THE CENTRIFUGE PERMEAMETER FOR UNSATURATED SOILS (CPUS)

By: John McCartney[1] and Jorge Zornberg, Advisor[2]

Abstract: This paper describes the development of a new centrifuge permeameter capable of providing an accelerated measurement of relevant variables necessary to describe fluid flow processes through soils, aggregates, and rocks. The permeameter system is capable of precisely controlling low inflow rates (0.1 ml/min) within a rotating centrifuge environment, capable of imposing an acceleration field 600 times that of normal gravity onto a specimen. The benefits of using this system alleviate concerns with conventional testing techniques.

INTRODUCTION

Several fields of science and engineering rely on an 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. The 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 to characterize the unsaturated hydraulic properties of soils, aggregates, and rock have been noted in the literature. This paper highlights the shortcomings of conventional measurement techniques and focuses on the development of an improved experimental technique.

BACKGROUND

The flow of water 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 forces as the amount of water in the pores decreases. Further, the relationship between the hydraulic conductivity and the suction, referred to as the K-function, describes the change in the ability to flow through the porous material as water drains from the soil. Figure 1 shows an example of the WCC and K-function for a low-plasticity clay soil, which indicates that volumetric moisture content and hydraulic conductivity both decrease nonlinearly with increasing suction.

[1]Doctoral Candidate, Civil, Architectural and Environmental Engineering, The University of Texas at Austin

[2]Clyde E. Lee Assistant Professor, Civil, Architectural and Environmental Engineering, The University of Texas at Austin

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

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

Where t is time, r_0 is the radius from the center of rotation to the base of the specimen, z is the distance from the base in the direction toward the center of rotation, ω is the centrifuge angular velocity, and ρ is the liquid density. When ω is equal to zero, this equation is valid for 1-gravity situations. 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 Equation 1. As the WCC and K-function are sensitive to the porous material's mineralogy, particle size, and pore structure, material-specific testing is required.

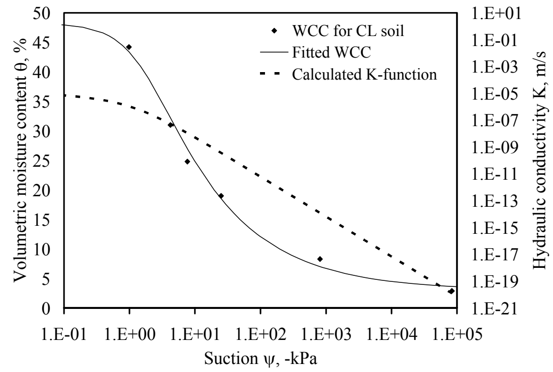

Figure 1: Water characteristic curve and K-function

CHARACTERIZATION OF UNSATURATED HYDRAULIC PROPERTIES

Conventional 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. Conventionally, the K-function and WCC are measured separately. This 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. During steady flow processes, the gradient in matric suction is measured, and the hydraulic conductivity is calculated using Darcy's law (K = *v/i*, where *v* is the flow rate and *i* is the hydraulic gradient). During transient flow processes, the suction and moisture content profiles with distance and time are measured. The K-function can be calculated from Equation (1) using inverse techniques.

Two main groups of techniques are used to define the WCC. The first group of "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 placement of 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 in an oven. 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 of "thermodynamic" techniques involve allowing water to evaporate from a specimen in a closed chamber with controlled relative humidity. Physical techniques are used for low suctions (< 1500 kPa) and thermodynamic techniques are used for higher suctions.

Conventional techniques to define the K-function and WCC have the disadvantage of requiring significant time to obtain limited data. For example, determination of the hydraulic properties for a low-permeability clay specimen may take over one year (more than one month for each data point in either the WCC or K-function). 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 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 that the material may be exposed to in the field.

Centrifuge Techniques. To alleviate the shortcomings of conventional unsaturated hydraulic property characterization, centrifuges have 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. Centrifuges were first used to define the WCC by soil scientists and petroleum engineers in the 1940's. Typically, a saturated specimen is placed upon a saturated ceramic plate which conducts liquid. Air enters the surface of the specimen as water exits through the ceramic during centrifugation. Because the bottom boundary is maintained saturated (zero suction), a distribution of suction develops with height. An analytical technique is used to associate the average moisture content (measured destructively) with the calculated surface suction to define a point on the WCC.

Centrifuges have also been used to define the K-function. Nimmo et al. (1987) developed the Internal Flow Control Steady-State Conductivity Apparatus (IFC-SSC), which uses a system of reservoirs to control the fluid flow rate and suction at the upper and lower surfaces of a specimen. By ensuring steady state flow conditions (measured by periodically stopping the centrifuge and weighing the specimen and reservoirs), different points on the K-function curve can be defined. Conca and Wright (1994) developed the Unsaturated Flow Apparatus (UFA), which uses a sophisticated rotary joint to pass a low fluid flow rate from the stationary world into the specimen. The UFA does not impose a suction value on the specimen, referred to as open-flow centrifugation.

Current centrifuge technology does not allow the direct acquisition of the relevant variables (suction, moisture, flow rate) in-flight during testing, which requires stipulating simplifying assumptions for data analysis. Specifically, the driving force due to the suction gradient in Equation (1) is assumed to be small compared to the centrifuge driving force. In this case, the hydraulic conductivity of the specimen is proportional to the steady flow rate, and 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 IFC-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. In addition, the SSC and UFA do not simultaneously determine the WCC and K-function.

CENTRIFUGE PERMEAMETER FOR UNSATURATED SOILS

The shortcomings listed above have driven development of an improved device to measure the unsaturated hydraulic characteristics of porous media, referred to as the Centrifuge Permeameter for Unsaturated Soils (CPUS). This device 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 accelerated definition of the WCC and K-function from a single specimen in a single test, as shown in Figure 2.

A low-flow fluid union has been developed to supply fluid inflow rates 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. CPUS is capable of three bottom boundary conditions: fixed suction (e.g., zero-suction using a saturated ceramic plate), fixed moisture content (e.g., a water table), and open-flow conditions.

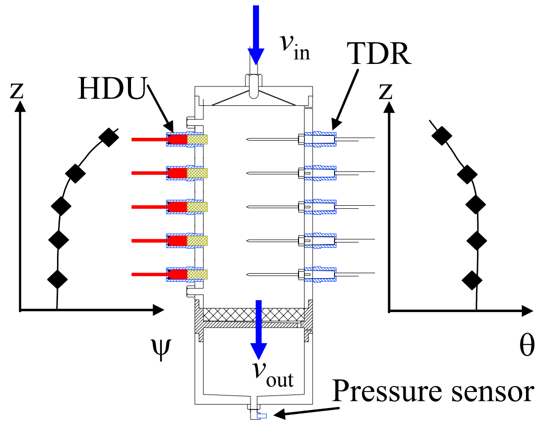

Figure 2: CPUS Permeameter with example of measured variables

An important feature of CPUS is that the relevant variables (suction, moisture content, flow rate) are measured continuously while the specimen is in-flight within the centrifuge. This permits measurement of transient and steady-state flow processes without changing the acceleration field (i.e., by stopping the centrifuge). Accordingly, a key component in CPUS is the incorporation of a data acquisition system that sustains 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 as it is highly sensitive to the moisture content of a 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. The 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 outflow from the specimen is collected in a reservoir, where the volume is monitored using a pressure sensor.

The CPUS system decreases significantly the time needed to obtain unsaturated hydraulic properties (tests that currently take years will be able to be accomplished within a day). The measurement of the suction, moisture content, and flux simultaneously allows the WCC and K-function to be defined in a single test on a single specimen. Also, this method of defining relationships between these variables is consistent with natural flow processes, unlike the axis-translation technique. Because of these advantages, CPUS encourages the use of experimentally-obtained hydraulic properties for practical problems.

REFERENCES

Benson, C. and Gribb, M. "Measuring Unsaturated Hydraulic Conductivity in the Laboratory and Field." *Unsaturated Soil Engineering Practice*, 113-168.

Conca, J., and Wright, J. (1992). "Diffusion and Flow in Gravel, Soil, and Whole Rock." *Applied Hydrogeology*. Vol. 1, pp. 5-24.

Klute, A. (1986). *Water Retention: Laboratory Methods. Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. SSSA. Madison, WI. 635-662.

Nimmo, J.R., Rubin, J., and Hammermeister, D.P. (1987). "Unsaturated Flow in a Centrifugal Field: Measurement of Hydraulic Conductivity and Testing of Darcy's Law." *Water Resources Research*. Vol. 23(1) pp. 124-134.