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The Centrifuge Permeameter for Unsaturated Soils (CPUS)

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ABSTRACT: This paper describes conventional technologies used to define the water characteristic curve and K-function for unsaturated soils, aggregates, and rocks, focusing on alternatives to overcome their shortcomings. The identified shortcomings are addressed through the recent development of a new centrifuge permeameter capable of providing expedited measurement of the variables necessary to describe unsaturated fluid flow processes through soils, aggregates, and rocks. The permeameter system is capable of precisely controlling low inflow rates (0.1 ml/min to 100 ml/min) within a rotating centrifuge environment capable of imposing an acceleration field 600 times that of normal gravity onto a specimen. A key component of the centrifuge permeameter is a data acquisition system capable of sustaining high g-levels, suitable to simultaneously measure suction and moisture in flight.

1 INTRODUCTION

Several fields of science and engineering require good understanding of the flow of liquid through porous materials under saturated (one liquid), unsaturated (liquid and gas), and multiphase (several liquids) conditions. Specifically, geotechnical engineers are concerned with the quantity of water flow through earth structures and the mechanical effects of water flow, geoenvironmental engineers are concerned with flow of water through landfill cover and liner systems and contaminant transport phenomena, hydrologists are concerned with groundwater recharge, agronomists are concerned with water availability for plants and migration of nutrients, and petroleum engineers are concerned with oil reservoir characterization. Key analyses conducted in these areas rely on the determination of parameters governing the flow of liquid through porous materials in the field or laboratory. However, significant shortcomings in using conventional experimental techniques used to characterize the unsaturated hydraulic properties of soils, aggregates, and rock have been noted in the literature. This paper identifies shortcomings of conventional measurement techniques and focuses on the development of an improved experimental technique that is in the final design stage.

Flow of liquid in unsaturated conditions through porous materials like soil, aggregates, and concrete can be described using three non-linearly related variables, namely the volumetric moisture content θ (or degree of saturation), the suction ψ (or inter-particle capillary pressure), and the hydraulic conductivity K. Specifically, the relationship between the volumetric moisture content and the suction, referred to as the Water Characteristic Curve (WCC), describes the increase in inter-particle capillary forces with decreasing water in the pores. Further, the relationship between the hydraulic conductivity and the suction, referred to as the K-function, describes the change in water's ability to flow through porous media as the pathways available for fluid to travel decrease.

The governing equation for flow through porous materials, referred to as Richards' equation, reveals the relevance of the K-function and WCC. Richards' equation for one-dimensional flow of liquid through an unsaturated material in a centrifuge is:

$$\frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t} = \frac{1}{\rho g}\left[K\frac{\partial^2 \psi}{\partial z^2} - \frac{\partial K}{\partial \psi}\left[\left(\frac{\partial \psi}{\partial z}\right)^2 - \rho\omega^2(r_0 - z)\frac{\partial \psi}{\partial z}\right] - K\rho\omega^2\right] \tag{1}$$

where t is time, r_0 is the radius from the center of rotation to the base of the specimen, ω is the centrifuge angular velocity, g is the acceleration due to gravity, and ρ is the liquid density. In addition, z is defined as

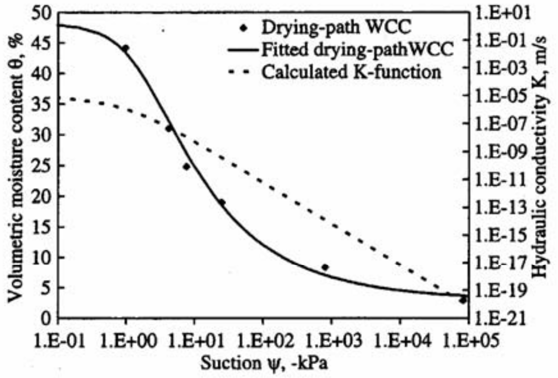

Figure 1. Example WCC and K-function for a low PI clay.

$r - r_0$, where r is the radius from the center of the specimen, and represents the distance from the specimen base in the direction toward the center of rotation. For ω equal to zero, Equation (1) represents the classic relationship valid for 1-gravity situations. Inspection of Equation (1) indicates that the K-function, the gradient of the K-function $\partial K/\partial \psi$, and the gradient of the WCC $\partial \theta/\partial \psi$, are necessary to solve it.

Figure 1 shows an example of a measured and fitted drying-path WCC and a calculated K-function for a low-plasticity clay (CL) soil.

This figure indicates that both volumetric moisture content and hydraulic conductivity decrease nonlinearly with increasing suction. The shapes of the WCC and K-function are typically quantified using power law, hyperbolic, or polynomial functions (Brooks and Corey 1946, van Genuchten 1980; Fredlund and Xing). These relationships must be fitted to experimental data unless predictive approaches are employed. Predictive relationships for the WCC and K-function are usually based on pore size distributions (Fredlund and Xing 1994; Burdine 1953), although the K-function can be predicted directly from the parameters of the WCC (Mualem 1976; van Genuchten 1980). The WCC in Figure 1 was fitted to experimental data using the van Genuchten model, while the K-function was predicted using the van Genuchten-Mualem model. The inputs of the for the K-function model are the parameters of the drying-path WCC and the saturated K of the soil.

Material-specific testing is recommended to define the WCC and K-function, which are not only sensitive to the pore size distribution, but also the porous media's mineralogy, density, and pore structure. The need for experimental testing is also recommended because the relationships shown in Figure 1 are not unique. The WCC in particular has significantly different wetting and drying paths. During drying, the largest pores drain first, but during wetting, capillarity prevents large pores from filling before small pores. Consequently, wetting of a dry media often leads to entrapment of gas, which prevents saturation of the media. These issues cause the wetting path to be relatively flat, at low moisture content, for high suctions (>100 kPa) with a steep increase in moisture content at lower suctions.

2 CONVENTIONAL CHARACTERIZATION OF UNSATURATED HYDRAULIC PROPERTIES

2.1 *1-g Laboratory techniques*

Several techniques have been used to obtain the K-function (Benson and Gribb 1997) and WCC (Klute et al. 1986) for unsaturated porous materials in the laboratory. Independent measurement of the K-function and WCC involves using multiple specimens, different specimen preparation techniques, and different techniques to control boundary conditions, which contribute to increased variability and testing time.

Conventional techniques to measure the K-function involve steady or transient flow of liquid through a specimen confined within a permeameter. Flow is either applied using ceramic plates or flow pumps. During steady flow processes, the gradient in matric suction is measured, and the hydraulic conductivity can be calculated using Darcy's law ($K = v/i$, where v is the discharge rate and i is the hydraulic gradient). During transient flow processes, the suction and moisture content profiles are measured as a function of depth and time. The K function can be calculated from Equation (1) using inverse techniques (Ishida et al. 2000).

Two main groups of techniques have been used to define the WCC. The first group ("physical" techniques) start with a liquid-saturated material and slowly forces water to flow out of the specimen by imposing a suction until reaching a condition at which the moisture content and suction are in equilibrium. The most commonly used physical technique is the axis translation technique, which involves placing a specimen on a ceramic plate that conducts only liquid, and applying an air pressure to the specimen. Liquid will flow from the soil through the ceramic plate, allowing air to enter the specimen. The air pressure is assumed to equal the suction, and the moisture content of the soil at equilibrium is measured destructively. Another technique, the hanging column, also involves a ceramic plate, but connects the bottom of the plate to a manometer tube. The manometer tube exit is held beneath the ceramic plate, imposing a negative pressure on the plate. The second group ("thermodynamic" techniques) involve allowing water to evaporate from a specimen in a closed chamber with controlled relative humidity. Physical techniques are used for relatively low suctions (<1500 kPa) and thermodynamic techniques are used for higher suctions.

Conventional techniques to define the K-function and WCC require significant time to obtain limited data. For example, determination of the hydraulic properties for a low-permeability clay specimen may take several months (one month was required to define the WCC in Figure 1 using a variety of physical and thermodynamic techniques). Also, conventional testing methods require the use of several specimens and destructive moisture content measurement. Problems specific to K-function testing include boundaries effects on the flow process, difficulties in distributing water from flow pumps to the specimen, and tedious testing procedures. Problems specific to WCC testing involve the change in air-liquid meniscus shape when applying positive or negative pressures during the axis-translation and hanging column techniques, diffusion of air across porous ceramics, and difficulty in controlling the stress state to which the material is subjected in the field.

2.2 *Centrifuge techniques*

To alleviate the shortcomings of conventional characterization of unsaturated hydraulic properties, centrifugation has been used to increase the body forces on a porous media. The centripetal acceleration field causes fluid to drain from the specimen at a rate quadratically proportional to the g-level (Dell'Avanzi et al. 2004).

Centrifuges were first used in the early 1930's to define the WCC by soil scientists (Gardner 1937) and petroleum engineers (Hassler and Bruner 1945). In these tests, a saturated specimen is typically placed upon a saturated ceramic plate which conducts only liquid. During centrifugation, the increased body force causes water to exit from the specimen through the ceramic. Air enters the surface of the specimen, and suction is developed in the specimen. Because the bottom boundary is maintained saturated (zero suction), a distribution of suction develops with specimen height. This suction distribution obtained at equilibrium (i.e. when flow ceases) is:

$$\psi(z)=\frac{\rho\omega^2}{2}\left[2r_0 z-z^2\right]+\psi_0 \tag{2}$$

where ψ_0 is the suction at the bottom boundary of the specimen, and is assumed to equal zero if a saturated ceramic plate is used as the bottom boundary condition. An analytical technique is used to associate the average moisture content (measured destructively) with the suction at the surface calculated from Equation (2) to define a point on the WCC (Forbes 1994).

Centrifuge testing has been used to define the K-function in geotechnical projects involving the design of ET covers (Zornberg et al. 2003). Nimmo et al. (1987) developed the Internal Flow Control Steady-State Centrifuge (IFC-SSC) method, which uses a system of reservoirs to control the fluid flow rate and suction at the upper and lower surfaces of a specimen. Conca and Wright (1994) developed the Unsaturated Flow Apparatus (UFA), which uses a sophisticated rotary joint to a low fluid flow rate into the specimen. The UFA uses open-flow centrifugation, which does not impose a suction value on the specimen.

For steady state conditions, the SSC and UFA use Darcy's law to determine the K-function:

$$K(\psi)=\frac{vg}{\left[\frac{1}{\rho}\frac{d\psi}{dz}-\omega^2\left(r_0-z\right)\right]} \tag{3}$$

where v is the discharge velocity applied to the specimen, equal to the flow rate divided by the specimen area. Points on the K-function curve are defined after ensuring steady state flow conditions (measured by stopping the centrifuge and weighing the specimen and reservoirs).

Current centrifuge technology does not allow the direct acquisition of the relevant variables (suction, moisture, discharge velocity) in-flight during testing. This has led to the need of stipulating simplifying assumptions for data analysis. Specifically, the driving force due to the suction gradient in Equation (3) is assumed to be small compared to the centrifuge driving force. In this case, the hydraulic conductivity is inversely proportional to ω^2. Accordingly, solution of Equation (1) is not necessary. However the small size of the specimen does not allow measurement of the suction gradient to ensure it is negligible. The UFA and SSC centrifuges must be periodically stopped to measure the specimen mass to ensure steady state flow, and the moisture content must be measured destructively at the end of the test.

The SSC and UFA do not simultaneously determine the WCC and K-function. In fact, the UFA cannot be used to define the WCC, as suction is not measured or controlled during open-flow testing. The SSC uses Equation (2) to define the suction profile, but it still must use an analytical technique to relate the average moisture content (measured destructively) with the calculated suction.

3. CENTRIFUGE PERMEAMETER FOR UNSATURATED SOILS

The shortcomings of available characterization of the unsaturated hydraulic characteristic of porous materials have driven development of an improved device, referred to as the Centrifuge Permeameter for Unsaturated Soils (CPUS). This device, which is in the final

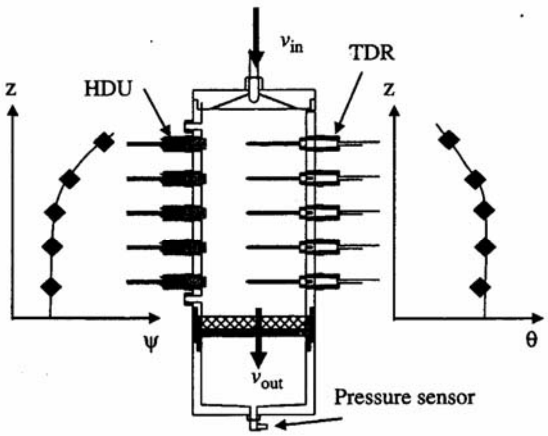

Figure 2 Moisture and suction measurements in permeameter.

design phase, incorporates the use of a low-flow hydraulic permeameter and a high-g centrifuge capable of continuously, non-destructively, and non-intrusively measuring suction, moisture content, and fluid flow rate in a single specimen during centrifugation. Accordingly, CPUS allows an expedited determination of the WCC and K-function from a single specimen in a single test. Figure 2 shows a schematic view of the CPUS permeameter and its instrumentation layout.

A low-flow fluid union has been developed to supply fluid from the stationary environment to the rotating specimen within the centrifuge. An infusion pump is used to supply flow rates ranging from 0.1 ml/min to 100 ml/min to the fluid union. The inflow is dispersed to the specimen using an overflow distribution cap. Outflow from the specimen is collected in a reservoir. CPUS is capable of imposing various bottom boundary conditions. Similar to the boundary conditions used in early centrifuges and the SSC, a fixed zero-suction boundary condition may be imposed at the base of the specimen using a saturated ceramic plate. Similar to the UFA approach, open-flow conditions can also be established by using a pervious bottom platen with a pore size similar to the porous material being tested to minimize flow impedance.

An important feature of CPUS is that the relevant variables (suction, moisture content, discharge velocity) are measured in-flight in a continuous manner during testing. This permits measurement of transient and steady-state flow processes without changing the acceleration field (i.e. without stopping the centrifuge). Accordingly, a key component in CPUS is the use of a data acquisition system capable of sustaining high g-levels. A 16 channel coaxial cable-tester allows the use of time domain reflectometry (TDR) to measure the dielectric constant of the porous media. The dielectric constant can be correlated with the volumetric moisture content of the porous media. A 32 channel solid-state data acquisition system, combined with a fiber-optic rotary joint for communication with the stationary environment, allows measurement and control of analog and digital instrumentation. Soil suction is measured using heat dissipation units (HDU), which involve a heating unit and thermocouple embedded within a ceramic sensor. The response of the ceramic to a constant current heat pulse, measured by the thermocouple, is highly sensitive to the suction within the ceramic. The volume of outflow in the reservoir is monitored using a pressure sensor.

Analysis of the data from the CPUS system involves inverse solution of Equation (1). However, simplified analyses such as that expressed by Equation (3) can also be used, with the added advantage of being able to verify the assumptions required for solution.

The CPUS system is expected to significantly decrease the time needed to obtain unsaturated hydraulic properties. Tests that currently take years will be accomplished within a reasonable amount of time due to both the increased flow under the centrifuge acceleration field and decreased specimen preparation time. Simultaneous measurement of the suction, moisture content, and discharge velocity allows definition of the WCC and K-function using a single test on a single specimen, which minimizes scatter due to inherent material variability. Also, measuring the WCC and K-function during a flow process is consistent with flow problems, unlike conventional techniques such as the axis-translation technique. Because of these advantages, CPUS encourages the use of experimentally-obtained hydraulic properties for practical problems which have been obtained from correlations or analytical evaluation.

4 PROTOTYPE MODELING

Development of the CPUS involved previous testing of several 1-g soil prototypes, which have been built to assess the instrumentation, boundary conditions, and soil placement conditions that will be used in the CPUS. In addition, the 1-g testing is useful to perform preliminary flow analysis and provide a basis for modeling of models. As part of this testing program, infiltration tests were performed on different soils using wide-diameter (203.2 mm) Plexiglas columns. This large diameter was selected to minimize the effects of leakage along the permeameter walls.

An infiltration test on a low-plasticity (CL) soil was conducted to highlight both the expected behavior of the CPUS permeameter and the limitations of 1-g column testing. To prepare the specimen, the soil was first moisture conditioned to a gravimetric moisture content of 6.5%. The soil was then compacted mechanically in 50 mm lifts to a height of 300 mm and a target dry density of 1500 kg/m^3, resulting in an initial θ of 12%. The soil was carefully compacted around the different sensors. TDR sensors were placed at elevations of 50 mm, 100 mm, 200 mm and 250 mm from the base of the column, and HDU sensors were placed at 100 mm and 200 mm from the base of the column.

A peristaltic pump was used to impose a constant influx of approximately 2×10^{-7} m/s to the soil surface. The flow rate was selected to be less than the saturated hydraulic conductivity of the soil (approximately 4×10^{-5} m/s) to ensure unsaturated flow conditions. Testing involved measurement of the volumetric moisture content and suction changes with time during infiltration. The progress of the wetting front was observed visually, and outflow from the column was measured using a tipping bucket rain gauge and collected in graduated cylinders. After reaching steady-state flow, the flow was either stopped or increased to develop a new steady-state flow condition. The columns were covered with foil to minimize evaporation, but an air gap between the cover and the silt surface allowed air escape. Air entrapment was allowed during infiltration, as this is representative of conditions in surface soils and those expected in CPUS. Flow was assumed to occur in one dimension, although air entrapment and heterogeneities may cause temporary localized flow during infiltration.

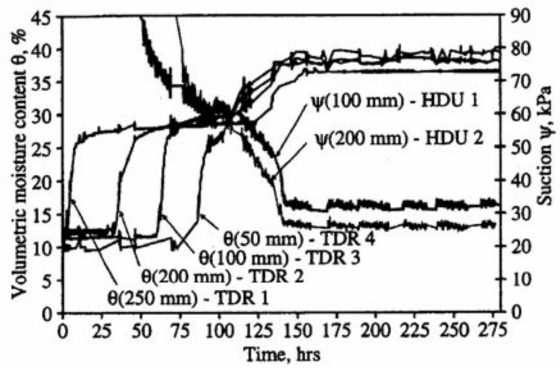

Figure 3. Moisture and suction measurements for 1-g prototype.

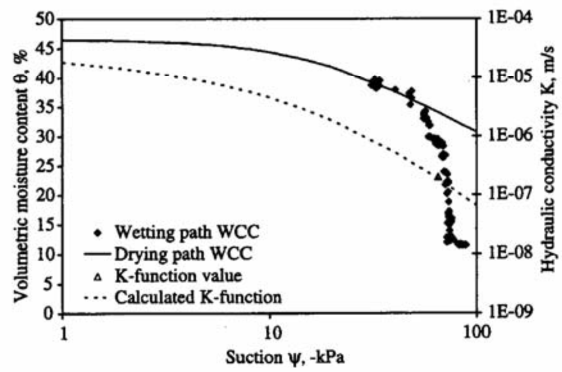

Figure 4. WCC and K-function developed from a 1-g prototype.

5 RESULTS

Figure 3 shows the volumetric moisture content and suction measured as a function of time at different depths in the soil profile. The data in this figure indicates that the advancing moisture front can be characterized by a moisture content of approximately 28% and a suction of 90 kPa. The front advanced at a rate of 3 mm/hr (8×10^{-7} m/s) through the cover. Once the front reached the base, the particular boundary condition being used in this column (filter paper placed upon a Plexiglas plate with a honeycomb mesh of 1.5 mm holes) caused a change in flow impedance, resulting in a capillary break. Flow breakthrough at the boundary occurred only when the suction near the base of the profile had to decrease to approximately 20 kPa, which caused the moisture content at the base to increase to approximately 39%. Further, moisture began to accumulate above the base, leading to an upward moisture front that advanced at a rate of 1.8 mm/hr.

Figure 4 shows the unsaturated hydraulic characteristics for the low-plasticity clay obtained from this infiltration test. The relationship between the suction and the volumetric moisture content from the two sets of HDR and TDR sensors allows determination of the wetting path of the WCC. The wetting path shows a steep increase in moisture content with decreasing suction during infiltration. This trend is different than that obtained for a drying-path in a similar CL soil (Figure 1), which showed a more gradual decrease in moisture content with increasing suction. A data point for the K-function value was obtained by assuming that a unit hydraulic gradient occurs during the initial infiltration stage (i.e. before the bottom boundary condition affected the flow process). Accordingly, the imposed specific discharge through the soil is then equal to the hydraulic conductivity. This data point fits well with the K-function calculated using the van Genuchten-Mualem model (van Genuchten 1980), with a saturated K of 4×10^{-5} m/s.

6 DISCUSSION

The column test results emphasize some of the shortcomings that may be addressed by CPUS. Specifically, a significant problem with the 1-g column testing is the length of time required for obtaining data. The results in Figure 4, which include only a small portion of the wetting path of the WCC and a single point on the K-function, were defined after 12 days of testing.

The influence of the bottom boundary condition observed in 1-g testing indicates that the column should be sufficiently long to minimize the effect of liquid accumulation at the base of the column. Although the boundary is expected to have some effect on the suction profile, analysis is facilitated when the upper portion of the column has a unit hydraulic gradient. A parameter evaluation indicated that the length of the column affected by the bottom boundary condition reduces for a specimen of a certain length due to centrifugation above a certain g-level (Dell-Avanzi et al. 2004). CPUS allows the use of special base platens customized for particular soil types to minimize the change in flow impedance that causes a capillary break.

CPUS allows measurement of the hysteretic behavior of the WCC, which cannot be made using other centrifuge techniques. Although possible in conventional testing, characterization of the hysteretic behavior typically requires significant amounts of time and complex testing procedures. In the centrifuge, after the specimen has reached a target moisture content (such as that attained at the end of the 1-g test presented herein), liquid can be drained by increasing the angular velocity of the centrifuge. Accordingly, different combinations of specific discharge and angular velocity can cover a wide spectrum of relevant suction values.

7 CONCLUSIONS

The centrifuge permeameter for unsaturated soils (CPUS) has been developed to alleviate shortcomings noted in available techniques for characterization of the unsaturated hydraulic properties of porous materials. It allows measurement of the variables relevant to unsaturated flow processes in an expedited fashion by allowing in-flight, continuous data acquisition. Most importantly, CPUS will encourage the use of experimentally-obtained hydraulic properties to solve problems in a wide range of engineering and science areas.

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