TECHNICAL NOTE

Effects of consolidation on permeability measurements for soft clay

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Recent sensitivity studies of the soil consolidation process (Pane, 1981), based on the governing equation for non-linear finite strain consolidation (Gibson, England & Hussey, 1967), show that a relatively small change in permeability results in an inordinately large change in the progress of consolidation and that the magnitude of this effect increases with the thickness of a soil deposit. This phenomenon is known in practice, and was previously analysed for non-homogeneous clay layers with a theory restricted to infinitesimal strains, and without consideration of the self-weight of the deposit (Schiffman & Gibson, 1964).

These studies confirm and re-emphasize the critical role that permeability plays in the consolidation process. Although this role has long been recognized, current technology and practice for obtaining and applying information on the permeability of soil deposits is in a primitive state. For example, Darcy's law, which is the generally accepted basis for analysing fluid transport through soil, and also the experimental methods commonly used to obtain permeability measurements using Darcy's law have been challenged extensively. Olsen (1966) stated that 'the evidence as a whole suggests that Darcy's law is obeyed in many natural sediments, but that exceptions may occur in very fine-grained clays, specifically montmorillonite, and also in shallow, unconfined clays or in granular soils containing small amounts of clay'. Mitchell & Younger (1967) noted that 'Since deviations from Darcy's law are most severe at low gradients and gradients in the field seldom are much greater than unity, whereas the gradients used in laboratory permeability tests and developed during consolidation tests are usually very large (one hundred or more), the applicability of laboratory test results for analysis of field behavior is subject to scrutiny'.

This Note presents evidence that very small gradients are required to obtain valid permeability measurements in soft clays. For higher gradients, similar to those commonly used in conventional constant head and falling head methods, substantial errors are introduced by seepage consolidation. This causes apparent deviations from Darcy's law. Also, void ratio variations in test specimens occur which preclude valid interpretations of experimental data in terms of the constitutive relations needed to analyse the consolidation process in practice.

PERMEABILITY TESTING

Direct approaches to permeability testing are commonly referred to as constant head, falling head and flow pump methods (Olsen & Daniel, 1981). In the constant head method, an externally controlled pressured difference is applied to a specimen and the seepage induced thereby is measured as a function of time. The falling head, or transient method, involves the use of a device in which the fluid volume varies with the fluid pressure. A permeability test is accomplished by charging this device with an increment or decrement of fluid volume, and associated pressure, and monitoring the increase or decrease in pressure as the fluid moves to or from the device through the specimen. The flow rate is obtained from a calibration of the compliance of the device together with the measured decay in the fluid pressure difference across the specimen with time. In the flow pump method, the flow rate entering or leaving the specimen is externally controlled and the pressure difference induced across the specimen is measured with a differential pressure transducer.

All these methods induce seepage through a specimen that tends to consolidate the specimen. One consequence of seepage-induced consolidation is that the flow rates entering and exiting a specimen are not equal. The outflow exceeds the inflow by the amount the specimen pore volume is reduced by consolidation. Consolidation also changes the void ratio of a specimen by an amount that varies non-linearly with distance between the inflow and outflow surfaces of the specimen. Moreover, the non-linear variation of void ratio results in a corresponding non-linear variation in

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the excess pore-water pressure across the specimen.

Experimentally these consequences of seepage-induced consolidation can be monitored only partially. Inflow and outflow rates for a specimen can be separately measured or controlled externally, or their difference can be defined by measuring the time rate of volume change of the specimen. The latter further enables the determination of the average void ratio of a specimen at any time during a test. Also the excess pore-water pressure difference across a specimen and the associated average hydraulic gradient can be measured or controlled. However, the distributions of void ratio and excess pore-water pressure within a specimen and their variations during seepage-induced consolidation cannot be measured with existing consolidation/permeability equipment.

RESULTS

The data presented here were obtained with experiments designed to show the consequences of seepage-induced consolidation on conventional permeability measurements in terms of the variation of apparent permeability values with the average hydraulic gradient i_{av}. Data for low average gradients ($i_{av} < 5$) were obtained with the flow pump method proposed by Olsen (1966). Data for higher average gradients ($10 < i_{av} < 80$) were obtained with the standard falling head method. Data for both low and high gradients were obtained on kaolinite specimens of average void ratios ranging from nearly 3·6 to 1·0.

The permeameter is shown in Fig. 1. For both the flow pump and the falling head components the controlled or measured flow rate is the outflow from the specimen. In the case of the falling head component this arrangement differs from that customarily used, i.e. fluid is withdrawn from the soil.

The material tested was a commercially available kaolinite with specific gravity 2·66, plastic limit 31·9% and liquid limit 53·6%.

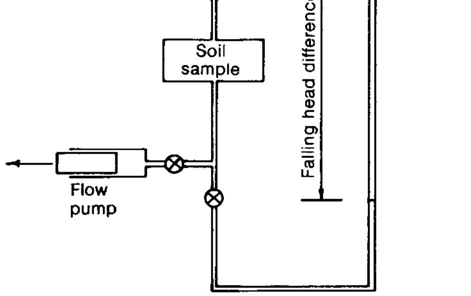

Fig. 1. Permeability apparatus

The specimens were prepared in the laboratory by mixing dry powder with deaired, distilled water at a water content of 2½ times the liquid limit. The specimens were poured into an Anteus model A-1 consolidometer and subjected to a back pressure of 40 lb/in^2. Step-loading consolidation tests were performed with permeability measurements made at the end of each load increment.

Figure 2 shows the variation of inflow and outflow rates with the average hydraulic gradient for the specimen tested with the flow pump at an average void ratio of 2·66. The outflow rate q_{out} is that generated by the flow pump. The inflow rate q_{in} is the difference between the outflow rate and the rate of volume reduction of the specimen, i.e.

$$q_{in} = q_{out} + dh/dt \tag{1}$$

where h is the thickness of the specimen. The average hydraulic gradient is the induced pressure difference across the specimen divided by its thickness. During this experiment, seepage reduced the average void ratio by less than 1%. Although the change in the distribution of void ratio was not measured, existing consolidation theory shows that this change in void ratio is concentrated at the outflow surface of the specimen. Furthermore, because flow through porous media varies as the

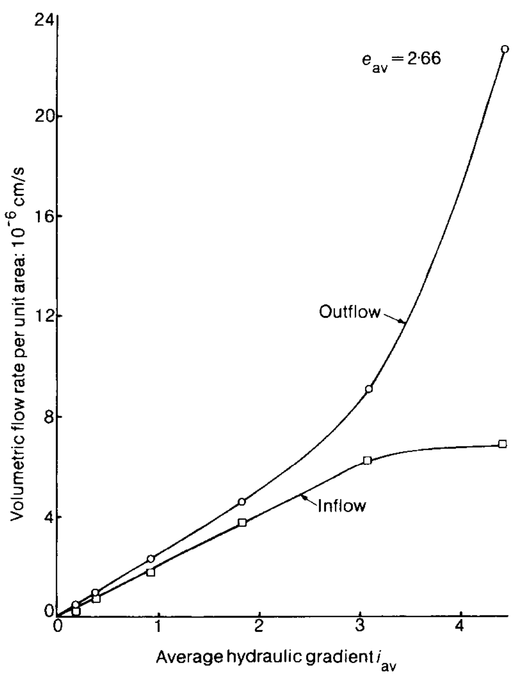

Fig. 2. Flow rate–hydraulic gradient relationships for flow pump method

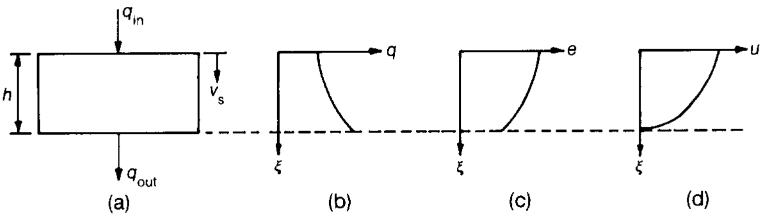

Fig. 3. Effects of seepage-induced consolidation

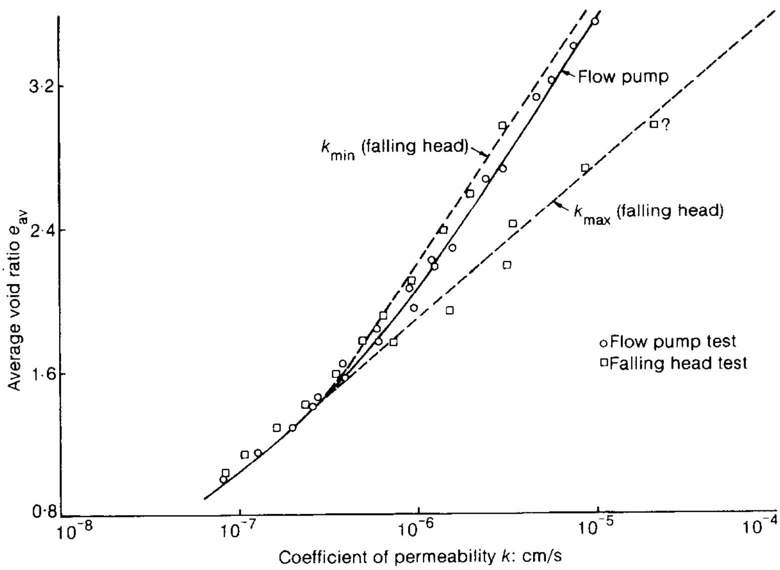

Fig. 4. Void ratio–permeability relationships

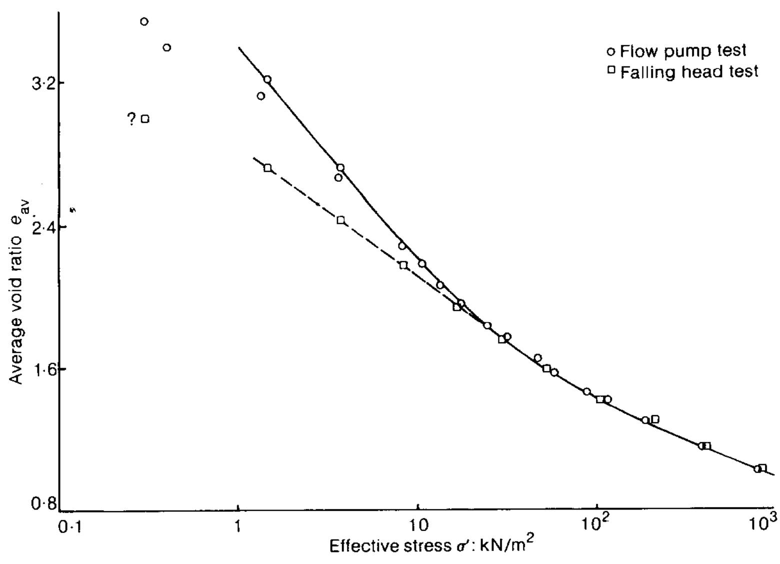

Fig. 5. Void ratio–effective stress relationships

fourth power of pore radii, the flow rate and excess pore pressure distribution are governed in large measure by the minimum void ratio of the specimen.

This is illustrated in Fig. 3, which shows that seepage-induced consolidation causes a non-uniform flow rate q, a non-uniform void ratio e and a non-linear variation of excess pore-water pressure u within the sample. Darcy's law states that

$$q = \frac{k}{\gamma_w}\frac{\partial u}{\partial \xi} = ki \qquad (2)$$

where k is the coefficient of permeability, γ_w is the unit weight of the pore fluid and ξ is the convective, Eulerian co-ordinate used in finite strain consolidation theory. This is a point function relationship. In common practice this relationship is applied to specimens of finite thickness. For this to be accurate, three conditions must be satisfied: the flow rate q must be constant throughout the sample, the void ratio e must be constant with sample thickness and the excess pore-water pressure gradient must be constant through the specimen. As shown in Figs 2 and 3(b)–(d), these conditions are violated by seepage-induced consolidation. This results in substantial uncertainties in permeability measurements which are compounded by high average hydraulic gradients in the flow pump test and in general in constant and falling head tests.

These uncertainties can be minimized by permeability tests made at the lowest possible gradient. The lower the gradient, the less the disturbance to the sample and the smaller the variations of the flow velocities and the void ratios. In the limit, these quantities approach their average values. This is shown in Fig. 2, where the inflow and outflow curves converge and become linear at average hydraulic gradients less than two.

The effects of using high gradients in conducting direct permeability measurements are shown in Figs 4 and 5 where results of falling head and flow pump tests on the kaolinite are plotted. The flow pump test results were obtained by using a slow flow rate such that gradients with magnitudes of less than 0·5 were measured. The falling head permeability test used gradients of 10–80. In Fig. 4 where the calculated, apparent permeability is plotted against the average void ratio, it is seen that the wide range of permeability values obtained by the falling head test can be attributed to the amount of water squeezed out of the sample by consolidation under the seepage gradient. The higher permeability values were obtained at the beginning of each falling head test when the higher prevalent gradients produced greater consolidation flow. Towards the end of each falling head test, a lower gradient (approximately 10) still existed, which might have been sufficient to allow consolidation to continue. The minimum permeability values in Fig. 4 are smaller than the values obtained by the flow pump test, even though the latter values were obtained at the lower gradients. This apparent discrepancy is explained by the fact that the falling head data contain the effect of consolidation under the high gradients used in the current and previous load steps. Also, there is a non-uniform void ratio distribution in the sample subjected to high seepage gradients. This makes it difficult to calculate a representative void ratio. The void ratios shown in Figs 4 and 5 were calculated on the assumption of a uniform distribution, whereas the distribution shown in Fig. 3(c) may be more realistic. If these causes could be accounted for properly, it might be reasonable to expect to find all the falling head permeability values to be higher than those determined by the flow pump. As shown in Fig. 2, the permeability, calculated for gradients of less than about two, appears to be almost free of gradient-induced consolidation, and is therefore the lowest value obtainable.

The range of permeability values obtained from the falling head test narrows as the sample consolidates under higher load increments and converges to the value obtained by the flow pump technique at void ratios of less than 1·4. It is surmised that at these void ratios, where the sample is no longer soft, the seepage-induced consolidation flow becomes insignificant.

The compressibility properties are plotted in Fig. 5 and correspond to the permeability values in Fig. 4. The deviation between the values obtained from the two techniques again arises because of the consolidation induced under previous seepage gradients and because of the uncertainties involved in calculating the appropriate void ratios. Also it is recognized that after a falling head test with a high gradient, portions of the sample have become overconsolidated.

PRACTICAL SIGNIFICANCE

The practical significance of the data is shown in the following example. A soft clay is assumed to be rapidly deposited on an impervious base to a height of 30 m at a uniform void ratio of 3·0. The deposit consolidates under its own weight until equilibrium is reached. At that time a surcharge of 100 kN/m^2 is added. Time–settlement curves for this case are given in Fig. 6. The constitutive data used in the analysis are shown as curves in Figs 4 and 5. The void ratio–effective stress data are those which were developed by the oedometer test in which flow pump permeability measurements were performed. The void ratio–permeability data are

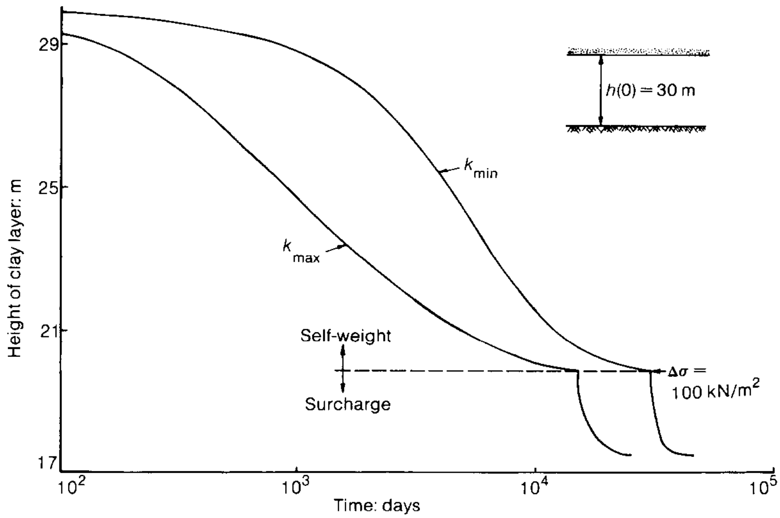

Fig. 6. Effect of permeability on the progress of consolidation using finite strain theory

taken as the extremes of the falling head measurements shown in Fig. 4. The largest permeability variation (at $e = 3{\cdot}0$) is a factor of 5·7. The time–settlement computations were performed on the basis of finite strain consolidation theory (Gibson *et al.*, 1967; Pane, 1981), which considers the non-linearity of the void ratio–effective stress and void ratio–permeability relationships in terms of laboratory derived curves and does not assume any functional form for these relationships.

Even though the maximum and minimum permeabilities converge as the void ratio decreases, with consolidation the times to final (99%) consolidation differ by a factor of two. Half-way through the self-weight phase the times of consolidation differ by a factor of 4·6. Clearly, during self-weight consolidation the permeability at the upper surface of the consolidating layer dominates the process.

CONCLUSIONS

Very small hydraulic gradients must be used in laboratory permeability tests to minimize errors arising from seepage-induced consolidation. These errors will be carried forward to practice in significant ways. The gradients must be such that the seepage-induced effective stresses are substantially less than the maximum past effective stress. In cases of normally consolidated soils, there will always be induced errors: the softer the clay, the greater the errors. These errors seem to be compounded by conventional constant and falling head permeability tests, because of the high gradients involved, and can be readily minimized by the flow pump method. In addition, this test can be performed in substantially less time than either a constant or a falling head test. In using conventional tests one is faced with a paradox. The use of high gradients reduces the time of testing but introduces substantial errors in the test results. However, the use of low gradients extends the testing time to unacceptable limits. The flow pump test solves both these problems.

If the clay is very soft and normally consolidated, even the lowest gradients can cause significant seepage consolidation. It may well be that indirect measurements, using inversion techniques, will be required for these cases (Znidarcic, 1982).

The laboratory data presented are based on gross changes in sample thickness and thus average void ratios. For a complete analysis consideration of the time-dependent void ratio distribution within the sample during the test is required.

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