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A field permeability measurement technique using a conventional self-boring pressuremeter

S. RATNAM*, K. SOGA† and R. W. WHITTLE‡

A new permeability measurement method using a conventional self-boring pressuremeter (SBP) is described. The SBP self-bores to a predetermined depth. It is then retracted a short way, leaving a well-defined cavity in the ground. Water is pumped into the cavity at a constant rate, and the permeability is derived from the change in injection pressure with injection flow rate. A sequence of tests at a given horizon involves cavities of varying lengths, including a flush bottom or zero length cavity. In homogeneous materials the data from variable cavity lengths can be used to determine the anisotropy ratio. In heterogeneous materials the same data may allow the scale dependence to be evaluated if the anisotropy ratio can be independently obtained. Potential measurement errors are discussed in relation to smearing, temperature effects and leakage along the instrument. Results from Gault clay, London clay and Bothkennar clay are presented, with corroborating laboratory and other field test results where available. The preliminary assessment of scale dependence at these sites corresponds well to the degree of heterogeneity identified for the tested clays through visual observation.

KEYWORDS: clays; *in situ* testing; permeability; site investigation

Nous décrivons une nouvelle méthode de mesurage de la perméabilité utilisant un pressiomètre conventionnel auto-forant (SBP). Le SBP fore à une profondeur prédéterminée. Il est alors rétracté sur une courte longueur, laissant une cavité bien définie dans le sol. L'eau est pompée dans cette cavité à un débit constant et la perméabilité est dérivée du changement de la pression d'injection selon les débits d'injection. Une séquence d'essais sur un horizon donné est réalisée sur des cavités de diverses longueurs, dont une cavité de fond ou de longueur zéro. Dans les matériaux homogènes, les données des longueurs variables de cavité peuvent être utilisées pour déterminer le taux d'anisotropie. Dans les matériaux hétérogènes, les mêmes données peuvent permettre d'évaluer la dépendance d'échelle si le taux d'anisotropie peut être obtenu de manière indépendante. Nous examinons les erreurs potentielles de mesurage par rapport à la rémanence, aux effets des températures et des fuites le long de l'instrument. Nous présentons les résultats obtenus sur de l'argile de Gault, de l'argile de Londres et de l'argile de Bothkennar, ainsi que les résultats corroborants d'essais en laboratoire et sur d'autres terrains. L'évaluation préliminaire de la dépendance d'échelle sur ces sites correspond bien au degré d'hétérogénéité identifié pour les argiles testées au moyen d'une observation visuelle.

INTRODUCTION

The build-up and dissipation of pore water pressures is an important soil behaviour characteristic, influencing the movement of geotechnical structures during and after construction. To estimate this time-dependent behaviour the permeability of the underlying material must be estimated, either from testing samples in the laboratory or from measurements in the field.

Soil deposits are typically inhomogeneous, stratified on the larger geologic scale and non-uniform on a smaller scale owing to features such as fissures and joints. The permeability can be scale-dependent, and it is difficult to represent all *in situ* features in a standard triaxial test given the small specimen size. Among the drawbacks to laboratory testing is the tendency to select the most uniform or most clayey samples, as they are easier to trim (Olson & Daniel, 1981).

Although laboratory tests do not in general take account of *in situ* features or stress states, they do allow the investigation of intrinsic properties. They are suited for testing relatively homogeneous natural deposits and engineered soils, and for performing comparative, pilot studies. They can also simulate the load conditions of final works, and indicate the influence of effective stress changes.

The advantage of *in situ* permeability testing is the potential for testing a representative volume of soil in an appropriate stress state. Typically, a hole is formed in the ground and a test is conducted either by using the same device that created the cavity (e.g. driven piezometers, cone penetrometer) or by inserting another device into the borehole (e.g. standpipe piezometers, packer tests). However, excessive disturbance will significantly alter the stress conditions around the test zone, and smearing of the material can mask the influence of layering or other fine features.

The self-boring technique (Baguelin *et al.*, 1972; Wroth & Hughes, 1972) can reduce the effects of soil disturbance and smear to a negligible level. A volume of soil equal to that of the instrument is slurried and flows up to the surface as the cavity is bored. Disturbance is confined to a thin zone of sheared material immediately adjacent to the probe, typically $< 1\%$ of the probe diameter (Hughes, 1973). An important advantage of self-boring is the well-defined test cavity shape, or geometry.

In situ permeability can be measured directly or assessed indirectly. Direct methods permeate fluid into the surrounding soil. Indirect techniques monitor the dissipation of excess pore pressure in the ground after expanding a cavity—for example the self-boring pressuremeter holding test (Clarke *et al.*, 1979) or the cone dissipation test. Direct permeability measurement using dedicated self-boring permeameter devices has been demonstrated by Baguelin & Jezequel (1974), Tavenas *et al.*

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(1983), Leroueil *et al.* (1992), Harwood *et al.* (1995), Znidarcic & Piccoli (1995) and Cambridge Insitu (1998).

This paper describes an 'add-on' to a conventional self-boring expansion pressuremeter (SBP) with an 87 mm diameter (D). The technique involves first self-boring to a predetermined test depth. Clean water is circulated through the SBP drill string to flush out all cuttings, and the SBP is then retracted a short way. This leaves a well-defined cavity in the ground (Fig. 1) with the top of the cavity sealed to the body of the instrument. At this stage a cavity expansion test can be carried out to obtain values for *in situ* stress, stiffness and strength. Thereafter water is pumped into the cavity below the probe via the drill string (Fig. 2), and the surrounding material is permeated. A sequence of tests at a given horizon involves cavities of varying lengths L including a flush bottom or zero length cavity. Because the geometry or L/D ratio under test always has a vertical flow component, the coefficient of permeability obtained is k_m, the mean permeability. Higher L/D ratios have a greater horizontal flow component compared with the vertical, and in homogeneous materials reconciling the effect of variable cavity length allows the anisotropy ratio R_k to be evaluated and hence k_v and k_h. In heterogeneous materials the anisotropy effect is masked by the influence of scale, and this paper demonstrates how the technique provides critical information for scale effects on measured permeability if R_k is obtained independently from laboratory testing.

Results from several stiff and soft clays sites using this new technique are presented, with corroborating laboratory and other field test results where available.

PERMEABILITY MEASUREMENT SYSTEM

A schematic of the new system is given in Fig. 2. The permeability components are independent of the SBP and associated equipment, utilising the self-boring system only as a means for obtaining a sealed path to an undisturbed cavity.

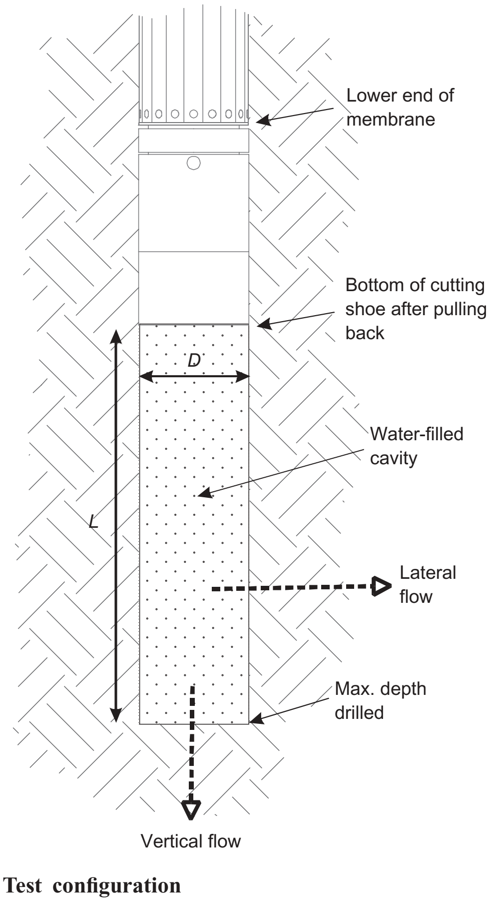

Fig. 1. Test configuration

After self-boring, there is a passage from the bottom of the instrument to the surface via the casing/inner rods (the drill string). To carry out permeability testing an adapter is fixed to the top of the drill string that seals it and provides an injection point. Fluid is delivered to the tip of the instrument via the same pathway by which the drilling fluid is delivered during self-boring, the difference being that for permeability testing the flow is in one direction. Water is supplied along this pathway at a constant flow rate using a stepper-motor-driven syringe pump located at the ground surface.

A flow control unit (FCU) is used to specify the required flow rate. This technique has been applied in the laboratory (Olsen *et al.*, 1991; Aiban & Znidarcic, 1989), but its use in the field was pioneered by Znidarcic & Piccoli (1995). Applying a constant flow rather than a constant head to low-permeability materials drastically reduces the test time, because changes in pressure are more easily measured than changes in flow. The response time for both tests is a function of the same seepage-induced consolidation, and hence the measured permeability is the same, as identical conditions are imposed on the soil (Aiban & Znidarcic, 1989).

The flow pump consists of two 30 ml medical syringes driven by a stepper motor in a push–pull arrangement. As one injects fluid, the other is being filled from a reservoir, so there are no pauses during a test to refill syringes. The flow rate is governed by the speed of pulses delivered to the stepper motor, and this is set by the FCU, where flows from 0·1 to 999 ml/h can be entered on a keypad. The delivery system is inherently accurate as it is driven by an electronic clock but has also been checked against a precision mechanical flow pump under laboratory conditions. Pressure in the system is measured at surface using a transducer with a resolution of at least 0·1 kPa. Time, flow rate, pressure and temperature are logged and plotted on a laptop computer using proprietary software.

The system must be de-aired before starting, and an automatic de-airing vent is fitted that releases any residual air in the system while maintaining the pressure during the test (Fig. 3(a)). It must also be shown that the system does not leak before being put in the ground. To check this, the SBP lower end is closed off, the pipework is filled with water, and the equipment is connected to the constant-flow pump. A proving test is run on the surface to demonstrate that even at the lowest flow rate the pressure in the system is still climbing. Once in the ground the only other potential leakage path is via the joints of the drill string. A drill string incorporating a double 'O' ring seal is used to avoid this (Fig. 3(b)).

TEST PROCEDURE

In principle a test is run by setting a modest flow rate (5 or 10 ml/h in a clayey material) and monitoring the response until an apparently stable pressure condition (i.e. pseudo-steady-state flow) is achieved. For tests in the field a satisfactory state means $\Delta P/\Delta t \approx 0$ while the test is observed for a minimum period of 5 min.

In practice the test is accelerated by manipulating the flow rate to save time in reaching the pseudo-steady-state condition corresponding to the flow rate of interest. The user first estimates the acceptable pressure range, based on the need to avoid fracturing the material under steady-state seepage condition (Bjerrum *et al.*, 1972). A brisk flow rate is set that raises the pressure quickly. The flow rate is then reduced to

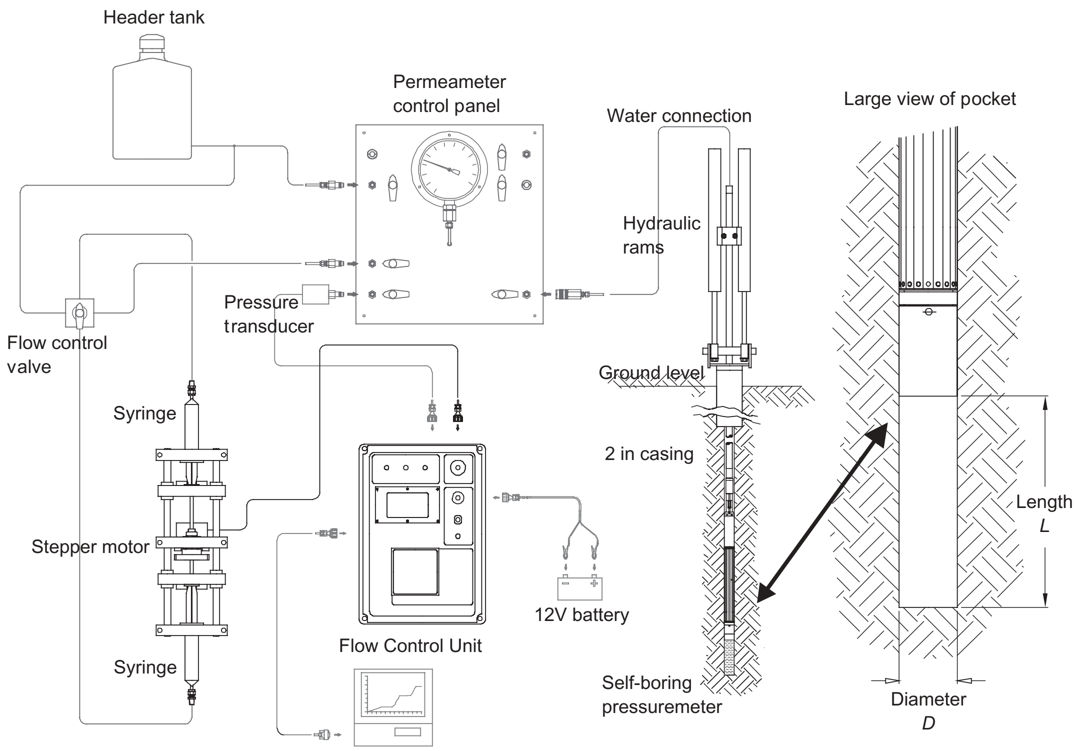

Fig. 2. Testing system

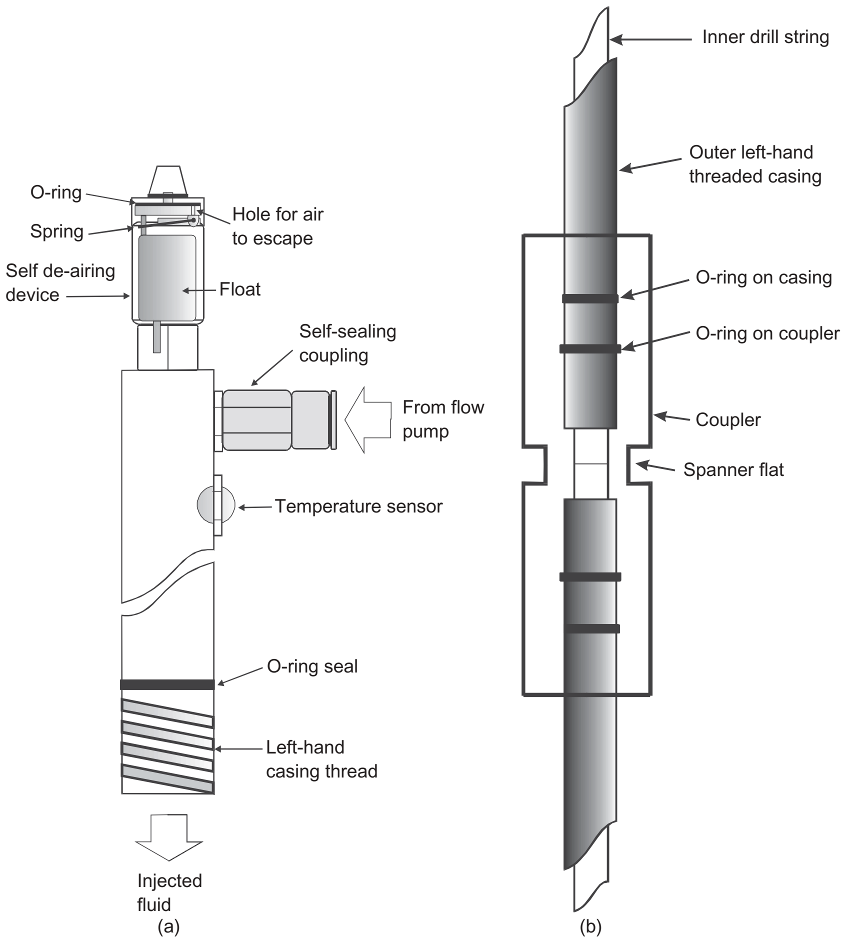

Fig. 3. Other system components: (a) de-airing vent; (b) joint sealing

the target flow rate and the pressure is monitored for a constant value. An example of this operation is given in Fig. 4 (Rectory Farm, Little Eversden, Cambridge, UK). In this example, a pseudo-steady state at a flow rate of 3 ml/h was reached in the previous stage and the test was continued to measure the constant pressure at a flow rate of 4 ml/h. The flow rate was increased to 150 ml/h for a short duration to raise the pore pressures quickly within the soil. The flow rate was then reduced gradually to 4 ml/h and the pressure was monitored to obtain the pseudo-steady-state condition. Using this technique, the time to establish the constant pressure condition was approximately 11 min. If the final flow rate had been set from the beginning, the process to reach the constant pressure would have taken 47 min. Further details of the theory behind this technique are given in Ratnam (2002). Using the accelerated approach about four to five levels of stable pressure conditions at different flow rates can be obtained within an hour of testing (Fig. 5).

The analysis is simple. A plot of steady-state pressures and corresponding flow rates is required to interpret the test (Fig. 6). The slope of the linear relationship ($\Delta Q\infty/\Delta H$) is combined with the relevant shape factor, F, for the cavity geometry (L/D) to determine the measured permeability from the expression $k_m = (F \times \Delta H/\Delta Q\infty)$. Numerical methods were used to determine appropriate shape factors (Ratnam *et al.*, 2001), summarised in Appendix 1. As shown in Fig. 6, the data do not go through zero for the simple reason that the transducer measuring water pressure is at an arbitrary height, usually at least a metre below the highest point in the system. However, it is the slope of the fitted line that is used to evaluate the permeability.

As the effective stresses around the cavity reduce during fluid injection, collapse of an open unsupported cavity is a concern when a large fluid injection flow rate is employed at

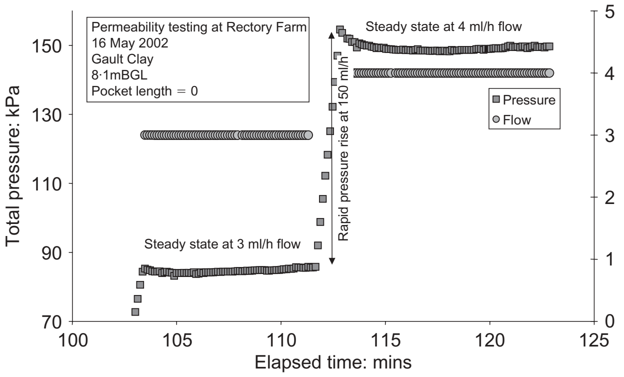

Fig. 4. Accelerated method to achieve constant pressure condition

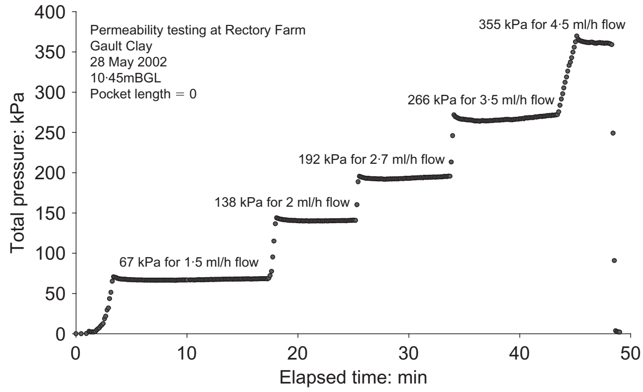

Fig. 5. A number of steady states

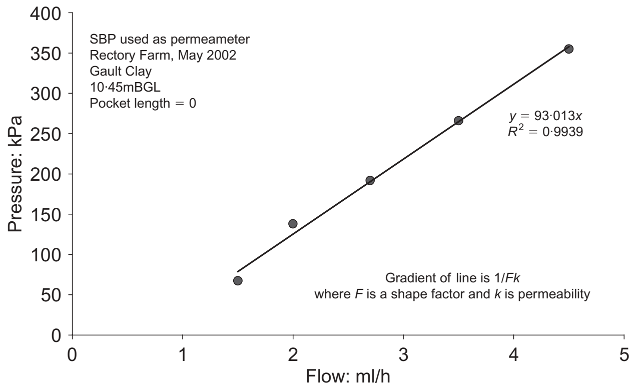

Fig. 6. An example of a linear pressure–flow relationship

large L/D ratios. Recent laboratory-scale tests using the same self-boring permeameter technique show that the cavity (tested up to $L/D = 4$) remained open for stiff overconsolidated Oxford clay (Hird & Srisakthivel, 2004). However, this may not be the case for soft normally consolidated clays, and it is important to check the stability of the unsupported cavity before conducting the test.

POTENTIAL MEASUREMENT ERRORS

Smearing

Whenever the instrument moves, the cavity wall is smeared. The bottom cavity is not smeared at all, but portions of the other cavities are smeared a number of times depending on where they lie in the sequence. For example, if the instrument is pulled back to $L/D = 1$ from $L = 0$ and then subsequently to $L/D = 2$, the first geometry is smeared once but half of the second geometry is smeared twice. To minimise smearing it is advisable to test the longest cavity first before pushing the instrument down for smaller L/D ratios. In this manner, each L/D ratio cavity is smeared by a cumulative equal amount, i.e. once when the cavity is drilled to $L = 0$ and once when the instrument is pulled back to the longest L/D ratio tested.

There is also another advantage to starting from a larger L/D ratio. The longer cavity requires a smaller head for a given flow. Hence, when reducing the cavity length, it is possible to arrange for the applied head for the first step in the shorter cavity to be greater than the head for the last step in the longer cavity. In this event there is no need to wait for pore pressures to return to ambient conditions between successive cavity tests. This cannot be done when moving from short cavities to long ones: in this case one must wait for pore pressures to return to the *in situ* conditions, i.e. at least as long as the previous step took to carry out.

Temperature effects

The present system has two temperature sensors, one located on the pressure transducer and the other on the injection point at the top of the drill string. These have shown that the pressure measurements are sensitive to temperature variation. For changes exceeding 3°C, the shift in the observed pseudo-steady-state pressures becomes significant. In a closed system, temperature fluctuation changes the volume and hence pressure in the delivery pipe, and is especially significant for softer items such as nylon lines that have a non-linear elastic characteristic. Attempts to calibrate for this effect have not been successful, the tendency being to over-correct. The best results are obtained by allowing only the minimum of pipework above ground level and testing at times when the temperature is not subject to abrupt change.

Temperature-related viscosity effects in the permeant fluid (water) have not been considered at this stage. The temperature below ground level is typically lower and more stable. Downhole measurements coupled with downhole pressurisation would be more desirable (Harwood, 1995), but this requires major alteration of the standard SBP, so discarding the principal advantage of the new method, i.e. that permeability measurements are gathered as part of a suite of engineering parameters.

Leakage along the instrument

If there is a path between the soil and the instrument, a hydraulic short circuit will be formed along the body of the probe from the cutting shoe edge. The precision of the boring usually ensures that the top end of the cavity is sealed by the soil pressing in against the instrument. However, separation (or 'blow off') can occur when the radial effective stress in the soil next to the probe is equal to the critical head defined by Bjerrum *et al.* (1972). If interconnected with other more pervious zones along the probe, the permeability measurement will be unreliable.

To circumvent this problem a procedure was devised for checking for axial leakage. Having established an apparent steady-state condition, the pressuremeter membrane is inflated to increase the cavity diameter (at a point above the permeameter cavity) by 1%, ensuring an intimate contact between membrane and soil. If there was a leak it is now stopped, and the plot of pressure against time climbs in response (Fig. 7). The cavity length is now the distance from the bottom of the borehole to the lower end of the membrane rather than the bottom of the instrument. The only penalty for axial leakage repaired in this manner is loss of the ability to test short L/D ratio cavities, as the minimum L/D ratio is now approximately 3.

Poor control of the self-boring can initiate leakage. The material must be slurried efficiently, otherwise momentary blocking inside the cutting shoe causes fracturing in the surrounding soil.

FIELD TESTING AND COMPARISON WITH OTHER DATA

Introduction

The data provided in the following section are a mixture of research data, gathered to prove and improve the new technique, and some results from commercial testing, where the scope for experimentation is limited. The data are presented as plots against depth. Where possible, depth is referred to a datum, otherwise to local ground level. The test geometry gives results for k_m, and if there is no other information then this is what is plotted. If there are other data then k_m is converted to k_v and k_h using where possible the same assumptions about R_k as the external data to make the comparison sensible.

Gault clay

The Gault clay test site is located in the village of Little Eversden, approximately 10 km south of Cambridge. The ground consists of topsoil over 4·5 m of silty clay and gravel (glacial till) overlying up to 45 m of Gault clay, sitting on the Lower Greensand. Testing at the site was conducted primarily between 5 and 18 mBGL. The engineering properties of Gault clay in the Cambridge area are similar within the same lithological level (Butcher & Lord, 1993). In this study rotary core samples were taken for laboratory testing.

Results obtained with the new technique (called 'Mark 2') together with some results from other methods are shown in Fig. 8. The other methods include a purpose-built self-boring permeameter (called 'Mark 1'), SBP holding tests, triaxial tests on horizontally and vertically cut specimens, and oedometer testing. For the field permeability determination, the k_v and k_h data are interpreted values from the measured permeability k_m, assuming an anisotropy ratio $R_k = 2$, obtained from the triaxial tests (Ratnam, 2002).

The results for each method at a given L/D are consistent with depth, within an order of magnitude or better. The triaxial tests fall within a narrow range (6×10^{-11} to 2×10^{-10} m/s) and agree reasonably well with the direct field tests, which give values between 8×10^{-11} and 5×10^{-10} m/s. The good match in the results is attributed to the relative homogeneity of Gault clay. This is further confirmed

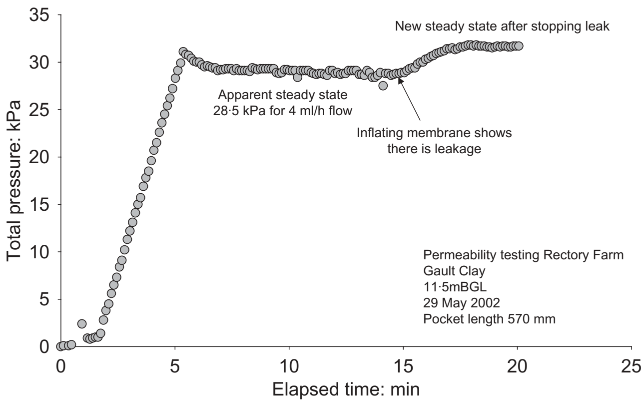

Fig. 7. Leakage demonstration

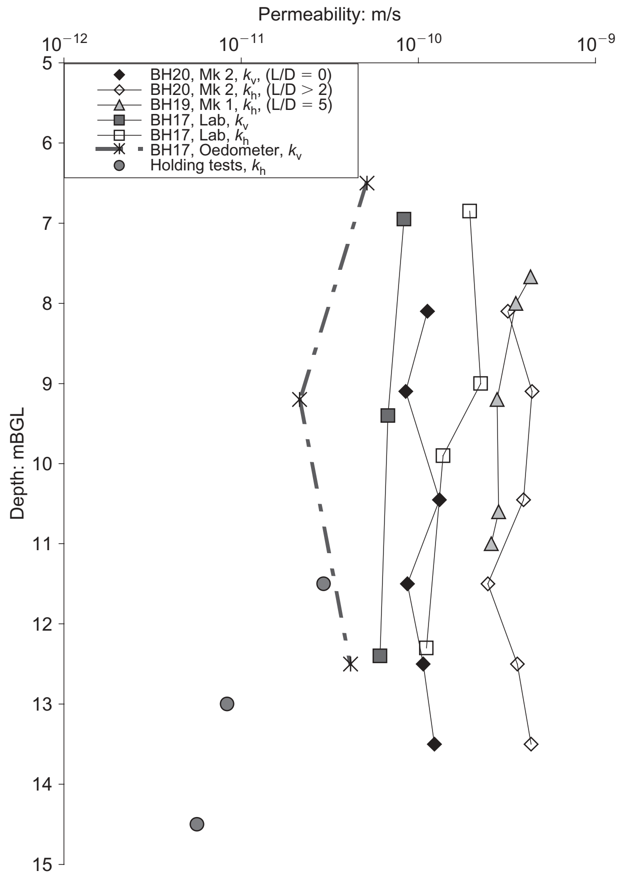

Fig. 8. Permeability of Gault clay at Rectory Farm site

by the laboratory measurements of k_v in comparison with the Mark 2 results for k_v.

Tests were also carried out with a purpose-built self-boring permeameter (Mark 1) with a fixed geometry of $L/D = 5$. Unlike the Mark 2 method, the cavity wall is supported at all times, and water permeates the soil via a perforated jacket. The Mark 1 and Mark 2 results for k_h agree well, indicating that stress changes due to the relaxation of the cavity wall are not a major issue for the measurement of permeability in heavily overconsolidated materials.

The indirect test methods (laboratory oedometer test and SBP holding test) give the lowest measurements, between 6×10^{-12} and 5×10^{-11} m/s, and are in reasonable agreement with each other. Lower measurements from indirect tests are widely established in the literature (e.g. Chandler *et al.*, 1990; Leroueil *et al.*, 1992).

Laboratory permeability testing (Ratnam, 2002) included investigation of the effect of hydraulic gradient, effective stress and permeation time on measured permeability, and additional tests to investigate the influence of smearing and fracturing. Minor changes in the measured permeability, between 7% and 18%, were observed when the gradients were varied between 2 and 200. Changes in effective stress from 30 kPa to 161 kPa had little influence on intact samples but a significant effect on (intentionally) fractured samples, permeability reducing as the effective stress increased and indicating the importance of avoiding fracturing the material during self-boring and permeability testing. Gross smearing by remoulding the clay in the laboratory had expected consequences, decreasing the permeability approximately tenfold. However, as the thickness of the smeared zone is considered to be small in self-boring, the effect of smearing on field permeability measurement is considered to be minor.

Bothkennar clay

The Bothkennar site adjacent to the River Forth in Scotland was chosen to validate the feasibility of the method in a soft clay deposit where the potential for cavity collapse is a concern. Data comparisons are made possible by previous extensive investigation (Leroueil *et al.*, 1992). The moisture content varies considerably across the site and with depth (Nash *et al.*, 1992), and the variation in the fabric profile presented by Leroueil *et al.* (1992) is of particular relevance to permeability measurement. This work is summarised in an earlier paper (Ratnam *et al.*, 2002).

The results from the Mark 2 field tests together with previous results are shown in Fig. 9. An R_k value of 2 obtained from triaxial tests has been used to allow comparison with published results. The Mark 2 results generally plot higher than data measured by piezometer or self-boring permeameter (PERMAC; Capelle, 1983). There is good correlation between Mark 2 k_h data and large-diameter radial flow cell (RFC) results, and there is good agreement between triaxial test k_v values and those derived from Mark 2 zero length cavities. Once more all direct methods give higher permeability than the indirect holding test results. Significantly, the difference between results for zero length and longest length Mark 2 cavities is often greater than that between techniques, indicating the importance of sample size.

The PERMAC tests give lower values than the Mark 2 methods, and this has been investigated. For constant flow arrangements leakage is the primary uncertainty. Assuming any system leakage is constant for different L/Ds, it is possible to estimate the degree of leakage by subtracting large L/D data from smaller L/D data and using the calculated data to estimate the permeability with a new subtracted injection geometry. Applying this check to Mark 2 data indicates that the maximum error due to leakage could be a factor of 2. However, this check should only be used as a guideline, because (a) the subtracted flow field only approximates the actual flow field for the subtracted injection geometry, owing to different boundary conditions, and (b) the permeability is scale-dependent (see next section).

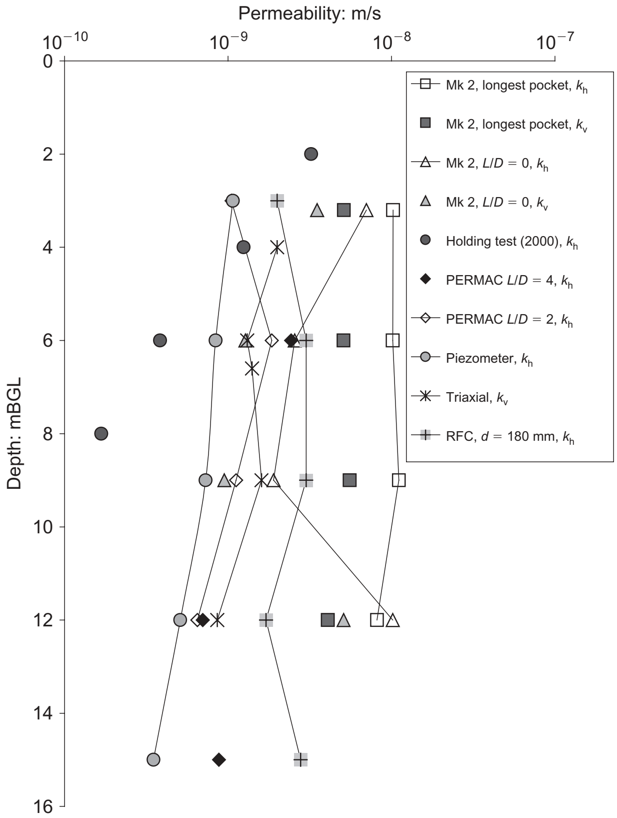

Fig. 9. Permeability of Bothkennar clay

Oddly, the PERMAC results are lower than the laboratory test results. The pushed-in piezometer data give the least permeable results of all the direct measurement techniques. Smearing and reconsolidation associated with pushed-in elements lead to an underestimate of permeability (Leroueil *et al.*, 1992). At 3 m and 12 m the PERMAC results are very close to the pushed-in piezometer data – where the PERMAC data diverge most from the piezometer profile (6 m) is where the PERMAC agrees best with the Mark 2 method. The difference possibly highlights the importance of careful self-boring to minimise excess pore pressure generation during drilling. The PERMAC instrument used at the Bothkennar site had interchangeable perforated elements with L/D ratios of 2 and 4 to study anisotropy (Leroueil *et al.*, 1992). The technique is flawed when tried in the same borehole, as the instrument must be retrieved and reinserted with the new L/D section, introducing smearing and other disturbance effects. This may explain why differences between L/Ds are less pronounced for the PERMAC than for the Mark 2.

There was a concern that the cavity might collapse as the effective stresses in the ground decrease with the pore pressure rising during the transient stage. To investigate this, the unsupported cavity, typically at $L/D > 2$, was left overnight after testing. When the instrument re-penetrated the cavity area the following day, no clay cuttings were returned in the drill water. As soon as fresh material was encountered beyond the $L = 0$ level, cuttings were observed. The integrity of the cavity during and for up to at least 15 h after testing was therefore confirmed.

London clay

Field permeability measurements of London clay using the new technique were conducted at three sites (Perry Oaks, Camden and Whitechapel).

The Perry Oaks site is located near Heathrow Airport, London, and a series of field and laboratory permeability tests were conducted as part of the long-term pile testing programme for Terminal 5 (Hight *et al.*, 2003). The site is located on a disused sewage treatment lagoon and consists of about 5 m of Terrace Gravel deposits underlain by approximately 55 m of very stiff London clay. Results from the field tests at five horizons are given in Fig. 10(a). At each horizon the permeability testing was sandwiched between a cavity expansion test, when the probe was at its highest point, and a holding test, when the probe was at its lowest. The indirect estimates of permeability from the holding tests again gave the lowest values. Some laboratory tests at shallow levels were carried out on samples taken from a site close to the self-bored positions. The laboratory values are smaller than the field permeability values, and an anisotropy ratio R_k of about 3 was found.

Self-boring permeameter tests were also performed at Whitechapel for the Crossrail project and at Camden for an Underground station redevelopment project. The measured mean permeability values are plotted with depth in Fig. 10(b) and 10(c) for the Whitechapel and Camden sites respectively. At the Whitechapel site, the permeability initially reduces with depth and then rises as the likelihood of encountering sand partings increases, indicating the heterogeneous nature of London clay reported by Hight *et al.* (2003). The test at 34 m is in a cavity of silt, where some core loss was reported in a nearby borehole. The permeability at this point exceeded the capacity of the constant flow pump, and a value for permeability was obtained by conducting a falling-head test down the pressuremeter casing. At the Camden site, tests were performed at three different depths in stiff to very stiff fissured grey clay with occasional sand partings, the frequency of the partings increasing with depth. The last horizon is immediately above the Lambeth Group. Again, the trend in relation to natural variability of London clay is similar to findings at the Whitechapel site.

All the Mark2 London clay data are compared in Fig. 11 with values reported in the literature for lateral permeability in this material from *in situ* tests, where the data are identified by approximate location. Table 1 gives the source, with remarks. All data are plotted against depth below ground level, but not to a common datum. The locations are more than 100 km apart in some cases, but nevertheless it appears that the new self-boring permeameter data are in the upper range of the previously reported data. This may reflect the least soil disturbance condition achieved by the self-boring technique, but may also be due to the relatively large sample size under test.

SCALE EFFECT

The test interpretation used above assumes that the medium has uniform permeability. However, the subsurface is often heterogeneous and spatially variable, and may include features such as fissures and sand/silt laminae. As a larger volume of the subsurface is tested preferred pathways are encountered, leading to equivalent values of permeability for various components of the subsurface at different scales.

Extensive reviews indicating an increase in permeability with test volume scale have been reported for varieties of geological materials ranging from clay-rich glacial tills and alluvium, to fractured rocks (Rovey & Cherkauer, 1995; Schulze-Makuch *et al.*, 1999). Most of these data are obtained by comparing laboratory tests, slug tests (piezometers and packer tests) and large pumping tests. In general, there is an overall increase in permeability as one moves from laboratory scale (tested volume $= 10^{-5}$–10^{-3} m^3) to borehole test scale (10^{-3}–10^{1} m^3) and large pumping test scale (10^{1} m^3 or more).

Butler & Healey (1998) dismiss this as the artefact of a skin effect due to inadequate development of boreholes and ignorance of anisotropy (pumping tests are both vertical and horizontal, whereas slug tests are predominantly horizontal). Stochastic analysis shows that the change in flow dimension (i.e. from one-dimensional in laboratory column tests to multi-dimensional in the field) can also affect the scaling effect (Neuman, 1994; Di Federico and Neuman, 1998). However, some recent data indicate that the scale effect is unrelated to the method of testing and interpretation (Schulze-Makuch and Cherkauer, 1998; Hyun *et al.*, 2002). Some theoretical and numerical investigations where spatial variability is explicitly resolved by the model have been able to reconcile data at different scales (e.g. Sanchez-Villa *et al.*, 1996; Rovey, 1998; Hyun *et al.*, 2002). Hence there is strong evidence that the scale effect is related to the degree of heterogeneity in the subsurface.

While larger test cavity lengths tend to capture the influence of fabric, the fixed length does not allow for an assessment of the scale effect. The unique capability of the Mark 2 technique is that this can be investigated by varying cavity size (L/D). The self-boring technique minimises the skin effect associated with borehole drilling, and therefore it is possible to examine more accurately whether the scale effect is real or not at least within the tested scales.

In this study, a single exponential relationship was used to relate permeability to scale of measurement:

$$K = c(\text{Length or volume scale})^m \tag{1}$$

where c is the permeability value at a length scale of 1 and m is the scaling exponent. If the exponent is zero, no scale variations should be observed in a perfectly homogeneous medium. Measures for length (volume) scale can be the distance water travels during a test, radius of influence (Rovey & Cherkauer, 1995), or volume of tested material (Schulze-Makuch *et al.*, 1999).

In this study the volume of influence for a given injection cavity size was used as the scale measure. In order to obtain this volume scale, finite element analysis was performed to calculate the spatial variation of excess pore pressures in the soil when injection pressure was applied at the cavity boundary. An FE program, FEMLAB 3·2, produced by COMSOL, Inc., was used for the analysis. A steady-state flow analysis was conducted with an FE model that has an anisotropic permeability ratio of 2. A predefined pore pressure was applied at an injection cavity, and the pore pressure profile within the soil was computed. The volume of the soil in which the excess pore pressure is more than 20% of the excess pore pressure applied at the cavity boundary was defined as the influence volume for the injection cavity of a given L/D. This value of 20% was arbitrarily selected, but it was considered to give a volume large enough to define the influence volume. The analysis was performed for different L/D values and the relationship between the influence volume and L/D was obtained. In this study, permeability measurements were done at different L/Ds (i.e. different influence volumes).

Figure 12 shows the log–log plots of influence volume against lateral permeability for the three clays investigated in this study. Although there is considerable scatter, several

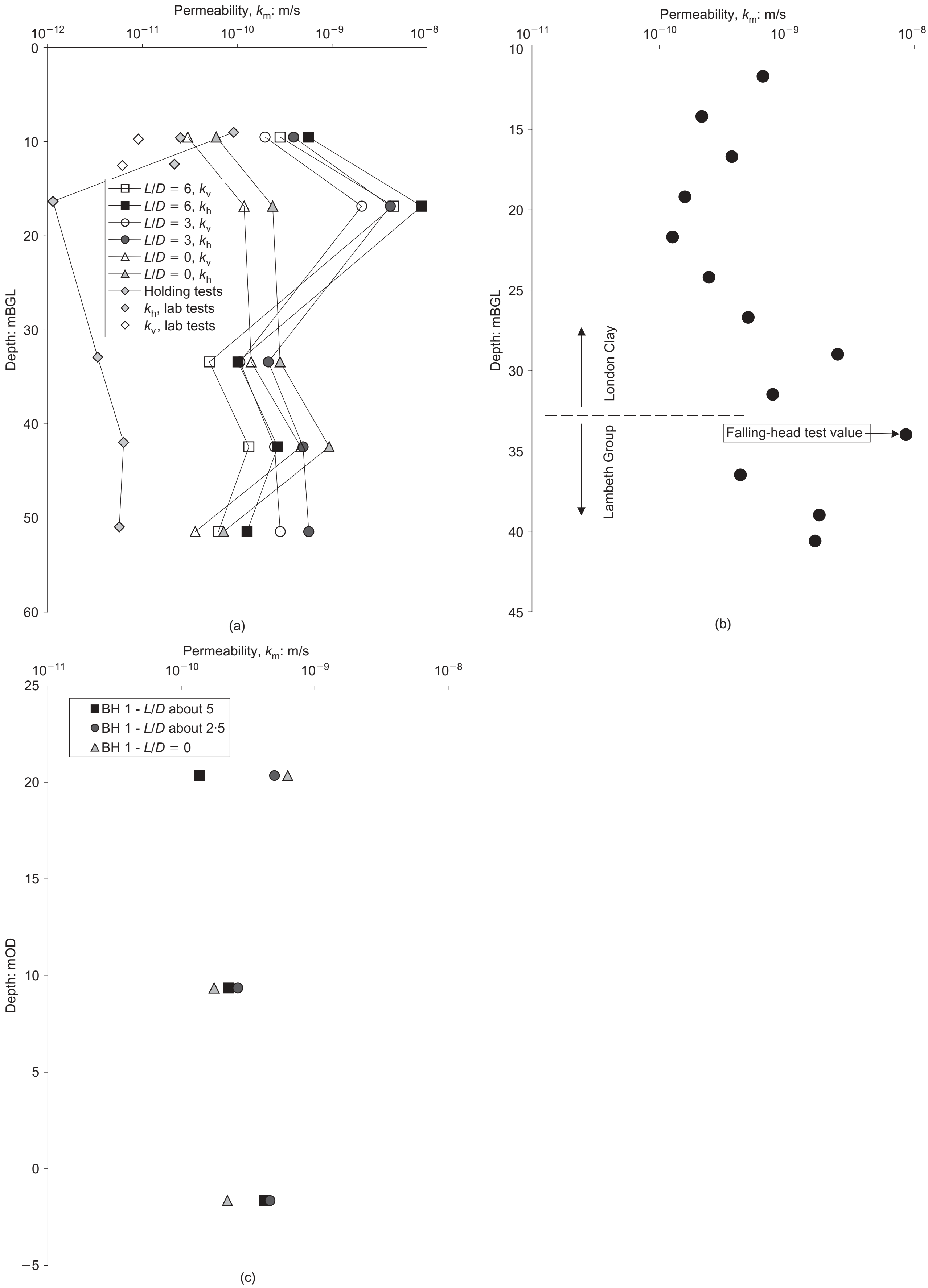

Fig. 10. Permeability of London clay: (a) Perry Oaks site; (b) Whitechapel site; (c) Camden site

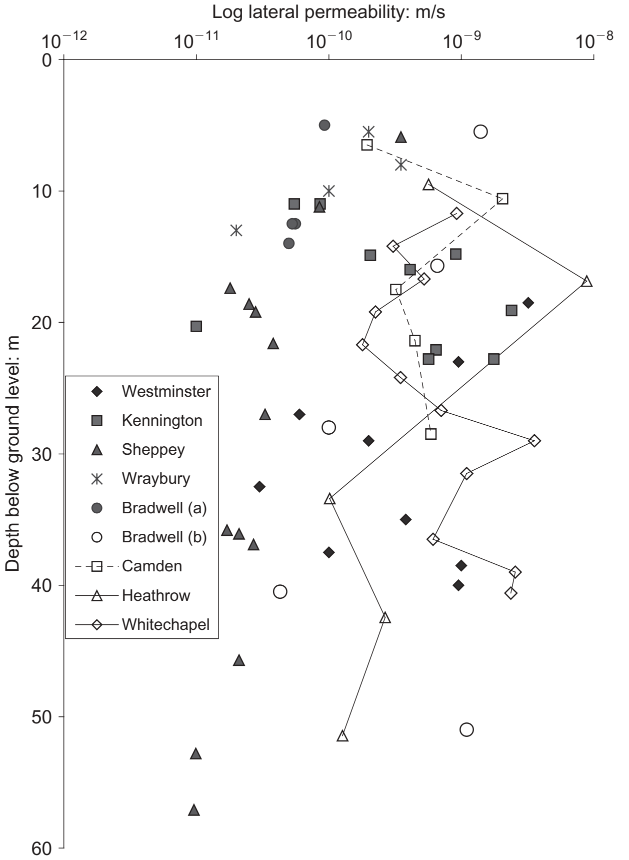

Fig. 11. Permeability of London clay, various techniques and sources

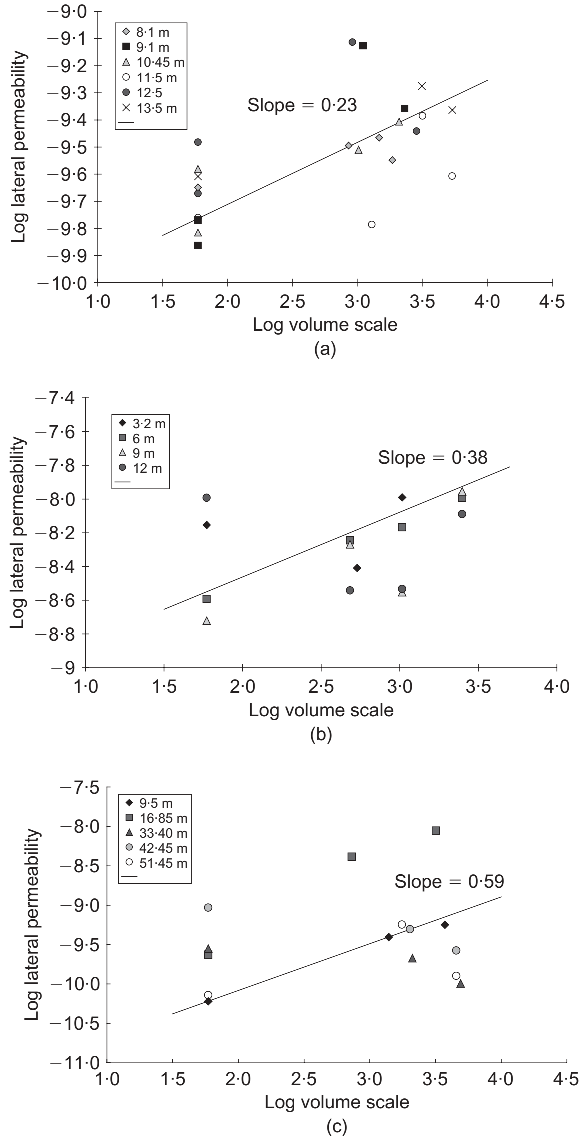

Fig. 12. Scale effect on permeability: (a) Gault clay; (b) Bothkennar clay; (c) London clay

data sets clearly indicate some degree of scale dependence. This preliminary investigation shows that it may be possible to obtain the scale dependence from this technique. The average values of the exponent m vary from 0·23 for the relatively homogeneous Gault clay to 0·38 for the soft Bothkennar clay with variable soil fabric and 0·59 for the microfissured London clay.

Schulze-Makuch *et al.* (1999) examined the scale effect for 39 geological materials (10 soil-like materials and 29 rock-like materials) and found that the value of the exponent depends on the type or types of flow present, as shown in Table 2. Homogeneous materials have an exponent of zero, whereas heterogeneous porous flow media and fracture and conduit flow controlled media have exponents of 0·5 and about 1·0 respectively. If it is assumed that the influence volume used in this study is proportional to the tested volume defined by Schulze-Makuch *et al.* (1999), the exponent value in the log–log plot will be the same for a given geological material. Obviously, the coefficient c depends on the scale measure selected, but it is the exponent that exhibits the degree of scale effect. The exponent values measured in this study are within the reported values and correspond well to the degree of heterogeneity identified for the tested clays through visual observation. The engineering implication is that there is a scale effect of more than one order of magnitude when permeability at the laboratory scale (say 10^{-4} m^3) is compared with that at a larger scale ($>$1 m^3) for design analysis for these natural clays. It should be noted that the data presented in this study are for demonstration only in order to present the potential benefit

Table 1. London clay permeability data

Location	Source	Instrument	Method	Permeability data
Heathrow	Cambridge Insitu (2001)	SBP (Mk2)	Constant flow	$1{\cdot}0\times10^{-10}$ to $8{\cdot}8\times10^{-9}$
Whitechapel	Cambridge Insitu (2002b)	SBP (Mk2)	Constant flow	$1{\cdot}8\times10^{-10}$ to $3{\cdot}6\times10^{-9}$
Camden	Cambridge Insitu (2002a)	SBP (Mk2)	Constant flow	$1{\cdot}9\times10^{-10}$ to $2{\cdot}0\times10^{-9}$
Westminster	Burland & Hancock (1977)	Casagrande standpipe	Falling head	$3{\cdot}0\times10^{-11}$ to $3{\cdot}2\times10^{-9}$
Kennington	Cambridge Insitu (1998)	SBP (Mk1)	Constant flow	$1{\cdot}0\times10^{-11}$ to $2{\cdot}4\times10^{-9}$
Sheppey	Dixon & Bromhead (1999)	Standpipe piezo	Uses equilibration data	$9{\cdot}6\times10^{-12}$ to $3{\cdot}5\times10^{-10}$
Wraybury	Garga (1988)	Hydraulic piezo	Constant head	$2{\cdot}0\times10^{-11}$ to $3{\cdot}5\times10^{-10}$
Bradwell (a)	Chandler *et al.* (1990)	SBP (PERMAC)	Constant head	$5{\cdot}0\times10^{-11}$ to $9{\cdot}3\times10^{-11}$
Bradwell (b)	Chandler *et al.* (1990)	Twin-tube piezo	Constant head	$4{\cdot}3\times10^{-11}$ to $1{\cdot}4\times10^{-9}$

Table 2. Summary of exponent *m* for different geological media (modified from Schulze-Makuch *et al.*, 1999)

Type of medium	N*	m	
		Average	Range
Homogeneous media	4	ND†	>0·19–0·65
Heterogeneous porous flow media	8	0·51	0·45–0·55
Double porosity media	16	0·72	0·55–0·83
Fracture flow media	7	0·96	0·80–1·13
Conduit flow media	4	0·90	0·67–1·11

* Number of geological media evaluated.
† Not determined because data were insufficient to calculate parameter.

of the new technique. With regard to the actual scale effect of these clays, further testing such as large-scale pumping tests that allows larger formation volume is needed to confirm the findings at larger scales.

CONCLUSIONS

The new field permeability measurement technique uses a conventional self-boring pressuremeter, and allows multi-parameter measurements of strength, stiffness, *in situ* stress and permeability from a single SBP drilling event.

The constant-flow method has been used in order to achieve a fast test rate in low-permeability materials. The equipment is able to measure permeabilities up to 10^{-7} m/s. For permeabilities greater than this a constant- or falling-head test could be carried out using the same arrangement for making and accessing the test cavity but dispensing with the constant flow control units.

The results from several stiff and soft clay sites using this technique tell a complex story. Some results correlate well with certain laboratory tests and field tests, but it is important to compare like with like. The anisotropy of the soil and increasing influence of fabric features on field horizontal permeability was evident from the data for greater L/D ratios, a finding that is difficult to reproduce in the laboratory.

The self-boring technique greatly reduces the effects of soil disturbance and smear, but cannot eliminate them completely. The extent to which poorly controlled self-boring (such as on drilling fluid pressure, instrument alignment and cutter position and speed) can influence the results has not yet been quantified, and further investigation is currently being conducted. Experience with dedicated permeameters suggests that hydraulic short circuits are a more significant source of uncertainty, but the Mark 2 system allows this problem to be detected and corrected by inflating the SBP membrane.

In a homogeneous material the technique allows the anisotropy ratio to be evaluated, but to date the step change in cavity lengths has been too large for consistent determination of this parameter, and the anisotropy data have been masked by scale effects. It is likely that tests for determining anisotropy should be confined to cavity lengths in the range $L/D = 0$ to 1.

The ability to alter the cavity length allows examination of the scale effect on permeability. For large-flow analysis this offers the possibility of calculating an upscaled permeability from small-scale measurements. A preliminary investigation has produced some encouraging results, but further research is needed to examine the scale effect in more detail.

A detailed specification of the testing procedure can be found at http://www.cambridge-insitu.com/tech_papers/mark2spec.htm

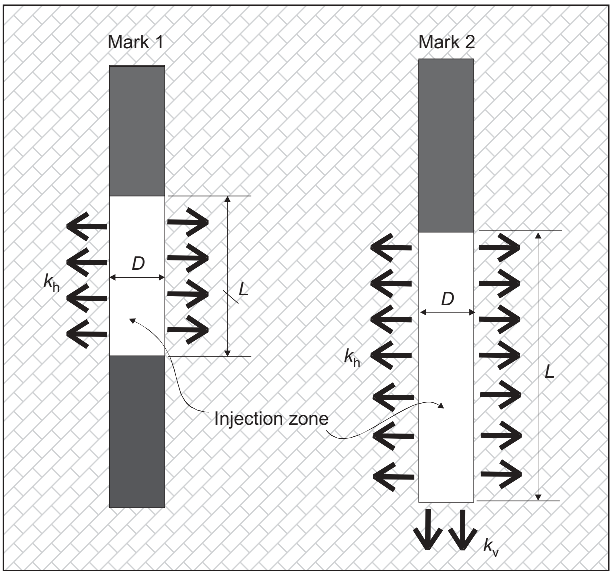

Fig. 13. Typical test cavity geometry

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APPENDIX 1. NUMERICALLY DERIVED SHAPE FACTORS (Ratnam *et al.*, 2001)

Figure 13 shows typical test cavity geometry.

For Mark 1 geometry:

$$\frac{F}{D} = 0{\cdot}5691\left[\frac{L}{D}\right] + 5{\cdot}2428\left[\frac{L}{D}\right]^{\frac{1}{2}} \tag{2}$$

For Mark 2 geometry:

$$\frac{F}{D} = 1{\cdot}1872\left[\frac{L}{D}\right] + 2{\cdot}4135\left[\frac{L}{D}\right]^{\frac{1}{2}} + 3{\cdot}1146 \tag{3}$$

The shape factors for the anisotropic condition can be derived from equations (1) and (2) by replacing L/D in the equations with $m \times L/D$, where m is the transformation ratio $\sqrt{(k_h/k_v)}$.

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