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The indirect estimation of saturated hydraulic conductivity of soils, using measurements of gas permeability. I. Laboratory testing with dry granular soils

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Abstract. A comprehensive knowledge of soil hydraulic conductivity is essential when modelling the distribution of soil moisture within soil profiles and across catchments. The high spatial variability of soil hydraulic conductivity, however, necessitates the taking of many *in situ* measurements, which are costly, time-consuming, and labour-intensive. This paper presents an improved method for indirectly determining the saturated hydraulic conductivity of granular materials via an *in situ* gas flow technique. The apparatus employed consists of a cylindrical tube which is embedded in the soil to a prescribed depth. Nitrogen at a range of pressures was supplied to the tube and allowed to escape by permeating through the soil. A 3-dimensional, axisymmetric, steady-state, finite element flow model was then used to determine the value of the soil intrinsic gas permeability which produces the best fit to the pressure–air flow data. Saturated hydraulic conductivities estimated from the application of the gas flow technique to 5 granular soils covering a wide range of permeabilities were in close agreement with values determined using a conventional permeameter. The results of this preliminary study demonstrate the potential of this approach to the indirect determination of saturated hydraulic conductivity based on measurement of gas flow rates in granular and structured soils.

Additional keyword: finite element modelling.

Introduction

When modelling the distribution of moisture within soil profiles and across catchment landscapes, it is important to have a comprehensive knowledge of the permeability characteristics of the soil medium. Soil permeability, however, is dependent on geological history, geomorphologic processes, and the level and nature of interaction with the biosphere. Consequently, soil permeability exhibits a high level of spatial variability (with variations sometimes exceeding 3 orders of magnitude; Rasmussen *et al.* 1993). As a result, a large number of soil permeability measurements are required to reliably characterise areas of interest.

Permeability data have traditionally been obtained through *in situ* measurements using water infiltration or pore water pressure dissipation tests (Ahuja *et al.* 1976; Lunne *et al.* 1997) or have involved the transport of numerous samples back to the laboratory where the hydraulic conductivity is estimated experimentally using a permeameter or oedometer (Head 1994; Holland *et al.* 2000). Both approaches are time-consuming, labour-intensive, and consequently expensive, thereby making adequate collection of permeability data unlikely in practice. Soil permeabilities determined with water as the infiltrating fluid can also be affected by the presence of encapsulated air in dry soils. In partially saturated soils, changes to the soil structure during wetting can also occur as a result of the interaction between electrolytes in the water and exchangeable cations in the soil (Blackwell *et al.* 1990), or due to changes in matric suction.

One alternative is to utilise pedotransfer functions such as those proposed by Jarvis *et al*. (2002) to estimate hydraulic conductivity; however, as these authors point out, direct measurements are more reliable for site-specific applications.

In this study, an indirect *in situ* method of determining soil hydraulic conductivity is undertaken that uses a gas as the infiltrating fluid in place of the traditional approaches that employ water. The advantage of using gas permeabilities to determine hydraulic conductivity is that *in situ* gas permeability measurements can be undertaken much more readily than corresponding water determinations, enabling more extensive surveys to be undertaken in the field. Furthermore, the problem of electrolyte interaction with the soil is no longer an issue nor is encapsulation (as

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long as the soil is sufficiently drained). In a study of the removal of volatile contaminants from unsaturated soils, Olson *et al.* (2001) presented 3 techniques for measuring air permeability in the unsaturated zone. These involved laboratory experiments on intact soil cores, field-scale air pump tests, and calibration of air permeability to air pressure measured in the field under natural and forced air pressure conditions using a numerical air flow model. The authors examined the effects of moisture content and soil homogeneity on air permeability values. Air permeability was estimated from measured air flows through each core at field moisture content, and corresponding observations of pressure difference across the sample. Air pressures in the unsaturated zone were simulated assuming a 1-dimensional transient flow model.

The relationship between saturated hydraulic conductivities and air permeabilities obtained *in situ*, with exhumed samples tested on site and in the laboratory, has also been examined for soils of various textures (Loll *et al.* 1999; Iversen *et al.* 2001*a*, 2001*b*, 2003, 2004), and as a means of assessing the waste containment applicability of certain fractured rock strata (Rasmussen *et al.* 1993). In each study the authors observed a strong linear relationship between the logarithms of the saturated water conductivity and air permeability. In the most developed of these studies, Iversen *et al.* (2004) used a simple finite element model to determine shape factors that allowed the complex 3-dimensional air flow distribution at the end of an embedded tube to be approximated as 1-dimensional flow for a limited set of conditions (homogenous porous medium, isotropic with respect to permeability; Liang *et al.* 1995).

The aim of this study is to validate an improved method for indirectly determining the saturated hydraulic conductivity of dry (or almost dry) granular materials via a gas-flow technique. The relationship between the gas supply pressure and gas flow is obtained for 5 granular soils in a laboratory setting using a simple gas permeation device. In a departure from previous studies a 3-dimensional, axisymmetric, steady-state finite element (FE) flow model, capable of simulating the 3-dimensional characteristics of the laboratory gas flow test results is then used to find the value of the gas permeability that provides the best fit to the supply pressure–gas flow curve. The saturated hydraulic conductivity is subsequently estimated via the calculation of the intrinsic permeability of the soil together with the known properties of water. Finally, the merit of this approach is assessed by comparison of the saturated conductivities obtained via the gas flow technique with values obtained using a conventional permeameter.

Methodology

Experimental determination of soil gas permeability

The gas permeability values, k_g, of 5 granular materials were determined by measuring the pressures required to achieve a range of gas flowrates through soil samples, within a controlled geometrical arrangement, similar to that employed in some previous studies (Iversen *et al.* 2001*a*, 2001*b*, 2003, 2004). The arrangement of the apparatus used to deliver the flow of pressurised gas into the soil samples is shown in Fig. 1. The device consists of a cylindrical tube that is embedded in the soil to a prescribed depth. Gas under a known pressure is supplied to the tube and allowed to escape by permeating vertically and radially through the soil, ultimately escaping to the atmosphere through the soil surface.

To obtain the results presented here, nitrogen gas at 200 kPa source pressure was fed to a flow meter (15 L/min capacity) and then delivered at constant flow rate to the headspace of a closed-ended, thin-walled, stainless steel tube, 500 mm long by 50 mm radius, which had been embedded 100 mm into the dry granular soil sample. Gas flow rates of $Q = 1$ to 15 L/min (across the end area of the tube) were then delivered to the soil. Once a steady gas flow was achieved, the pressure P in the headspace of the delivery tube was determined using a digital pressure meter (Comark C9551), which has a range of 14 kPa with a resolution of 1 Pa. To minimise any flow effects arising from the presence of the pressure meter in the measurement system, the tapping point for the pressure line was located in the back end of the delivery tube, away from the direct path of the compressed gas stream.

Tests were carried out on 300-mm-deep soil beds held in a 400-mm-diameter by 500-mm-high container. The sample size was chosen to facilitate ease of testing whilst at the same time being large enough to minimise boundary effects (but any boundary effects were incorporated in the FE analysis in any case). The chosen sample zone size was selected on the basis of a trial and error parametric study using the numerical model described below. An analysis was first performed with a very large sample zone (5 m deep with a radius 5 m), and a reference pressure-flow (P–Q) relationship for an approximate infinite half space obtained. Numerical studies were then undertaken with successively smaller sample zone sizes and the calculated P–Q relationships compared with that obtained for the reference solution. Figure 2 shows that by that reducing the sample size to 400 mm diameter by 300 mm deep, the results deviated by <3% from the ''infinite'' half space solution. The slight divergence from the true solution is considered acceptable when the simplification to the experimental procedure it engenders is considered. The accuracy of results obtained using a sample zone of reduced size was also confirmed experimentally, by performing tests in a large diameter calibration chamber (1 m diameter by 1 m deep).

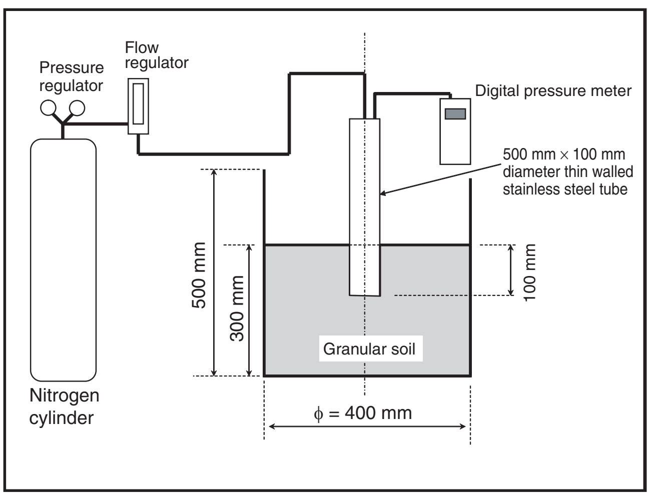

Fig. 1. The gas flow permeability apparatus and spatial arrangement of the gas flow experiment.

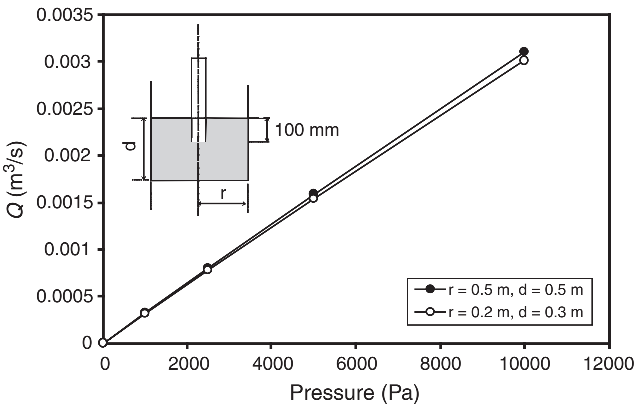

Fig. 2. Effect of test geometry on the pressure/flow relationship.

The gas flow apparatus was trialled using five granular soils with different particle characteristics: fine ballotini (glass beads); 'dark mineral sand' (ilmenite); fine granular industrial silica; fine natural 'Stockton beach' (silica) sand and a 'coarse river sand fraction' ($\leq$4 mm; silica and lithic fragments). Sieve analyses were undertaken for all samples and the particle size distributions are shown in Fig. 3. The grain size distributions for the 4 finer materials are quite narrow with the bulk of material retained on 1 or 2 standard sieves. The coarse sand sample displayed a wider range of particle sizes (0.3–4 mm).

The soil beds were prepared by raining air-dried, free-flowing soil samples from a container fitted with 15-mm-diameter holes drilled into its base maintained at a fixed height of 0.75 m from the soil surface. This method of bed preparation produced a loosely packed sample of consistent density. The specific gravity of the soil particles, as well as the bulk density and porosity of each of the prepared samples is presented in Table 1.

In order for the inherent variability of the *P*–*Q* relationship to be assessed, measurements were carried out in triplicate, with the sample beds being repacked before each trial. Repeated measurements were also undertaken for individual sample beds to assess whether the gas flow through the bed produced structural changes that might influence the *P*–*Q* relationship.

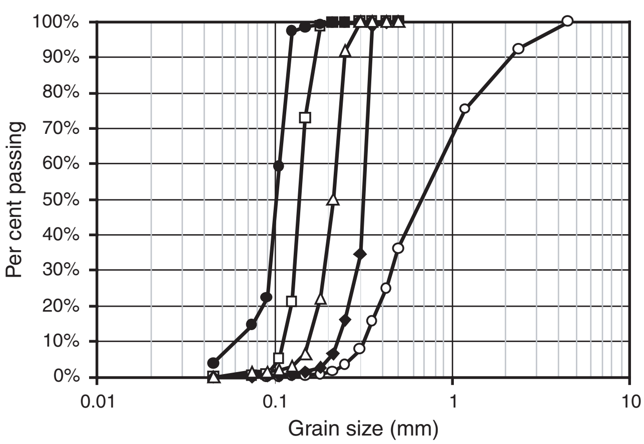

Fig. 3. Particle size distribution of the soils examined in this study. ○, Coarse beach sand; ◆, Stockton beach sand; △, silica; □, dark mineral sand; ●, ballotini.

Table 1. Basic properties of the prepared samples

	Specific gravity	Bulk density (10^{-3} kg/m^3)	Porosity
Coarse sand	2.57	1.957	0.240
Stockton sand	2.60	1.849	0.289
Industrial silica	2.60	1.815	0.302
Dark mineral sand	3.93	2.454	0.376
Ballotini	2.44	1.776	0.272

Numerical modelling of the transport process

In the approach described here, gas is delivered to the soil at a series of selected flow rates, via a controlled geometrical arrangement and allowed to disperse within the soil under steady-state conditions. The pressure in the gas delivery tube, *P*, corresponding to each applied flowrate, *Q*, is measured to obtain the *P*–*Q* relationship for each soil sample. This pressure–flow relationship is theoretically dominated by the intrinsic permeability, K_{int}, of the granular medium, and as such, a numerical model employing the intrinsic permeability can be used as the basis for quantitatively estimating the gas flow permeability, k_g, of the deposit. The intrinsic permeability of the system is determined through a trial and error process, so that the *P*–*Q* relationship predicted by a numerical model of the gas flow process matches the *P*–*Q* relationship obtained from the experimental procedure.

Previous studies examining air flow through particulate materials (such as Shang *et al.* 1999) have found a linear relationship between air flow rate and the pressure gradient if the air flow velocity is less than a critical value; in other words, Darcy's law was found to be valid. For the purposes of this study, it is also assumed that Darcy's law (Darcy 1856) adequately describes the flow of gas through the granular medium, i.e.:

$$Q = k_g A \frac{\Delta h}{L} \tag{1}$$

Here, Q (m^3/s), the measured volumetric flow rate of gas through the end area of the tube, A (=7.85 × 10^{-3} m^2), is proportional to the difference in pressure head, Δh (m), over the flow path length L (m). The proportionality constant k_g (m/s) denotes the gas permeability of the porous medium. Rewriting Eqn 1 in terms of fluid velocity (U, m/s) and intrinsic permeability (K_{int}, m^2) we obtain:

$$U = -\frac{K_{\mathrm{int}}}{\mu_g} \nabla P \tag{2}$$

where μ_g is the dynamic gas viscosity (kg/m.s).

If the gas density is denoted by ρ_g (kg/m^3) then the continuity equation for steady-state compressible flow can be written as follows:

$$\nabla \cdot \{\rho_g U\} = 0 \tag{3}$$

Combining Darcy's Law with the continuity equation leads to:

$$\nabla \cdot \left\{ -\rho_g \frac{K_{\mathrm{int}}}{\mu_g} \nabla P \right\} = 0 \tag{4}$$

At the pressures involved in this experiment, the gas can be assumed to behave as an ideal gas, therefore:

$$\rho_g = \frac{PM_g}{RT} \tag{5}$$

where M_g is the molecular weight of the gas (kg/mol), R is the universal gas constant (J/K.mol), and T is the absolute temperature (K). Combining Eqn 4 and 5 leads to the following expression:

$$\nabla \cdot \left\{ -\frac{K_{\mathrm{int}} M_g}{\mu_g\, RT} P \nabla P \right\} = 0 \tag{6}$$

Equation 6 is used as the basis of the numerical model for the gas permeation process. The values assigned to various constants used in this work are shown in Table 2. For the purposes of this study it was assumed that the granular materials were isotropic.

To ascertain the value of K_{int} from the experimental pressure-flow data, a 3D axisymmetric model was constructed within the FEMLAB finite element software package. The geometry of the model, indicating the boundary conditions, is shown in Fig. 4. The mesh used consisted of 1652 Lagrange quadratic elements. At the commencement of a simulation run, a gas delivery pressure (boundary condition 2) was specified, and a value of K_{int} for the soil was assumed. The model was then run and the resultant steady state gas flow into the soil was determined by integrating the gas flowrate across surface (2) in the following manner:

$$Q = -\frac{2\pi K_{\text{int}}}{\mu_g}\int_{r=0}^{r=a} r\frac{dP}{dz}dr \tag{7}$$

This procedure was then repeated for various gas delivery pressures until a P–Q curve was generated. The predicted curve was then compared to that obtained experimentally and if necessary the value of K_{int} varied until an adequate match between the predicted and observed P–Q curves was obtained.

Using the 3D finite element model in conjunction with the gas flow experiment introduces a considerable degree of flexibility, not present in past studies where the use of FE modelling has been limited to the determination of so-called 'shape factors' (e.g. Iversen *et al.* 2004), which only apply for a limited set of conditions. While the full advantage to be gained from the integrated use of the FE model are not realised in this preliminary study, they will become apparent in an extension to this work, in which the gas-flow technique is used to determine *in situ* the saturated hydraulic conductivity of clay soil profiles as a function of depth.

Table 2. Values assigned to constants used in the numerical model

Parameter	Value assigned
Gas viscosity (μ_g, kg/m.s)	1.85×10^{-5}
Water viscosity (μ_w, kg/m.s)	1×10^{-3}
Water density (ρ_w, kg/m^3)	1×10^{3}
Universal gas constant (R, J/K.mol)	8.314
Molecular mass nitrogen (M_g, kg/mol)	2.8×10^{-2}
Temperature (T, K)	293.15
Acceleration due to gravity (g, m/s^2)	9.81

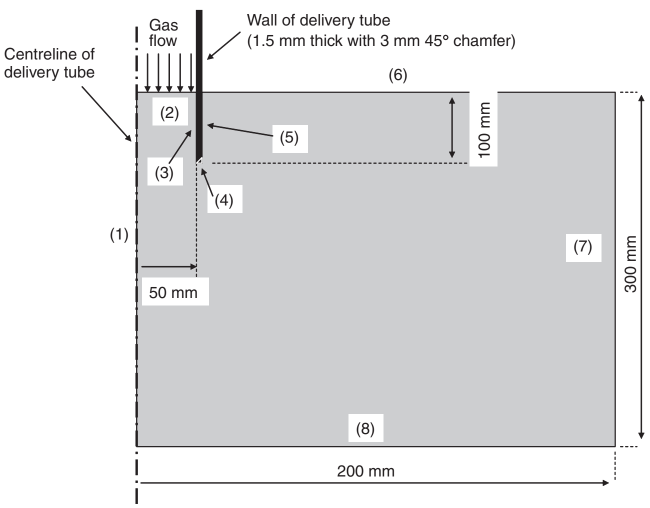

Fig. 4. Geometry of numerical model. Boundary conditions: (1) axis of symmetry; (2) P = delivery tube headspace pressure (Pa); (3) $U = 0$; (4) $U = 0$; (5) $U = 0$; (6) $P = 101325$ Pa; (7) $U = 0$; (8) $U = 0$.

Validation of the approach

In order to validate the experimental approach described above, the saturated water conductivity (k_w, m/s) of the 5 soils was first estimated from intrinsic permeabilities obtained in the gas flow experiments using Eqn 8:

$$k_w = \frac{K_{\text{int}}\rho_w g}{\mu_w} \tag{8}$$

where μ_w is the dynamic viscosity of water (kg/m.s), ρ_w is the density of water (kg/m^3), and g is the value of acceleration due to gravity (m/s^2).

These estimated values were then compared to the saturated hydraulic conductivity as measured by the more conventional constant head permeability test.

The arrangement of the constant head permeameter used is shown in Fig. 5 and is of standard design (Head 1994). To ensure that the soil sample densities employed in the constant head permeameter tests were comparable to those utilised in the gas permeability experiments, the samples were prepared in the same manner (i.e. rained down from a fixed height from a bucket with a perforated base). Once the soil sample was in place the unit was sealed and the soil sample saturated by allowing a steady flow of water to pass through it while being gently tapped to remove air bubbles. The flow of water was allowed to continue (for approximately 1 h) until a steady differential pressure and flow rate were established. Once established, the saturated hydraulic conductivity was determined via the following:

$$k_w = \frac{Q_w}{A}\frac{\Delta L}{(h_1 - h_2)} = 12.048\frac{Q_w}{(h_1 - h_2)} \tag{9}$$

where h_1 and h_2 are the piezometric heads measured at 2 points in the permeameter, separated by a height of ΔL, under a steady volumetric flow of water (Q_w (m^3/s)).

In order to assess the uncertainty in the value of the saturated hydraulic conductivity values obtained, 3 samples of each soil type were tested with 3 determinations of k_w made for each sample.

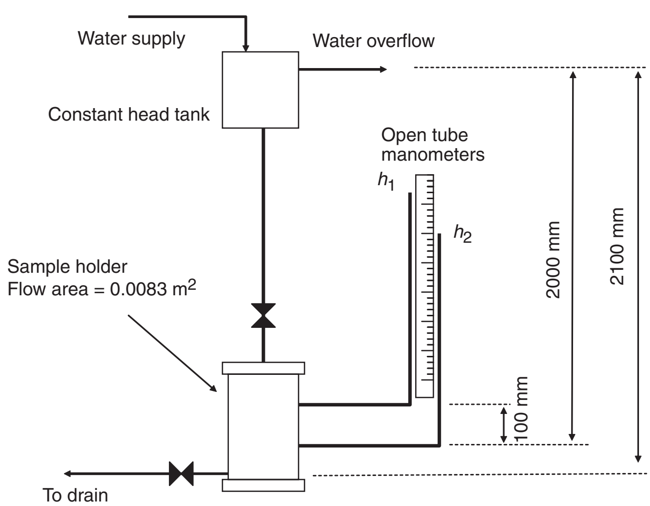

Fig. 5. Schematic of the constant head permeameter used in this study.

Results and discussion

The experimentally determined pressure-flow curves for the 5 sample soils are shown in Fig. 6. Each curve represents the averaged response from 3 separate gas flow procedures, each carried out on a newly prepared sample. It is clear that the 5 soils tested exhibited a relatively wide range of permeabilities, with *P–Q* curve slopes ranging from 3.3×10^{-7} m^3/s.Pa for the coarse sand fraction to 1.96×10^{-8} m^3/s.Pa for the ballotini.

Examination of the *P–Q* data obtained for each of the prepared soil samples, for each soil type, indicate that the variability in the *P–Q* slope between repeated trials ranged from ±3% (coarse sand), through ±7% (dark mineral sand), to ±10% (Stockton sand), suggesting that the preparations did not produce perfectly identical samples. In all cases, however, an acceptably linear relationship between pressure and gas flow rate was maintained. The gas flow behaviour through the bed was not observed to change in response to repeating testing of individual samples.

It is apparent that for the gas flow rates examined, the pressure–flow relationships can all be reasonably approximated by straight lines, although closer inspection reveals a consistent resupinate trend in all curves, with a slightly greater departure from linearity observed for the finer/less permeable samples. In all cases there is a tendency for the curves to be slightly convex at low flow rates, before inflecting and becoming slightly concave at higher flows. This behaviour is not reproduced by the theoretical model results, which, instead, predict truly liner behaviour, as indicated by the straight lines in Fig. 6. This inconsistency between measured and predicted behaviour suggests that the actual gas flow behaviour involves greater physical complexity than the theoretical model accounts for; the theoretical model possibly fails to account for second-order phenomena such as inertial effects (Forchheimer 1914). Nevertheless, for range of samples tested, and the data obtained, the assumption that Darcy's Law is applicable would appear to be justified, at least to a first approximation.

The *P–Q* curves for all 5 soil samples can be successfully simulated using the finite element numerical model based on the compressible Darcy flow described by Eqn 6 as shown by the straight lines in Fig. 6. The intrinsic permeability values, which produced the best fit to the experimental data, are shown in Table 3. The error margins are determined from the range of values lying between straight lines which are found to lie as bounds to the experimental data, that is, lines of maximum and minimum slope that incorporate the extreme data points that lie either side of the best fit line.

The saturated water conductivity test results for the same 5 soil samples are also listed in Table 3. The data obtained once again indicates that the coarse sand fraction is the most permeable, with the ballotini sample much less permeable (by almost 2 orders of magnitude when compared with the coarse sand results). Once again there was some variability observed when repeat samples of the same material were analysed, particularly for the Stockton sand (21%). In general, the degree of variability in the water permeability measurements (in percentage terms) was of the same order as or slightly higher than observed for the corresponding gas permeability experiments. This may in part be due to the different scales of the 2 experimental apparatus, as the chamber used for determining the water conductivity was considerably smaller

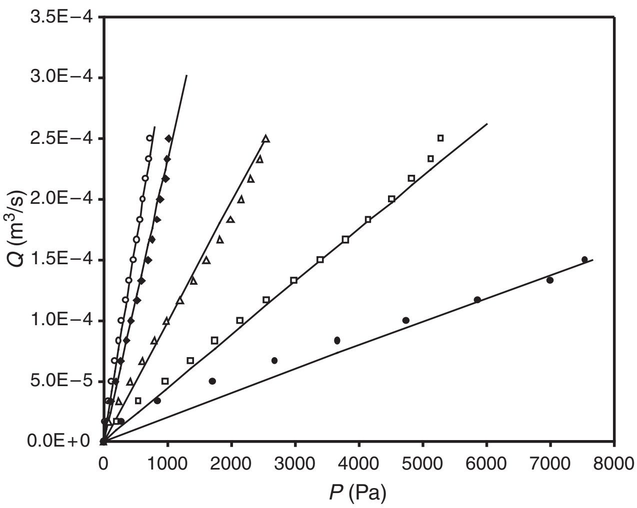

Fig. 6. Pressure versus gas flow data obtained for 5 granular soil types. ○, Coarse beach sand; ◆, Stockton beach sand; △, silica; □, dark mineral sand; ●, ballotini; —, numerical fit to data.

Table 3. Intrinsic permeabilities and saturated hydraulic conductivities obtained for 5 soil samples

Soil type	Intrinsic permeability (K_{int}, m^2) (gas flow experiments) Average	s.d.	Saturated water conductivity (k_w m/s) (water flow experiments) Average	s.d.
Coarse sand	1.03×10^{-10}	3%	1.38×10^{-3}	9%
Stockton sand	7.14×10^{-11}	10%	5.96×10^{-4}	26%
Silica	3.12×10^{-11}	12%	3.03×10^{-4}	10%
Dark mineral sand	1.40×10^{-11}	9%	1.60×10^{-4}	6%
Ballotini	6.35×10^{-12}	61%	6.65×10^{-5}	11%

than that employed for the gas measurements, making it harder to fill in a consistent manner.

The main aim of this study was to assess the potential of using gas permeability data in conjunction with an appropriate numerical model to predict the saturated hydraulic conductivities of different soil types. Using Eqn 8 it is possible to convert the intrinsic permeability values obtained from the gas experiments to water conductivities.

A comparison of the k_w values predicted for the 5 soil types from the gas flow tests, with those obtained experimentally from the conventional hydraulic permeameter, is shown in Fig. 7. There is good agreement in all of the tested soils, with excellent estimates obtained for the dark mineral sands and the silica (within the limits of the errors incurred in the experiments). Whilst the variability in results is seen to be greatest for the fine (ballotini) soil, it is apparent from Fig. 7 that the likely error, in absolute terms, is acceptable. In the worst result, the gas permeability approach appears to slightly under-predict k_w for the coarse sand sample by around 25%. Considering the range of permeabilities examined in this study this is an excellent result.

In previous studies (such as Iversen *et al.* 2004), the use of finite element modelling has been restricted to the determination of shape factors which quantify the flow area to flow path length ratio in situations, such as ours, where these parameters are not directly quantifiable. In such cases, the Darcy equation:

$$Q = -\frac{K_{\text{int}}}{\mu_g} A \frac{\Delta P}{L} \tag{10}$$

is expressed as follows:

$$Q = -\frac{K_{\text{int}}}{\mu_g} \Delta P \, SF \tag{11}$$

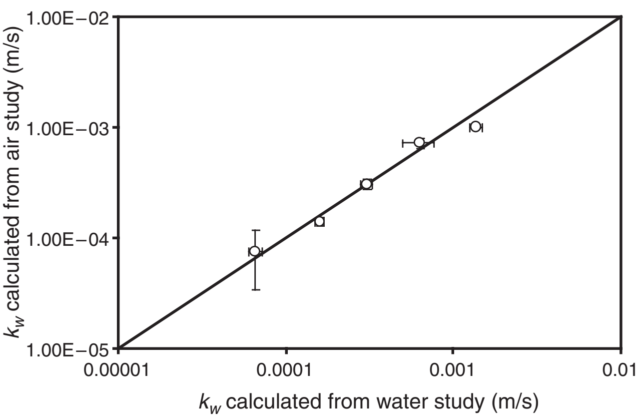

Fig. 7. A comparison of experimentally determined saturated water conductivity values against those calculated from gas permeability data. Error bars represent ± 1 standard deviation.

where SF is the shape factor. Liang *et al.* (1995) proposed the following expression for SF in terms of the tube inner diameter, (D_t), and insertion length (L_i):

$$\frac{SF}{D_t} = 0.4862\frac{D_t}{L_i} - 0.0287\left(\frac{D_t}{L_i}\right)^2 + 0.1016 \tag{12}$$

Interestingly, for the experimental geometry employed in this study, the shape factor as determined from our finite element model is close to 0.75, which compares favourably to the SF value of 0.72 predicted by Eqn 12. In simple cases where the solid medium is homogenous and isotropic with respect to permeability, the use of a shape factor determined from Eqn 12 could be used as an alternative to the finite element modelling of the process to determine intrinsic permeabilities to within an accuracy of a few per cent. In more complicated scenarios, however, such as permeability varying with depth or with direction the process must be modelled using the finite element approach.

It is important to appreciate the limitations of the proposed test method in regard to its applicability to different soil types and in relation to the nature of the results obtained. The measurement of permeability based on gas flow techniques is clearly most suited to granular soils, and is generally unsuitable for application to homogenous cohesive soils. In general, the range of permeabilities that can be measured using this technique is unlikely to extend much beyond the range exhibited by the soils employed in this study. Soils with greater permeability than the coarse sand are unlikely to offer enough resistance to gas flow to develop a reliably measurable pressure in the delivery tube (at least for the maximum flows that can be practically achieved using typical equipment). Soils with lower permeabilities are unlikely to permit gas flow of sufficient magnitude to enable reliable measurement, and pressures inside the tube become so great that they may cause the tube to 'pop out' of the soil or induce fluidization of the particulate material.

The approach does, however, offer an alternative method of permeability measurement in structured cohesive soils, such as desiccated soils, pedal soils (Fityus *et al.* 2004) or cohesive soils with an interconnected macropore structure, such as bioturbated tidal-flat muds. In this case, the soil may be considered to have a dual/multiple porosity behaviour, comprising rapid fluid movement through cracks, fissures, and/or holes, with simultaneous, slower fluid movement through the soil peds/intact regions. In general, the flow through the intact regions of cohesive soil will be orders of magnitude smaller than the flow through macro-voids, and consequently measurements in such soils using the proposed technique will effectively measure only the macro-void porosity. They will, however, have the advantage of not adversely affecting the water content, and hence the soil structure which may be water content-dependent, during the measurement.

Some consideration must also be given to the nature of the values being measured. In partially saturated soils, where water may be tightly held in the capillaries at grain-to-grain contacts, the conductivity of gas may be significantly impeded. The measured gas permeability may still be useful for practical purposes; however, values of hydraulic conductivity determined from the intrinsic permeability will underestimate the true hydraulic conductivity, as water-filled capillaries do not pose the same impediment to air as for bulk water flow. Hence, the approach described here is strictly only reliable for granular soils in a dry or near-dry condition. The same limitation will not apply, however, to structured cohesive soils. This is because unsaturated, structured, cohesive soils commonly hold most of their moisture in their micropore structure, whilst the macro-voids remain free of bulk water.

Development of this approach as a portable tool for the *in situ* measurement of hydraulic conductivity in unsaturated structured soils is continuing. It offers the advantages of giving quick, reliable results, without the errors associated with sample disturbance and sample reactivity to water.

Conclusions

This paper demonstrates the potential of a new approach to the indirect determination of hydraulic conductivity based on measurement of gas flow rates in dry granular and structured soils. Its ability to give estimates of hydraulic conductivity to an acceptable accuracy has been demonstrated for a range of granular soils of differing permeability. The approach has the potential to provide rapid and reliable estimates of hydraulic conductivity *in situ*, and is well suited to routine application in engineering and agriculture.

Its extension and validation for use in structured clay soils is continuing, and it is expected that its greatest advantages will be realised in this application.

Acknowledgments

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