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Evaluation of the flow pump and constant head techniques for permeability measurements

S. A. AIBAN* and D. ZNIDARČIƆ

This paper presents a comparison between the constant head and flow pump experimental techniques for evaluating the permeability of soils. The specimens used in both methods were prepared in the laboratory under controlled conditions to ensure repeatable results. A conventional triaxial cell was used to confine the samples, and full saturation of the specimens was ensured by applying a constant level of back pressure. Accurate flow (inflow and outflow) measurements were obtained using precision burettes and a calibrated flow pump with known flow rates. Fine and coarse materials were tested under different conditions, and effects of different variables including void ratio, hydraulic gradient, specimen size and soil type were studied using the two methods. Experimental procedure, equipment and findings are presented.

KEYWORDS: clays; laboratory equipment; permeability; seepage; silts.

L'article compare deux techniques expérimentales, basées sur une charge constante et l'emploi d'une pompe respectivement, pour évaluer la perméabilité des sols. Les échantillons employés selon les deux méthodes ont été préparés dans le laboratoire sous des conditions contrôlées afin d'assurer des résultats reproductibles. Une cellule triaxiale conventionnelle a été utilisée pour contenir les échantillons et la saturation complète des échantillons a été assurée par l'application d'un niveau constant de pression inverse. Des mesures exactes d'écoulement (entrée et sortie) ont été effectuées en employant des burettes de haute précision et une pompe calibrée avec des écoulements connus. Des matériaux fins et grossiers ont été testés sous des conditions variées et les deux méthodes ont été utilisées pour étudier les effets de variables telles que l'indice des vides, le gradient hydraulique, les dimensions des échantillons et le type du sol. L'article présente la procédure expérimentale, les appareils utilisés et les résultats obtenus.

INTRODUCTION

Interest in accurate measurement of soil permeability, especially for fine grained materials, has increased significantly in the past few years. The increased interest is mainly due to the need to predict accurately fluid movement through soils associated with the disposal of hazardous wastes. For conventional geotechnical problems such as slope stability, leakage from reservoirs and other seepage related analyses, it is often sufficient to know the permeability within one order of magnitude or to determine that permeability is not larger than a specified, usually small, value. However, problems associated with the disposal of hazardous wastes require accurate knowledge about the permeability values even when they are very small and the material would be considered impervious for conventional engineering purposes.

The increased need for permeability testing and the requirement of higher accuracy encourage evaluation and improvement of existing methods of permeability measurement. Conventionally, the constant head and the falling head laboratory testing techniques have been used to determine soil permeability. These two methods are used in almost every geotechnical laboratory owing to their simplicity and the availability of equipment at reasonable costs. The constant head method is used for testing soils with relatively high permeability such as sands, while the falling head method is used for soils with relatively low permeability such as silts and clays (Olson & Daniel, 1981; Head, 1983).

Several disadvantages inherent in both methods have been discussed by Gubta & Swartzendruber (1962); Olsen (1966); Remy (1973); Hardcastle & Mitchell (1974); Olsen, Nichols & Rice (1985) and others. In both methods flow rates are obtained using conventional volume measurement techniques where the maximum practical resolution is of the order of 10^{-3} ml (Alva-Hurtado & Selig, 1981). With this

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resolution accurate measurements of hydraulic conductivity of soil with low permeability can be achieved only if the tests last for a long period of time or the imposed gradients are very high. Both of these requirements are undesirable for the following reasons. Prolonged testing is undesirable from a commercial point of view and may lead to a reduced experimental programme, resulting in lower quality data, in order to meet budgetary and time constraints of a project. In addition, there is an increased chance of bacterial growth in the sample which may cause a change in the hydraulic conductivity and the nature of the material. Temperature fluctuation may also have a considerable effect on measurements in prolonged testing. If the burettes are replaced by capillary tubes in order to increase resolution and shorten the testing time, contamination of the tubes, which is certain to take place, leads to an undetermined, but non-zero, contact angle between the water and the glass, which affects the imposed gradient and produces erroneous results (Olsen, 1965; Olson & Daniel, 1981).

The higher imposed gradient will usually produce a large variation of effective stresses within the sample, causing it to become less homogeneous. As the fluid head is applied at either end of the sample, reduction of effective stress occurs and local swelling of the soil takes place. This increases the void ratio and some of the inflowing water is used up to accommodate such a volume increase (Al-Tabbaa & Wood, 1987). The magnitude of the increase in the void ratio is clearly dependent on the magnitude of the applied head. In addition, the pressure gradients in situ are generally quite low, hence high gradient testing may cause a significant discrepancy between laboratory obtained permeability values and the values prevalent in the field.

An additional difficulty for the falling head test is the continuous change of hydraulic gradient during the test. The test is always done when the sample is in a transitional state and the effective stresses within the sample change continuously which in turn causes volume and therefore permeability variations. Whereas the analysis of the test accounts for the changing gradient the corresponding volume and permeability changes are usually ignored. In order to avoid or minimize the problems with changing gradients several constant head systems for measuring permeability of low permeability soils have been developed (Hardcastle & Mitchell, 1974; Tavenas, Leblond, Jean & Leroueil, 1983; Daniel, Trautwein, Boynton & Foreman, 1984; Dunn & Mitchell, 1984). Even in these techniques, a small head variation takes place (Tavenas *et al.*, 1983). The other problems described were not avoided in these apparatuses.

Although it was in 1966 that Olsen proposed the flow pump technique for measuring permeability of fine grained soils, it has not been widely used and only in the past few years has it received wider attention (Pane, Croce, Znidarčić, Ko, Olsen & Schiffman, 1983; Olsen, Nichols & Rice, 1985). In the flow pump techniques a known constant quantity of flow is forced through the sample by the pump and the corresponding pressure difference, from which the hydraulic gradient is evaluated, is measured by a differential pressure transducer. This is exactly the opposite concept of the conventional constant head test, in which a known constant gradient is imposed across the sample and the corresponding flow quantity is measured. The advantages of this test arise from the fact that it is much easier to control small flow rates precisely than to measure them accurately. The measurement of the imposed gradient poses no problem when using a sensitive differential pressure transducer. With the flow pump technique the samples are subjected to steady state conditions as in the constant head test. Even though these two techniques are expected to give the same permeability values, because they impose identical conditions on the sample, it is important to compare them experimentally and to evaluate their advantages or disadvantages.

Al-Tabbaa and Wood (1987) reported results of permeability measurements on Speswhite kaolinite using the falling head test. The present Authors discussed that paper and compared the results with available data obtained with the flow pump (Znidarčić & Aiban, 1988). Good agreement is noted, indicating that the falling head test appears to give the same permeability as the constant head and flow pump tests, provided the tests are performed at low gradients. However, the falling head tests reported by Al-Tabbaa and Wood (1987) required nearly 24 h for permeability measurement, whereas the tests reported here lasted 1 h. In the case of the flow pump the experiments could have been completed within a few minutes.

This Paper presents results of an experimental programme in which the same soil samples were subjected to both test methods. Both the flow pump and the burettes for the constant head test were connected to the same triaxial cell and in this manner the two tests could be performed without removal and possible disturbance of the specimen. The equipment used is described and detailed design of the flow pump is given.

EQUIPMENT DESCRIPTION

The equipment used to perform the laboratory experiments consists of a conventional triaxial cell, the flow pump and the constant head assembly. The system includes pore water back pressure facilities and differential pressure transducers. The equipment layout is shown in Fig. 1. The constant head assembly consists of two identical chambers, one for the inflow and the other for the outflow. A third, similar chamber, is used to apply the cell pressure. Each chamber contains two burettes. One burette has a capacity of 25 ml with 0·1 ml subdivisions. The other burette has a capacity of 1 ml with 0·01 ml subdivisions. The burettes mounted in the cell pressure chamber are used to measure volume change during consolidation. Each chamber has a pressure gauge and is connected to the pressure supply through a pressure regulator.

The flow pump consists of two major components: a driving mechanism and stainless steel syringe. The driving mechanism used is a model 901 single syringe infusion–withdrawal pump manufactured by Harvard Apparatus Company. The pump is driven by a variable speed motor with speed reproducibility of 1·5%. The motor is attached through a gearbox to a worm gear which drives the syringe piston. The gearbox has a selection knob for twelve discrete speeds over a range of 5000 to 1. The motor speed can be controlled over the ratio of 10 to 1 so that the overall possible speed range has a ratio of 50 000 to 1 giving the piston velocities ranging from $2{\cdot}12 \times 10^{-8}$ m/s to $1{\cdot}06 \times 10^{-3}$ m/s with contin-

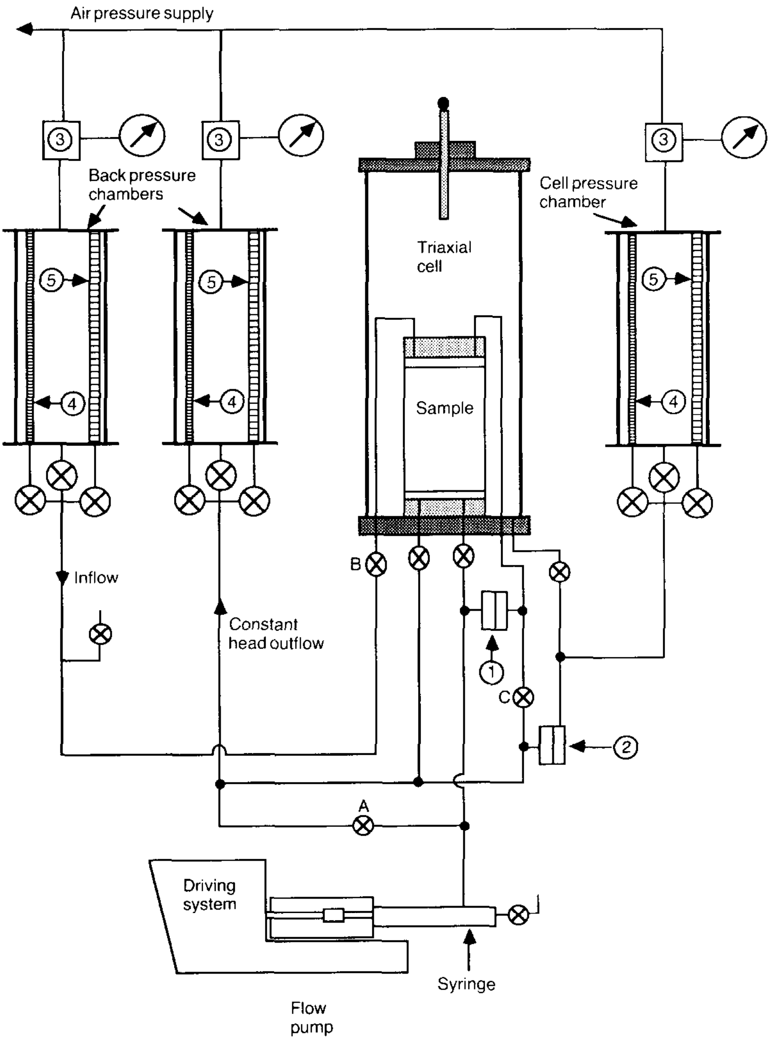

Fig. 1. Experimental equipment; (1) differential pressure transducer for head difference across sample, (2) differential pressure transducer for cell pressure, (3) pressure regulators, (4) 1 ml burettes, (5) 25 ml burettes

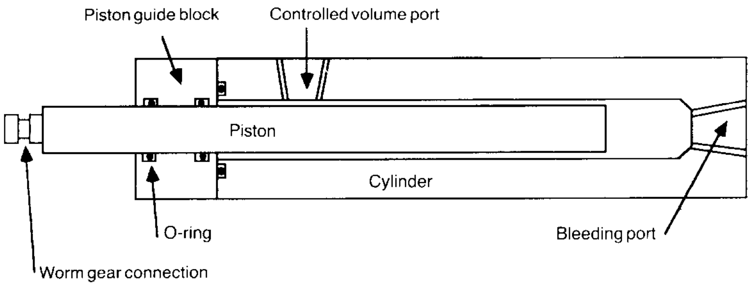

Fig. 2. Stainless steel syringe

uous control in between. The pump can be operated in both infusion and withdrawal modes. That means the permeability of the sample for flow in opposite directions can be obtained.

The stainless steel syringe is shown in Fig. 2. It was custom designed and built having in mind the need for it to have a low compliance and leak free system which could be easily flushed and deaired. The cylinder is made from a solid stainless steel block 38 mm square and 280 mm long, in which a hole of 16 mm dia. and 256 mm in length is drilled. A stiff thick walled cylinder is thereby obtained. The cylinder is provided with two ports for connecting pipes and valves. The controlled-volume port is connected to the system in which the volume control is needed and the bleeding port is provided at the other end of the cylinder for easy flushing before testing. The piston has a 12·7 mm dia. and is 320 mm long and is made from stainless steel. The maximum possible piston travel is 260 mm giving a total syringe capacity of 33 ml in a single stroke. With the stated speed range of the driving system the range of the flow rates that the syringe can impose ranges from $2{\cdot}7 \times 10^{-6}$ ml/s to $1{\cdot}3 \times 10^{-1}$ ml/s with any desired value in between. These flow rates have been found to satisfy most needs in geotechnical laboratory work and enable the use of the same system for permeability testing of materials of a wide range of permeabilities.

The piston is guided by a stainless steel block which is attached to the cylinder. Two O-ring seals are furnished between the piston and the block and an additional O-ring is placed between the block and the cylinder. The piston surface is ground to provide the best seal possible in the application where movement reversal is present. This design, rather than a piston sealed on the inner wall of the cylinder, is chosen for its simplicity and the better quality seal that can be achieved. The piston is provided with a special connection to be attached to the worm gear of the driving system.

The resolution of the flow pump for the volume control is controlled by the resolution of the time measuring unit. If it is assumed that the elapsed time can be measured reasonably well within one second the resolution of the described system is of the order of 10^{-6} ml which is three orders of magnitude better than the conventional means of volume change measurement.

If a reduction, or increase, in flow rate or the resolution of the system is desired, it can readily be achieved by replacing the piston and the guide block with one having different size.

Differential pressure transducers used are manufactured by Validyne Engineering Corporation, model DP-215. The transducer used for measurements of head difference across the sample has a capacity of 56 kPa and the one used for measuring the difference between the cell pressure and the back pressure has a capacity of 875 kPa. Both transducers are connected to a microcomputer based data acquisition system.

Figure 1 would have been far simpler if the flow pump test alone were needed. Three hydraulic lines—the cell pressure, inflow and outflow—are required, with the appropriate connections for the pressure transducers. The inflow chamber need not be fitted with burettes, as the outflow is controlled by the flow pump rate at each given speed.

SAMPLE PREPARATION AND TESTING

The experimental study undertaken consists of preparation of fine-grained specimens in the laboratory and then testing them with the described system. The specimens were consolidated isotropically to different void ratios at which permeability tests were performed, and the results were compared over a wide range of void ratios. Two types of materials were investigated: Speswhite fine china clay and Bonny silt. The Speswhite clay used is a commercially available white kaolinite in powder form. The clay has a specific gravity of 2·66, a plastic limit of 32% and a liquid limit of 54%. The Bonny silt used was brought from a dam site close to the Colorado–Kansas border. The specific gravity of the silt is

2·63, the liquid limit is 25% and the plastic limit is 21%. A comparison between the constant head method and the flow pump technique on both soils was performed.

Kaolinite specimens

Two kaolinite samples were prepared: one of specimen height 76 mm, the other of specimen height 25 mm. The samples were prepared by mixing a predetermined amount of clay powder with water at a moisture content of 133%, which corresponds to a liquidity index of 4·6. The slurry was consolidated one-dimensionally under an axial stress of about 100 kPa in a 203 mm dia. tube. The level of 100 kPa was selected as the consolidation pressure in order to produce a sample with a relatively high void ratio that could still be trimmed easily while minimizing sample disturbance. Once the sample had consolidated and the estimated final height was reached, the load was released and the specimen was extruded by pushing it in the same direction as the consolidation settlement took place. The sample was then trimmed to a diameter of 71 mm.

Bonny silt

The Bonny silt sample was prepared by mixing the silt at a moisture content of 20%. An amount sufficient to make a 75 mm high specimen in a 71 mm dia. mould was determined and then divided equally into three parts. The sample was statically compressed in three equal layers (each layer was one part of the mix). The top of the first and the second layers were scarified to a depth of about 3 mm before the subsequent layer was placed. Each layer was compressed to become 25 mm thick. The sample was then carefully extruded from the mould.

Experimental procedure

The experimental programme was designed to provide comparisons between the two techniques for materials with wide range of permeability values. In addition, the problem of seepage-induced consolidation during the permeability measurement was studied by testing specimens of the same material having different heights. In a tall specimen the influence of consolidation is more pronounced than in a short one.

All specimens were tested initially under an isotropic effective stress of 30 kPa. Once the samples had consolidated the permeability measurements were performed. One or more flow pump tests were first conducted on each specimen, followed by one or more constant head tests. For each test both the inflow and outflow quantities were measured and the head difference across the sample was monitored and recorded continuously. The flow direction was always from top to bottom of the specimens so that the inflow rate was always measured by the burettes connected to the top of the specimen. The outflow rate from the base of the specimen was either controlled by the flow pump or measured by the burettes connected to the base of the specimen in the constant head tests. In the flow pump test the pump was operated in the withdrawal mode, which caused pore pressure reduction at the bottom of the specimen and a corresponding compression owing to the increase in effective stress. The back pressure at the top of the specimen was not changed in the flow pump test, hence no effective stress change and corresponding volume change took place at the top. On the contrary, in the constant head tests the back pressure at the top of the sample was increased, whereas the back pressure at the bottom was left unchanged. This caused flow to be in the same direction as in the flow pump tests but because the cell pressure remained constant the effective stress at the top of the specimen decreased to cause expansion in this part of the specimen. Although the difference in the specimen's volume change characteristics between the flow pump and constant head tests were small due to the small pressure changes, it is believed that this difference in test conditions is responsible for the minor discrepancy in the results.

Each flow pump test was started by engaging the motor in the flow pump driving system while keeping valve A (Fig. 1) open. This initial step, lasting a few minutes, was needed to compensate for any slack in the gear train and to collect reference readings from the differential pressure transducer. The permeability test started when valve A was closed and the water started to flow through the sample. In all the tests closing of the valve was associated with an instantaneous increase in the pressure difference across the sample. This is seen in Figs 5, 7 and 9 in which the initial constant differential pressure readings correspond to the reference data collection at the beginning of the test. The first differential pressure increase takes place at the moment of closing the valve A. The test continued until the pressure difference across the sample and the inflow rate measured by the burette connected to the top of the sample stabilized. At that point the flow pump was stopped, and the differential pressure decay was monitored so that the reference reading of the differential pressure transducer could again be checked.

Selection of syringe speed was based on an estimate of the soil permeability. When there was doubt about the range of the expected permeability, the test was started at the smallest available flow rate. If the chosen rate did not result in a measurable head difference, the test was stopped and the sample was allowed to equilibrate until any differential pressure across the sample diminished. A higher flow rate was chosen and the procedure was repeated until the appropriate head difference (or the required gradient) was reached.

Based on the flow rate measured with the flow pump, burettes appropriate for the constant head test were selected. The water levels in both the inflow and outflow burettes were recorded and valve C, connecting the top and bottom of the sample, was closed. The outflow burette connected to the bottom of the specimen was kept open, while the inflow burette was closed and a head difference close to that which resulted from the flow pump was arranged by applying the required air pressure to the inflow burette. Valve B, connected to the inflow burette, was then opened and the water levels in the inflow and outflow burettes were monitored throughout the test. A steady state condition was reached when the inflow rate was equal to the outflow rate and when both rates were nearly constant. The inflow burette was closed and, similar to the flow pump test, the differential pressure decay was monitored so that the reference reading of the differential pressure transducer could be checked. The valve connecting the top and bottom of the sample was opened and the sample was again allowed to equilibrate. The effective stress was then increased, the sample was then allowed to consolidate for at least 12 h and the volume change was measured using the 25 ml burette. The permeability tests were performed at the new void ratio in the same way as described. The procedure was repeated several times until the pressure limit of the system was reached.

To avoid a change in water content, the cell pressure was released at the end of the experiment without allowing the specimen to drain. The cell was then dismounted, and the height of the sample and its diameter at mid-height were measured. The dry weight and final moisture content were also determined. At this point the final volume was known and, as the volumetric change during consolidation was known, the volume of the sample after each load increment could be calculated. The diameter as well as the height was calculated assuming isotropic compression, although end platen friction caused some necking of the sample. The coefficient of permeability k, for both test methods, was calculated using the following relation

$$k = \frac{qH}{Ah} \tag{1}$$

where q and h are the flow rate and head difference across the sample at steady state, respectively. H is the height of the specimen and A is the area of the sample.

RESULTS AND DISCUSSION

Results of the flow pump and constant head permeability tests are summarized in Tables 1–3 and in Figs 3 and 4. Figs 5–10 present examples of recorded head differences and flow quantities

Table 1. Results of permeability tests on Speswhite clay 76 mm thick (specimen 1)

Void Ratio e	Flow pump test*: k: m/s Inflow $\times 10^{-9}$	Flow pump test*: k: m/s Outflow $\times 10^{-9}$	Flow pump test*: i	Flow pump test*: p: kPa	Constant head test*: k: m/s Inflow $\times 10^{-9}$	Constant head test*: k: m/s Outflow $\times 10^{-9}$	Constant head test*: i	Constant head test*: p: kPa
1·63	2·3	2·9	11·5	8·8	2·8	2·8	8·4	6·4
1·63	2·4	2·8	12·0	9·2	2·8	2·8	10·4	7·9
1·52	1·7	2·5	14·1	10·6	2·0	2·0	10·0	7·5
1·52	1·7	2·3	7·1	5·8	—	—	—	—
1·39	1·5	1·6	11·0	8·2	1·6	1·6	10·9	8·1
1·32	1·0	1·6	11·6	8·5	1·2	1·4	11·8	8·7
1·27	0·93	1·3	14·3	10·4	1·0	1·0	12·6	9·2
1·22	0·83	1·2	6·4	4·6	—	—	—	—
1·22	0·93	1·0	17·9	13·0	—	—	—	—
1·19	0·73	1·0	6·9	5·0	0·87	0·87	13·1	9·4
1·19	0·85	0·96	19·9	14·3	—	—	—	—

* k is the permeability at steady state flow, i is the hydraulic gradient at steady state flow and p is the differential pressure across the specimen at steady state flow.

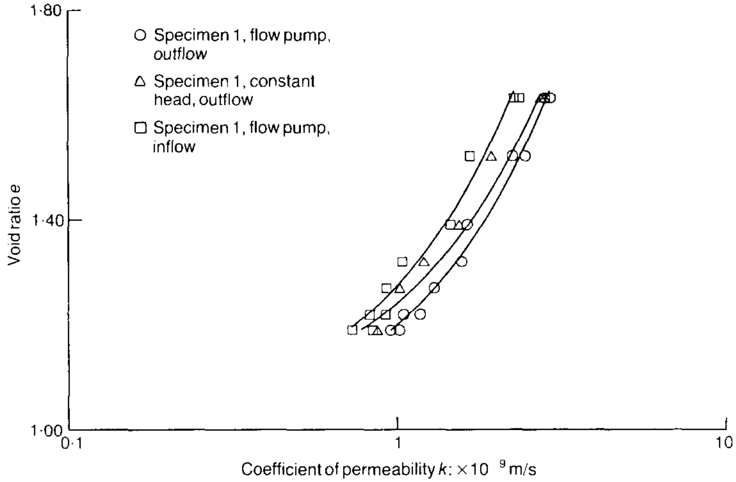

Fig. 3. Void ratio-permeability relationship for kaolinite specimen 76 mm thick (specimen 1)

for both flow pump and constant head tests. The small cyclic pressure variations seen in Figs 5, 6, 9 and 10 are caused by the operation of the air pressure regulator that controls the back pressure. They are absent in Figs 7 and 8, because these tests were of short duration and performed within one cycle of pressure variation which usually takes 0·1 h. The variation in magnitude of these pressure fluctuations is caused by the interference of the two pressure regulators that control the inflow and outflow pressures in the constant head tests. It is also possible that the regulator performance was not ideally repeatable for two different pressure settings.

Table 1 and Fig. 3 contain permeability values for the kaolinite specimen 1 (76 mm high) obtained by both flow pump and constant head techniques at different void ratios and with different gradients. For each test two values of permeability were calculated: one from the inflow rates and the other from the outflow rates. Ideally, these two quantities should be identical at steady state. However, a noticeable difference exists between permeability values calculated from inflow and outflow rates for the flow pump tests. Such a difference does not exist in the case of constant head tests. Permeability values obtained for these lie between the two values

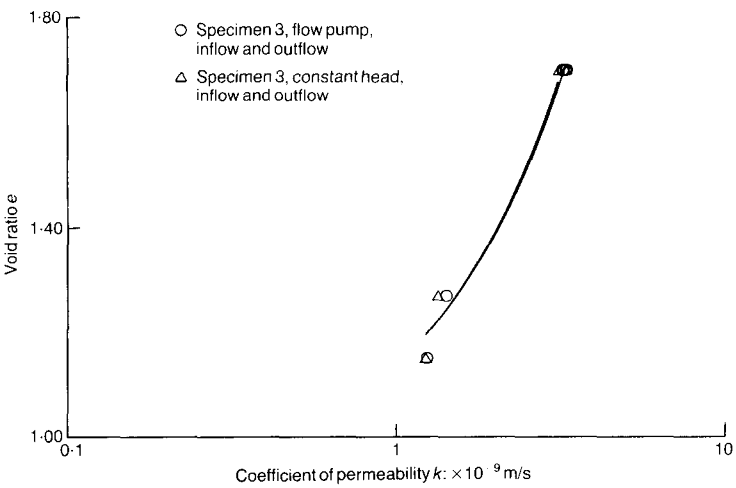

Fig. 4. Void ratio–permeability relationship for kaolinite specimen 25 mm thick (specimen 3)

found from the flow pump test at the same void ratio. The resolution of the inflow burette readings was 0·01 ml which means that the resolution of the flow rate measurement was of the order of 3×10^{-6} ml/s for a test with a steady state flow duration of 1 h. This produced an accuracy in the permeability calculated from the burette readings of the order of 1×10^{-10} m/s for the given specimen size and the imposed gradients.

The observed permeability difference was of the same order of magnitude and in most cases it would be considered insignificant. However, the outflow rates were consistently higher than the inflow rates, indicating that the volume of the specimen decreased during the test. The differences became smaller as the sample was consolidated to lower void ratios. Both observations indicate that seepage-induced consolidation was taking place. This is confirmed by measurements of the differential pressure and flow quantities for the permeability test at a void ratio of 1·39 with a gradient of 11·0, presented in Fig. 5. The pressure difference across the sample increases gradually during the test and apparently stabilizes after about 0·7 h. The inflow rate (slope of the presented curve) increases gradually throughout the test and the accuracy of volume reading prevents positive detection of a steady state condition from this diagram. It appears, however, that the flow rate towards the end of the test approached the outflow rate imposed by the flow pump which is indicated by the straight line in the figure.

Figure 6 presents an example of the head difference and flow quantities recorded during the constant head test on specimen 1 at void ratio 1·27 and a gradient of 12·6. The inflow and outflow rates have similar slopes towards the end of the test although the head difference continuously changes during the test. The head difference reduction in this test was caused by the decrease of water level in the inflow burette and the corresponding increase of water level in the outflow burette. The head variation caused the flow rates to change continuously throughout the test and steady state was never reached. Although this phenomenon is insignificant in most cases, strictly speaking the test is of the falling head type rather than constant head type, and it should not be analysed by assuming that the steady state condition has been reached.

Despite the head variability the inflow and outflow rates do not show any measurable difference, which indicates that the seepage-induced consolidation was not a significant factor in this test. This can be explained by realizing that in the flow pump tests the sample compressed owing to the increase in the effective stress (pore pressure reduction), whereas in the constant head test the sample expanded owing to the effective stress decrease (pore pressure increase). Thus the constant head test was performed under the overconsolidated regime to cause smaller volume changes and faster consolidation.

Besides the reasons stated the difference

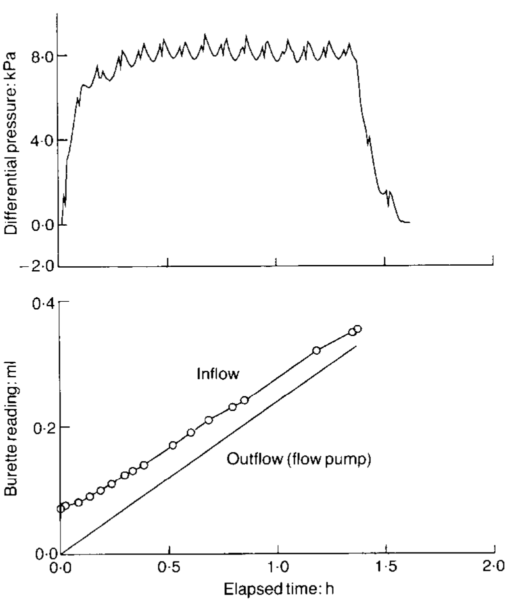

Fig. 5. Flow pump results for kaolinite specimen 76 mm thick (i = 11·0)

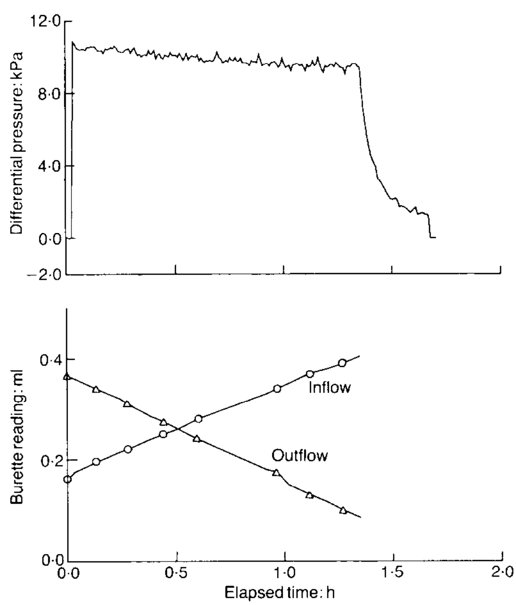

Fig. 6. Constant head results for kaolinite specimen 76 mm thick (i = 12·6)

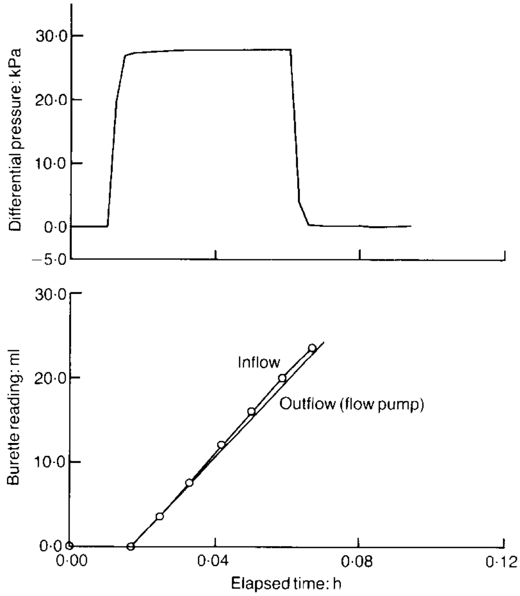

Fig. 7. Flow pump results for Bonny silt specimen (i = 36·9)

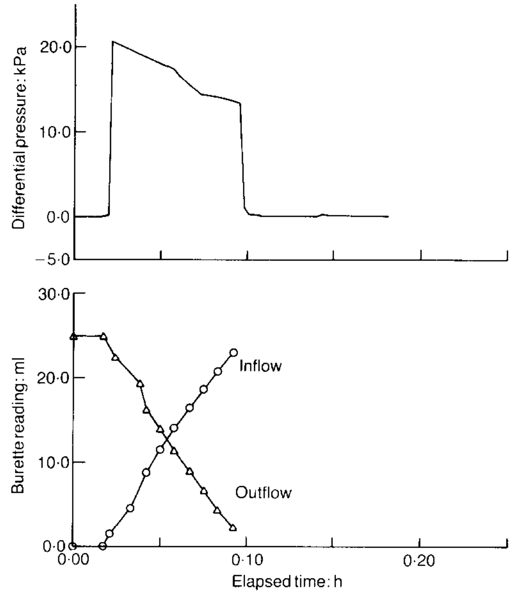

Fig. 8. Constant head results for Bonny silt specimen (i = 22·4)

between the inflow and outflow rates for the flow pump tests could have been caused by the delayed compression of the sample after the preceding isotropic effective stress increment. The effective stress increased in the flow pump tests and amplified the effect, whereas in the constant head experiments the effective stress decrease compensated such volume changes.

Figures 7 and 8 present head differences and flow rates for specimen 2 on Bonny silt during the flow pump and constant head tests respectively. Good agreement between inflow and outflow rates was obtained (Table 2) and there was no indication of seepage induced consolidation. This is no surprise, as the silt material is far less compressible than the clay specimen, and for the effective stress changes imposed by the head difference the volume change is negligible. Both tests were performed during much shorter time periods. As with the clay specimens, in the constant head test the imposed head decreased with time. The larger change was related to the higher flow rate and to the size of the burette used in this test.

Figures 9 and 10 present observed head differ-

Table 2. Results of permeability tests on Bonny silt (specimen 2)

Void ratio e	Flow pump test*				Constant head test*			
	k: m/s		i	p: kPa	k: m/s		i	p: kPa
	Inflow $\times 10^{-7}$	Outflow $\times 10^{-7}$			Inflow $\times 10^{-7}$	Outflow $\times 10^{-7}$		
0·79	9·4	9·7	14·0	10·6	—	—	—	—
0·79	9·4	9·5	14·3	10·8	—	—	—	—
0·79	9·0	9·2	36·9	27·8	8·3	8·4	22·4	16·9
0·79	9·0	9·2	36·9	27·8	8·7	8·9	21·9	16·5
0·79	8·7	9·2	14·7	11·1	—	—	—	—
0·79	9·0	9·2	38·8	27·8	—	—	—	—
0·72	3·8	3·9	35·9	26·7	—	—	—	—
0·72	3·8	3·8	89·3	66·5	3·6	3·7	23·5	17·5
0·72	3·8	3·9	36·2	26·8	—	—	—	—

* k is the permeability at steady state flow, i is the hydraulic gradient at steady state flow and p is the differential pressure across the specimen at steady state flow.

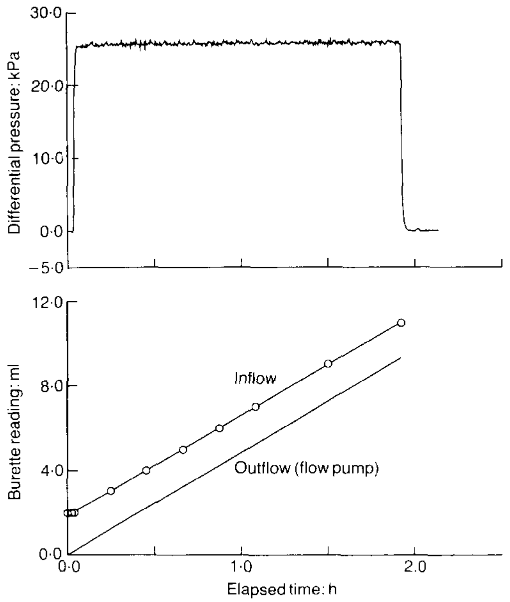

Fig. 9. Flow pump results for kaolinite specimen 25 mm thick (i = 104·0)

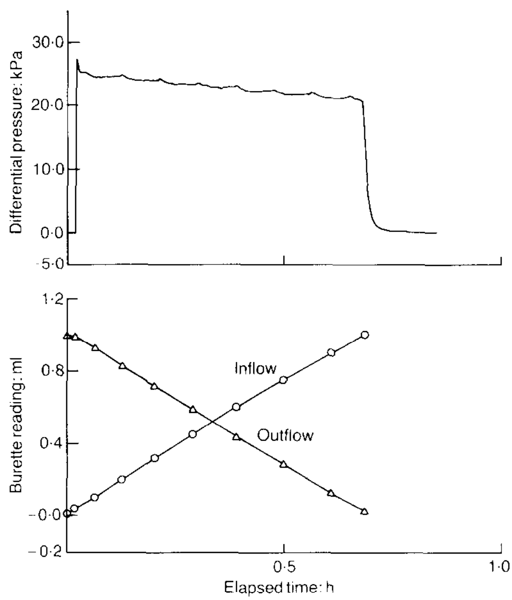

Fig. 10. Constant head results for kaolinite specimen 25 mm thick (i = 91·2)

ences and flow rates for specimen 3 which was a 25 mm high kaolinite sample at a void ratio of 1·70 and subjected to a gradient of 104·0. Despite the high gradient the seepage induced consolidation was not apparent in the results and, as indicated in Table 3 and Fig. 4, near perfect agreement between inflow and outflow rates for both flow pump and constant head tests was obtained. This is not surprising as the specimen had a height equal to one third the height of specimen 1. The shorter sample will have a volume change three times smaller for the same change in the effective stress and any consolidation process would be completed in a much shorter time. The additional benefit of testing a shorter sample is a smaller effective stress change for the same imposed gradient. The flow pump test for this specimen could have been completed in a few minutes, as the steady state was reached instantaneously (Fig. 9) and there was no need to

Table 3. Results of permeability tests on Speswhite clay 25 mm thick (specimen 3)

Void Ratio e	Flow pump test*			Constant head flow*		
	k: m/s $\times 10^{-9}$	i	p: kPa	k: m/s $\times 10^{-9}$	i	p: kPa
1·70	3·3	21·0	5·4	—	—	—
1·70	3·3	21·0	5·4	3·1	10·3	2·7
1·70	3·2	21·2	5·5	—	—	—
1·70	3·3	104·0	26·8	3·3	91·2	23·5
1·70	3·2	106·1	27·3	—	—	—
1·70	3·2	107·1	27·6	—	—	—
1·27	1·4	134·7	32·8	1·3	60·4	14·7
1·27	1·4	134·7	32·8	—	—	—
1·15	1·2	159·8	38·5	1·2	91·2	22·0

* k is the permeability at steady state flow (the same for inflow and outflow), i is the hydraulic gradient at steady flow and p is the differential pressure across the specimen at steady state flow.

accumulate a significant quantity of water to increase the accuracy of flow rate measurement as in the constant head test.

CONCLUSIONS

Experimental results presented verify that the constant head test and the flow pump test yield the same values for the coefficient of permeability, when the same sample is tested under similar conditions with both techniques. The head difference across the sample in a constant head test decreases with time, whereas the flow pump technique maintains a constant head difference once the steady state is reached. In order to reduce the influence of the seepage induced consolidation on the test results a shorter sample with smaller applied head should be tested. The flow pump technique allows for much shorter experiment duration than that of the constant head test, provided that the seepage induced consolidation is negligible. Even in the cases when the transient stage of the test requires longer time, a good estimate of the permeability can be obtained within a few minutes with the flow pump technique. The comparison between the two testing techniques was performed on two different soil types whose permeability values differ by two to three orders of magnitude. The same flow pump was used for both materials while for the constant head tests different burette sizes were needed. The use of the flow pump is equally appropriate for both low and high permeability soils but its advantages are more apparent when testing less permeable soil, where the constant head test required prolonged testing time.

The flow pump technique, besides being faster and having higher resolution for flow rate measurements, has additional benefits which makes it a better and more desirable testing method than the constant head procedure. The permeating fluid is completely enclosed in a stainless steel container and, depending on the back pressure system used, the fluid–air or fluid–fluid interface can be completely avoided. This is a desirable feature that reduces the amount of air dissolved in the water during the test. When the tests are performed with hazardous chemicals as permeants, the flow pump provides a convenient way of preventing direct contact with the fluid. By using the flow pump technique for permeability testing the problem of capillary tube contamination is excluded and there is no need to have two immiscible fluids in the system to indicate level change in the measuring burettes as in the case of the constant head test. The technique is better suited for automatic data acquisition, and the resolution in the flow rate measurement is at least three orders of magnitude better than for the conventional methods.

One disadvantage of the flow pump technique is the slightly higher initial cost for the equipment. However, this cost should be offset by savings in testing time in commercial laboratories. In addition, the flow pump can be used as a general volume control device with various applications, such as: compliance measurement and free air detection in the pore pressure measuring system, leak detection and leak calibration, K_0-testing and infiltration testing for partially saturated soils.

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