing of large specimens, up to 200 mm in diameter, 200 mm high in the present study, thus reducing the problem of sample representativity. Falling head tests in the oedometer are equally reliable and much simpler and faster to perform. The use of high gradients minimizes the errors due to leakage and volume changes of the specimen. In addition, the complete permeability – void ratio relationship may be defined within a practical time frame.

(3) The indirect methods of evaluating k or e vs. k relationships from consolidation tests of all kinds should be disqualified due to the important errors produced by the abusive assumptions in the methods of interpreting the test results on the basis of Terzaghi's consolidation theory.

(4) The falling head test in the oedometer appears as the best practical method of determining the permeability characteristics of natural clays.

7. Acknowledgements

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