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The in situ measurement of permeability in dry granular soils

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Summary: This paper describes a new approach to the measurement of permeability in unsaturated granular materials using airflow. The apparatus employed consists of a cylindrical tube that is einbedded in the soil to a prescribed depth. Air under a known pressure, is then supplied to the tube and allowed to escape by permeating through the soil. For a particular soil a plot of supply pressure vs. air flow can be obtained. which can then be used to back-calculate the permeability of the medium. Fundamental relationships can then be used to estimate the saturated hydraulic conductivity from the calculated airflow permeability. The paper provider, an outline of the numerical solution used to predict air flow rates for the experimental arrangement and provides a validation of the approach through comparison with experimental data.

INTRODUCTION

All soils are, to some extent, permeable materials. Conventionally, the coefficient of permeability of soils is estimated in the laboratory using a permeameter or oedometer or in situ using water infiltration or pore water pressure dissipation tests. In this paper, a method is described that uses air as the infiltrating fluid, in place of the traditional approaches that employ water. There is a large body of research devoted to the study of air flow in granular media. This has usually been pursued in fields outside geotechnical engineering. For example, chemical engineers study gas flow through packed beds, and agricultural engineers study the flow of gas through grains.

Gu et al (1992) developed a theoretical model for predicting the interstitial air pressure distribution for bulk solids flowing in a conical mass flow bin. This theoretical model is based on continuum mechanics theory. Both theoretical model and experimental results indicate that the magnitude of air pressure increases with increases in the size of the hopper outlet or the surcharge level, and with decreases in powder permeability. Shang et al (1999) developed a theory and methodology for investigating the permeability of basalt and wood particle aggregates. From their experimental research and analysis, they determined that there exists a linear relationship between air flow rate and the pressure gradient, if the air flow velocity over the characteristics length of the particle bed was less than 3 m/s. In other words, Darcy's law was found to be valid for describing the fluid flow process in particle aggregates.

Olson et al (2001) presented three techniques to measure 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. They examined the effects of moisture content and soil homogeneity on air permeability values. Air permeability was measured air flow at various rates through each core at field moisture content, and observing the pressure difference across the sample. Air pressures in the unsaturated zone were simulated assuming a one-dimensional transient flow model.

In this paper a new approach to the measurement of permeability in unsaturated granular materials using an airflow technique is described. Three-dimensional axisymmetric steady-state flow model was used to simulate the laboratory test results by using the new apparatus. The apparatus employed consists of a cylindrical tube that is embedded in the soil (fiom the surface) to a prescribed depth. Air under a known pressure is supplied to the tube and allowed to escape by permeating through the soil and escaping to the atmosphere. For a particular soil, a plot of supply pressure vs. air flow can be obtained, which can then be used to back-calculate the permeability of the dry medium. From this estimate of air permeability, the saturated hydraulic permeability of the soil may be also estimated.

It is planned to develop the approach to include permeability measurements in soils with macro-void structures such as compacted clay soils and cracked clay soils. The use of air makes gives the approach the potential for use in unsaturated soils where water would change the moisture content of the soil, and hence, the unsaturated permeability of the soil.

METHODOLOGY

In our approach, air 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 air delivery tube, coiresponding to each applied flow rate, is measused and a graph of flow rate vs. pressure is produced.

The pressure-flow relationship is theoretically dominated by the intrinsic permeability of the granular medium (this is described below), and as such, it can be used as the basis for quantitatively estimating the air flow permeability. This is achieved through numerical modelling of the air flow process, and using a trial and error process to match predicted and measured pressure-flow responses.

This paper describes the preliminary development and validation of the approach. The steps involved that are described in this paper include:

- A review and development of theory to describe the compressible flow of air through a granular medium.
- Development of an air flow apparatus.
- Development of a numerical model to simulate the air flow apparatus
- An experimental program to undertake pressure-flow curves using the apparatus in a range of different granular soils
- An experimental program to determine the permeability of the same granular materials using conventional methods.
- Generation of theoretical pressure-flow curves using the numerical model and permeability values measured by conventional methods
- Evaluation of the approach by comparing the theoretical and measured pressure-flow curves.

These are described in the following sections.

FLOW THEORY

Darcy (1856) found that rate of flow is directly proportional to the pressure gradient causing flow. The proportionality coefficient is permeability. Darcy's Law can be used to model fluid flow in porous granular media (Carman, 1956; Bear, 1972; Coussy, 1995; Shang et al. 1999). Darcy's Law states that the velocity vector is determined by the gradient of pressure, the fluid viscosity and the structure of porous media.

$$u = -\frac{K}{\mu} \nabla p \qquad (1)$$

In (1), K denotes the intrinsic permeability of the porous medium (m^2), μ denotes the fluid viscosity (kg m^{-1} s^{-1}), p is the fluid pressure (Pa) and u denotes the fluid velocity vector (ms^{-1}). If the fluid density is ρ (kg m^{-3}), then the continuity equation for steady state compressible flow is:

$$\nabla.\{\rho u\} = 0 \qquad (2)$$

Combining Darcy's law and the continuity equation shows,

$$\nabla.\{-\rho \frac{K}{\mu} \nabla p\} = 0 \qquad (3)$$

In the case of a compressible fluid, the density, ρ (kg m^{-3}) is dependent on pressure. The ideal gas law states that:

$$pV = nRT \qquad (4)$$

Where n is the number of moles of gas molecules in a volume of gas V (m^3) at absolute temperature T (°K), and R (mN/kg°K) is the universal gas constant. If the molar mass of the gas molecules is M (kg/mole), then combining with (3) and (4) gives

$$\nabla.\{-\frac{KM}{\mu RT}p\nabla p\} = 0 \qquad (5)$$

Equation *(5)* is the macroscopic governing equation for compressible fluid flow in a finite domain.

The permeability of a granular material with respect to a particular fluid is a function of the physical characteristics of both the medium and the permeating fluid. The permeabilities with respect to different fluids can be related by an intrinsic property of the medium, called the intrinsic permeability (*K*). The relationship between the permeabilities of a medium with respect to water (the hydraulic conductivity, k_w) and air (k_w) is given by

$$K = \frac{k_w \mu_w}{\gamma_w} = \frac{k_a \mu_a}{\gamma_a} \qquad (6)$$

Where μ_w and μ_a are the dynamic viscosities of water and air respectively, and γ_w and γ_a are the unit weights of the respective fluids.

AIR FLOW PERMEABILITY APPARATUS

An experimental apparatus was developed to deliver a flow of pressurised air into a soil, across an interface of controlled geometry. The apparatus is comprised of

- A thin-walled stainless steel tubular delivery lance, the dimensions of stainless tube is 100 mm diameter and 500mm height. (Other sizes were trialled, but a discussion of this is beyond the scope of this paper)
- An air flow regulator (or flow meter) with a capacity up to 40 litres per minute.
- A digital pressure meter to measure pressure inside the delivery lance. The Pressure meter used, *Comark C9551* has a range of 140 mbar with a resolution of 0.1 mbar.
- A source of pressurised air (compressor or portable compressed air cylinder) to supply air flow to the tube.

The detail of the apparatus is shown in the Figure 1. Note that the pressure meter was tapped into the back end of the delivery lance, so that it was not in the direct stream of the compressed air. In this way any dynamic flow effects were minimised.

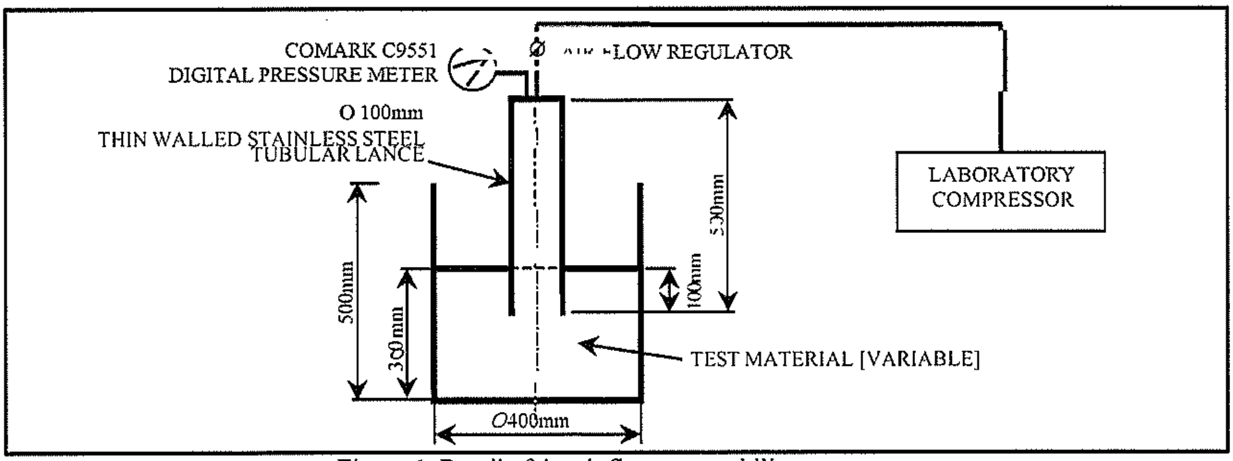

Figure 1; Detail of the air flow permeability apparatus

NUMERICAL MODEL

The FEMLAB finite element software was employed for the numerical model. The geometry of the air flow apparatus is reasonably approximated using an axisymmetric formulation and the air flow behaviour described by equations (5). An illustration of the basic model (not to scale) is shown in Figure *2*, along with the boundary conditions used. Note that a large domain is modelled, so that the condition of zero flow at the bottom and right boundaries is reasonable. The values used in the model are discussed in a following section.

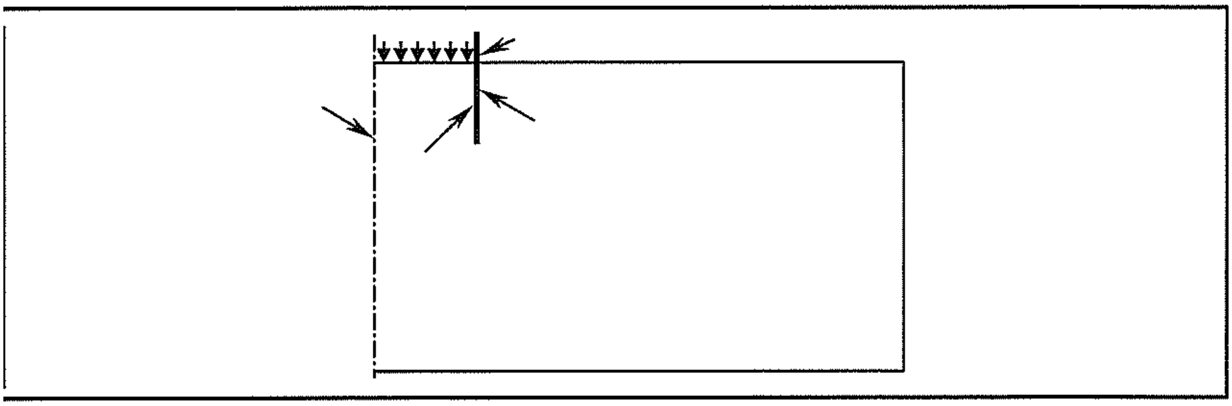

Figure 2. Geometry of numerical model, showing boundary conditions (u = velocity; p = pressure).

EXPERIMENTAL PROGRAM

The air flow apparatus was trialled using five granular soils with different particle characteristics, ranging from fine to coarse sands. The granular materials used were: "dark mineral sand" (ilmenite), "light mineral sand" (garnet), "Stockton Beach sand" (silica), "fine fraction of Stockton Beach sand" (~<300μm), "coarse fraction of Stockton Beach sand" (~>300μm). Sieve analyses were carried out for each of the samples to determine the particle size distribution. For each material, the particle sizes lie between 0.06mm and 2mm. These are presented in Figure 3.

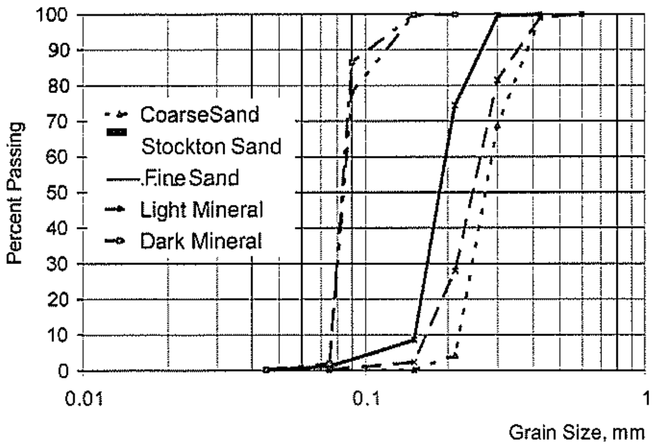

Figure 3. Grain size distributions of soils used in laboratoiy tests.

Experimental work involved determining the pressure-flow relationships, and the hydraulic conductivity for each material.

Determination of pressure flow curves,

The air flow permeability trials were made on samples prepared in large containers (400 mm diameter and 500 mm height) on samples of 400 mm diameter and 300 mm in height. This sample size was chosen to facilitate ease of testing whilst at the same time being large enough to minimise boundary effects. The sample size was selected from a trial and error parametric study using the numerical model described above. First, an analysis was performed with a very large sample zone (2m wide and 2m radius), and a reference solution for an infinite half space obtained. Then, numerical studies were conducted considering successively smaller sample sizes. For a given applied pressure, the calculated flows were compared with that predicted in the reference solution. It was found that the differences resulting from reductions down to a size of 600mm diameter and 500mm height were less than 1%, and that a sample size of 400 mm diameter and 300 mm in height, corresponded approximately, to a difference of only 3%. This is considered to be an acceptable when considered in regard to the simplifications it provided in the experimental work.

To get consistent relative density in the prepared sand samples, a standardised sample preparation technique was adopted. This involved raining the sample from a bucket with holes size of 20 mm diameter, maintained at a fixed height above the sand surface, to produce a loose packing arrangement.

Determination of the pressure-flow curves for the prepared samples proceeded as follows:

- The 100 mm diameter stainless steel tubular lance was pushed to embed it 100 mm into the sample.
- A supply airflow rate was adjusted to a selected level at the in line flow regulator. Setting ranged from 5 litres per minute to 40 litres per minute.
- A digital pressure meter was used to measure the pressure inside the 100 mm diameter tubular lance after steady state flow conditions had established (usually within 10-15 seconds)
- Flow rates and coiresponding pressures were measured at 5 l/min intervals between 5 l/min and 40l/min.
- The process was repeated five times using freshly prepared samples for each sand type.

Pressure-flow curves were produced from the average measured values. They are shown in the results sections that follow.

Determination of hydraulic conductivity: constant head method.

In order to know the actual permeability of the samples used, constant head permeability tests were carried out in the laboratory. Each sample was prepared in the same way as those used for the air flow tests, and so achieved comparable relative densities. The measured permeability values are shown in Tablelbelow.

GENERATION OF THEORETICAL PRESSURE FLOW CURVES

The numerical model described above was used to generate theoretical pressure flow curves for comparison with the experimental results. The required values of the air flow permeability were calculated from the measured hydraulic conductivity values using equation (6). The parameters used for the calculation were

- Dynamic viscosity of air μ_a (20 "C) was 1.85×10^{-5} kg m^{-1} s^{-1} and of water μ_w (20 "C) was 1×10^{-3} kgm^{-1} s^{-1}.
- Unit weight of air γ_a (at atmospheric pressure) was 11.8N/m^3 and of water γ_w was 9.81 kN/m^3.

By substituting these values for water and air, equation (6) becomes $k_w = 16k_a$. The estimated intrinsic and air permeabilities are shown with the measured hydraulic conductivity values in Table 1.

	Intrinsic Permeability m^2	**Hydraulic Conductivity** ms^{-1}	**Air Permeability** ms^{-1}
Dark Mineral	$9.0 \cdot 10^{-12}$	$9.0.10^{-5}$	$5.6 \cdot 10^{-6}$
Light Mineral	$1.0 \cdot 10^{-11}$	$1.0 \cdot 10^{-4}$	$6.3.10^{-6}$
Fine Sand	$3.3 \cdot 10^{-11}$	$3.3 \cdot 10^{-4}$	$2.1 \cdot 10^{-5}$
Stockton Sand	$5.8 \cdot 10^{-11}$	$5.8 \cdot 10^{-4}$	$3.6.10^{-5}$
Coarse Sand	$7.9 \cdot 10^{-11}$	$7.9 \cdot 10^{-4}$	$4.9 \cdot 10^{-5}$

Other parameters used in equation (5) were estimated as follows. Air is approximately 21 percent oxygen and 78 of nitrogen. As the molecular molar weight for oxygen and nitrogen are 32g/mole and 28g/mole respectively, the average molecular molar mass for air is estimated 29g/mole. The universal gas constant is R is 8.31mN/kg°K and T is approximately 300°K for the conditions under which the testing was performed. Numerical model output is shown in Figure 4.

RESULTS AND DISCUSSION

The calculated and measured flow verses pressure results for dark mineral sand are presented in Figure 5. It is apparent that in both cases, the relationship between air pressure and air flow is linear and that the slope is similar (0.0016 l/min/Pa). The good agreement between the numerical and measured results confirms that the characteristics of the air flow device can be accurately described by the numerical model.

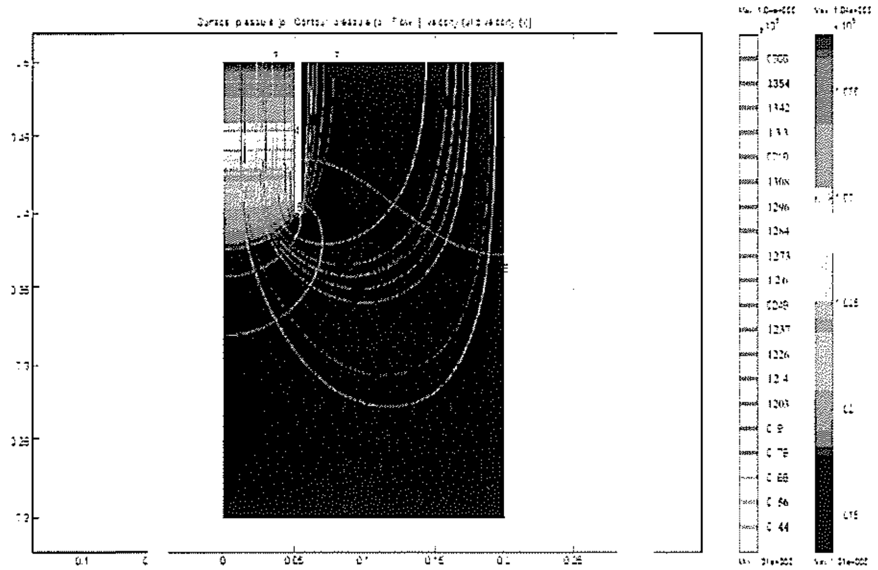

Figure 4: FEMLAB numerical model output

The calculated and measured flow verses pressure results for all of the considered soils are also presented in Figure 5. As for the results for dark mineral sand, it can be seen that there is good agreement between the measured and predicted values for all of the tested soils.

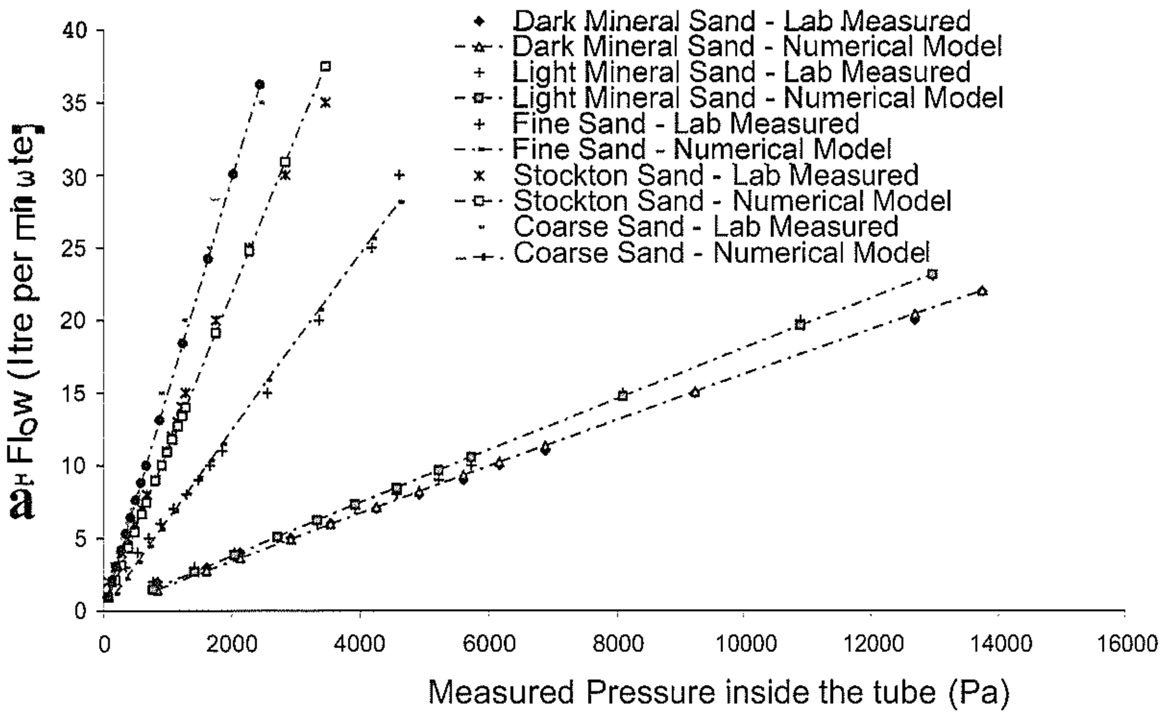

Figure 5: Airflow vs. pressure relation at boundary 3 for all Sand

From the results of Figure 5, it is also apparent that each material has unique flow vs. pressure graph slope and each passes through the origin. In general, the coarser the material the steeper the slope of the flow vs. pressure line, and the finer the material the flatter the slope. As the unique line (slope) for each material is related to permeability, it confirms that the proposed approach has the potential to serve as a useful method for the estimation of the saturated hydraulic conductivity. The method is simple and robust. Many more permeability tests can be carried out in the field than by conventional permeability tests in the laboratory, so this device and approach may be a useful adjunct to conventional permeability assessment methods. The method could be useful for assessing the infiltration capacity of soil, or assessing the suitability of a site for bio-venting.

As mentioned above, one advantage of this approach is that it offers a portable, simple and low cost device that can be deployed by a single operator to estimate in situ hydraulic conductivity quickly, accurately and efficiently, without the need for undisturbed laboratory test samples, heavy field test equipment or large excavations. Another advantage is that in using air as the permeating fluid, it can be deployed in heavy clay soils to measure the macro-void permeability, without causing moisture content changes that would in turn. affect the permeability being measured. Useful applications of this type include the assessment of the hydraulic properties of compacted clay fills, and the deteimination of crack depths in expansive clays (Moe, et al. 2003). Development work in both of these areas is continuing.

A number of issues remain to be addressed before the method can be considered for widespread use in geotechnical practice. These include how to interpret flow through partially saturated granular soils. However, the device does have the potential to enable peimeability measurement at any depth in a soil profile, by employing a longer delivery lance, or seating it in the bottom of a drilled borehole.

CONCLUSIONS

An experimental apparatus, designed for the in-situ measurement of hydraulic conductivity, has been shown to hold great potential to estimate permeability in dry granular soils, as well as clay soils with macro-void stsucture. A numerical model developed to simulate the flow of pressurised air through soils has been shown to accurately simulate the flow vs. pressure characteristics for a range of sandy (fine granular) soils. With the slight modification to the device and the method presented in this study, there is potential to estimate permeability for partially saturated granular soils at any depth in a soil profile, or to measure the macro-void permeability in heavy clay soils or to determine crack depths in expansive clays. Determination of crack depths in expansive clays will be the subject of ongoing research.

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