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A new laboratory method for the measurement of unsaturated coefficients of permeability of soils

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ABSTRACT: A new laboratory method was recently developed at the University of Saskatchewan, Saskatoon, for the direct measurement of the unsaturated coefficients of permeability. The method was verified in a testing program involving residual and saprolitic soils from Hong Kong. The method makes use of the pressure plate concept for the direct control of the pore-air and pore-water pressures in the soil specimen. The test procedure is similar to the "inflow equal outflow" method. The coefficients of permeability measured ranged from 10^{-6} m/s to 10^{-10} m/s. The choice of porous disks had to have the right relationship between the air entry value and the saturated coefficient of permeability. Experimental results are presented. The experimental results were compared with predicted permeability functions obtained from soil-water characteristic curves along with the saturated coefficients of permeability.

1 INTRODUCTION

The permeability function is often required in the numerical modelling of water and solute transport in unsaturated soil problems. Although techniques are available for the prediction of the permeability function from soil-water characteristic curves together with the saturated coefficient of permeability, measurement of the permeability function is required for confirmation of the correct function.

The coefficient of permeability can decrease by several orders of magnitude as the degree of saturation of the soil decreases (or as the suction of the soil is increased). The unsaturated coefficients of permeability corresponding to changes in soil suction, are difficult to measure because their variation can be over several orders of magnitude. The variation in the coefficient of permeability over several orders of magnitude makes it difficult to design a single apparatus that can be used for testing all soils. In addition, when dealing with residual and saprolitic soils, the highly heterogeneous nature of the soils adds further complications to the laboratory measurement.

2 NEW DIRECT LABORATORY METHOD

A new methodology was developed to provide a direct measurement of unsaturated coefficients of permeability with special attention given to the nature of residual and saprolitic soils from Hong Kong. The methodology is likely suitable for most soils.

The method makes use of the pressure plate concept for the direct control of the pore-air and pore-water pressures in the soil specimen. The pore-water pressure was controlled at both ends of the soil specimen with the assistance of high (or low) air entry porous disks. The air pressure was controlled through an air inlet.

It was not possible to install small tensiometer tips at two points in the soil specimen for the measurement of pore-water pressures due to the coarse and fragile nature of the soils. Therefore, it became important to ensure that the coefficients of permeability of the soil were always lower than the adjacent air entry porous disks.

The set up in Figure 1 was used for determining the coefficient of permeability at suction values ranging from 10 kPa to 100 kPa. The air entry values of the soils being tested were low, generally less than 10 kPa. The soils would be unsaturated and their coefficients of permeability were anticipated to be low. Consequently, 100 kPa high air entry ceramic disks were used. The 100 kPa high air entry ceramic had a saturated coefficient of permeability of approximately 1×10^{-7} m/s.

The set up in Figure 2 was used for measuring the coefficient of permeability at suction values less than 1.5 kPa. At low suctions, the soil has its highest coefficient of permeability and highly permeable porous disks were required. On the basis of hydraulic conductivity and air entry tests conducted on steel, brass and corundum porous disks, porous brass disks were selected. The brass porous disks have an air

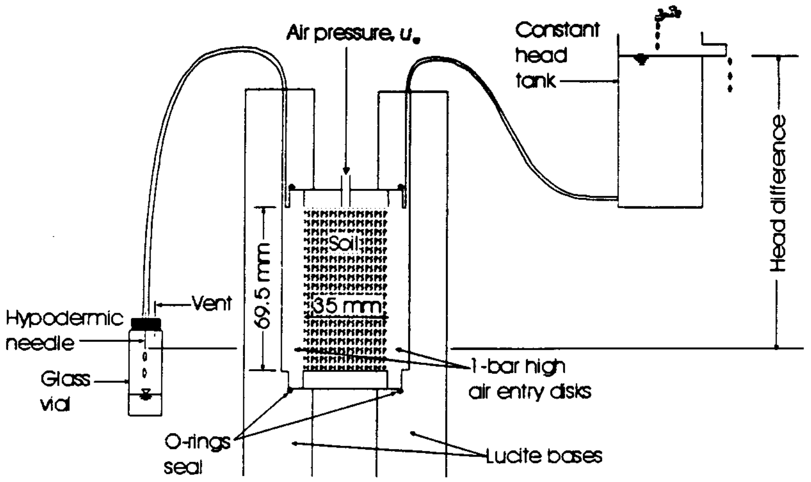

Figure 1 - Permeameter set up for matric suctions greater than 10 kPa

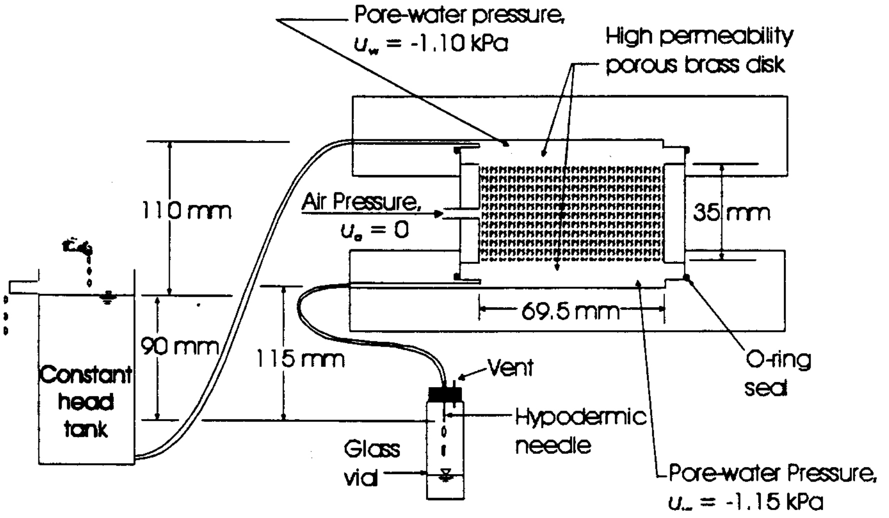

Figure 2 - Permeameter set up for low matric suctions of less than 1.5 kPa.

entry value of about 1.5 kPa and a coefficient of permeability of 4.5 × 10^{-5} m/s.

3 TEST PROCEDURE

The soil specimen was trimmed into the transparent Lucite specimen ring holder. The specimen ring holder has a height of 35mm and a diameter of 69 mm.

The soil specimen in the permeameter was saturated prior to performing the permeability tests. Saturation of the soil specimen was achieved by maintaining a positive head of water at both ends of specimen. The air inlet was open to the atmosphere so water could rise into the air inlet, driving out air from the specimen.

In tests conducted using the set up in Figure 1, an air pressure was applied to the air inlet. The water head at one end of the specimen was lowered in order to maintain a head gradient across the specimen.

The difference between the applied air pressure and the average water pressure gave the average matric suction in the soil specimen when equilibrium was attained.

In tests conducted using the set up in Figure 2, the air pressure was maintained at atmospheric condition by leaving the air inlet to the permeameter open to the atmosphere. Negative water pressure was applied to both ends of the specimen. The head at the outflow end was maintained at a slightly lower value in order to maintain a positive head gradient across the specimen for flow to occur.

Initially, water would flow from the soil specimen in response to both the applied air pressure and the total head gradient across the specimen. Once a matric suction corresponding to the applied air pressure and the applied water pressures was established, water would flow only under the influence of the total head difference across the specimen. When the flow rate from the specimen became constant with time, the inflow to the specimen was assumed to be

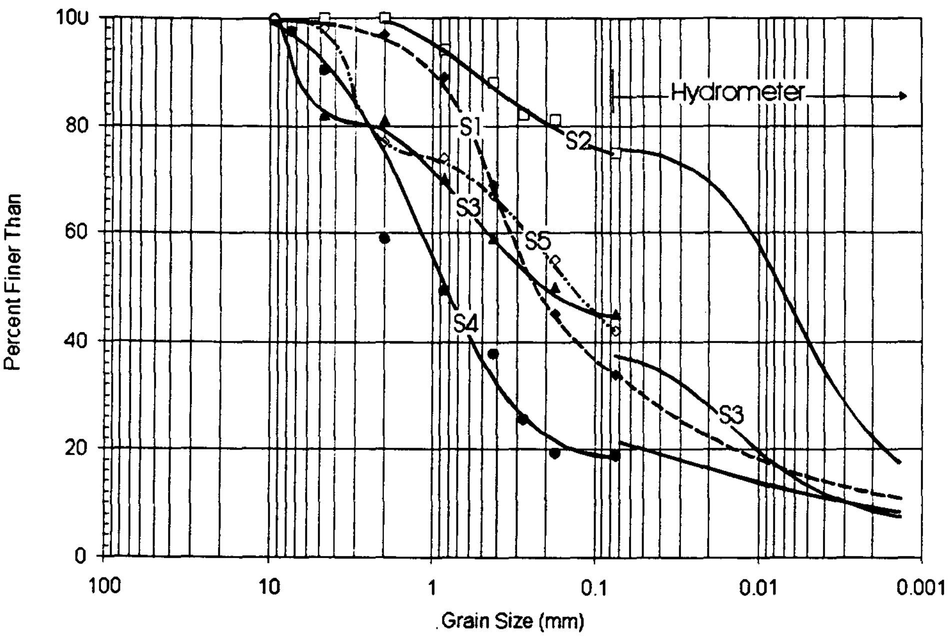

Figure 3 - Grain size distribution curves for the five saprolitic soils.

equal to the outflow from the specimen. The coefficient of permeability corresponding to the applied matric suction was then computed from the steady outflow rate.

Tests were also conducted under positive pore-water pressures (i.e., negative matric suctions and the specimens were saturated).

4 SOILS TESTED

Measurements of the permeability function were conducted on five saprolitic soils from Hong Kong. Only one specimen of each soil was tested. The soils were highly heterogeneous and specimen preparation was difficult. Grain size distribution curves for the five saprolitic soils are presented in Figure 3. The grain size curves were each obtained using a separate specimen from the same block sample as the specimen used for the permeability test. Color description and specific gravity values for the five saprolitic soils are presented in Table 1.

In an earlier research program (Gan and Fredlund, 1998) saturated permeability tests and soil-water characteristic tests were conducted on the above five saprolitic soils. These tests are not described in this paper but the results are presented. The saturated permeability tests were conducted using a double ring permeameter under constant head conditions. The saturated coefficients of permeability for the five saprolitic soils are presented in Table 2. The soil-water characteristic curves are presented in Figure 4. A total of 13 soil-water characteristic curves were obtained.

Table 1. Color description and specific gravity values

Soil Identificaton	Description	Specific gravity
Soil S1	Light whitish yellow spotted light brown	2.61
Soil S2	Reddish brown spotted with white	2.67
Soil S3	Light whitish brown striped with black	2.66
Soil S4	Greyish brown mottled with light yellow	2.63
Soil S5	Light greyish brown mottled orangish yellow	2.58

Table 2 – Coefficients of saturated permeability.

Soil	This test program		Previous test program (Gan and Fredlund, 1998)	
	ksat (m/s)	gradient, i	*ksat* (m/s)	gradient, i
S1	2.84E-09	10.6	2.05E-05	2.2
	6.26E-08	3.3	2.66E-06	4.4
S2	7.66E-09	15.8	2.37E-05	3.4
			3.36E-05	4.3
S3	1.11E-08	15.7	8.23E-06	1.1
	1.20E-06	1.43	5.83E-06	1.5
S4	2.29E-06	1.43	3.92E-05	4.3
	8.45E-09	15.7	2.23E-05	2.1
S5	1.16E-08	1.43	8.08E-06	1.2
			8.60E-05	11.5

5 RESULTS AND DISCUSSION

The coefficients of permeability as a function of matric suction for the five saprolitic soils are presented in Figure 5. The highest coefficient of permeability measured was 2.29×10^{-6} m/s (i.e., k_{sat} for S4) which is more than one order of magnitude lower than the saturated coefficient of permeability of the porous brass disk. The highest coefficient of permeability measured using setup No. 1 was 10^{-8} m/s (i.e., S5 and S3 at a matric suction of 10 kPa) which was more than one order of magnitude lower than the saturated coefficient of permeability of the ceramic disks. Hence, the ceramic disks and the porous brass disks should not have presented any significant impedance effects in any of the tests. The lowest coefficient of permeability measured was about 10^{-10} m/s (i.e., S2 at a matric suction of 100 kPa). The coefficients of permeability measured span a range of 4 orders of magnitude.

In general, the shapes of the coefficient of permeability functions (Figure 5) loosely resemble the shapes of the soil-water characteristic curves (Figure 4).

The permeability functions were also predicted for each of the five saprolitic soils from the soil-water characteristic curves and the corresponding

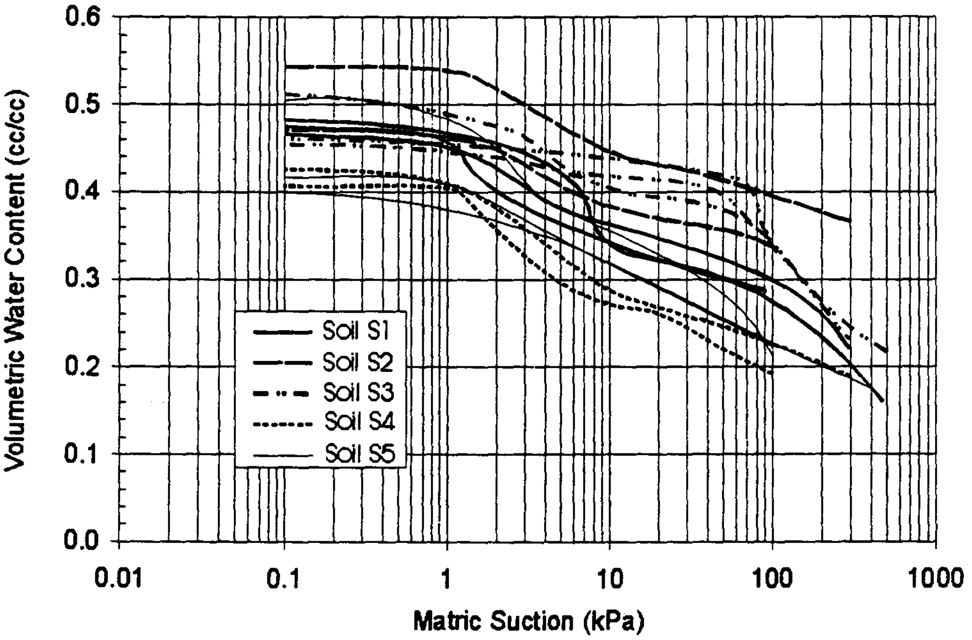

Figure 4 – Soil-water characteristic curves for the five saprolitic soils.

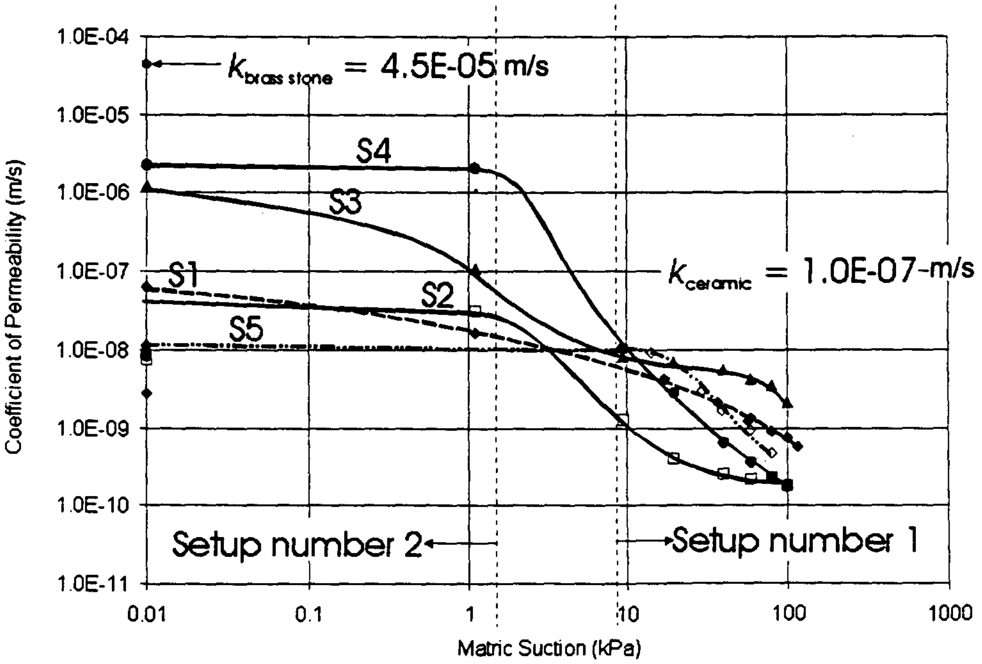

Figure 5 – Experimental permeability functions for the five saprolitic soils

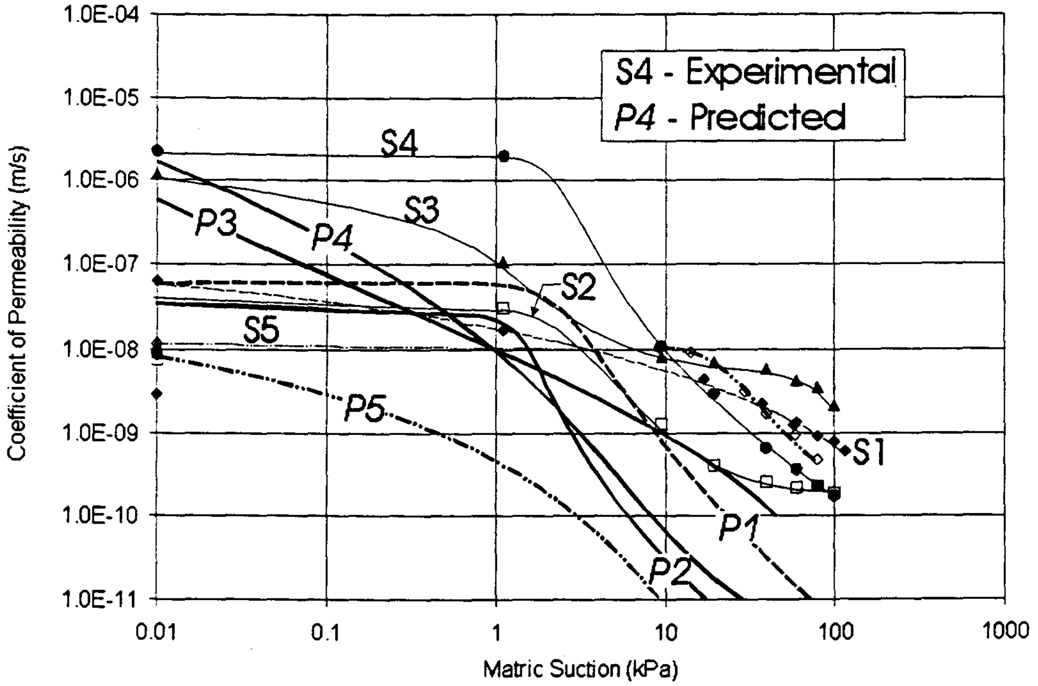

Figure 6 – Comparison of predicted permeability functions with experimental values.

saturated coefficient of permeability. The saturated coefficients of permeability obtained using setup No. 2 in this test program were used in the predictions. The coefficients of saturated permeability from Gan and Fredlund (1998) which were obtained using a double ring permeameter under constant head conditions were significantly higher than the values obtained using setup No. 2 (see values presented in Table 2). The high values from Gan and Fredlund (1998) were due in large part to significant side-wall leakage. Trimming of heterogeneous saprolitic soils was difficult and the resulting specimens often had rough and jagged sides. As a result, the specimens do not fit snugly in the permeameter rings. Side-wall leakage can be largely eliminated by the application of a small matric suction less than the air entry value of soil, in conducting the permeability test using the setup in Figure 2.

The theory for the prediction of the permeability functions has been presented by Fredlund, Xing and Huang (1994). The soil-water characteristic curve is first best-fit using a non-linear regression analysis. Then the procedure involves integrating along the soil-water characteristic curve, starting from saturated conditions. The end result is a series of computed points that can be connected to form the predicted permeability function. The theory has been programmed into the computer software package called SoilVision (Fredlund, 1996),

The predicted permeability functions for the five saprolitic soils are presented in Figure 6, together with the experimental data for comparison. The predicted permeability functions show considerable variation from the experimental permeability functions. Possible explanations for the deviations would include the followings:

1.) the saprolitic soils from Hong Kong are highly heterogeneous.
2.) the highly heterogeneous soils have a variation in the soil-water characteristic curves (Figure 4).

6 CONCLUSIONS

One of the main difficulties encountered in the measurement of the permeability function over a wide range of matric suctions is the availability of porous disks with the right combination of air entry value and coefficient of permeability. Two conditions related to the porous disks must always be satisfied:

1.) the ceramic disk must remain saturated, and
2.) the coefficient of saturated permeability of the porous disks should be about one order of magnitude greater than the coefficient of permeability of the soil being tested.

The experimental permeability functions have the characteristic "S" shape similar to the soil-water characteristic curves. The experimental results thus appear to be reasonable.

The predicted permeability functions deviate from the experimentally measured functions probably as a result of the highly heterogeneous nature of the soils.

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