RING PERMEAMETRY: DESIGN, OPERATION AND ERROR ANALYSIS

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ABSTRACT

Assessment of slope stability, soil management or contaminant transport problems usually requires numerous, yet accurate point measurements of permeability. This technical note describes a new method for the rapid field assessment of permeability in near-surface soils or unconsolidated sediments. The procedure is known as 'ring permeametry' and is an *ex situ* core-based method giving measurements which can be guaranteed to be stratum-specific, unlike measurements from some *in situ* techniques. The potential sources of precision and bias error within the method are quantified and their effect on the uncertainty of permeability estimates is illustrated. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

The permeability of soils and unconsolidated sediments typically varies by several orders of magnitude even in areas of the same geological formation (Chappell and Ternan, 1992). Numerous point measurements of permeability are therefore required to derive accurate areal estimates. The point measures that are collected are themselves subject to uncertainty because of the possible effects of the measurement technique on the soil or rock under test. Indeed, uncertainty related to instrument/technique error can be larger than the spatial uncertainty (e.g. Kanwar *et al*., 1987; Picornell and Guerra, 1992; Paige and Hillel, 1993; Sherlock *et al*., 1995). This means that the assessment of slope stability, soil management or contaminant transport problems requires numerous point measurements of permeability where each value is determined to a relatively high level of accuracy (e.g. Ternan *et al*., 1987; Jetten *et al*., 1993; Collison and Anderson, 1996). The choice of method to determine permeability is dependent on the prevailing site conditions such as the presence of a water-table or depth of each stratum, but also on the desired accuracy of the results and the time taken to undertake a series of tests.

When permeability estimates are required for a soil or unconsolidated sediment that is above a water-table at the time of testing, techniques of *ex situ* core-based permeametry, *in situ* infiltrometry and (*in situ*) borehole permeametry can be undertaken (Boersma, 1965; British Standards Institution, 1990; Hendrickx, 1990; Youngs, 1991; Reynolds, 1993). Where the strata to be measured are each between 0·05 and 0·2 m in depth, which is not uncommon in soil and drift (Chappell and Ternan, 1992), then stratum-specific testing can become difficult with techniques of (a) *in situ* infiltrometry using, for example, a pressure infiltrometer, cylinder permeameter, double-ring infiltrometer or air-entry permeameter, and (b) borehole permeametry using, for example, a Guelph permeameter or Talsma well permeameter. In particular, if a slowly permeable stratum underlies the stratum under test then drainage from the test soil may be impeded giving an artificially low permeability estimate (Jones, 1951; Boersma, 1965). With *ex situ* core permeametry an undisturbed soil core is extracted from the ground within a plastic or metal ring and then tested with the lower core surface maintained at atmospheric pressure. The results of such *ex situ* tests relate to the soil sampled within the core and are totally

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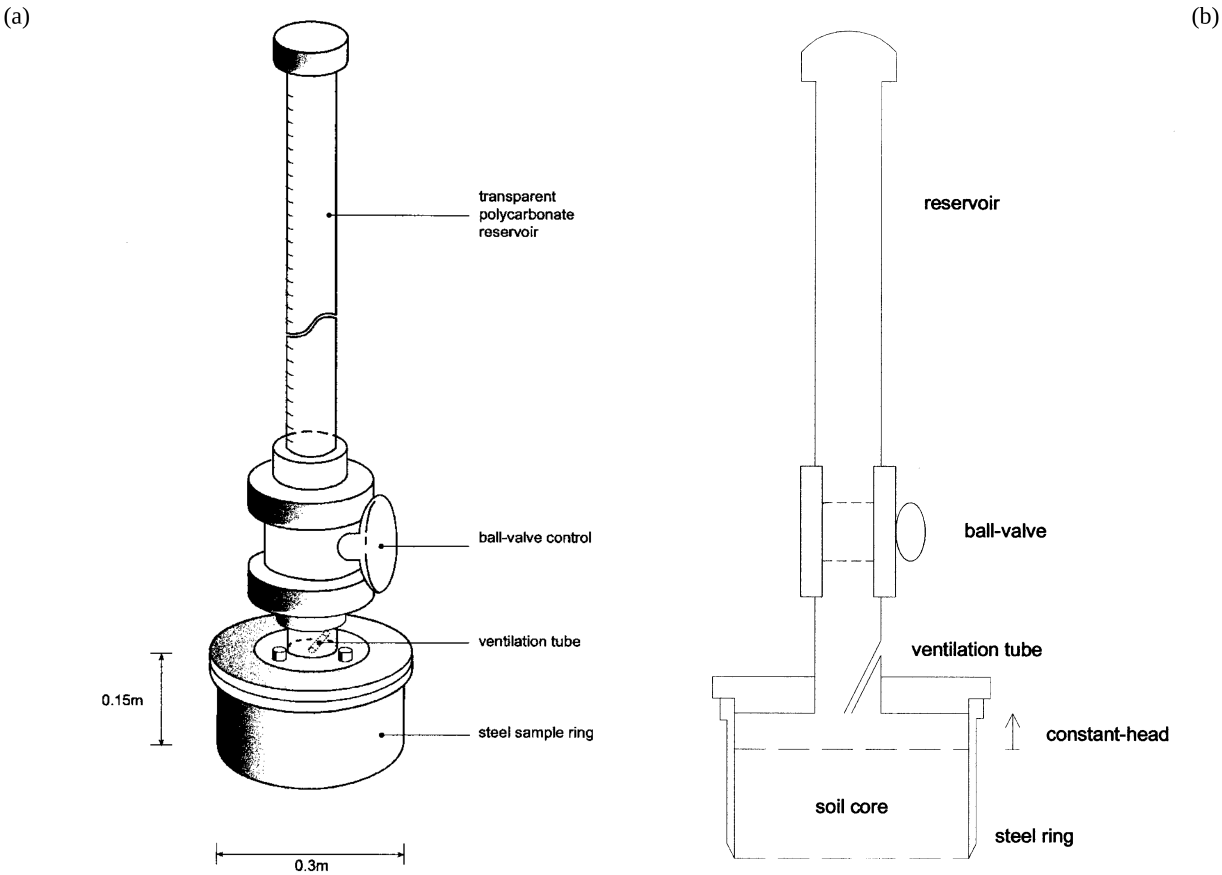

Figure 1. The ring permeameter shown in (a) three-dimensional oblique view and (b) schematic cross-section

independent of properties above or below the soil volume under study. *Ex situ* core-based methods do, however, have the potential to be in error as a result of the coring process. Furthermore, traditional core permeametry (e.g. British Standards Institution, 1990) is laboratory-based making it more time-consuming and therefore more costly in comparison to field-based procedures.

This paper describes an alternative *ex situ* core permeametry technique that is field-based, allowing cost savings per measurement. Given that all methods of permeability measurement are potentially subject to error, the paper details those design features and procedures that mitigate error and then describes a complete error analysis for this new technique. Despite the increasing demands of quality assurance in commercial data collection, very few permeability methods have been subjected to such error analysis.

The in-field and *ex situ* core permeametry method described here is known as ‘ring permeametry’. Several studies already report results derived from ring permeametry (e.g. Bonell *et al*., 1983; Ternan *et al*., 1987; Chappell and Ternan, 1992; Sherlock *et al*., 1995; Chappell and Franks, 1996) though this is the first study that details the technique in any systematic manner.

INSTRUMENT DESIGN

Figures 1a and 1b show the main components of a ring permeameter. The unit is a portable device designed specifically for use in the field. The method allows measurement after minimal carriage of soil cores from the excavation site. In contrast, laboratory permeametry requires samples to be transported over greater distances, with a greater chance for soil disturbance to occur before measurements are taken. Further, if organic-rich, eluvial or swelling soils are allowed to dry significantly before measurements are taken in the laboratory, the soil structure will be affected and the permeability values will not be representative of the field situation. When ring permeametry measurements are taken in the field there is often the opportunity to use local catchment waters within the unit. Where laboratory measurements utilize tap or distilled water, solute concentrations may be different, which can affect core throughflow rates and hence apparent permeability values (Hendrickx, 1990). By conducting the sampling, testing and possibly data analyses in the field, ring permeametry is more rapid and thus less costly than laboratory permeametry. Moreover, if the core extraction proves problematic or an atypical result is recorded at a particular location, the test results can be flagged or an additional core may be tested.

As with a constant-head laboratory permeameter, the ring permeameter is used to derive permeability by direct transformation of Darcy's law:

$$K_s = \frac{Q}{A} \frac{L}{\mathrm{d}H} \tag{1}$$

where K_s is the saturated hydraulic conductivity or permeability (m s^{-1}), Q is the steady reservoir discharge through the soil core (m^3 s^{-1}), A is the cross-sectional area of the soil core (m^2), L is the length of the soil core (m), and dH is the change of hydraulic head between the inflow and outflow ends of the soil core (m). The term 'permeability' is used interchangeably with the term 'saturated hydraulic conductivity' or K_s but is distinct from the term 'intrinsic permeability' or k (m^2) which refers to a fluid-independent measurement.

The unit incorporates particular design features that may make it significantly more accurate than typical laboratory permeameters. Insertion of any ring into a soil may disrupt the outer edge of the soil core. Ring insertion may open the structure of an indurated stony soil, while within a wet clay-rich soil the insertion may generate a gap between the soil core and the ring, and tend to compact the outer edge of the soil core. These edge effects will have a much greater relative influence on measurements taken on small cores, such as those used in laboratory tests. The ring permeameter encloses a soil core that has a cross-sectional area 1163 per cent larger than that of a typical laboratory permeameter; cross-sectional areas are 0·0707 m^2 (dia. 0·3 m) for the ring permeameter and 0·0078 m^2 (dia. 0·100 m) for the standard laboratory permeameter (British Standards Institution, 1990). Other laboratory permeameters use cores of only 0·0044 m^2 (Hendrickx, 1990). Even during careful ring insertions for ring permeametry, a small gap 0·001 to 0·005 m in width may be produced between the soil core and ring. The larger arc of the ring allows this to be sealed more easily (by compacting clay around the core edge). Further, the relative error associated with presence of the sealed outer zone is smaller with a larger core.

During operation of the ring permeameter a measurable volume of 0·0032 m^3 of water can be discharged through a soil core. This water input is maintained by a constant-head mechanism. Typically, a constant head (h) of 0·04 m, soil core length (L) of 0·10 m and a hydraulic gradient (dH/L) of 1·4 m m^{-1} is established for measurement, though an h of up to 0·09 m and dH/L of up to 2·8 m m^{-1} can be used with slowly permeable soils. The permeameter maintains the constant head using the Mariotte principle (Youngs, 1991) with the ventilation tube ported below a ball valve (Figure 1). As water moves through the soil core, air is pulled from the ventilation tube into the water reservoir, and reservoir water supplies the constant head on the soil core. The ball valve is incorporated into the design to ensure that water is not lost from the reservoir when being righted (after filling) for attachment to the permeameter ring.

The range in permeability that has been measured by the authors is $5{\cdot}4\times10^{-8}$ to $3{\cdot}2\times10^{-3}$ m s^{-1} (0·0054 to 1100 cm h^{-1}) (Ternan *et al*., 1987; Chappell and Ternan, 1992; Sherlock *et al*., 1995; Chappell and Franks, 1996; Chappell, unpublished). The highest recorded value was measured on an organic layer of a podzolic soil and was calculated from complete emptying of the permeameter reservoir in 10 s. Values of K_s in excess of 0·001 m s^{-1}, however, are considered as approximate values in ring permeametry as the flow through the soil core may be turbulent and hence not represented by Darcy's law. The least conductive soil measured was an acrisol compacted by caterpillar-tracked vehicles. Here a fall in reservoir level of 0·010 m over 8 h was used to

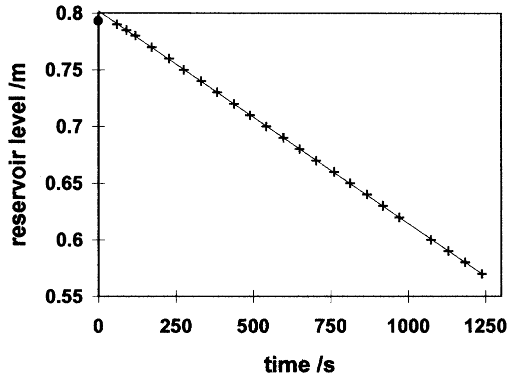

Figure 2. A typical reservoir level versus time trace. The linear regression to find the rate of reservoir-level change omits the first reading (•). (Data: CN6 (Czech Rep.), trace $r^2 = 1\cdot0$, $Q = 8\cdot08\times10^{-7}$ m^3 s^{-1}, $L/dH = 0\cdot923$, $K_s = 10\cdot5\times10^{-6}$ m s^{-1})

estimate the conductivity. The need for accuracy generally restricts application of the ring permeameter technique to soils with a permeability in excess of 1×10^{-7} m s^{-1}. Nevertheless, the constraints on the upper and lower limits of the technique allow the unit to measure K_s over a range of five orders of magnitude. Most soils and unconsolidated sediments have a saturated hydraulic conductivity that lies within this range (Chappell and Ternan, 1992).

The ring permeameter is recommended for use with all soils and unconsolidated sediments, except those which contain either (i) numerous cobble or larger sized stones, or (ii) gravel or larger sized indurated material. In these cases, ring insertion disrupts the soil within the inner part of the core. Permeametry on monoliths encased in gypsum or fibreglass (e.g. Bouma and Dekker, 1981) is more appropriate for measurement of such media but has the disadvantage of being slow and labour-intensive (Reynolds, 1993). This technique is also recommended if marked stratification is observed within a sampled core, as such layering may give a different permeability in the horizontal compared to vertical direction.

FIELD OPERATION

In describing the field operation of the ring permeameter, particular emphasis is placed on those areas of the technique where significant errors could be introduced if the prescribed method is not followed.

The first stage of ring permeametry involves forming a flat surface on the horizon from which the undisturbed soil core is to be extracted. This operation should be performed by ‘picking’ clods away from the surface using a sharp knife. Slicing of the soil surface should be avoided as this may cause smearing. Surface preparation may not be required if soil cores are to be extracted from an undisturbed ground surface. The steel permeameter ring is insterted into the soil typically to a depth of 0·10 m, either by careful use of a hammer plate and sledge hammer or by use of a hydraulic press (e.g. Tindall *et al*., 1992). Edge effects are minimized if the core is inserted under the steady force of a hydraulic press. On excavation of the core, care should be taken not to disturb the core when soil is removed from the outer edge of the ring. Further, 0·02 to 0·05 m of undisturbed soil should be left protruding beneath the base of the core. The excavated core should be transferred onto a levelled permeameter stand, typically a bottle crate covered with plastic or metal gauze. The base of the core should be trimmed flush with the base of the metal ring by picking away small clods of soil with a sharp knife. To guarantee that preferential flow does not move down the inner edge of the ring, a 0·01 m band of clay should be compacted around the inner edge of the ring using a metal rod and then smeared. The core should be brought to ‘field saturation’ (Bonell *et al*., 1983) by the addition of approximately 0·0035 m^3 of water (i.e. the maximum that can be ponded on a 0·10 m deep soil core in the 0·15 m deep ring). The soil surface must be protected from smearing by pouring the water onto a sponge, thick gauze or large leaf.

The constant-head/reservoir device (Figure 1) should be filled with water and the ball valve closed. The device is then inverted and attached to the permeameter ring. The test is started by opening the ball valve.

Discharge through the soil core is measured by recording the fall in water level in the transparent reservoir tube over time. A typical reservoir level versus time trace is shown in Figure 2. With the exception of the first reading taken when the permeameter system has not reached equilibrium, a linear relationship between reservoir level and time is observed (r^2 is typically greater than 99 per cent). Very occasionally a slight curvilinear relationship is observed due to the core being less than 'field saturation'. In such circumstances, either the later part of the trace should be used or the reservoir refilled and the test repeated. Permeameter discharge (Q) is then simply the product of the rate of reservoir-level change ($\mathrm{m\,s^{-1}}$) and cross-sectional area of the head/reservoir device ($4{\cdot}30\times10^{-3}\,\mathrm{m}^2$). As the lower core surface is at atmospheric pressure, the change in hydraulic head ($\mathrm{d}H$) from the upper to lower surface of the core is simply the length of the soil core plus the constant head (typically 0·04 m).

Solution of Equation 1 gives a K_s value representative of the particular water temperature and hence water viscosity at the time of the test. It is recommended (e.g. British Standards Institution, 1990) that K_s values are standardized to a particular temperature so that they can be compared with measurements collected at other times and locations. With a K_s value at a known water viscosity, intrinsic permeability (k) can be calculated also.

ERROR ANALYSIS

Uncertainty in measurements of permeability relate to both 'precision errors' ($\varepsilon_{\mathrm{precision}}$) and 'systematic bias errors' ($\varepsilon_{\mathrm{bias}}$) (Kempthorne and Allmaras, 1986; Figliola and Beasley, 1991). These errors are propagated as percentage uncertainties, which are given by:

$$\varepsilon_{\mathrm{precision}} = 100\left(\frac{\delta x}{|x_{\mathrm{best}}|}\right) \tag{2}$$

$$\varepsilon_{\mathrm{bias}} = 100\left[\frac{(x_{\mathrm{meas}} - x_{\mathrm{best}})}{|\min(x_{\mathrm{meas}}, x_{\mathrm{best}})|}\right] \tag{3}$$

where δx is the absolute uncertainty in the quantity concerned, and x_{best} is the best estimate of that quantity (Taylor, 1982). For systematic bias errors, percentage uncertainty is the deviation of the best estimate (x_{best}) from the measured value (x_{meas}), normalized by whichever is the smallest value. This allows systematic errors of any magnitude to be calculated. To examine the combined effect of individual errors, the percentage uncertainties are added either directly or in quadrature. Errors can be added in quadrature only if they are independent. Using the propagation of precision errors as an example, addition in quadrature of 2 per cent uncertainties would follow:

$$100\left\{\sqrt{\left[\left(\frac{\delta x_1}{|x_{\mathrm{best1}}|}\right)^2 + \left(\frac{\delta x_2}{|x_{\mathrm{best2}}|}\right)^2\right]}\right\} \tag{4}$$

With the ring permeameter, the precision errors relate to the measurement of (i) the rate of change of reservoir level, and (ii) the dimensions of the core, ring and constant head. These errors can be readily quantified. Systematic bias is introduced into permeametry results by instrument/technique errors. These errors relate to artificial compaction, fracturing, smearing or leakage, or an inadequate description of the test flow-field or other theoretical approximation. In contrast to the precision errors, such errors tend to be difficult to quantify precisely. Moreover, these bias errors can be large for inexperienced users, but modest when the unit is used by trained operators following the prescribed method. Those individual bias errors that could result from poor technique will be illustrated first.

Large bias errors would be observed if an inexperienced user generated and then failed to seal a large gap between the ring and core. Precise quantification of this error is very difficult, but can be shown to be dependent on the soil's conductivity. This effect can be illustrated using the following example values and assumptions:

(1) the inner area of each soil core has an example K_s of either $3{\cdot}2\times10^{-4}$, $3{\cdot}2\times10^{-6}$ or $3{\cdot}2\times10^{-8}\,\mathrm{m\,s^{-1}}$ (115, 1·15 or 0·0115 $\mathrm{cm\,h^{-1}}$);
(2) a core-ring gap of the three example soil cores is represented by a theoretical band of very high conductivity media ($K_s = 3{\cdot}2\times10^{-3}\,\mathrm{m\,s^{-1}}$) around the outer 0·005 m of each ring permeameter core;
(3) the effective conductivity of each core is equal to an area-weighted, arithmetic mean of the inner and outer K_s values.

Given these, the soil with a K_s of $3{\cdot}2\times10^{-4}\,\mathrm{m\,s^{-1}}$ would have an apparent K_s of $5{\cdot}09\times10^{-4}\,\mathrm{m\,s^{-1}}$, that with a K_s of $3{\cdot}2\times10^{-6}\,\mathrm{m\,s^{-1}}$ an apparent K_s of $2{\cdot}13\times10^{-4}\,\mathrm{m\,s^{-1}}$, and that with a K_s of $3{\cdot}2\times10^{-8}\,\mathrm{m\,s^{-1}}$ an apparent K_s of $2{\cdot}10\times10^{-4}\,\mathrm{m\,s^{-1}}$. The percentage uncertainties would therefore increase from +59 per cent, i.e.

$$100\left[\frac{\left(5\cdot09\times10^{-4}-3\cdot2\times10^{-4}\,\mathrm{ms}^{-1}\right)}{3\cdot2\times10^{-4}\,\mathrm{ms}^{-1}}\right] \tag{5}$$

for the conductive soil, to +6549 per cent for the soil with an intermediate conductivity, to +655 569 per cent for the slowly conductive soil. Slowly conductive soils that have been sampled or prepared poorly, therefore, have errors that are too high to make the measurements useful. The sealing stage of the ring permeametry technique is therefore critical to estimation of accurate K_s values. Permeability measurements on small laboratory cores, where the core-ring gap has not been sealed, may therefore have unacceptably large errors (cf. Hill and King, 1982; Rogers and Carter, 1987).

Where a clay-rich soil core is incorrectly trimmed, with the operator drawing a blade or spade across the soil surface, then the surface may become smeared. Closure of the macropore structure by smearing can reduce the K_s by as much as two orders of magnitude (Chappell and Ternan, 1992). For example, if the true K_s of a 0·10 m undisturbed core was $1{\cdot}00\times10^{-6}\,\mathrm{m\,s^{-1}}$ and a 0·004 m deep smeared layer with a K_s of $1{\cdot}00\times10^{-8}\,\mathrm{m\,s^{-1}}$ was created on the surface, the measured K_s would be $2{\cdot}0\times10^{-7}\,\mathrm{m\,s^{-1}}$ which is the length-weighted harmonic mean K_s of the two layers, i.e.

$$\frac{0\cdot096\mathrm{m}+0\cdot004\mathrm{m}}{\left[\left(\dfrac{0\cdot096\mathrm{m}}{1\cdot00\times10^{-6}\,\mathrm{ms}^{-1}}\right)+\left(\dfrac{0\cdot004\mathrm{m}}{1\cdot00\times10^{-8}\,\mathrm{ms}^{-1}}\right)\right]} \tag{6}$$

and the error would be –400 per cent. This simple example also illustrates the potential for impeded drainage from test soils during *in situ* infiltrometry methods. The role of smearing on K_s measurement has been extensively researched with borehole permeametry. Some studies suggest that during hand drilling of auger holes for such permeametry, the resultant soil smearing can introduce bias errors of between –33 and –85 per cent (Talsma, 1960; Bonell *et al*., 1983; Reynolds *et al*., 1983). Others, however, infer considerably larger errors of between 10 000 and 1 000 000 per cent due to auger-hole smearing (Kanwar *et al*., 1987; Picornell and Guerra, 1992; Paige and Hillel, 1993; Sherlock *et al*., 1995). In borehole permeametry, the effects of auger-hole smearing can be reduced by brushing the walls with a coarse brush or spiked roller. Reynolds (1993) and Everitt (1994) do, however, suggest that this process gives very variable effects. As previously discussed, smearing of ring permeameter cores can be avoided by care in the core trimming and water application stages.

Where the ring permeameter is used in accordance with the prescribed method, bias errors can be reduced significantly, though some bias and precision error remains. To illustrate the effects of these errors in the uncertainty in permeability estimates, uncertainty analysis is undertaken for a hypothetical soil with a K_s of $1{\cdot}00\times10^{-6}\,\mathrm{m\,s^{-1}}$ ($0{\cdot}36\,\mathrm{cm\,h^{-1}}$). This is the mean value for a 'typical' soil or unconsolidated rock (Chappell and

Ternan, 1992). Measurements are assumed to be made under a constant head of 0·04 m applied to a soil core 0·10 m in length, a hydraulic gradient of 1·4 m m^{-1} and a stable reservoir water displacement of 0·10 m. These data would require a volumetric reservoir water displacement of 0·00043 m^3 in 4344 s (*c*. 1 h 12 min).

Propogation of precision errors

The ring permeameter reservoir comprises a polycarbonate tube with a cross-sectional area of 0·00430±(5·80×10^{-5}) m^2. Water level within this reservoir can easily be measured to within ±0·001 m, and timing the appearance of bubbles above the flange of the head/reservoir device can be achieved to within ±0·5 s. The resultant error in the permeameter discharge (Q) is therefore:

$$100\left\{\sqrt{\left[\left(\frac{5\cdot 80\times 10^{-5}\ \mathrm{m}^2}{0\cdot 00430\ \mathrm{m}^2}\right)^2+\left(\frac{0\cdot 001\ \mathrm{m}}{0\cdot 10\ \mathrm{m}}\right)^2+\left(\frac{0\cdot 5\ \mathrm{s}}{4344\ \mathrm{s}}\right)^2\right]}\right\}=\pm 1\cdot 7\ \text{per cent} \tag{7}$$

which gives Q as 9·9×10^{-8}±(1·7×10^{-9}) m s^{-1}. The height of the soil core and constant head of water applied to the soil core are estimated from a series of measurements of the distance between the upper surface of the core and upper rim of the permeameter ring. The absolute error in these measurements is ±0·005 m, including that associated with an imperfectly level core base. In the calculation of the inverse hydraulic gradient $L/\mathrm{d}H$, the terms L and $\mathrm{d}H$ are not measured independently, so the errors must be added directly. The resultant error in $L/\mathrm{d}H$ is therefore:

$$100\left[\left(\frac{0\cdot 005\ \mathrm{m}}{0\cdot 10\ \mathrm{m}}\right)+\left(\frac{0\cdot 005\ \mathrm{m}}{0\cdot 14\ \mathrm{m}}\right)\right]=\pm 8\cdot 6\ \text{per cent} \tag{8}$$

This gives $L/\mathrm{d}H$ as 0·714±0·06 m m^{-1}. The steel ring of the permeameter is constructed to give a cross-sectional area of 0·0707±0·00094 m^2 or a percentage uncertainty of ±1·3 per cent. The total precision uncertainty in the K_s is therefore:

$$\sqrt{\left(1\cdot 7^2+8\cdot 6^2+1\cdot 3^2\right)} \tag{9}$$

which gives ±8·9 per cent ($\varepsilon_{precision}$) and it is therefore dominated by errors in the estimation of the inverse hydraulic gradient.

Propagation of bias error

Bias errors associated with the prescribed method relate to the incorporation and compaction of clay at the edge of the soil core. Vertical flow through this outer band of soil may be one order of magnitude less than that through the undisturbed soil (Chappell and Ternan, 1992). If a 0·005 m band of clay seal (surface area 0·0046 m^2) is assumed to be one order of magnitude less permeable, then the area-weighted, apparent K_s would be:

$$\frac{\left(1\cdot 00\times 10^{-6}\ \mathrm{ms}^{-1}\times 0\cdot 0661\ \mathrm{m}^2\right)+\left(1\cdot 00\times 10^{-7}\ \mathrm{ms}^{-1}\times 0\cdot 0046\ \mathrm{m}^2\right)}{0\cdot 0707\ \mathrm{m}^2}=9\cdot 41\times 10^{-7}\ \mathrm{ms}^{-1} \tag{10}$$

This would represent a percentage uncertainty in the K_s of –6·27 per cent (ε_{bias}), i.e.

$$100\left[\frac{\left(9\cdot41\times10^{-7}\,\mathrm{ms}^{-1}-1\cdot00\times10^{-6}\,\mathrm{ms}^{-1}\right)}{9\cdot41\times10^{-7}\,\mathrm{ms}^{-1}}\right] \tag{11}$$

Total uncertainty

The total (precision and bias) uncertainty with use of the ring permeameter in accordance with the method described would be ±8·9 per cent ($\varepsilon_{precision}$)−6·27 per cent (ε_{bias}), or simply ±10·9 per cent (ε_{total}) if the precision and bias errors are added in quadrature. The uncertainty in our example calculation of K_s would therefore be $1{\cdot}00\times10^{-6}\pm(8{\cdot}9\times10^{-8})-(6{\cdot}27\times10^{-8})\,\mathrm{m\,s^{-1}}$ (or $0{\cdot}36\pm0{\cdot}032-0{\cdot}023\,\mathrm{cm\,h^{-1}}$).

CONCLUSIONS

Permeametry methods can be very sensitive to systematic bias errors. The design of the ring permeameter and the operational procedures described reduce combined bias and precision error to approximately 11 per cent. The technique's simplicity and rapidity are supplementary advantages.

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