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Low gradient permeability measurements in a triaxial system

H. W. OLSEN,* R. W. NICHOLS* and T. L. RICE*

Permeability measurements were conducted with the flow-pump method on sand, sandy silt and silty clay specimens in a conventional triaxial system by introducing and withdrawing water at known constant flow rates into the base of a specimen with a flow-pump, and by monitoring the head difference induced across the length of the specimen with a sensitive differential pressure transducer. The results show that the previously reported advantages of the flow-pump method, compared with conventional constant head and falling head methods, were realized for permeability measurements in conventional triaxial equipment. These advantages are that direct flow rate measurements are avoided together with the associated errors that arise from the effects of contaminants on capillary menisci and the long periods of time involved in flow rate measurements; permeability measurements can be obtained much more rapidly and at substantially smaller gradients; errors from the small intercept in the otherwise linear flow rate versus hydraulic gradient relationship, and also from seepage-induced permeability changes, can easily be recognized and avoided or minimized. The results further show that the initial transient response of a specimen that precedes the steady state condition needed for a permeability measurement can require a substantial period of time. In this study the response times varied from a fraction of a minute for a sand specimen to more than 200 minutes for a silty clay specimen. Errors in permeability measurements from this transient response can easily be avoided with the flow-pump method but not with constant head and falling head methods.

Des mesures de perméabilité ont été effectuées par la méthode de la pompe à écoulement sur des échantillons de sable, de limon sableux et d'argile sableuse dans un système conventionnel triaxial par introduction et soutirage de débits constants prédéterminés dans la base de l'échantillon à l'aide d'une pompe à écoulement en mesurant la différence de charge induite le long de l'échantillon à l'aide d'un capteur sensible de pression différentielle. Les résultats obtenues confirment les avantages connus de la méthode de la pompe à écoulement par rapport aux méthodes conventionnelles de la charge constante et de la charge variable pour les mesures de perméabilité avec les systèmes triaxiaux conventionnels. Ces avantages sont les suivants: on évite des mesures directes de débit aussi bien que les erreurs associées qui sont le résultat des effets des polluants sur les ménisques capillaires et on diminue le temps indispensable aux mesures de débit; on peut obtenir des mesures de perméabilité beaucoup plus vite et pour des gradients beaucoup plus faibles. Il est possible de déceler et par conséquent d'éviter ou de minimiser facilement des erreurs causées par le petit intercept dans la relation débit–gradient hydraulique non linéaire et aussi par des changements de perméabilité dus à la percolation. Les résultats montrent aussi que la réponse initiale transitoire d'un échantillon qui précède l'état stationnaire nécessaire pour une mesure de perméabilité peut exiger une période de temps considérable. Dans cette étude les temps de réponse ont varié depuis une fraction de minute dans le cas d'un échantillon de sable jusqu'à plus de 200 minutes dans le cas d'un échantillon d'argile sableuse. Avec la méthode de la pompe à écoulement il est possible d'éviter dans les mesures de perméabilité des erreurs causées par cette réponse transitoire, mais pas avec les méthodes de charge constante ou de charge variable.

NOTATION

- A cross-sectional area of the specimen
- k permeability
- k_{app} apparent permeability
- L length of the specimen
- Q volumetric flow rate generated by the flow-pump
- t time
- u pore pressure in the specimen in excess of atmospheric pressure
- Δh_i head difference across the specimen length induced by an externally controlled constant flow rate
- Δh_t total head difference across the specimen length
- Δh_0 head difference across the specimen length for the zero-flow condition
- σ_c' effective consolidation stress in the specimen

INTRODUCTION

Difficulties with conventional constant head and falling head methods for measuring the permeability of fine-grained soils have long been recognized. The use of high gradients can cause sub-

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* US Geological Survey, Denver.

stantial errors from seepage-induced changes in the permeability of a test specimen. These permeability changes vary with the magnitude of the applied gradient and thereby cause deviations from Darcy's law. Such deviations have been attributed to seepage-induced consolidation and to the migration of particles within a specimen that are not directly involved in its load-carrying fabric (Mitchell & Younger, 1967; Gairon & Swartzendruber, 1975; Pane, Croce, Znidarcic, Ko, Olsen & Schiffman, 1983).

In contrast, the use of low gradients with conventional methods is impractical and unreliable. The time required to measure very low flow rates is often excessive (Remy, 1973; Olson & Daniel, 1981). Moreover, the control of low gradients and the measurement of very low flow rates are limited by experimental errors arising from contaminant effects on capillary menisci involved in flow rate measurements, and also by the expansion and contraction of equipment components in response to temperature variations in the testing environment (Olsen, 1965, 1966). In addition, errors associated with long testing times can arise from bacterial growth and from fabric changes brought about by changes in pore solution chemistry during permeation (Gupta & Swartzendruber, 1962; Hardcastle & Mitchell, 1974).

Approaches for minimizing and avoiding these difficulties with conventional methods were developed in research studies about two decades ago. The falling head method was improved with applications of differential and compliant transducers (Bianchi & Haskell, 1963; Overman, Peverly & Miller, 1968; Nightengale & Bianchi, 1970; Remy, 1973). In addition, the flow-pump method was introduced with the use of a multispeed flow-pump to maintain a constant flow rate of water entering or leaving a rigidly confined specimen while the head difference induced thereby was measured with a sensitive differential pressure transducer (Olsen, 1966, 1969, 1972).

These approaches share two advantages over conventional methods. First, they avoid direct flow rate measurements and the experimental errors associated therewith. Second, they enable permeability measurements to be conducted much more rapidly and at substantially smaller gradients. The second advantage arises because long time periods and/or high gradients are not needed to produce measureable flow rates, and also because transducers allow pressures to be measured with a high degree of resolution and accuracy.

In addition, the flow-pump method has three unique capabilities that facilitate recognition and avoidance or minimization of phenomena that cause errors in permeability measurements.

(*a*) The head difference across a specimen can be measured at the zero-flow condition, i.e. when the flow across one boundary of a specimen is prevented. Furthermore, the zero-flow condition can be used as a reference for measuring head differences induced by externally imposed flow rates.
(*b*) The head difference induced by an externally imposed constant flow rate can be monitored and recorded continuously with time in terms of the electrical output of the differential pressure transducer.
(*c*) A sequence of permeability measurements can be conducted on a specimen with successively increasing flow rates in a reasonable period of time.

The significance of the zero-flow condition became apparent in the first studies conducted with the flow-pump method on a rigidly confined specimen of kaolinite (Olsen, 1969). A small head difference was found at the zero-flow condition. Moreover, this head difference was found to be an intercept in the otherwise linear flow rate versus hydraulic gradient relationship, similar to that shown in Fig. 3 (see later) for data obtained in this study. With constant head and falling head methods, the intercept is obscure because the head difference for the zero-flow condition is not measured. However, the existence of the intercept appears to be corroborated in studies, based on constant head measurements, wherein measureable flows were observed under zero gradients (Hansbo, 1960; Miller & Low, 1963; Gairon & Swartzendruber, 1975).

Although the cause of the intercept has not been established, its existence is consistent with irreversible thermodynamic relationships for steady state liquid transport through soil that take into account not only the component of flow caused by a hydraulic gradient but also the osmotic components of flow caused by electrical, chemical and thermal gradients (Mitchell, 1976). Moreover, existing data show that the intercept in the flow rate versus hydraulic gradient relationship can arise from osmotic flows because the magnitude of the intercept was varied by superimposing electrical and chemical gradients on a kaolinite specimen during hydraulic permeability measurements (Olsen, 1969). In that study it was suggested that the intercept which occurs in the absence of externally imposed electrical and chemical gradients could arise from a source of such gradients within a specimen. Conceivable sources of such gradients include variations in the composition and density of the materials and chemical reactions among the constituents.

The second unique capability of the flow-pump method, i.e. for continuous monitoring of the head difference imposed by an externally imposed flow rate, enables the process of steady state hydraulic flow through a specimen to be distinguished from the initial transient response of the specimen. This Paper includes data on the initial transient response of sand, sandy silt and silty clay specimens.

The third unique capability of the flow-pump method, i.e. the conduct of a sequence of permeability measurements at successively increasing flow rates in a reasonable period of time, provides a convenient approach for defining deviations from Darcy's law that reflect errors from seepage-induced changes in the permeability of a test specimen. For this the constant head method is restricted by difficulties in direct flow rate measurements, and falling head methods are not appropriate because the imposed seepage force decreases with time during a permeability measurement.

The third capability of the flow-pump method was recently exploited by Pane *et al.* (1983) in a study of the permeability of soft kaolinite in a conventional oedometer wherein the specimen was free to consolidate in response to the seepage force imposed to conduct a permeability measurement. Deviations from Darcy's law, determined from flow-pump permeability measurements, provided a basis for showing that substantial errors can arise in conventional permeability measurements from seepage-induced consolidation, and also that the lowest possible gradients must be used to minimize this error in permeability measurements on soft clays.

This investigation examines the capability of the flow-pump method for permeability measurements in conventional triaxial equipment wherein a specimen is free to deform both axially and radially in response to the seepage force imposed to conduct a permeability measurement.

EQUIPMENT AND PROCEDURES

Figure 1 presents a scheme of the experimental equipment wherein a flow-pump and a differential pressure transducer were connected to a conventional triaxial system. The flow-pump consists of an actuator A whose piston is controlled by a variable speed drive (not shown). The actuators used in this study were Hamilton gas-tight syringes which have precision-bore glass barrels and pistons with Teflon seals. The

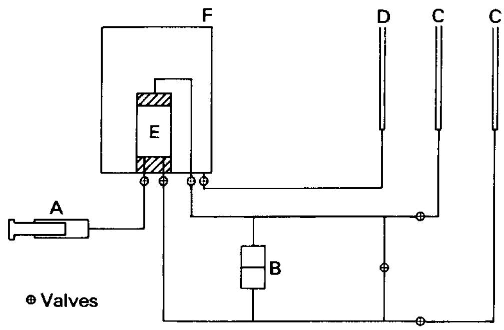

Fig. 1. Scheme of the experimental equipment

variable speed drive was a Harvard Apparatus model 906 infusion–withdrawal pump. This pump controls the piston by means of a worm gear driven by a variable speed direct current motor through a transmission box with 12 combinations of gears between the worm gear and the motor. A controller on the direct current motor allows the worm gear rotation to be controlled at speeds intermediate between those determined by the gear selector. These features enable the piston to be advanced or withdrawn at any constant rate ranging from about 10^{-1} to less than 10^{-5} cm/s. The syringes used in this study had capacities ranging from 20 cm^3 to 0·5 cm^3. Accordingly, the flow-pump could produce flow rates ranging from about 10^{-1} cm^3/s to 10^{-6} cm^3/s.

The differential pressure transducer B was a Validyne variable reluctance model P300D operated with a Validyne power and signal conditioning unit, model MC1. The output of the transducer was monitored with a digital voltmeter and also with a Soiltec model 210 strip-chart recorder. With this system differential pressures could be monitored over arbitrary ranges from a maximum range of $\pm 34{\cdot}5$ kN/m^2 (± 352 cm H_2O) to a minimum range of $\pm 0{\cdot}981$ kN/m^2 (± 10 cm H_2O) with a resolution of about 0·1 cm H_2O.

Whitey ball valves, Swagelok fittings with Nylon ferrules and metal tubing were used to minimize the compliance of those parts of the system involved in permeability measurements. The triaxial cell pressure and the specimen pore pressure were controlled pneumatically through the permeant (C) and cell fluid (D) standpipes (Fig. 1).

Conventional procedures were used to prepare each specimen E 3·56 cm in diameter and 7·62 cm long and to mount it in a triaxial cell D jacketed by a cylindrical membrane sealed with O rings to the base pedestal and the top cap. Each specimen was mounted between porous discs 0·635 cm thick having a permeability of about 10^{-4} cm/s. Air bubbles were removed by repeatedly flushing the permeant lines with de-aerated water and initially backpressuring the specimen to 621 kN/m^2.

The differential pressure transducer was used to ensure that the assembled system was free of leaks and air. The plumbing allowed one side of the transducer to be open to externally controlled pressure through one of the permeant standpipes C while the other side of the transducer was open to all the permeant lines leading to the base pedestal, top cap and flow-pump. Therewith, leaks could be recognized in terms of a variation in differential pressure with time. Finally, the presence of undissolved air in the permeant lines and the specimen was checked by compressing the permeant with the flow pump and monitoring the associated rate at which pressure increased while the permeant system was isolated from the standpipes.

EXPERIMENTS AND RESULTS

The experimental equipment described was used for permeability measurements on three specimens having a wide range of permeabilities. One specimen consisted of 20–30 mesh Ottawa sand mounted between porous discs having a permeability of about 10^{-4} cm/s. This permeability is low compared with that of Ottawa sand; therefore, the data obtained do not represent the permeability of Ottawa sand, but rather the permeability of the composite porous disc–Ottawa sand system. Because the permeability of this system is in the range of that for sand, the porous disc–Ottawa sand system tested is hereinafter referred to as the sand specimen. The other specimens consisted of sandy silt and silty clay whose characteristics are shown in Table 1. They were trimmed from NX rotary cores taken from a confining bed at a depth of about 100 m in an aquifer system near Provo, Utah. The cores were provided by and tested for the US Geological Survey, Water Resources Division.

Table 1. Selected characteristics of the sandy silt and silty clay specimens

	Specimen	
	Sandy silt	Silty clay
Sand (4·76–0·075 mm)	30%	23%
Silt (0·075–0·005 mm)	56%	50%
Clay (<0·005 mm)	14%	27%
Specific gravity	2·70	2·69
Plastic limit	Non-plastic	19%
Liquid limit	Non-plastic	32%
Plasticity index	Non-plastic	13%
Natural water content	17%	24%

Table 2. Test conditions and scope of permeability data

Specimen and test	Stresses for each loading and rebound step: kN/m^2		Scope of permeability data
	σ_c'	u	
Sand			
S1	69	345	$\Delta h_i \sim f(t, Q)$
Sandy silt			
A1	345	1034	$\Delta h_i \sim f(t, Q)$
A2	689	689	$\Delta h_i \sim f(t, Q)$
Silty clay			
B1	69	1309	$\Delta h_i \sim f(t)$
B2	138	1240	$\Delta h_i \sim f(t)$
B3	276	1102	$\Delta h_i \sim f(t)$
B4	551	816	$\Delta h_i \sim f(t)$
B5	1102	276	$\Delta h_i \sim f(t)$
B6	276	1102	$\Delta h_i \sim f(t)$
B7	69	1309	$\Delta h_i \sim f(t, Q)$

The test conditions and scope of the permeability measurements on each specimen were as follows (Table 2). The sand specimen was tested after one loading step where the effective chamber stress σ_c' was 69 kN/m^2 while the pore pressure in excess of atmospheric pressure, u, was maintained at 345 kN/m^2. Under these conditions the scope of permeability data obtained included measurements of the time response of the head difference Δh_i induced across the length of the specimen by each of several externally controlled constant flow rates Q applied to the specimen. For the sandy silt specimen, the same scope of permeability data was obtained after each of two loading steps designated by tests A1 and A2. For the silty clay specimen, permeability data were obtained after each of seven loading and rebound steps designated as tests B1–B7. For test B7, the scope of permeability data obtained is the same as for the tests on the sand and the sandy silt specimens. For tests B1–B6, each permeability measurement involved the use of only one externally controlled constant flow rate.

The characteristics of the data obtained during permeability measurements with the flow-pump method are illustrated in Fig. 2. This figure shows, for test A1 on the sandy silt specimen, a segment of the recorder chart where the differential transducer output was monitored against time. The transducer output indicates the head difference across the specimen when

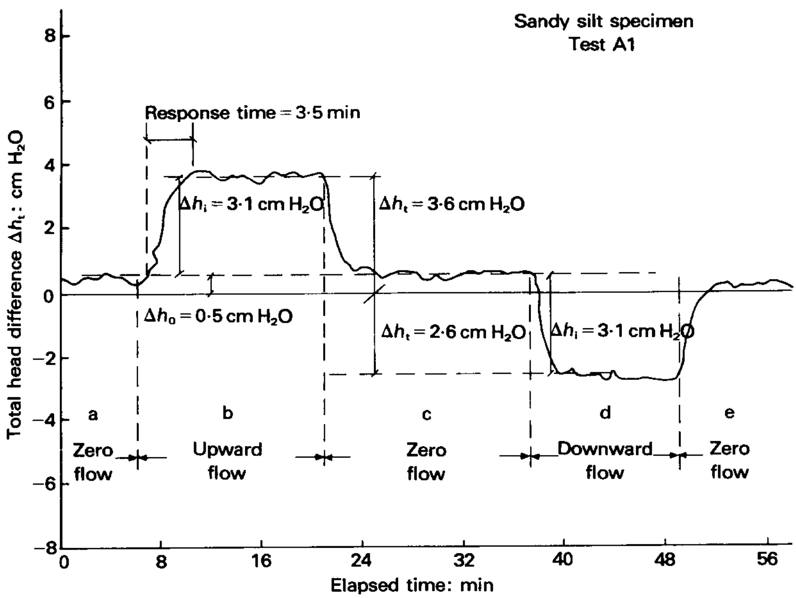

Fig. 2. Segment of the permeability data for the sandy silt specimen at $\sigma_c' = 345$ kN/m^2

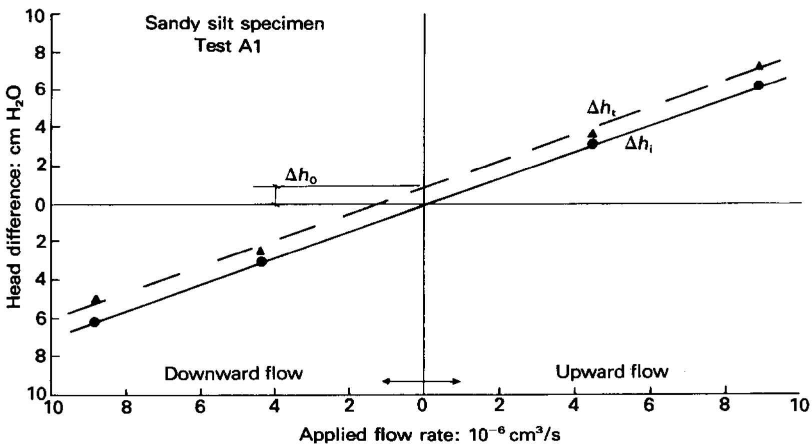

Fig. 3. Steady state total head difference Δh_t and induced head difference Δh_i versus externally applied flow rate for the sandy silt specimen, at $\sigma_c' = 345$ kN/m^2

the flow-pump was

(*a*) shut off so that no flow was either transmitted into or withdrawn from the base of the specimen (zero flow)
(*b*) introducing flow into the base of the specimen (upward flow)
(*c*) shut off (zero flow)
(*d*) withdrawing fluid from the base of the specimen (downward flow)
(*e*) shut off (zero flow).

The principal features of the data in Fig. 2 are fourfold. First, the head difference Δh_0 across the specimen for the zero-flow condition is not equal to zero. Moreover, Δh_0 is not constant but varies somewhat between successive periods of zero flow. Second, the head difference induced by upward flow equals that induced by downward flow when the induced head difference Δh_i is defined as the total head difference Δh_t minus the head difference Δh_0 for the zero-flow condition. Third, an interval of time, hereinafter called the response time, elapses after the flow rate is changed before the induced head difference

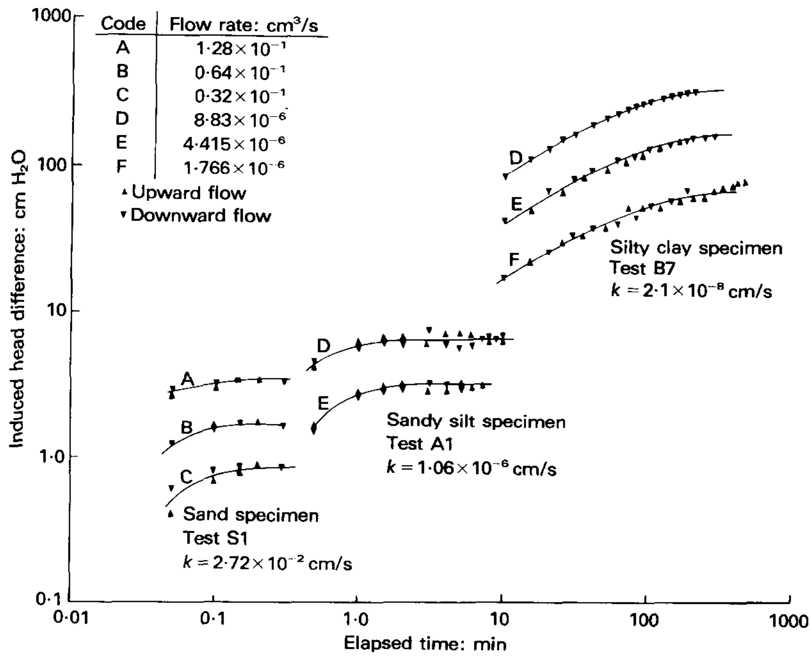

Fig. 4. Time response of head difference induced by a constant flow rate for various flow rates on each of the specimens

increases to a steady state value. Finally, small variations occur in the steady state head difference values which reflect fluctuations in the constancy of the imposed flow rates and the stability of the signal conditioning and recording system. These features of the data in Fig. 2 are identical with those reported by Olsen (1966, 1969) for flow-pump permeability measurements on kaolinite.

Figure 3 shows flow rate versus gradient relationships for test A1 based on the data in Fig. 2 together with additional data obtained at a higher flow rate. The relation for the total head difference Δh_t has an intercept arising from Δh_0 for the zero-flow condition. Moreover, deviations from linearity in this relation reflect variations in Δh_0 during the course of measurements such as those illustrated in Fig. 2. The relation for the induced head difference Δh_i avoids both the intercept and the deviations from linearity arising from the occurrence and variation in Δh_0. This study is based on the latter relation, and thereby minimizes further consideration of Δh_0.

Figure 4 shows the time response of the induced head difference for the sand, sandy silt and silty clay specimens. The data points in these figures were derived, at convenient time intervals, from the continuous linear recordings of the total head difference versus time, such as that illustrated in Fig. 2. For each flow rate on each specimen, with one exception, the data points are from tests wherein the externally applied flow rate was both introduced into (upward flow) and withdrawn from (downward flow) the base of the specimens. For flow rate D on the silty clay specimen, data were only obtained for downward flow.

Figure 4 shows that the time responses of the induced head difference for upward and downward flows are approximately the same. Accordingly, an average response curve was fitted to all the data points for each flow rate on each specimen. For the tests on the sand and sandy silt specimens, steady state conditions are evident in both the data points and the fitted response curve. However, for the tests on the silty clay specimen, the arrival at the steady state is not clearly defined by the data points.

Figure 5 shows, on a linear scale, the time response of the induced head difference for each of the tests on the silty clay specimen. The closely spaced data points, which were derived from the continuous recordings of the total head difference versus time, show that, for each test, the induced head difference response is reasonable in that it generally approaches the steady state asymptotically. However, deviations from this general trend occurred in most of these tests which give rise to apparent steady states before

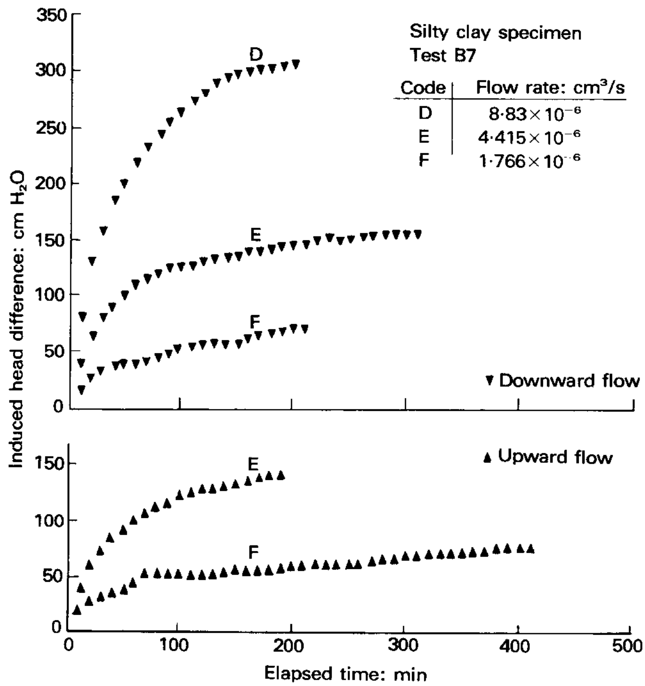

Fig. 5. Linear plot of time response for head difference induced by a constant flow rate for various flow rates on the silty clay specimen

the final steady states at which the tests were terminated. In consequence, it is possible that these final steady states are also apparent steady states, and that the tests were terminated prematurely.

Therefore, for this study, steady state values for the tests on the silty clay specimen were inferred by extrapolating the fitted response curves in Fig. 4 to steady state conditions. This approach appears to be reasonable because all the fitted response curves are geometrically similar on the logarithmic plot in Fig. 4.

Figure 4 shows that the response time varies dramatically among the three specimens from a fraction of a minute for the sand to more than 200 minutes for the silty clay specimen. This figure also shows the permeability values obtained for each of the specimens. The large variation in response time is associated with the correspondingly large variation in the permeability of the specimens.

Figures 6–8 present apparent permeability response curves derived from the data in Fig. 4, where the apparent permeability is defined by

$$k_{\text{app}} = \frac{L}{A} \frac{Q}{(\Delta h_i)_t}$$

L and A are the length and cross-sectional area of the specimen respectively, Q is the externally applied flow rate and $(\Delta h_i)_t$ is the induced head difference at time t. It should be noted that k_{app} decreases as Δh_i increases with time, and k_{app} becomes the permeability k when Δh_i reaches a constant steady state value. It is further to be noted that the fitted curves are extended somewhat beyond the data points. In Figs 6 and 7, the extended curves are horizontal, consistent with steady state conditions having been clearly defined before the tests were terminated on the sand and sandy silt specimens. In Fig. 8, the extended curve becomes horizontal at a value of permeability slightly below the data points. The extension of this curve is consistent with the extrapolation of the fitted response curves for the tests on the silty clay specimen in Fig. 4. These figures show, for each of the specimens tested, that the variation in the apparent permeability with time is not affected by differences in the applied flow rate.

Figures 9–11 show the consistency of the data with Darcy's law. The data points in these figures were derived from the fitted response curves in Fig. 4, and from corresponding curves for test A2 (see Table 2) on the silty clay specimen that are not shown in Fig. 4. With one exception (the response curve for flow rate D,

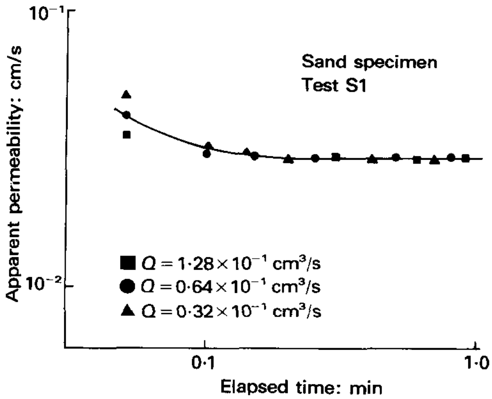

Fig. 6. Variation in apparent permeability with time for different flow rates in the sand specimen

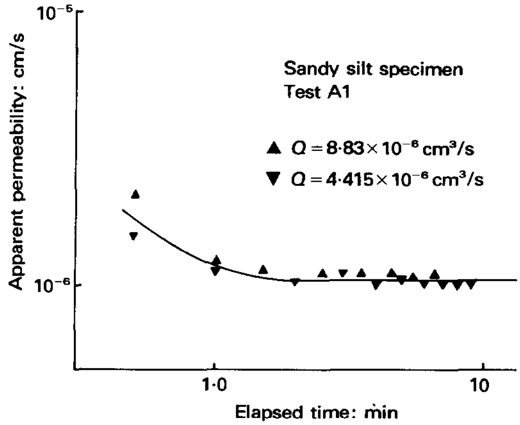

Fig. 7. Variation in apparent permeability with time for different flow rates in the sandy silt specimen

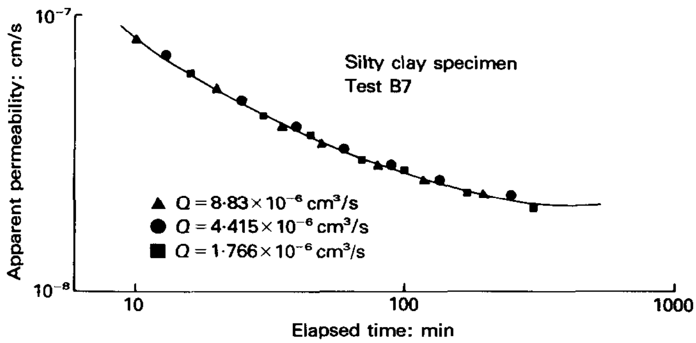

Fig. 8. Variation in apparent permeability with time for different flow rates in the silty clay specimen

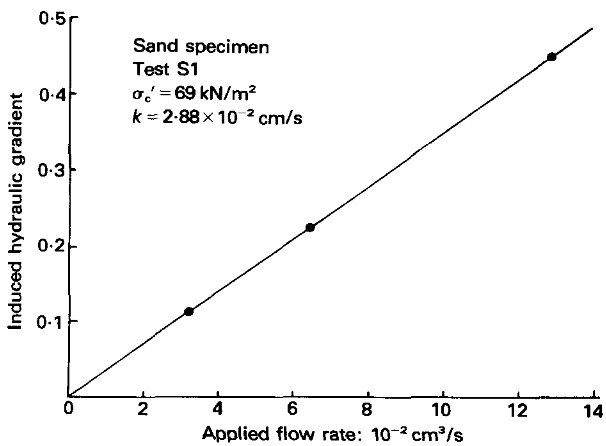

Fig. 9. Steady state hydraulic gradient versus flow rate for the sand specimen

test B7, Fig. 4), each fitted response curve is based on data from two tests wherein the same flow rate was introduced into (upward flow), and withdrawn from (downward flow), the base of the test specimen. Accordingly, each datum point in Figs 9–11 (except for the datum point in Fig. 11 that was derived from the response curve for flow rate D, test B7, Fig. 4) represents the average of two steady state values for the induced hydraulic gradient generated by the same externally applied flow rate. These figures show that, for each test, the data points are consistent with a linear relation drawn through the origin. Therefore, no deviations from Darcy's law were found in these materials over the range of test conditions employed.

In addition, the silty clay specimen was used to examine the variation in the response time and permeability of a specimen over a range of consolidation states. These data were obtained following each of the loading steps noted in Table 2 and are presented in Figs 12 and 13. The response curves in Fig. 12 were all obtained with the same externally applied flow rate of $8{\cdot}83\times10^{-6}$ cm^3/s. After each load step, this flow rate was both introduced into (upward flow) and withdrawn from (downward flow) the base pedestal of the triaxial cell. Similarly, the response curves in Fig. 13 were all obtained with an externally applied flow rate of $4{\cdot}415\times10^{-6}$ cm/s after the maximum consolidation load of 1102 kN/m^2 and the subsequent load decrements during rebound of the specimen. Only downward flow was employed at the 276 kN/m^2 load step in Fig. 13. The steady state values of the induced head difference were used to calculate a permeability value for each test. The calculated permeability values are shown in Fig. 14 versus the effective consolidation stress σ_c' for each of the load steps used to consolidate and rebound the specimen. It is recognized that a correlation of permeability with void ratio would have a more fundamental and practical significance than the correlation in Fig. 14. However, adequate void ratio values for this purpose were not obtained in this study.

Figures 12–14 show that the response curves and the permeability values vary in a consistent and reasonable manner with both increasing and decreasing increments of load used to consolidate and rebound the specimen. These results further show that the variation in the response time for a given material in a range of void ratios is relatively small compared with the variation in the response time for different materials having vastly different permeability values (Fig. 4 and Table 2).

DISCUSSION

The previously reported advantages of the flow-pump method, compared with conventional constant head and falling head methods, are based on permeability studies in oedometers on specimens that were rigidly confined (Olsen, 1966, 1969, 1972) and also on specimens that were free to consolidate one dimensionally in response to the seepage force imposed to conduct a permeability measurement (Pane *et al.*, 1983). Those advantages are

(*a*) direct flow rate measurements are avoided together with the associated errors that arise from the effects of contaminants on capillary

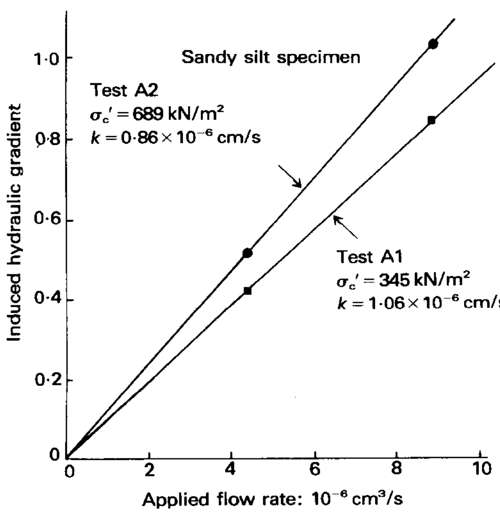

Fig. 10. Steady state hydraulic gradient versus flow rate for the sandy silt specimen

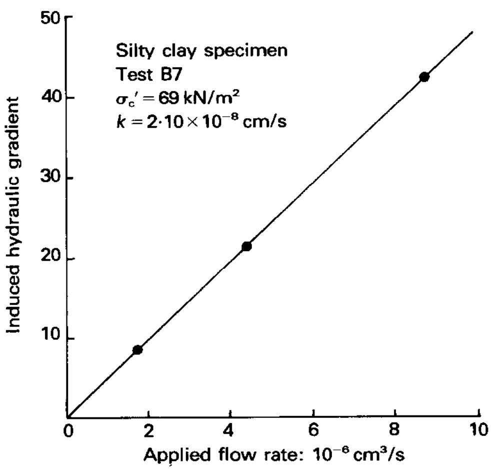

Fig. 11. Steady state hydraulic gradient versus flow rate for the silty clay specimen

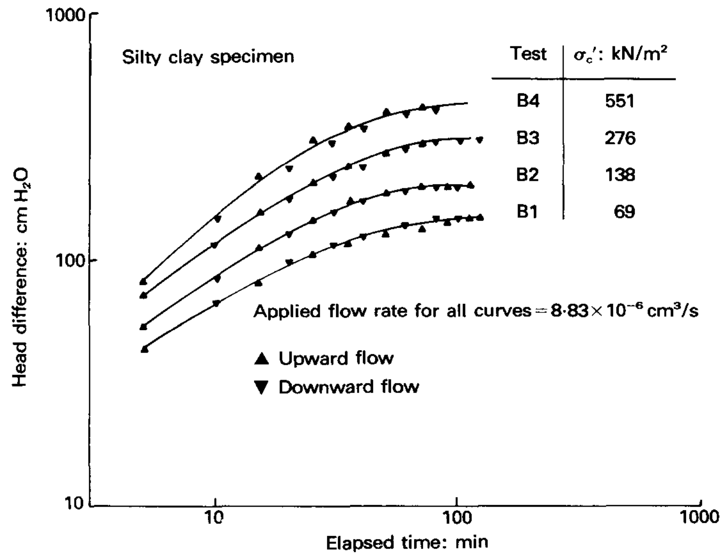

Fig. 12. Time response of head difference induced by a constant flow rate, for the silty clay specimen, after consolidation under effective chamber pressures σ_c' of 69 kN/m^2, 138 kN/m^2, 276 kN/m^2 and 551 kN/m^2

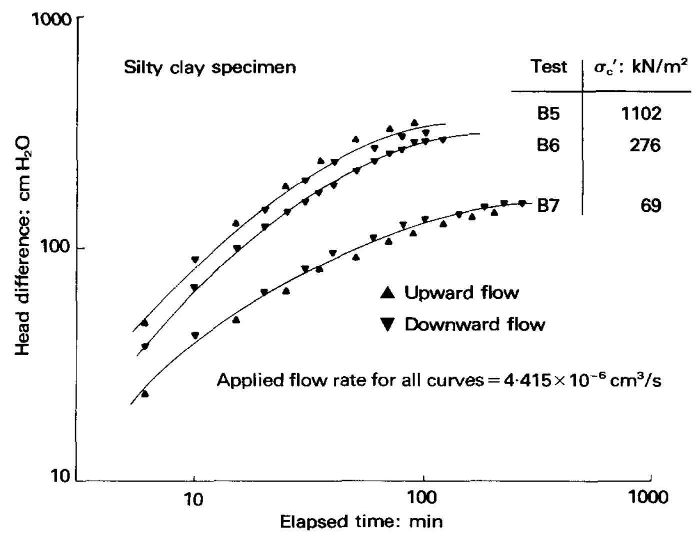

Fig. 13. Time response of head difference induced by a constant flow rate, for the silty clay specimen, after consolidation under an effective chamber pressure σ_c' of 1102 kN/m^2 and then rebounded under σ_c' values of 276 kN/m^2 and 69 kN/m^2

menisci and the long periods of time involved in flow-rate measurements

(*b*) permeability measurements can be obtained much more rapidly and at substantially smaller gradients

(*c*) errors from the small intercept in the otherwise linear flow rate versus hydraulic gradient relationship and also from seepage-induced permeability changes can be easily recognized and avoided or minimized.

These advantages were realized in this study for permeability measurements in a conventional triaxial system where a stress-controlled axisymmetric specimen is free to deform both axially and radially in response to the seepage force imposed to conduct a permeability measurement. Specifically, in regard to the previously recognized sources of error, the results herein show that the small intercept in the otherwise linear flow rate versus gradient relationship was readily avoided in the permeability measurements. The results also show that seepage-induced changes in the permeability of the specimens were avoided because no deviations from Darcy's law were found in the hydraulic gradient versus flow rate relations for steady state conditions.

In addition, the results herein clearly show a phenomenon that has received little attention in previous studies, i.e. the initial transient response that precedes the steady state flow condition required for a permeability measurement. The results show that the response time can be significant, ranging from a fraction of a minute for the sand specimen to more than 200 minutes for the silty clay specimen. That such large response times can occur in permeability measurements is corroborated in the recent study by Tavenas, Leblond, Jean & Leroueil (1983). They point out the need 'to wait for a few days after the application of the gradient before making the flow and k measurements' when conducting constant head permeability tests in triaxial equipment.

The conceivable sources of this initial transient response include

(*a*) undissolved air in the equipment and/or the specimen
(*b*) compliance in the equipment
(*c*) the inertia that must be overcome in changing the velocity of the pore fluid from zero to its steady state value
(*d*) time-dependent changes in the volume or distribution of pore space in a specimen.

It is not reasonable that undissolved air was present in the system. The back pressures used were generally very high (Table 2). Moreover, even though the back pressure for test B5 on the silty clay specimen was relatively low, its response curve is not anomalous from those for the related tests on this specimen shown in Figs 11 and 12.

The effect of equipment compliance on the response time depends on both the rigidity of the equipment and the magnitude of the externally applied flow rate. Because these factors are the same for data on both the sandy silt and the silty clay specimens, the substantially larger response times for the silty clay specimen cannot be attributed to equipment compliance.

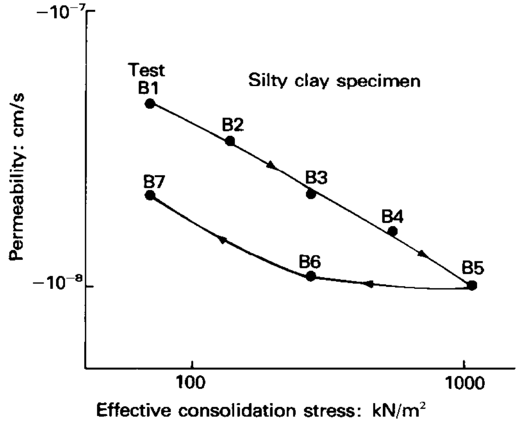

Fig. 14. Variation in permeability with effective chamber pressure σ_c' for the data in Figs 11 and 12

Therefore it appears that the response times reported herein, at least for the silty clay specimen, reflect the behavior of the specimens rather than the equipment. In this regard, the inertial effect probably is not significant (Terzaghi, 1943). However, time-dependent changes in the volume or distribution of the pore space could arise from seepage-induced consolidation and/or particle migrations (Mitchell & Younger, 1967; Pane *et al.*, 1983).

The substantial response times for the silty clay specimen are significant regarding the advantages of the flow-pump method, compared with constant head and falling head methods. In the constant head method, the flow rate measurement problems restrict its capability to monitor the initial transient response, and to differentiate therefrom the process of steady state hydraulic flow. The falling head method appears to be fundamentally inapplicable because the initial transient response is modified continuously by the falling head throughout the duration of a measurement, and therefore the steady state flow condition required for a permeability measurement is never reached. Therefore, only the flow-pump method provides a reasonable approach for taking into account the response time involved in conducting permeability measurements on clayey materials.

In view of this, the only significant limitation of the flow-pump method for permeability measurements on clayey materials arises from the limitations of the flow-pump itself. The slowest flow rate obtainable with the system used in this study is $1{\cdot}77 \times 10^{-6}$ cm^3/s. This flow

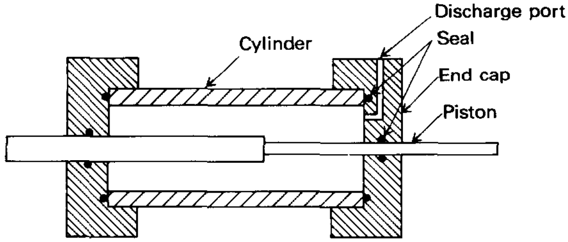

Fig. 15. Scheme of an actuator with a differential area piston

rate was used to obtain the minimum response curve shown in Fig. 4 for the silty clay specimen.

Although this capability is adequate for many soils, the full potential of the flow-pump method will require the development of equipment for producing even smaller flow rates. One step we are taking for this is to replace the syringe with the actuator illustrated in Fig. 15, whose piston has a differential diameter of 0·0254 mm (0·001 in). As the piston moves in this actuator, the quantity of fluid displaced equals the distance moved by the piston times its differential area. This actuator will produce a minimum flow rate of 10^{-7} cm^3/s when operated with the variable speed drive used in this study. This flow rate will induce a minimum gradient of about 1·0 on a standard triaxial specimen having a permeability of 10^{-8} cm/s.

Our experience in this study suggests that the flow-pump and the differential transducer have significant potential applications for triaxial testing in addition to the conduct of permeability measurements.

One of these applications became apparent during the development of the experimental system. The differential transducer was found to be a sensitive tool for detecting leaks in the system and for identifying where leaks were occurring. It was further found that the flow-pump and the differential pressure transducer could be used to test the compressibility of the fluid in the permeant lines and the specimen. This provides a sensitive method for detecting the presence of undissolved air in both the specimen and the permeant system.

The other potential applications of the flow-pump involve its capability for changing the volume of a triaxial specimen during either the consolidation or the shear phases of a test. For example, a triaxial specimen can be consolidated one dimensionally (the K_0 condition) at a constant rate of deformation (a CRD test) by synchronizing the rate of vertical deformation of a specimen (using a deformation-rate-controlled loading press) with the rate at which the specimen volume is reduced (using a flow-pump to withdraw pore fluid) such that the average cross-sectional area of the specimen remains constant during the consolidation process. Other combinations of vertical deformation and volume change rates can be used for shear tests under a variety of partially drained conditions. It is to be recognized that these potential applications of the flow-pump for triaxial testing are equivalent in principle to those of the digital pressure controller developed by Menzies, Sutton & Davies (1977).

CONCLUSION

The previously reported advantages of the flow-pump method, compared with conventional constant head and falling head methods, were realized in this study for permeability measurements in conventional triaxial equipment. These advantages are that

(*a*) direct flow rate measurements are avoided, together with the associated errors that arise from the effects of contaminants on capillary menisci and the long periods of time involved in flow rate measurements
(*b*) permeability measurements can be obtained much more rapidly and at substantially smaller gradients
(*c*) errors from the small intercept in the otherwise linear flow rate versus hydraulic gradient relationship and also from seepage-induced permeability changes can easily be recognized and avoided or minimized.

In addition, the results herein show that the initial transient response of a specimen that precedes the steady state condition needed for a permeability measurement can require substantial periods of time. The response times in this study varied from a fraction of a minute for a sand specimen to more than 200 minutes for a silty clay specimen. Errors in permeability measurements from this transient response are easily avoided with the flow-pump method, but not with constant head and falling head methods.

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