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Measurements of the permeability of London Clay using a self-boring permeameter

R. J. CHANDLER,* S. LEROUEIL† and N. A. TRENTER‡

The coefficient of permeability of the London Clay at Bradwell, Essex, has been measured using various methods, including a self-boring permeameter. The results are compared with in situ permeability measurements made using conventional borehole piezometer techniques, and with laboratory permeability determinations. The self-boring permeameter can be successfully used in stiff clays, and the self-boring technique has potential advantages over the conventional in situ method that uses borehole piezometers. Laboratory samples show that the ratio of horizontal to vertical permeability of the London Clay at the site is approximately 2. The in situ horizontal permeability measured with the self-boring permeameter is about four times that measured on 51 mm dia. laboratory samples.

KEYWORDS: clays; field tests; permeability.

Le coefficient de perméabilité de l'argile de Londres à Bradwell (Essex) fut mesuré par plusieurs méthodes, y compris l'emploi d'un perméamètre autoforeur. L'article compare les résultats avec des mesures de perméabilité effectuées à l'aide des techniques traditionnelles employant des piézomètres dans des trous de forage, accompagnées de déterminations de perméabilité faites dans le laboratoire. On démontre que le perméamètre autoforeur peut s'utiliser effectivement dans des argiles raides et que la technique d'autoforage possède des avantages potentiels par rapport à la méthode traditionnellement employée en place en utilisant des piézomètres dans des trous de forage. Des échantillons de laboratoire indiquent que sur cet emplacement la perméabilité horizontale de l'argile de Londres à une valeur à peu près deux fois supérieure à celle de la perméabilité verticale. La perméabilité horizontale mesurée à l'aide du perméamètre autoforeur a une valeur approximativement quatre fois supérieure à celle mesurée sur des échantillons de laboratoire ayant un diamètre de 51 mm.

NOTATION

- C_k ratio $\Delta e : \Delta \lg(k)$
- D diameter of permeameter
- e void ratio
- e_0 in situ void ratio
- F shape factor
- G specific gravity of soil grains
- H applied head of water
- k coefficient of permeability
- k_0 k at e_0
- k_{h0} horizontal permeability at in situ voids ratio
- k_{v0} vertical permeability at in situ voids ratio
- L length of perforated element of permeameter
- Q measured flow
- Q_∞ flow under steady state conditions
- r_k ratio of horizontal to vertical permeability at in situ permeability
- S degree of saturation
- t time
- w water content
- σ_{v0}' vertical effective stress in situ

Discussion on this Paper closes 3 July 1990; for further details see p. ii.

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INTRODUCTION

In a recent investigation undertaken for UK Nirex Ltd, a self-boring permeameter (Tavenas *et al*, 1983c) was used to measure the in situ permeability of London Clay. The results showed an encouraging consistency, indicating that the permeability reduces with depth, and demonstrating that the test method can be used successfully in stiff clays. Additionally, both conventional in situ and laboratory permeability testing were carried out, enabling comparison to be made between different methods of measurement of the coefficient of permeability over a range of depths.

GEOLOGICAL AND GEOTECHNICAL BACKGROUND

Geology and hydrogeology

The investigation site is located close to Bradwell, Essex, immediately to the south of the estuary of the River Blackwater. Earlier investigations at a nearby location, less than 1 km from the present site, have been reported by Skempton (1961), Skempton & Henkel (1960) and Skempton & La Rochelle (1965). Skempton (1961) reviewed in some detail the geology of the area, and summarized the geotechnical properties of the London Clay at the site.

Ground level lies between 0·5 m and 8·0 m above Ordnance Datum. The recent investigations have shown that the geological sequence is capped by drift deposits: recent alluvium on the lower ground, and terrace sand and gravel on the higher areas. The underlying stiff fissured London Clay becomes progressively sandier towards its base, below which it is replaced by the sandy clays, silts and sands of the Oldhaven Beds. Beneath the Oldhaven Beds there is a varied sequence of hard clays and silts with occasional sands—the Lower London Tertiaries—which rest with marked uncomformity on the Cretaceous Upper Chalk erosion surface. A major structural anomaly, presumed to be a monocline, affecting both Cretaceous and Tertiary strata and aligned 015° east of north, crosses the site at its eastern end. The general geological succession for the site as indicated by the boreholes sunk during the investigation, and by previous boreholes, is shown in Fig. 1.

Generally weathered for the top 5–8 m, the London Clay varies in thickness from 20 to 62 m, being generally thinner at the east end of the site as a consequence of the structural anomaly. The difference in thickness may be directly attributed to uplift and to greater erosion and downcutting into the London Clay surface before the deposition of the overlying Drift deposits.

Fissure and joint spacing throughout the London Clay were in the range of extremely closely to very closely spaced (i.e. up to 60 mm spacing) in the upper 25–35 m, becoming closely spaced (60–200 mm) below this depth. Subhorizontal fissures are typically more closely spaced than subvertical fissures. All fissures and joints are closed, tight and unstained below the weathered zone.

Conventional hydraulic and also Westbay system (Black *et al.*, 1986) piezometers were installed at various depths, the former in the

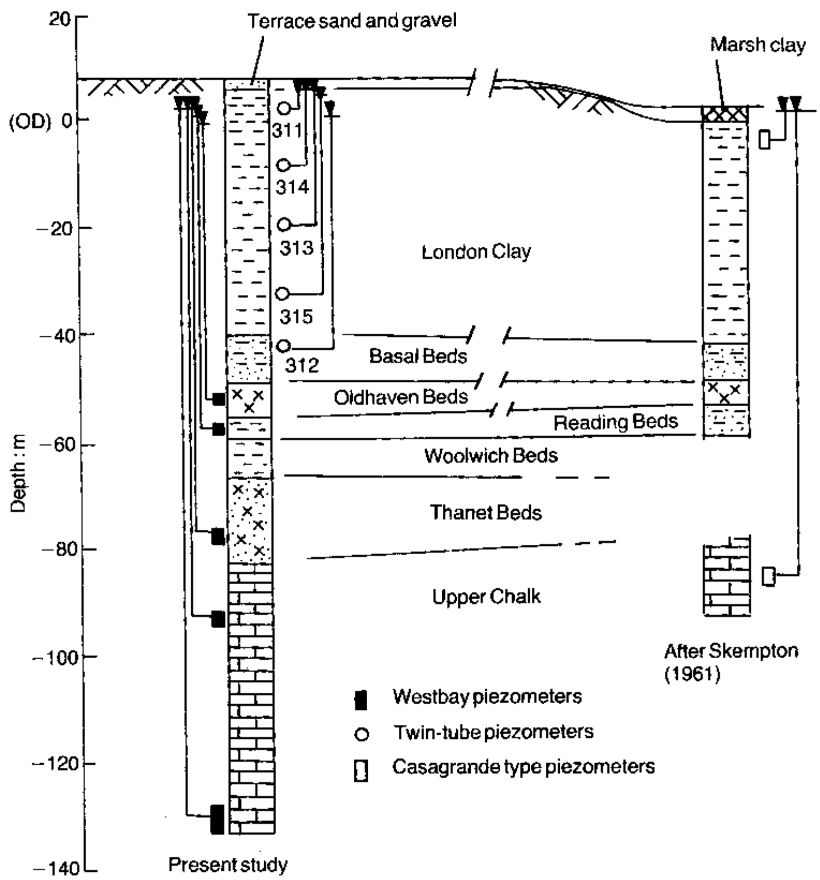

Fig. 1. Geological succession of site

London Clay, the latter in the more permeable Oldhaven Beds and deeper strata. The Westbay system consists of borehole casing with valved measurement ports at the depths at which pore pressure measurements are required. These are measured with a special probe lowered to the valve ports. A 150 mm diameter borehole was used through the London Clay, which was grouted over its full depth. The Westbay system was installed below this, in a 100 mm dia. boring, inflatable packers being used to seal the casing against the borehole walls above and below each measurement port.

All these instruments indicated piezometric levels between ground level and Ordnance Datum as shown in Fig. 1. Examination of the relative levels shows that hydrostatic conditions exist within the upper 20 m or so of the London Clay, but below that there is a small downward pressure gradient into the Oldhaven Beds, and a slight upward gradient from the Upper Chalk, again into the Oldhaven Beds. These flows are presumed to be the consequence of former water abstraction from the strata beneath the London Clay.

Similar basic conclusions regarding the geology were reached by Skempton (1961), whose findings are compared with those of the present study in Fig. 1. The only significant difference is that the profile reported by Skempton is overlain by alluvium (Marsh Clay), which is consistent with the lower ground level (a little below +2 m OD) at the location where his studies were conducted. The piezometric data reported by Skempton were obtained using Casagrande type piezometers with 9·5 mm dia. standpipes, with the piezometer tip set in 100 mm dia., 460 mm long sand pockets.

Geotechnical properties

Figure 2 shows the general geotechnical index properties of the London Clay at the site. They illustrate the remarkable uniformity of the London Clay here, particularly to depths of about 25 m. Below this, rather more scatter in the index and other properties becomes apparent. The water content profile given by Skempton (1961) is also plotted in Fig. 2; this agrees well with the present data, the only variation being near the ground surface, where the higher water contents reported by Skempton presumably reflect the lower ground surface and the presence of the alluvial Marsh Clay.

There are significant differences between the other index properties obtained in the two studies, and these are compared in Table 1. The present data are averaged over depths to −25 m OD, those from Skempton to about −30 m OD. Comparison shows that the ranges of the various properties are comparable, but that the absolute

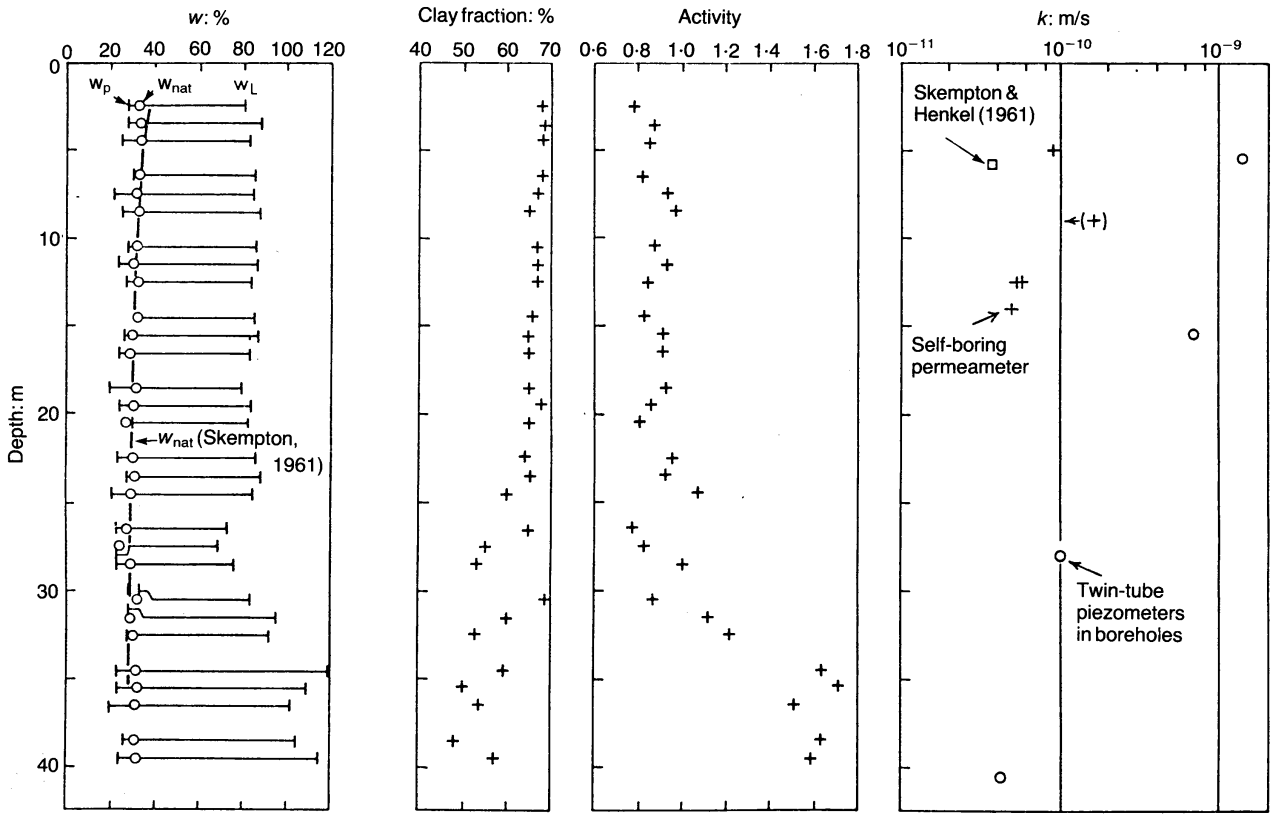

Fig. 2. Geotechnical index properties of London Clay at site

Table 1. Comparison of index properties for the London Clay at Bradwell

Property	Skempton (1961)		Present study	
	Average	Range	Average	Range
Liquid limit: %	95	90–100	85	81–88
Plastic limit: %	30	25–35	26	21–30
Plasticity index: %	65	—	59	53–64
Clay fraction: %	52	—	66	60–69
Activity	1·25	—	0·89	0·78–1·07

values of all the properties in Table 1 differ between the two studies. In particular, considerably lower values of activity were recorded in the present study. It is not immediately clear how these differences have arisen, but it may be the consequence of systematic differences between the test procedures used. For example, the specified procedures (British Standards Institute, 1961, 1975) for liquid limit tests have changed in the period between the two investigations.

Illustrated in Fig. 3 are plots of mineral content against depth for mica (illite), smectite, kaolinite/chlorite, and quartz from the London Clay and from the underlying Lower London Tertiaries. The tests were made on samples taken at 1 m intervals (or closer) from borehole 202, using X-ray diffraction techniques, and surface area measurement for the smectite. The plots again illustrate the remarkable uniformity of the London Clay.

Tables 2–4 provide detailed soil descriptions at the locations of in situ tests and sampling depths from which laboratory test specimens were obtained.

SELF-BORING PERMEAMETER TESTING

Method

The use of the self-boring technique to measure the permeability of clays in situ was first suggested by Baguelin *et al.* (1974), who saw the advantages of the method in limiting the disturbance to the soil before determining its permeability. The apparatus as initially developed had a fine-grained porous element which was consequently subject to clogging. Roctest Ltd of Montreal overcame this problem by replacing the fine-grained porous element with a perforated metal tube (Fig. 4(a)). During installation of the permeameter in the ground an internal membrane is inflated within the probe to seal the perforations; when the selected depth is reached, the membrane is deflated and the permeability test carried out. Fig. 4(b) shows the drill-bit detail.

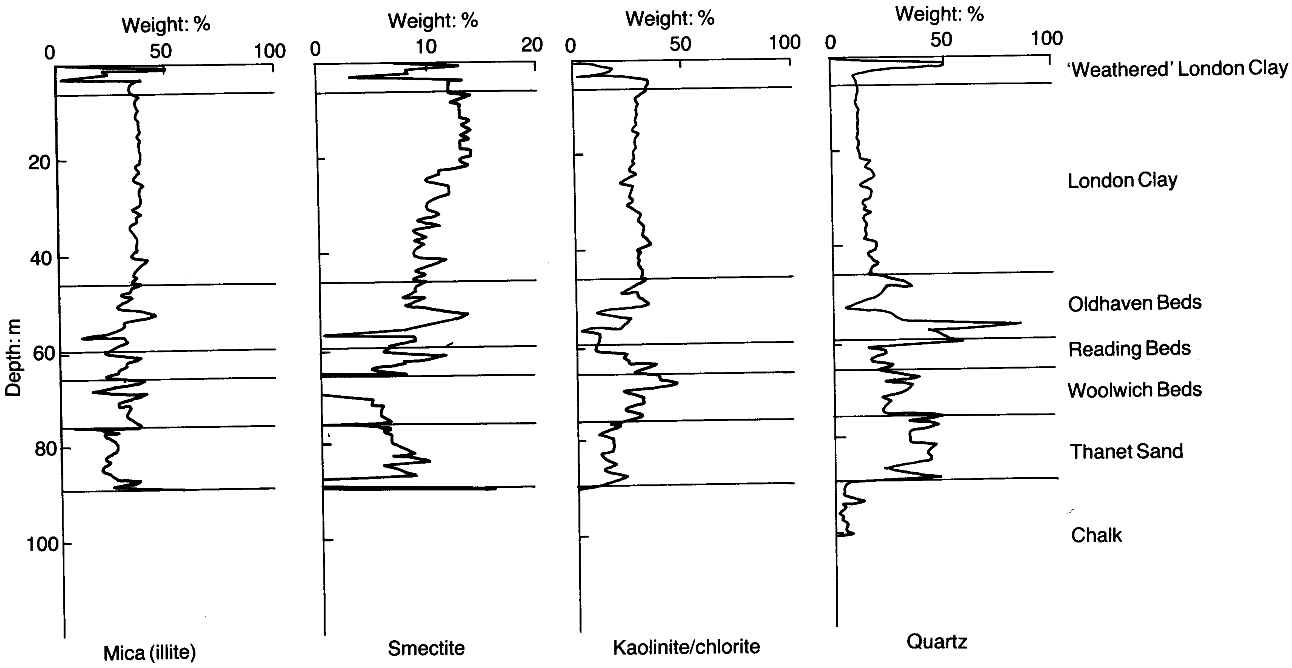

Fig. 3. Mineral content of clay samples

Table 2. Description of strata adjoining PERMAC tests, based on examination of samples from boreholes sunk about 5 m distant from PERMAC tests. Weathering zones are based on Chandler & Apted (1988)

Test depth: m	Description
5·0	Very stiff brown with occasional grey gleying fissured clay with a trace of orange-brown rootlets. Subhorizontal and subvertical fissures: planar, smooth, extremely closely spaced. Weathered London Clay (Zone II)
9·0	Very stiff grey-brown fissured clay with a trace of light grey in-filled rootlets or worm burrows. Subhorizontal and subvertical fissures: occasionally extremely closely spaced. Subhorizontal joints: smooth, planar, medium spaced; subvertical joints also probably medium to closely spaced. London Clay (Zone I)
12·5	Very stiff grey-brown fissured clay with a trace of light grey in-filled rootlets or worm burrows. Subhorizontal and subvertical fissures: planar, smooth, very closely spaced; subhorizontal fissures occasionally extremely closely spaced. Subhorizontal joints: smooth, planar, medium to closely spaced; subvertical joints also probably medium to closely spaced. London Clay (Zone I)
14·0	(as 12·5 m)

The apparatus used at Laval University and in this study, the 'PERMAC' is 73 mm in diameter (D) and has interchangeable perforated elements with lengths (L) from 73 mm to 584 mm, giving L/D ratios of 1, 2, 4 and 8. Ratios of 2 and 8 were used in this study. A detailed description of the apparatus and its operation, as well as test results on Canadian soft clays, was presented by Tavenas *et al.* (1983c, 1986).

The apparatus can be used to measure the coefficient of permeability k with either a constant or a variable head. In the present study only constant head permeability tests were carried out, using a Mariotte's bottle (Fig. 4(c)). This very simple and inexpensive item of equipment applies a constant head with an accuracy of about 1 cm of water, and is thus ideal for this purpose.

The interpretation of the constant head permeability test is based on the equation

$$k = Q_{\infty}/FH \tag{1}$$

in which Q_{∞} is the flow under steady state conditions, H the applied head of water, and F a shape factor (Hvorslev, 1951). Various shape factors have been established in the past for isotropic soils (e.g. Olson & Daniel, 1981). Shape factors appropriate to the PERMAC apparatus (a cylindrical porous element extended above and below by impervious segments) have been established for isotropic soils by Tavenas *et al.* (1989) using finite element methods, and have been confirmed experimentally. The same methods were used by Diene (1989) to obtain shape factors for use with anisotropic soils. This method gives shape factors $F = 0{\cdot}53$ for $L/D = 2$ and $1{\cdot}29$ for $L/D = 8$. In computing these shape factors D is taken as 73 mm, and the ratio of horizontal to vertical permeability in situ, $r_k(=k_{h0}/k_{v0})$ is assumed to be 2; this latter value was obtained in the laboratory, as discussed below. For comparison, the corresponding values of F obtained using the expression proposed by Brand & Premchitt (1980) for isotropic soils are 0·68 and 1·49.

Aspects of testing in London Clay

The PERMAC apparatus has been used successfully at Laval University since 1982, but always in soft sensitive clays having coefficients of permeability of the order of 10^{-9} m/s. In contrast, the London Clay at Bradwell is stiff to very stiff, with a liquidity index approaching zero and a much lower permeability. For example, La Rochelle (1960) and Skempton & Henkel (1960) reported $k = 3{\cdot}7 \times 10^{-11}$ m/s for the London Clay at Bradwell. The combination of the stiffness of the clay and its low permeability requires particular care to be taken during permeability testing.

Considerable experience has been gained with the use of self-boring techniques in stiff clay, and in particular in the London Clay (Wroth & Hughes, 1974; Windle & Wroth, 1977), and, accordingly, modifications were made to the PERMAC apparatus. A drill bit similar to the one suggested by Wroth and his co-workers was used (Fig. 4(b)), and heavy sections were used for the rods and thrust tubes. In order to minimize vibration, as well as to prevent buckling of the rods and thrust tubes, and also to ensure vertical installation of the permeameter, annular packing pieces were used to guide both the rods within the thrust tubes and the thrust tubes within the borehole casing. The borehole was drilled by standard cable percussion methods using a clay cutter, casing being taken down to about 2 m above the depth selected for the permeability test, after which the self-boring permeameter was inserted below the base of the borehole to the test

Table 3. Description of London Clay at depths of conventional in situ permeability tests. Weathering zones based on Chandler & Apted (1988)

Borehole	Test depth: m	Description
311	5·0	Stiff brown fissured clay with occasional grey gleying and rootlets. Subhorizontal and subvertical fissures: planar, smooth, extremely closely to very closely spaced. Weathered London Clay (Zone II)
314	15·0	Very stiff grey-brown clay with occasional light grey gleying; some in-filled rootlets or worm burrows. Subhorizontal and subvertical fissures: planar, smooth, very closely to closely spaced. London Clay (Zone I)
313	27·5	Very stiff grey-brown clay with rare to occasional light grey in-filled rootlets or worm burrows and light brown silt partings. Subhorizontal and subvertical fissures: planar, smooth, extremely closely to very closely spaced. London Clay (Zone I)
315	39·8	Very stiff dark grey-brown clay with occasional light brown silt partings. Subhorizontal and subvertical fissures: planar, smooth, extremely closely spaced. London Clay (Zone I)
312	49·6	Very stiff, grey-brown, very silty clay with frequent light brown sandy silt lenses. Subhorizontal and subvertical fissures: planar, rough, extremely closely to very closely spaced. London Clay (Zone I)

Table 4. Description of material at test depth, based on boreholes sunk 5–10 m from borehole 822. Weathering zones based on Chandler & Apted (1988)

Depth of sample: m	Description of material
4	Very stiff brown clay with occasional grey gleying and light brown rootlets, Lithorelicts 20–30 mm in size. Weathered London Clay (Zone IIIA)
10	Very stiff grey-brown fissured clay with a trace of light grey in-filled rootlets or worm burrows. Subvertical and subhorizontal fissures: planar, smooth, very closely spaced. London Clay (Zone I)
14	As above, but also with medium to closely spaced smooth, planar subhorizontal and probably subvertical joints. (Zone I)
20	Very stiff dark grey-brown clay, fissures with occasional light grey in-filled rootlets or worm burrows. Subhorizontal and subvertical fissures: very closely spaced, smooth, planar. Subhorizontal and probably subvertical joints: medium to closely spaced, smooth, planar. (Zone I)

depth. The permeability test was generally started the following day.

The low permeability of the London Clay resulted in a correspondingly small rate of flow. It was therefore necessary to ensure that the volume changes measured with the Mariotte's bottle were corrected both for the compressibility of the system and for temperature effects. To this end, a second Mariotte's bottle was mounted adjacent to the first, but with its connecting plastic tube sealed at its lower end. The variations of water level in this second Mariotte's bottle were used to correct the volume change observed in the permeability measurement device. Typically, the total volume changes recorded on the second 'dummy' bottle were less than 2 cm^3 over a period of two days, much of this occurring in the first 100 min, where it plays little or no part in the interpretation of the test. Laboratory calibrations suggest that most of the observed initial volume change results from the presence of small air bubbles. In the worst case (with the measuring element having $L/D = 2$) the correction was less than 10% of the nominal flow rate once the first 100 min had passed. After correcting the measured flow Q in this manner, Q_∞ may be computed from a plot of total Q versus time (Fig. 5). Alternatively, and more satisfactorily, Q_∞ may be determined from a plot of flow rate versus $1/t^{1/2}$, where t is time. As has long been recognized

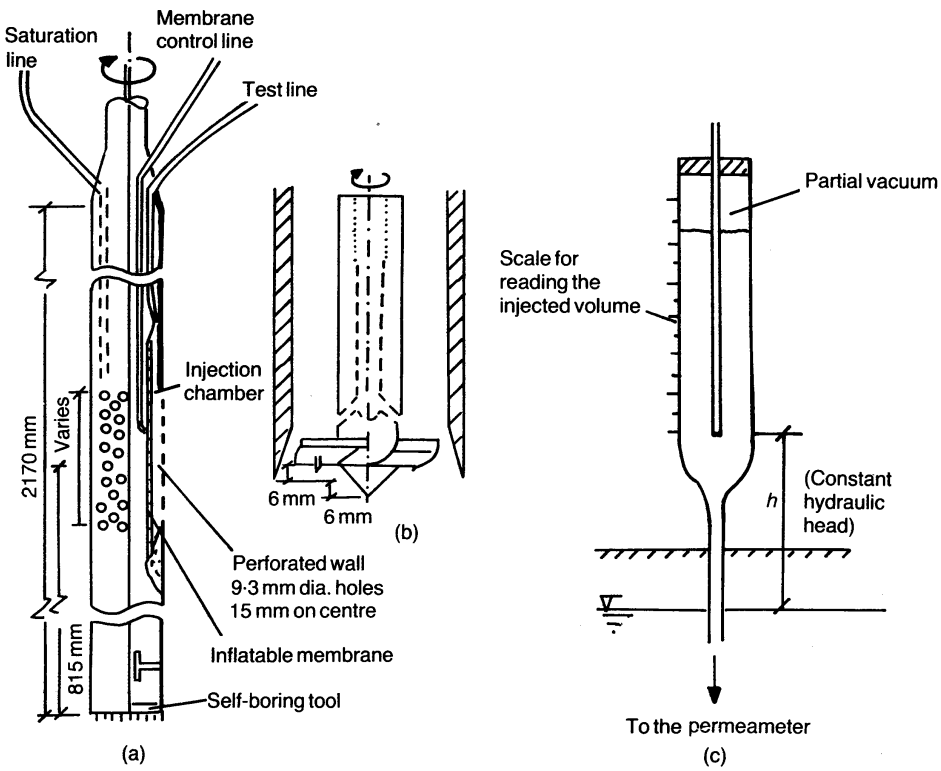

Fig. 4. Self-boring permeameter: (a) apparatus; (b) detail of drill bit; (c) Mariotte's bottle

(Gibson, 1963), the advantage of the latter plot is that extrapolation to $1/t^{1/2} = 0$ enables a reasonable estimate to be made of Q_∞. This method has been used here (Fig. 6).

Test programme and results

Five constant-head in situ permeability tests were carried out with the PERMAC apparatus, in two adjacent borings; an L/D ratio of 8 was used at depths of 5 m, 12·5 m and 14 m, while $L/D = 2$ was used at depths of 9 m and 12·5 m. A water level at an elevation of 5·85 m OD was observed within the borehole casing, corresponding to the water table in the terrace sands and gravels. Noting that the piezometric data in the London

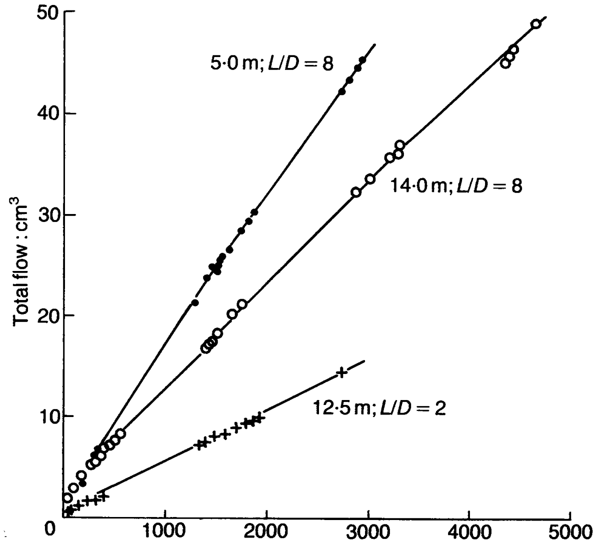

Fig. 5. Measured flow Q versus time

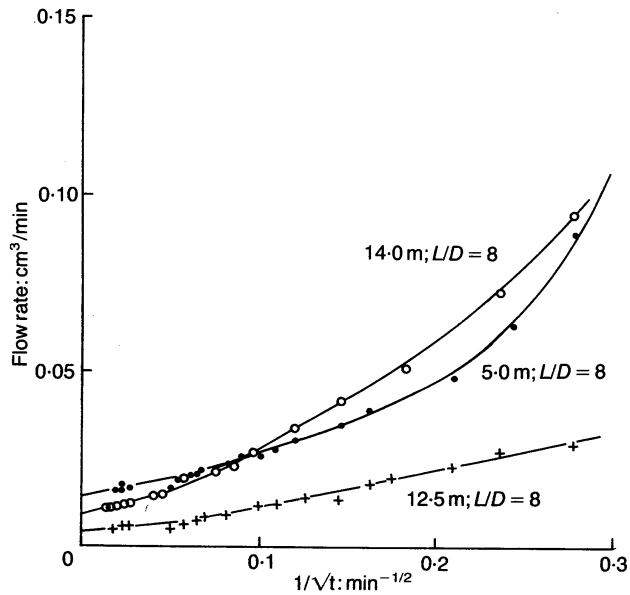

Fig. 6. Flow rate versus $1/t^{1/2}$

Clay at the appropriate depths indicated hydrostatic conditions, the excess head of water of 1·95 m, which was applied in all tests, was easily determined. The tests took 2–3 days each to complete; descriptions of the soil at the test depths are given in Table 2.

Figure 5 shows test results obtained at depths of 5 m, 12·5 m and 14 m, with permeameters having L/D ratios of 8, 2 and 8 respectively. It proved impossible to evaluate Q_∞ on the basis of transient flow. On the other hand, the estimation of Q_∞ by extrapolation of the $1/t^{1/2}$ plot was straightforward. The values of k_h obtained in this manner for all five tests are listed in Table 5, and are shown in Fig. 7. Except for the test at 9 m, the coefficient of permeability decreased with depth from $9{\cdot}3 \times 10^{11}$ m/s at 5 m to $5{\cdot}0 \times 10^{-11}$ m/s at 14 m.

Table 5. Summary of conventional in situ permeability determinations (boreholes 311–315) and self-boring tests (boreholes 851–852)

Borehole	Depth: m	L/D	Shape factor: m	k: m/s
311	5·5	6·67	2·73	$1{\cdot}4 \times 10^{-9}$
312	51·0	19·67	5·74	$1{\cdot}1 \times 10^{-9}$
313	28·0	5·00	3·06	$1{\cdot}0 \times 10^{-10}$
314	15·7	5·50	3·24	$6{\cdot}6 \times 10^{-10}$
315	40·5	6·75	3·67	$4{\cdot}3 \times 10^{-11}$
851	5·0	8	1·29	$9{\cdot}3 \times 10^{-11}$
	9·0	2	0·53	$(1{\cdot}6 \times 10^{-10})$
	12·5	2	0·53	$5{\cdot}6 \times 10^{-11}$
852	12·5	8	1·29	$5{\cdot}3 \times 10^{-11}$
	14·0	8	1·29	$5{\cdot}0 \times 10^{-11}$

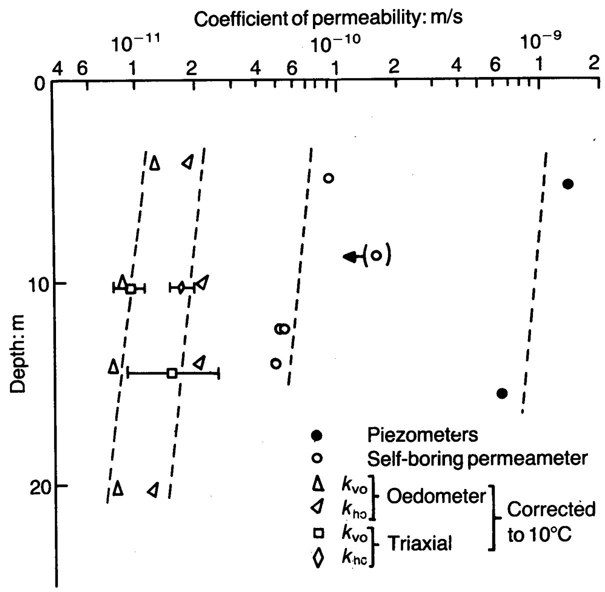

Fig. 7. Measured coefficients of permeability

The test performed at 9 m apparently yielded a rather higher value of k_h. However, this test is believed to have been unsatisfactory for the following reasons. There is a risk with this model of self-boring permeameter that there could be upward leakage along the length of the permeameter. In such a case, the flow would be controlled by the head of water between the Mariotte's bottle and the water level in the casing, resulting in a calculated permeability higher than the correct value for the soil.

In order to check if there was indeed leakage of water past the permeameter, the water level within the borehole casing was increased by about 1 m, thus decreasing the head of water applied by the Mariotte's bottle by a factor of about 2. This water level change was applied about one day after the start of each test. In four of the tests there was no change in the flow rate, but in the test at 9 m the measured flow rate was approximately halved. Clearly in this test the seal was unsatisfactory, and the calculated permeability must have been incorrect.

Finally, it should be noted that the two tests performed at a depth of 12·5 m with L/D ratios of 2 and 8 yielded very similar values of k_h, helping to confirm the appropriateness of the shape factors that were used.

OTHER IN SITU PERMEABILITY MEASUREMENTS

Five constant head 'in-flow' in situ permeability determinations were carried out in a group of closely spaced borings, designated Nos 311–315, situated about 400 m from the site of the self-boring permeameter tests. Twin-tube low air-entry piezometers were used, installed in sand pockets, each at the base of a separate boring. They are shown at the appropriate depths, together with their equilibrium piezometric levels, in Fig. 1. The deepest (No. 312) was in the sandy Oldhaven Beds, but the remaining four were within the London Clay, although spaced over a range of depths down to 40 m. A description of the clay at the relevant depths is given in Table 3.

Of these four piezometers, the shallowest was in a 0·15 m dia. boring and the remainder in 0·20 m dia. borings, all drilled using cable percussion techniques. Sand pockets surrounded the piezometer tips, the lengths of which were between 1·0 m and 1·35 m, giving L/D ratios of 5·0–6·7. The sand pockets were sealed using bentonite pellets, which were allowed time to swell before the remainder of the borehole was backfilled with a bentonite/cement grout.

Following installation, equalization appeared to be complete after a period of about two months; it is interesting to note that a similar response time of about 60 days was recorded by Skempton & Henkel (1961) for their piezometer at Bradwell. The permeability tests were then carried out, again using the constant head technique. Excess heads in the range 1·85–3·15 m were used, with larger heads being applied to the deeper piezometers. The tests were carried out over a period of 2–3 working days; as with the PERMAC tests Q_∞ was determined by plotting flow rate against $1/t^{1/2}$. Shape factors were computed from Brand & Premchitt's (1980) formula, yielding values in the range 2·73–3·67 m. Shape factors for anisotropic soils (Diene, 1989) would have been smaller by 15–20%, yielding correspondingly higher permeabilities.

The coefficients of permeability obtained in this manner ranged from $1{\cdot}4 \times 10^{-9}$ m/s at a depth of 5·5 m to $4{\cdot}3 \times 10^{-11}$ at 40·5 m. As will be seen from both Figs 2 and 7, and from Table 5, these permeabilities are considerably higher than were obtained from tests using the self-boring permeameters.

LABORATORY PERMEABILITY TESTS

Four U100 open-drive samples from a borehole (No. 822) adjacent to the site of the PERMAC tests, taken from depths of 4, 10, 14 and 20 m were used for laboratory permeability determinations. Ten tests were carried out at Laval University: eight oedometer cell tests, four on vertical and four on horizontal samples; and two triaxial cell tests, one on a specimen trimmed horizontally, one trimmed vertically. The samples (still in their sampling tubes) were transported by air to Laval without any apparent disturbance problems. A further triaxial cell test was carried out at the City University. A summary of these tests is given in Table 6; a constant head was applied in all tests. A description of the clay at the sample depths is given in Table 4.

Oedometer cell tests

The oedometer specimens were 50·8 mm dia. and 19 mm high; they were installed in special cells connected at the bottom to a device applying a constant head of water, thus allowing the direct measurement of the coefficient of permeability (Tavenas *et al.*, 1983b). In the present study, a constant head was applied using a Mariotte's bottle. The specimens were loaded to a vertical stress approximately equal to the vertical effective stress and, after equalization, a permeability test was performed. The vertical stress on the specimen was then increased in steps as in the conventional oedometer tests, and the permeability was determined at different void ratios, following equalization at each applied load. Vertical permeability determinations made at void ratios of 0·87 and 0·68 on a specimen taken from 4·1 m depth are shown in Fig. 8; the volume change versus time relationships are reasonably linear, and allow the determination of k_v values.

The logarithm of the permeability versus void ratio relationships obtained from specimens taken at 4·1 m depth and trimmed both horizontally and vertically are shown in Fig. 9. It is interesting to note that these relationships are approximately linear in the void ratio range studied, and that the slope $C_k = \Delta e/\Delta \lg(k)$ is, for the vertical permeability, about 0·42, and thus is approximately equal to $0{\cdot}5e_0$. This is in agreement with the relationship $C_k = 0{\cdot}5e_0$ obtained by Tavenas *et al.* (1983a) for soft clays (Fig. 10).

The vertical permeability corresponding to the initial void ratio of each of the samples (k_{v0}) was found to decrease from $1{\cdot}4 \times 10^{-11}$ m/s at 4 m to

Table 6. Summary of laboratory permeability tests

Depth: m	Type of test	Hydraulic gradient, i	e_0*	k_0: 10^{-11} m/s
4·06	k_v, oedometer	52	0·87	1·4
4·13	k_h, oedometer	52	0·89	2·4
10·13	k_h, oedometer	52	0·82	2·8
10·19	k_v, oedometer	52	0·82	1·1
10·29	k_h, triaxial	30	0·84	1·95–2·55
10·35	k_v, triaxial	30	0·83	1·07–1·46
14·08	k_v, oedometer	52	0·83	1·0
14·12	k_h, oedometer	52	0·84	2·7
14·50	k_v, triaxial†	50	0·83	1·2–3·4
20·20	k_h, oedometer	52	0·81	1·5
20·26	k_v, oedometer	52	0·85	1·0

* Void ratios were calculated assuming $S = 1{\cdot}0$, and using $G = 2{\cdot}72$; permeability was measured at a temperature of 20°C
† Test at City University

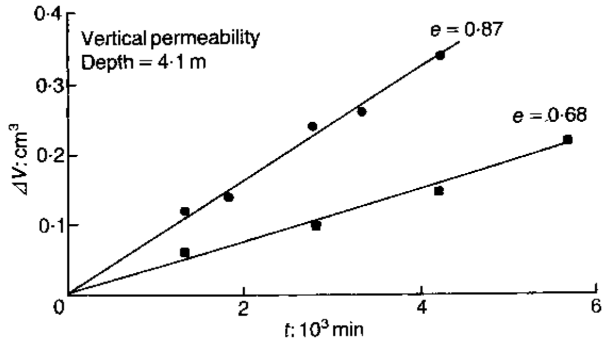

Fig. 8. Vertical permeability determinations from oedometer cell test

$1{\cdot}0 \times 10^{-11}$ m/s at 20 m. The values of k_{h0} obtained vary from $2{\cdot}8 \times 10^{-11}$ m/s to $1{\cdot}5 \times 10^{-11}$ m/s; they indicate an anisotropy ratio r_k varying from 1·4 to 2·7, with an average value of 2·1.

For comparison with the in situ determinations of permeability (Fig. 7) using the PERMAC apparatus, the foregoing laboratory values of per-

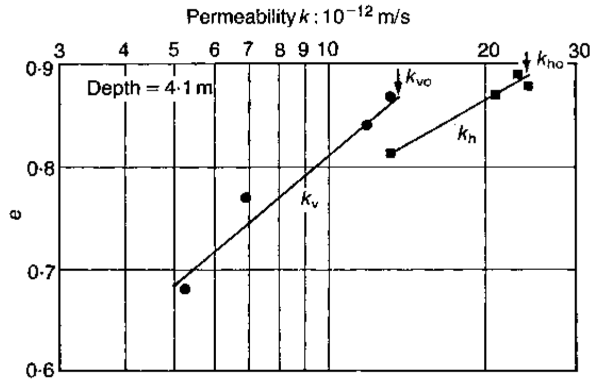

Fig. 9. Logarithm of permeability versus void ratio relationships

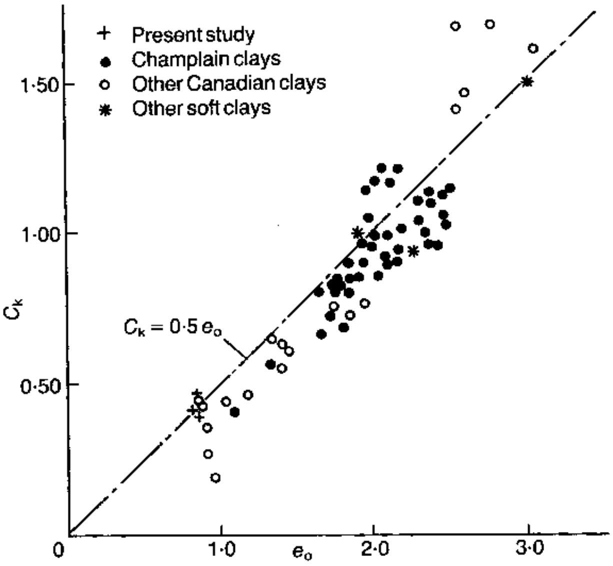

Fig. 10. Variation of C_k with e_0 for various clays

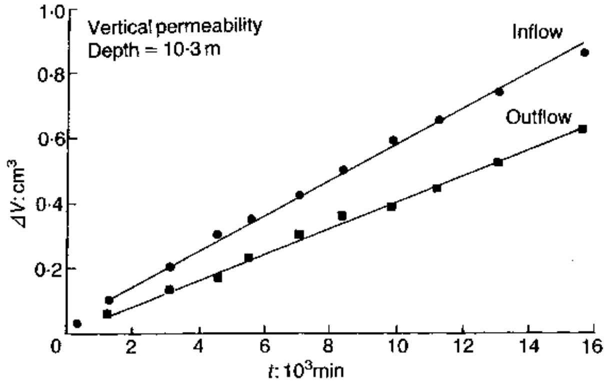

Fig. 11. Vertical permeability determinations from triaxial cell test

meability have been divided by a factor of 1·3. This is to allow for the effects of temperature on permeability, since the laboratory tests were carried out at 20°C, while in situ the ground temperature is assumed to have been about 10°C.

Triaxial cell tests

Two constant-head permeability tests were carried out in a triaxial cell designed for this purpose (Tavenas *et al.*, 1983b). The test specimens were taken from borehole No. 822 from a depth of 10 m; one was trimmed so as to measure the vertical permeability, the other to measure the horizontal permeability. They were 50·8 mm dia. and 50·8 mm high, and were initially consolidated under an isotropic effective stress equal to 164 kPa ($1{\cdot}86\sigma_{v0}'$), and then submitted to a permeability test using an hydraulic gradient of 30.

The results of the vertical permeability test are shown in Fig. 11. They show a difference between the inflow and the outflow of 0·2 cm³ in 10 days, which can be attributed to slight swelling of the sample or a small leakage of the system. The inflow and outflow relationships give coefficients of permeability of $1{\cdot}46 \times 10^{-11}$ m/s and $1{\cdot}07 \times 10^{-11}$ m/s respectively. The corresponding measured values of horizontal permeability were $2{\cdot}55 \times 10^{-11}$ m/s and $1{\cdot}95 \times 10^{-11}$ m/s. Both values have been plotted in Fig. 7, again corrected for temperature; they show excellent agreement with the values measured in the oedometer cells.

DISCUSSION

Comparison with other London Clay results

The coefficient of permeability quoted by Skempton & Henkel (1960) for the London Clay at Bradwell was a little lower than that obtained in the tests with the PERMAC apparatus (Fig. 2). This result was for a rising head test (Hvorslev, 1951) on a piezometer at a depth of 6 m, which gave $k = 3{\cdot}7 \times 10^{-11}$ m/s. This result should not be compared directly with those of the present study, since the different measurement and calculation techniques may yield somewhat different values for the coefficient of permeability. Rising head tests were not used in the recent investigation, so a direct comparison cannot be made.

Skempton & Henkel also carried out laboratory permeability tests on six samples from depths similar to those used in their in situ determination; these gave values of k varying from 2×10^{-11} to 7×10^{-11} m/s, with an average of $4{\cdot}5 \times 10^{-11}$ m/s.

In situ measurements of the permeability of London Clay were also reported by Garga (1988) (Note that Garga's quoted values of the coefficient of permeability are all over-estimated by 10^4). These were conventional constant-head borehole piezometer tests at depths to 12·8 m, carried out in unweathered 'blue' London Clay at Wraysbury, Middlesex, having the following index properties: liquid limit 72%, plastic limit 20% and clay fraction 57%. This is less plastic than the London Clay at Bradwell. There is no record of the time required for equalization of pore pressures before beginning the test, but the tests themselves were carefully carried out, each being kept running for about four months. Garga observes that if the tests had been terminated after two weeks, the permeability values would have been overestimated by 20–30%.

Garga's four in situ tests yielded values of the coefficient of permeability in the range $3{\cdot}4 \times 10^{-10}$–$2{\cdot}0 \times 10^{-11}$ m/s, decreasing with depth. He also determined the coefficient of permeability of laboratory samples, but only indirectly from triaxial dissipation and oedometer consolidation tests. Allowing for differences in the techniques used and the inherent variations between sites, these permeability determinations are comparable with those made at Bradwell.

In the present study, laboratory samples tested at in situ void ratios (but at 20°C) gave values of the vertical permeability k_{v0} from $1{\cdot}0 \times 10^{-11}$ m/s to $1{\cdot}4 \times 10^{-11}$ m/s. The corresponding horizontal permeability k_{h0} varied between $1{\cdot}5 \times 10^{-11}$ and $2{\cdot}8 \times 10^{-11}$ m/s, indicating an average permeability ratio r_k of 2·1. These r_k values are higher than those found in soft marine clays, which are typically about 1·1 (Larsson, 1981; Tavenas *et al.*, 1983a). The higher values of r_k for London Clay can be explained by the structural anisotropy resulting from its comparatively high degree of overconsolidation.

The coefficient of permeability measured with the self-boring permeameter at Bradwell varied from 5·0 to $9{\cdot}3 \times 10^{-11}$ m/s. This permeability has been calculated assuming an r_k value of 2, and is thus an estimate of the horizontal permeability. As will be seen from Fig. 7, when appropriate temperature corrections are made the permeability measured in situ is four times the horizontal permeability measured in the laboratory. A broadly similar conclusion may be reached from Garga's results.

In situ permeability measurement techniques

The conventional in situ tests at Bradwell, although also showing a decrease in the coefficient of permeability with depth, gave values almost exactly an order of magnitude higher than did the self-boring permeameter. It is not immediately apparent why this should be so, but there are several possible reasons.

(*a*) Conventional drilling causes stress relief, which makes it necessary to ensure pore pressure equalization in the ground around the piezometer before starting the test. Subsequent equalization can take weeks, if not months, in London Clay; once it is complete, the ground immediately surrounding the piezometer is at a lower effective stress, with a consequent increased permeability. This effect will be enhanced if it is accompanied by the opening of joints and fissures.

(*b*) An inadequate piezometer seal.

(*c*) The use of bentonite pellets as a borehole seal may result in some of the apparent flow being the consequence of further hydration of the bentonite. This is most likely to occur when, as in the present case, the test is carried out by increasing the head.

(*d*) Garga's (1988) observation that a substantial time period is required in London Clay to achieve steady state flow indicates the care that is required in extrapolating the Q versus $1/t^{1/2}$ plot in order to estimate the permeability accurately. Although this point applies to both types of permeability test, the larger diameter of the conventional test borehole renders this test the more likely to overestimate the magnitude of the coefficient of permeability.

There thus appear to be a number of advantages in using the self-boring permeameter rather than making conventional borehole in situ permeability measurements. The major benefit is that the permeameter is installed with the minimum of disturbance to either the fabric of the soil, or to the in situ stresses. As a consequence, smear effects may be expected to be minimal, and, more importantly, stress changes are similarly minimal. Consequently the test may be started shortly after installation of the permeameter.

As has been seen, a drawback of the PERMAC apparatus is that upward leakage may occur past the permeameter. It is, however, easy to check that leakage is not occurring. Leakage has not been observed when the PERMAC apparatus has been used in soft clays.

CONCLUSIONS

The self-boring permeameter (PERMAC) can be used to carry out constant-head permeability tests in stiff clays. The advantages of the self-boring permeameter over the conventional borehole constant-head piezometer test are that both smear and the need for pore pressure equalization before testing are minimized, and the adequacy of the seal in the ground may be easily checked.

At Bradwell, laboratory tests carried out on the London Clay at effective stresses close to in situ values show that the ratio of horizontal to vertical permeability, r_k, is about 2. The self-boring permeameter yielded coefficients of horizontal permeability about four times those measured at corresponding void ratios in 51 mm dia. laboratory specimens.

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