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Manuscript title: Measurements of permeability of saturated and unsaturated soils

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Abstract

The management and engineering assessments of geotechnical assets within the national transportation inventory require an appropriate knowledge of permeability of saturated and unsaturated soils. Determination of the permeability of saturated soils can be carried out using direct measurements, whereas that of unsaturated soils is often made using indirect methods based on Soil Water Retention Curve (SWRC). In this study an attempt was made to develop a novel approach for measuring the saturated and unsaturated permeability of soils. The tests were conducted on 100mm diameter reconstituted and compacted samples of glacial till. Suctions were generated by circulating low humidity air through a slender sand column located at the centre of the samples. Measurements of suction were made by two tensiometers located radially at the base of the samples. The drying process was terminated when the observed suctions reached or approached the limiting capacity of the tensiometers (1500 kPa). Combinations of suction measurements and volumetric strains during the drying process were used to determine the permeability by adopting analytical solutions as applicable to a radial flow condition.

Keywords: permeability; clays; compaction; partial saturation; pore pressures; suction

INTRODUCTION

The research findings of Dawson *et al.* (2016) have suggested that almost 8% of the UK transport network's geotechnical assets (slopes and embankments) are at risk of failure because of rapidly changing climatic conditions. This geoinfrastructure is being exposed to changing temperature and rainfall patterns leading to prolonged drying and wetting which is impacting the operational stability, leading to failure. The UK Climate Change Risk Assessment Report (HM Government, 2017) has promoted an industrial awareness for a better understanding of the materials that were used to form these key assets. Zdravkovic *et al.* (2018) and Tsiaampousi *et al.* (2017) have shown that conventional analyses of slopes by assuming soils above the water table to be completely dry cannot realistically model the in situ soil behaviour.

Soils in the vadose zone are in an unsaturated state which makes the stability analysis complex and hence often advanced numerical tools are required. For these tools to provide realistic outputs, it is necessary that the changes in the permeability in response to suction and stress changes must be correctly modelled (Potts *et al.,* 2001). The relevance of permeability under a changing environment is also important to understand various geo-environmental issues, such as the soil-atmosphere interactions and land-fill covers for waste containments (Miller *et al.,* 1998; Yesiller *et al.,* 2000; Hauser, 2008; Sinnathamby *et al.,* 2014). To ensure the resilience and integrity of geotechnical infrastructure, several researchers in the past have focused on numerical modelling to assess and quantify the effects of climate change on slopes (O'Brien, 2004; Jenkins *et al.,* 2009; Murphy *et al.,* 2010). The operational accuracy of numerical models associated with unsaturated soils depends upon material characteristics inputs, such as permeability which is typically determined using the Soil Water Retention Curve (SWRC) (Fredlund, 2000; Aubertin *et al.,* 2003). The permeability of an unsaturated soil is not a constant value and the accurate assessment of this parameter with laboratory measurements is not as simple as that of saturated soils, particularly under external loading conditions (Cai *et al.,* 2014). There are mainly two approaches for determining the permeability of unsaturated soils, namely the steady state and unsteady state methods (Fredlund and Rahardjo, 1993). The unsteady state (i.e. instantaneous profile method) and the steady state methods have been used by several researchers in the past (Klute, 1965; Watson, 1966; Klute, 1972; Baker *et al.,* 1974; Daniel, 1982; Paige and Hillel, 1993; Meerdink *et al.,* 1996; Fujimaki *et al.,* 2003; Schindler *et al.,* 2010; Gallage *et al.,* 2013; Cui *et al.,* 2018;

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Chen *et al.,* 2019; Tao *et al.,* 2019). Unsaturated permeability also can be determined using empirical formulations, macroscopic models, or statistical models involving SWRCs (Leong and Rahardjo, 1997; Patil and Singh, 2016).

Measurements of the permeability of unsaturated soils at high suction values is a challenging task for researchers and practicing engineers. In the steady state method, known suction values can be imposed by using the axis-translation technique (Sivakumar, 2016), or the vapour equilibrium and osmotic techniques. In the last two approaches, suction values are deduced from readily available calibration charts. In the unsteady state approach, the suction within the soil changes continuously and so consequently do the volumetric variables, such as the water content and the specific volume. For both steady state and unsteady state approaches, additional complexities would arise if the investigations were to be carried out under external loading (Cai *et al.,* 2014). In many investigations permeability values have been determined under zero external stress conditions and this is not a realistic in situ scenario where many deep-seated slope failures have been reported (Hughes *et al.,* 2007). This paper reports an alternative approach conducted as a proof of concept to measure the permeability of saturated and unsaturated soils subjected to external loading under unsteady state conditions based on directly measured suctions and volumetric variables.

EXPERIMENTAL WORK

The system developed in this study is depicted in Figure 1. It is made of stainless steel and is able to accommodate a soil sample of 100mm diameter and maximum height of 140mm. A detailed description of the equipment is available in Lynch et al. (2019). However, for completeness, the important features are described here. The equipment consists of two high-capacity tensiometers, capable of measuring suctions up to 1500 kPa, placed at radial distances of 15mm (T1) and 35mm (T2) from the centre of the pedestal. The accuracy of the tensiometers was verified by conducting tests on saturated soil samples with high initial suctions as a part of a separate study and was found to be the same as any transducer that measures pressures in the positive range. The tensiometers are located radially opposite to each other (Figures 1*b*) in conjunction with two air circulating ports (each 5mm diameter) for drying the soil samples positioned at the centre of the pedestal and the top cap. The tensiometers were attached to the pedestal from the base and sit flush with the pedestal when fastened. The saturation of the tensiometers was carried out using the standardized procedure detailed in the relevant research literature (Take *et al.,* 2003; Ridley *et al.,* 2003; Toll *et al.*, 2013).

The investigation was conducted on glacial tills collected from a cutting in the greater Belfast area. The material had a specific gravity of 2.75, liquid limit of 37% and plastic limit of 19%. The gravel, sand and silt contents in the soil were 16, 35 and 33% respectively. A typical particle-size distribution curve is shown in Figure 2. Three tests were conducted on the chosen soil. One test was carried out on a reconstituted sample (G1), whereas the other two (G2 and G3) were tested on compacted samples. In the case of the reconstituted sample, a consolidation chamber was used to consolidate the slurry (prepared with an initial water content of 35%) at a vertical pressure of 800 kPa. A slurry mass was pre-calculated to achieve a sample length of about 100mm. To ensure the unhindered circulation of low humid air, a tiny hole was created in the centre of the sample. This part of the operation was challenging due to presence of gravel particles within the soil matrix. In order to alleviate this issue a compressible slender rod was placed in the centre of the slurry in the consolidation chamber. The compressible slender rod comprised a piston (5mm diameter) supported on a spring located inside a slender tube of 6 mm diameter. At the end of the consolidation process, the slender rod was taken out and the hole was backfilled with uniformly graded fine sand. The sample was subsequently saturated at low mean effective stress using BS 1377 Part 6 1990 procedure and reconsolidated at 50 kPa of effective mean stress in a standard triaxial test set up. At the end of the reconsolidation process the sample was removed under undrained conditions, the backfill sand was flushed out by applying vacuum and subsequently the hole was refilled with fresh sand.

In the case of compacted samples, dry crushed materials were mixed at water contents of 12 (G2) and 13% (G3). The optimum water content of the glacial till was 12.5%. This implies the sample compacted at a water content of 12% was maybe on the dry side of optimum, whereas the sample at 13% was on the wet side. As in the case of the reconstituted sample, a slender rod was used to form a hole in the centre of the sample during the compaction process. These samples were saturated and reconsolidated at an effective mean stress of 50 kPa in a standard triaxial test set up. The bulk densities of samples G2 and G3 after the saturation stage were 2.24 and 2.21 Mg/m^3 respectively. The backfilling of sand prior to saturation, removal and refilling of sand in the hole was carried out following the same procedure as in the case of the reconstituted sample. The sample was assembled and enclosed in a rubber membrane in the newly developed chamber (Figure 1) and a confining pressure of 50 kPa was applied.

The top cap and the pedestal had provision to circulate air through the cylindrical sand column located at the centre of the sample. The relevant air circulating lines were connected in a closed loop to the vapour chamber containing saturated sodium chloride solution (Figure 1). Low-humidity air was supplied at the bottom of the sample, whereas the flushed air was taken back to the vapour chamber (the line was completely immersed in the saturated salt solution). The circulation of low-humidity air was carried out using a pump (located outside the chamber on the low-humidity air supply line) operated at 3.0V with a line pressure of 5 kPa. The vapour chamber was placed on a scale that had an accuracy of 0.01 g. The mass of the vapour chamber was continuously monitored. The volume change of the sample was measured by monitoring the flow of water into the stainless steel chamber. A full description of the testing procedure is reported by Lynch *et al.* (2019).

RESULTS AND DISCUSSION

Suction evolution and volumetric strains

The experiments conducted on each sample lasted for about three weeks during which the suctions within the samples gradually increased and the drying process was terminated when the suctions approached the capacity of the tensiometers (1500 kPa). The nature in which the tests were conducted was considered to be transient whereby the suctions read by the two tensiometers (T1 and T2), the volumetric strain (ε_v) (i.e. change in volume/initial volume) and the volumetric water strain (ε_{vw}) (i.e. change in water volume/initial volume of water) changed continuously during the drying process. The relevant experimental observations are presented separately for each sample in Figures 3 to 5. The low-humidity air was circulated through the sand column located at the middle of the sample. Therefore, as one would expect the suction within the samples nearer to the sand column would be higher than that away from it. This was observed in all the samples tested as a part of the investigation. It was reported (Lynch *et al.*, 2019) that the humidity of the air entering at the base of the sample was not the same as that at the exit point located at the top of the sample. Therefore, a suction gradient might have prevailed along the length of the samples, as well. It can only be quantified by incorporating tensiometers at the top of the sample. Such a facility is not included in the current set up; however, as a proof of concept the subsequent presentation and analyses are based on suction measurements obtained at the base of the samples.

As illustrated in Figure 3a, in case of the reconstituted sample (G1), the difference in suction values obtained from both the tensiometers (T1 and T2) was approximately 100 kPa during

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the initial phase of the drying process, but it reduced to approximately 60 kPa after about 6 days and remained constant thereafter. However, slightly different observations were made in the other two compacted samples (G2 and G3) whereby the differences in suction values measured by T1 and T2 generally remained the same (approximately 20 kPa), but began to diverge as the drying process progressed (Figures 4a and 5a). The time at which the differences became significant varied depending on the initial compaction water content of the samples. Although the observations are based on a limited number of samples tested, it is conjectured that a higher permeability of the compacted samples possessing bimodal pore size distributions (which will be discussed later) may be the main cause of the differences in suctions read by tensiometers T1 and T2 as compared to those in the reconstituted sample.

The volumetric strains in terms of specific volume and water volume are an integral part of the materials presented in this paper. As such, Figure 3b shows the strains in terms of total volume and water volume with respect to time. The observations confirm that there was reasonably good agreement between the volume of voids and the volume of water until the suction value of about 300kPa in Figure 3. At this stage, it is believed that air entered into the voids and, as one would expect, the stated strains begun to diverge. This has been clearly witnessed in Figure 3b. Since samples G2 and G3 possess bimodal pore size distributions (Sivakumar *et al.*, 2007; 2010), the divergence of the above two strains can take place at a relatively low suction and this has been witnessed in Figures 4 and 5. The rate of air flow through the sand column in the present investigation is considerably low (the magnitude is not available); however, under higher flow rates there could have been development of a “dry fringe zone” around the sand column that could have consequently reduced the evaporation rate significantly (Shahraeeni *et al.*, 2012). Since the observations shown in Figures 3b to 5b do not suggest any rapid reduction in the evaporation rate, it can reasonably be assumed that the drying process is progressive away from the sand column.

Evaluation of Permeability of soils

The experimental model adopted in this study mimics reasonably well a field scenario where the permeability measurements are made based on the pumping rate and the drawdowns in two observation wells. Here in this investigation, the pumping rate is represented by the water extracted from the sample, measured using the volume of water entering into the vapour chamber during the drying process. The observation wells are represented by the measured pressures of water at two predetermined radial distances (T1 and T2). The scenario is shown in Figure 6, where A_1 and A_2 represent the locations of two tensiometers T1 and T2 respectively, located at radial distances of r_2 and r_3 from the centre of the sample. V_r is the radial velocity of the water towards the sand column due to the suction gradient. The radial velocity V_r through a saturated soil sample, proposed by Basu *et al.* (2006), can be expressed as given in Equation 1:

$$V_r = \frac{k_r}{\gamma_w}\frac{\delta u}{\delta r} \qquad \text{[Equation 1]}$$

Where: k_r, Radial permeability [m/s]; γ_w, Unit weight [kN/m^3]; u, Pore water pressure [kPa]; r, Radius of the measurement point [m]

The volume of water received at an arbitrary distance r from the centre of the cylindrical sample should be equal to the volume change in the cylindrical soil sample between the outer surface and r, provided the sample remains saturated. This relationship is expressed numerically in Equation 2. The left side of the equation is the radial discharge passing the circumference of the sample at radius r, and the right side of the equation is equal to the volume change between radius r and the outside of the sample.

$$2\pi r V_r = \pi(r_4^2 - r^2)\frac{\partial \varepsilon_v}{\partial t} \qquad \text{[Equation 2]}$$

where: r_4, Radius of the sample [m]; ε_v, Volumetric strain; t, Time [s]

Rearranging Equation 2 to obtain an expression for V_r and substituting in Equation 1 yields:

$$\frac{\partial u}{\partial r} = \frac{\gamma_w}{2rk_r}(r_4^2 - r^2)\frac{\partial \varepsilon_v}{\partial t} \qquad \text{[Equation 3]}$$

The term $\frac{\partial \varepsilon_v}{\partial t}$ was measured directly using the testing apparatus, however, $\frac{\partial \varepsilon_v}{\partial t}$ was replaced with the water volumetric strain, $\frac{\partial \varepsilon_{vw}}{\partial t}$, given that the sample did not remain saturated during the drying process. Furthermore, the intention of the work was to measure water permeability (if the sample is saturated $\frac{\partial \varepsilon_v}{\partial t} = \frac{\partial \varepsilon_{vw}}{\partial t}$). Equation 3 also requires two boundary conditions to be evaluated in order to calculate radial permeability. These conditions were satisfied by data obtained from the tensiometers (i.e. replacing r with r_3 and u with u_2, as well as r with r_2 and u with u_1). Solving Equation 3 using the aforementioned boundary conditions, yielded an expression for radial permeability during the drying of the sample:

$$k_r = \frac{\gamma_w\left[r_4^2 \ln\left(\frac{r_3}{r_2}\right) - \left(\frac{r_3^2 - r_2^2}{2}\right)\right]}{2(u_1 - u_2)}\frac{\partial \varepsilon_{vw}}{\partial t} \qquad \text{[Equation 4]}$$

Where: u_1, Pore water pressure read using Tensiometer 1 [kPa]; u_2, Pore water pressure read using Tensiometer 2 [kPa]; r_2, Radius at Tensiometer 1 [m]; r_3, Radius at Tensiometer 2 [m]; r_4, Radius of sample [m]; $\frac{\partial \varepsilon_{vw}}{\partial t}$, Water volumetric strain rate [s^{-1}]

Figures 3, 4 and 5 show the suction measurements taken during the drying process together with the relevant volumetric strains in both the water and void phases. The readers should note that the suction measurements were made at the base of the samples and it was highlighted in the early stage of this article that there could be a suction gradient along the sample length; however, as a proof concept, the information shown in Figures 3 to 5 could provide a basis for calculating permeability to a first level of accuracy. It is also known that the radius of the sample continuously changed during the drying process. An approximate reduction in the diameter of the sample may be about 2mm (based on the measured volumetric strain). This is significantly small compared to the diameter of the tensiometers (10mm) that read suctions at two radial distances.

The permeability values were calculated at selected time periods using Equation 4 and those values are shown graphically in Figure 7. In this case the permeability was plotted against p+s (p is the applied mean net stress on the soil and was kept constant at 50 kPa and s is suction). In all three cases, the permeability of the samples reduced with increasing suction during the drying process, except for a marginal increase in permeability in the case of the compacted samples (G2 and G3) at the very early stages of the drying process. This may have been caused by the non-equilibrium conditions (i.e. a steady state was not achieved).

Samples G2 and G3 were compacted at water contents of 12% and 13% respectively and the corresponding permeability values with respect to suction are shown in Figure 7b. The degrees of saturation at selected suction values are also included in this figure. It should be noted that any compacted sample would have a bi-modal pore size distribution (Delage *et al.*, 1995; Thom *et al.*, 2007; Sivakumar *et al.*, 2010). An increase in the dry density will cause a reduction of the volume of voids between the larger aggregates (collection of particles). Under seepage conditions, water has to flow through the macro voids as well as micro voids. The resistance to flow through macro voids relies on the available macro porosity. In a sample where the bulk density (or the dry density) is higher, as in the case of G2, water would find more resistance to flow through the macro voids as compared to the sample having lower bulk density (as in the case of G3). This postulation agrees favourably with the observations shown in Figure 7b where the reduction in the permeability with an increase in suction is considerably less in G2 than in G3. This also corroborates that the reduction in the degree of saturation in G3 is more prominent than in G2 due to the fact that G3 possessed more macro voids which can be readily emptied with an increase in suction.

Validity of the permeability measurements using the new procedure

Validity of the permeability measurements reported in Figure 7 requires further discussion as it was carried out based on transient measurements of suction and the outflow. A total head difference (within the context of this work, a suction gradient) is essential to cause flow of water through the soil. Such suction gradient will inevitably lead to different degree of saturation along the radial directions, i.e. soil close to the sand column will be less saturated than that away from it. Therefore the calculated values of permeability shown in Figure 7 are based on average conditions. Nevertheless, the findings from this research are in close agreements with various independent permeability measurements, which are summarized below.

(a) As a part of this study, a separate permeability test was carried out on a reconstituted saturated sample of glacial till at an effective consolidation pressure of 800 kPa using the relevant British Standard procedure (BS 1377 Part 6 (1990)) [not described in this paper]. The permeability value obtained from this sample is indicated by a solid star in Figure 7a. The permeability measurements using the standard procedure (BS 1377 Part 6 (1990)) and the procedure reported in this article were found to have an excellent correlation. One would expect the permeability of the sample that was taken through the drying process to be lower than that of the saturated sample, but that can only be true if the sample had undergone a significant desaturation process. Some information was extracted from Lynch *et al.* (2019) on the aspect of degree of saturation during drying and is included in Figure 7a. The observations suggest that the sample taken through the drying process did not become significantly desaturated even at a very high suction value. Therefore, as demonstrated by the relevant British Standard test comparison, the permeability of those samples (either taken through the drying process or consolidated to the same effective stress) would yield permeability of the same order of magnitude.

(b) Sivakumar *et al.* (2017) carried out permeability measurements on saturated Glacial till samples compacted at various initial water contents, following BS 1377 Part 6 (1990). The reported permeability value of 3.6×10^{-10} m/s by Sivakumar *et al.* (2017)

for sample compacted at 12.5% agrees favourably with the permeability value of sample G2 in this study, compacted at the same water content as shown in Figure 7b.

(c) In situ permeability measurements were carried out by Lynch (2017) on Glaciall till at the same site from where the samples in this study were collected. The field falling head permeability tests were carried out in accordance with BS EN ISO 22282; 2 (2012) at selected depths and the results are shown in Figure 8a. In general the permeability values obtained from the field measurements are in good agreement with the relevant values reported in Figure 7.

(d) The permeability values were calculated using Fredlund *et al.* (1994)'s approach in conjunction with the soil water retention curve of Glacial till reported by Lynch *et al.* (2019) and are shown in Figure 8b. The saturated permeability of samples G1, G2 and G3 were assumed to have values of 1.1×10^{-8}, 4.5×10^{-8} and 1.2×10^{-8} m/s respectively. The calculated values of permeability from the approach suggested in this paper and that by Fredlund *et al.* (1994) are in good agreement.

CONCLUSIONS

Laboratory investigations were undertaken on reconstituted and compacted samples of glacial tills. A modified approach was adopted to induce radial flow of water in cylindrical samples each containing a cylinder sand column at the centre. The drying of the samples was achieved by circulating low-humidity air through the sand column. The water and sample volume changes were monitored together with measurements of suction via tensiometers located at the base of the samples at two radial distances. The test results enabled the calculations of both saturated and unsaturated permeability during the drying process. An existing analytical tool available for radial consolidation was modified to model the testing conditions in the investigations.

The permeability of a reconstituted sample decreased gradually as the suction increased during the drying process. The permeability values obtained in the case of compacted samples were found to be influenced by the initial compaction conditions prior to the tests. A significant reduction in the permeability value with suction is attributed to the available macro porosity in lightly compacted samples (i.e. low bulk or dry density). Soils possessing higher dry or bulk density, where the available macro voids are limited, offer a greater resistance to the flow of water and consequently the reduction in permeability with an increase in suction is notably smaller as compared to soils with higher macro voids.

Comparisons of permeability measurements based on British Standard procedures for both laboratory and in situ conditions are found to be in close agreements with the results obtained using the new approach. In addition, the predicted values of permeability from the new approach also agreed favourably with a readily available analytical tool for predicting unsaturated permeability based on water retention curve. The findings have given confidence in adopting the modified approach for determining the permeability of saturated and unsaturated soils during the drying process under external loading conditions.

Notation

k_r	Radial permeability (m/s)
γ_w	Unit weight (kN/m^3)
u	Pore water pressure (kPa)
r	Radius of the measurement point (m)
r_4	Radius of the sample (m)
ε_v	Volumetric strain
t	Time (s)
u_1	Pore water pressure read using Tensiometer 1 (kPa)
u_2	Pore water pressure read using Tensiometer 2 (kPa)
r_2	Radius at Tensiometer 1 (m)
r_3	Radius at Tensiometer 2 (m)

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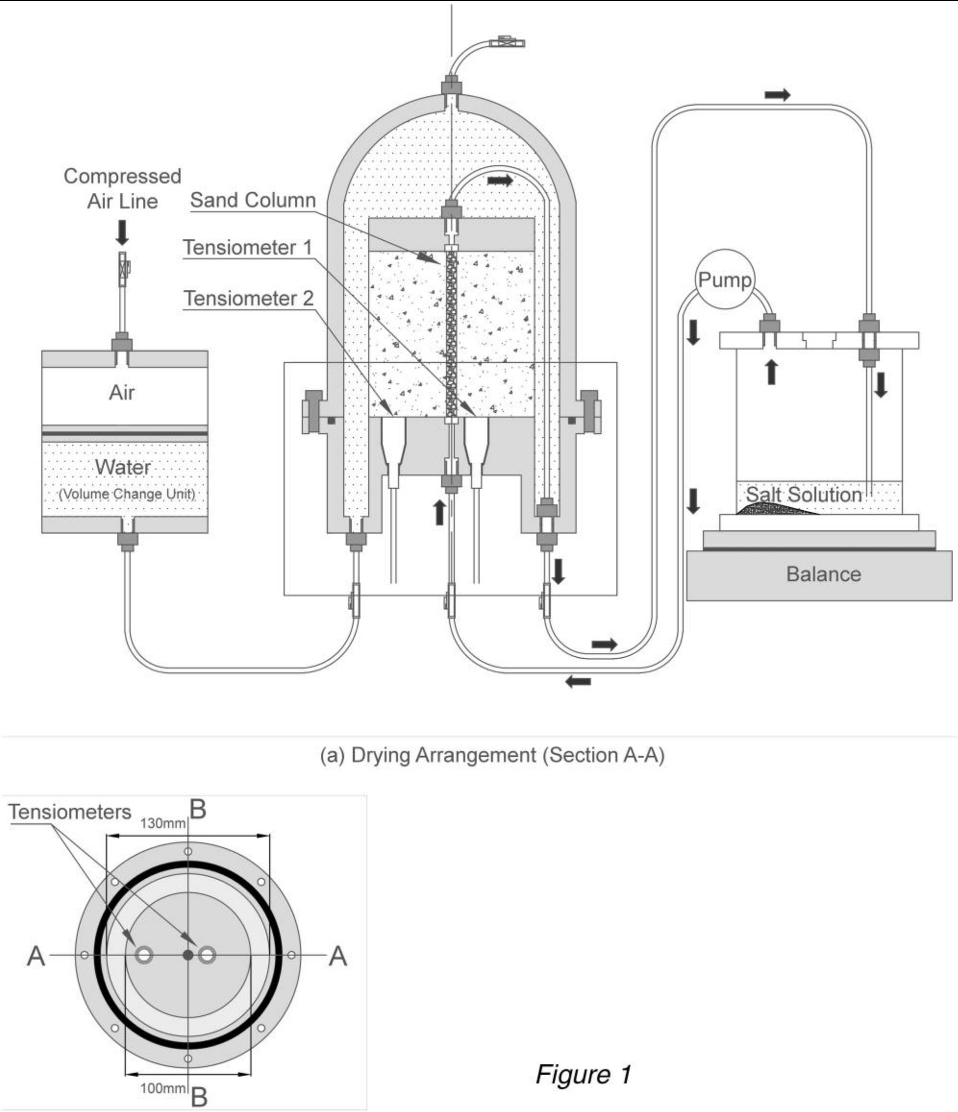

(a) Drying Arrangement (Section A-A)

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Figure 1

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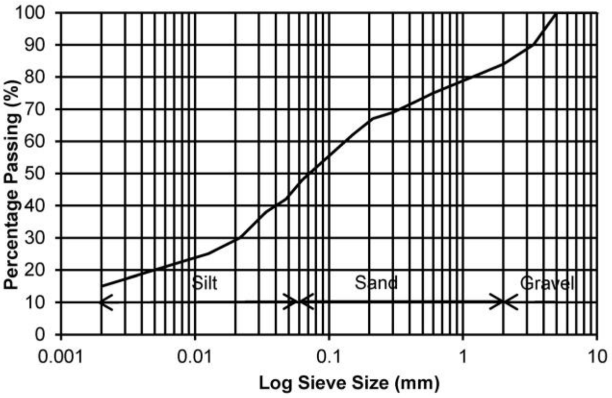

Figure 2

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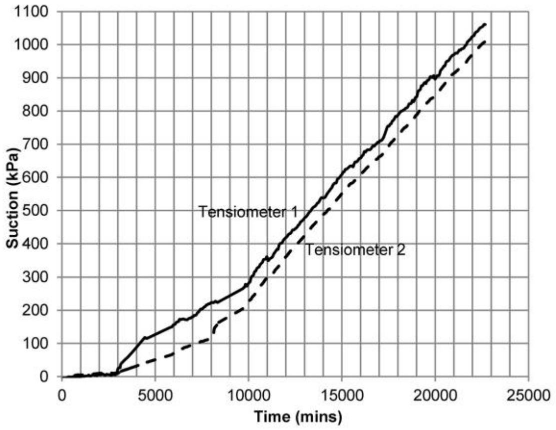
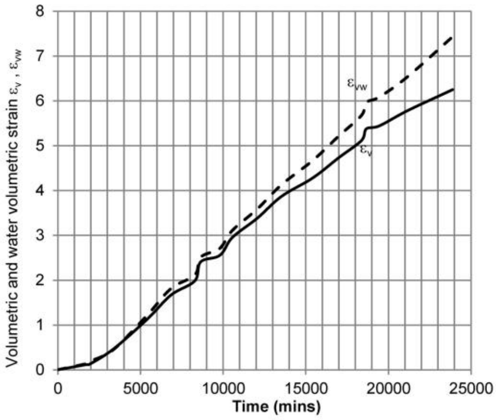


(a) Suction evolution



(b) Volumetric strains (voids and water voids)

Figure 3

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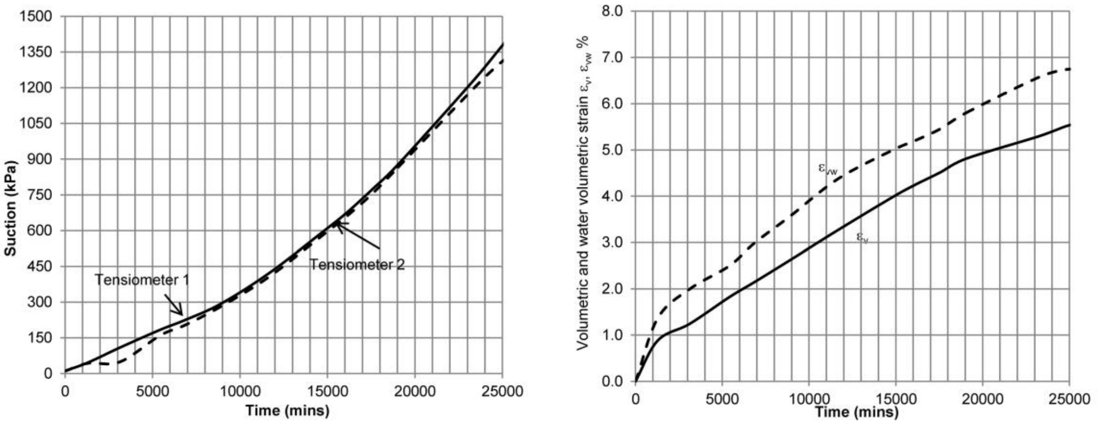

(a) Suction evolution

(b) Volumetric strains (voids and water voids)

Figure 4

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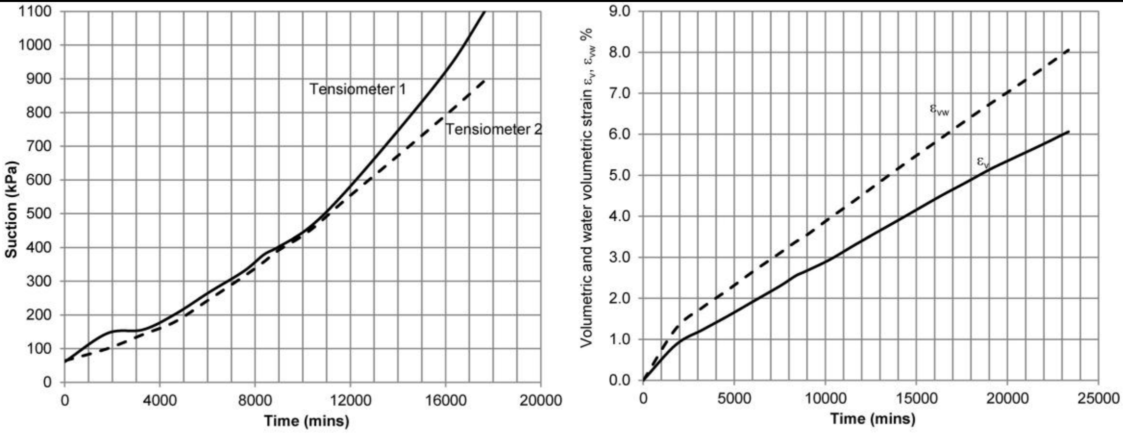

(a) Suction evolution

(b) Volumetric strains (voids and water voids)

Figure 5

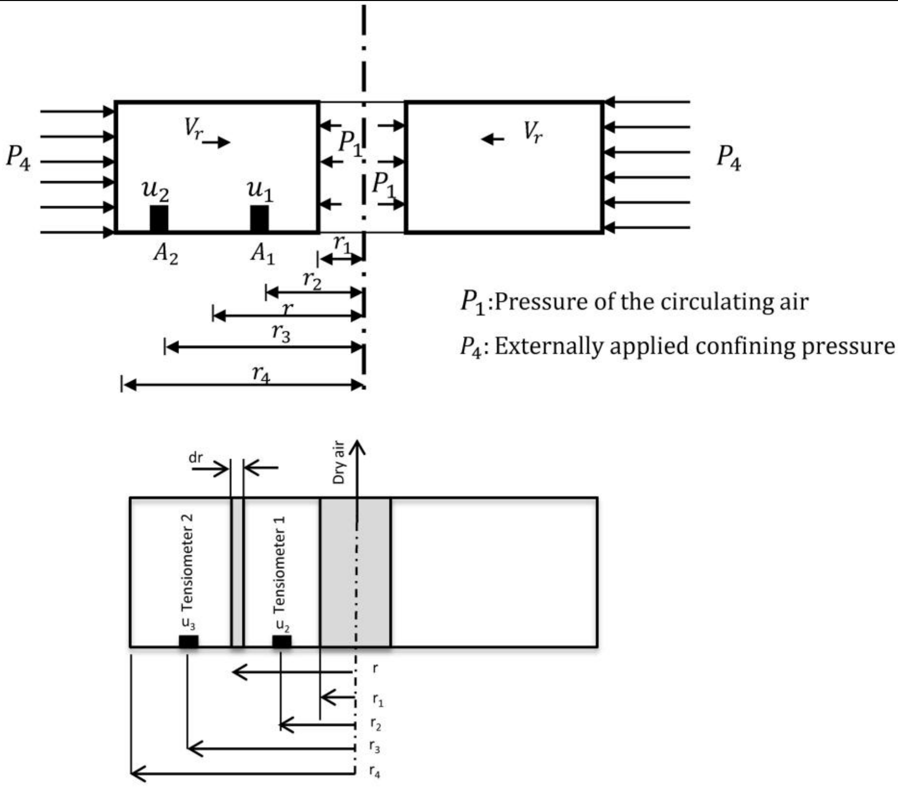
V_r
V_r
P_1
P_1
P_4
P_4
u_2
u_1
A_2
A_1
r_1
r_2
r
r_3
r_4
P_1:Pressure of the circulating air
P_4: Externally applied confining pressure
dr
Dry air
Tensiometer 2
Tensiometer 1
u_3
u_2
r
r_1
r_2
r_3
r_4

Figure 6

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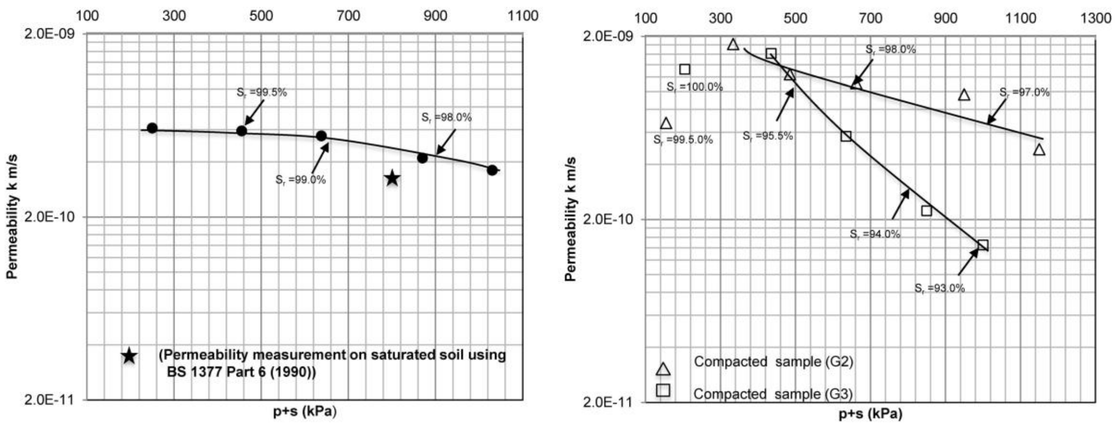

(a) Reconstituted sample

(b) Compacted sample

Figure 7

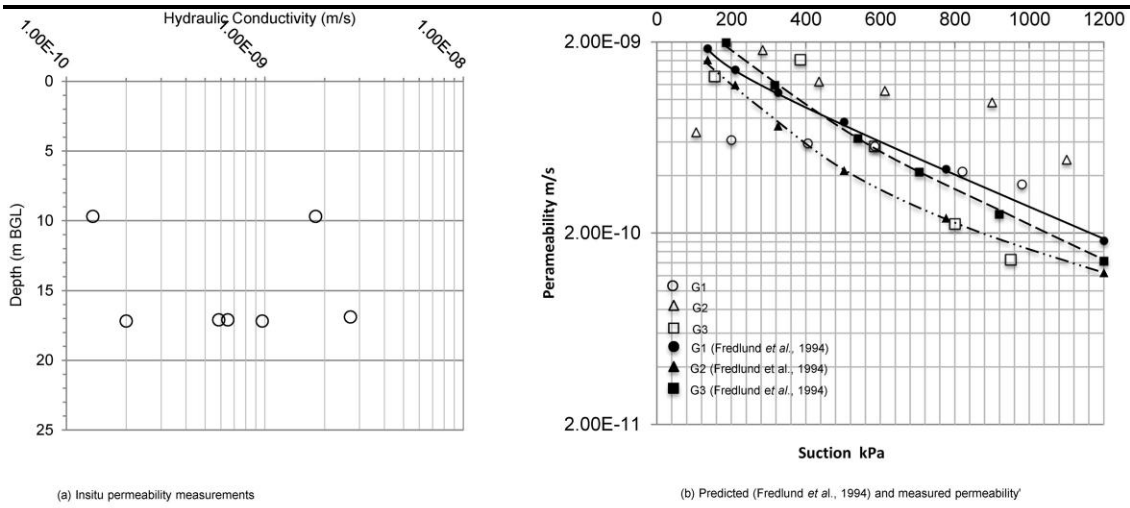
Hydraulic Conductivity (m/s)
1.00E-10
1.00E-09
1.00E-08
Depth (m BGL)
0
5
10
15
20
25
(a) Insitu permeability measurements
0
200
400
600
800
1000
1200
2.00E-09
2.00E-10
2.00E-11
Perameability m/s
Suction kPa
G1
G2
G3
G1 (Fredlund et al., 1994)
G2 (Fredlund et al., 1994)
G3 (Fredlund et al., 1994)
(b) Predicted (Fredlund et al., 1994) and measured permeability'

Figure 8