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TDR System for Hydraulic Characterization of Unsaturated Soils in the Centrifuge

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Abstract

A centrifuge permeameter has been developed to provide expedited determination of the hydraulic properties of unsaturated soils. The centrifuge permeameter is an acrylic cylinder mounted on a swinging bucket. The hydraulic properties of a soil specimen are measured using the centrifuge permeameter by controlling the water flow rate through the specimen and measuring changes in moisture content and suction. This paper focuses on the development of a time domain reflectometry (TDR) system used to infer changes in volumetric moisture content during transient and steady-state infiltration of water in the centrifuge permeameter. The TDR system includes a vertically-oriented TDR waveguide partially embedded within the permeameter wall, along with a cable tester and coaxial multiplexer located on-board the centrifuge. Results of a 1-gravity calibration program for a low-plasticity clay indicate that the embedded TDR waveguide has adequate accuracy despite the low dielectric permittivity of the acrylic. Results from an infiltration test indicate that both transient and steady-state fluid flow can be measured accurately with a vertical waveguide embedded in the permeameter wall.

Key Words Centrifuge, unsaturated soils, hydraulic conductivity function, SWRC

Introduction

The hydraulic properties of unsaturated soils that are commonly used in geotechnical engineering applications include the soil water retention curve (SWRC), the hydraulic conductivity function (K-function), and shrink/swell curves. The SWRC governs the retention of water in the soil voids with increasing suction, the K-function governs the changes in hydraulic conductivity as less water is retained within the soil pores, and the shrink/swell curves govern the changes in volume of the soil structure during outflow or inflow of water in the soil voids. An array of testing approaches and several different soil specimens are often required in practice to fully characterize the hydraulic properties of a soil over the range of conditions expected in the field (Benson and Gribb 1997[1]; Wang and Benson 2004[8]). Further, a significant amount of time is required to determine these properties. Because of these challenges, engineers often rely on limited data, published databases, correlations, or predictive relationships for the hydraulic properties of unsaturated soils. Although these empirical approaches may be the only feasible alternatives for some projects, their use could potentially lead to ambiguous and costly designs. This is all the more evident because the hydraulic properties for a given soil are not unique, but changes upon wetting and drying. Accordingly, it is recommended to use experimental techniques in practice.

The shortcomings of available experimental techniques used to determine the hydraulic properties of unsaturated soils has driven development of a new device, 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 in order to provide an expedited determination of the SWRC and K-function from a single soil specimen. One of the main advantages of CPUS over previous centrifuge permeameters is its monitoring system. The goal of the monitoring system is to provide independent, continuous, non-destructive, and non-intrusive measurements of suction, volumetric moisture content, and fluid flow rate in a soil specimen during centrifugation. This paper focuses on an important component of the monitoring system that involves the use of time domain reflectometry (TDR) to infer the volumetric moisture content in the soil specimen.

Centrifuge Testing for Unsaturated Soils

Centrifugation was used by researchers such as Nimmo *et al.* (1987[4]), Conca and Wright (1992[2]), and Dell'Avanzi *et al.* (2004[3]) to provide an expedited determination of the SWRC and K-function. Centrifugation increases the body forces on a soil specimen by imposing a centripetal acceleration a equal to:

$$a = \omega^2 r = N_r g \tag{1}$$

where ω is the angular velocity, r is the radius, g is the acceleration of gravity, and N_r is the ratio between centripetal acceleration and g. N_r is typically referred to as the "g-level". Centrifugation increases the potential gradient for fluid flow, which decreases the time required to attain steady-state fluid flow by a factor of N^2. Experience from conventional hydraulic characterization tests indicates that definition of the K-function is best characterized using steady-state fluid flow (Benson and Gribb 1990). By rapidly reaching steady state, the SWRC and K-function can be defined for a single soil specimen in a reasonable amount of time. The time to reach steady-state will vary with the initial conditions, g-level, and imposed flow rate.

Centrifuge testing has been used to determine the K-function in geotechnical projects involving the design of ET covers (Zornberg *et al.* 2003[9]). Nimmo *et al.* (1987[5]) 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 boundaries of a specimen. Conca and Wright (1992[2]) developed the Unsaturated Flow Apparatus (UFA), which uses a rotary joint to supply water from a flow pump outside the centrifuge to the rotating specimen. Both approaches were developed for use in medical centrifuges, so the specimen size was small. For steady state conditions, the SSC and UFA use Darcy's law to determine the K-function:

$$K(\psi) = \frac{v_m}{\left[\dfrac{\omega^2 r}{g} - \dfrac{1}{\rho_w g}\dfrac{d\psi}{dr}\right]} \quad (2)$$

where $K(\psi)$ is the hydraulic conductivity value corresponding to a particular suction ψ (or volumetric moisture content θ), ρ_w is the density of water, and v_m is the imposed fluid discharge velocity. Points on the K-function may be defined using Equation (2) after reaching steady state flow conditions for a given combination of ω and v_m. If the suction gradient in Equation (2) is assumed to be negligible, the hydraulic conductivity is given by:

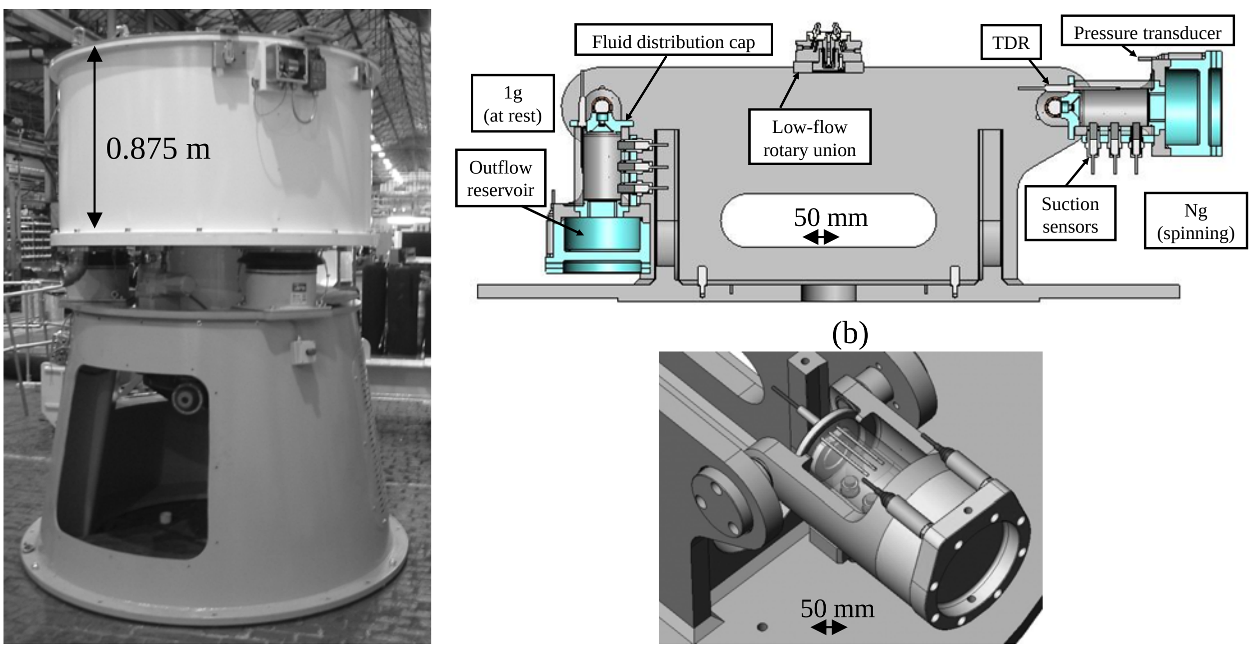
$$K(\psi) = \frac{v_m g}{\omega^2 r_m} \quad (3)$$

where r_m is the mid-radius of the specimen. This assumption is valid only for thin soil specimens (*i.e.*, where the suction or water content don't vary significantly with radius), and for open-flow boundary conditions. Open-flow boundary conditions imply that the suction at the surface or base of the soil specimen is not controlled, but is free to obtain the particular suction value associated with the flow rate. The hydraulic conductivity (or impedance to flow) of the bottom support plate is an important consideration to obtain open-flow boundary conditions. The SSC and UFA 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 major disadvantage of these approaches is that the small size of medical centrifuges does not allow instrumentation for direct acquisition of the relevant variables (suction, moisture content, fluid discharge velocity) during centrifugation. Accordingly, the SWRC cannot be determined without making simplifying assumptions as to the suction or moisture content distribution with radius, or by measuring these variables outside of the centrifuge.

Centrifuge Permeameter

CPUS incorporates a high-g centrifuge, a permeameter, a flow pump with a low-flow rotary union, and a data acquisition system. The goal of this system is to determine both the SWRC and K-function for a single soil specimen during centrifugation. The centrifuge, shown in Figure 1(a), was developed by Thomas Broadbent and Sons, LLC, of Huddersfield, UK. The centrifuge has a maximum speed of 875 RPM and a radius of 0.78 m. A cross-section of the permeameter environment is shown in Figures 1(b) and 1(c). The permeameter is an acrylic cylinder with a height of 142 mm and a diameter of 71 mm. This diameter, which is slightly less than a typical 76.2-mm diameter Shelby tube sample, permits an undisturbed specimen to be trimmed to the diameter of the permeameter. The wall thickness of the permeameter is 25 mm, which allows instrumentation to be placed within the walls of the permeameter. Two identical permeameters are mounted on swinging buckets that are attached opposite to each other on a steel support frame. The swinging buckets allow the direction of highest acceleration to be aligned with the axis of the permeameter whether at rest (vertical) or spinning (horizontal). The distance from the central axis of the centrifuge to the mid-plane of the permeameters is 0.6 m, which corresponds to an average g-level of 514 g.

Fluid is supplied to the permeameters by a two-channel medical infusion pump, which has a flow capacity ranging from 1.0 to 100.0 mL/hr. As the pump cannot operate within the centrifuge environment, the fluid is passed through a 2-channel low-flow rotary union. The rotary union is designed to prevent water loss and heat generation. Because a "flow" boundary condition is desired for the permeameter, the rotary union is designed to operate without the fluid being pressurized. Inside the rotary union, water drips from a stationary needle into a rotating channel. The rotating channel is inclined in the direction of centrifugation, so the water flows under its own weight from the channel, through a flexible metal tube, to the permeameter. The top cap of the permeameter consists of a 20-mm diameter cylindrical reservoir. A series of eight 0.75-mm diameter inclined tubes are evenly spaced about the circumference of the reservoir at a height of 5 mm. During operation, water from the infusion pump is supplied through the rotary union to the reservoir in the top cap of the permeameter. After the water level in the reservoir reaches the level of the inclined tubes, it spills over into the channels. This permits even distribution of water over the upper boundary of the specimen. An outflow collection reservoir is built into the base of each swinging bucket, where the water level is monitored using a pressure transducer.



(a) (c)

Figure 1: (a) CPUS centrifuge; (b) CPUS permeameter hanger; (c) CPUS permeameter

The on-board data acquisition system has two components: the transducer interface system and the TDR system. The transducer interface system includes solid-state hardware (no moving disc-drives), with 32 channels for various transducers (load cells, pressure transducers, thermocouples) and on-board digitization, amplification, and filtering. Communication between the data acquisition system and the stationary environment is possible either via an Ethernet connection through a slip-ring stack, or a fiber optic rotary joint. The TDR system used in this study is the Mini-Trase®, developed by SoilMoisture, Inc. of Goleta, California. This TDR system includes a cable tester (model 6050X), a 16-channel coaxial multiplexer (model 6021C16), and mini-buriable waveguides (model 6111). The waveguides used in this study have three, 80-mm long cylindrical prongs. A schematic of the waveguides is shown in Figure 2.

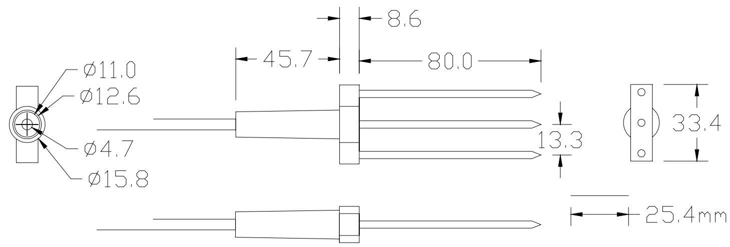
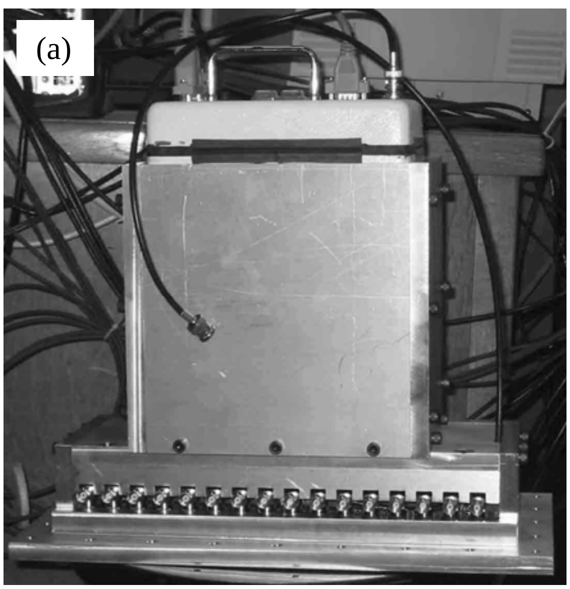


Figure 2: Schematic of mini-buriable waveguide

The Mini-Trase was selected as it is a robust cable tester, typically used for field applications. The cable tester and coaxial multiplexer were installed on permeameter hanger on the central axis of the centrifuge. A RS232 cable was passed through a set of electrical slip rings in order to control the cable tester during centrifuge operations. The cable tester also has on-board data storage. The electrical boards in the cable tester and the multiplexer board were supported with paper forms and potted with non-conductive epoxy to prevent damage. The aluminum container used to confine the cable tester and multiplexer is shown in Figures 3(a) and 3(b).



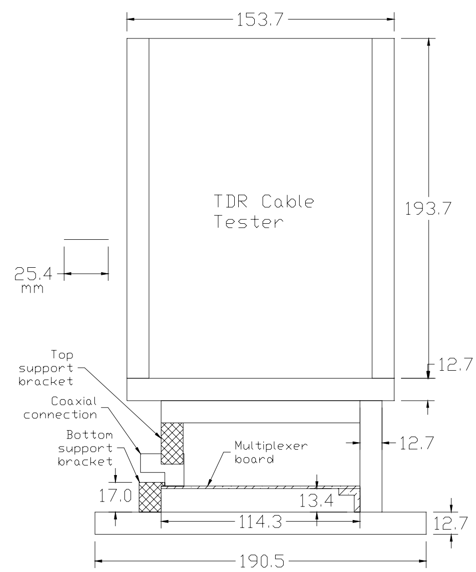
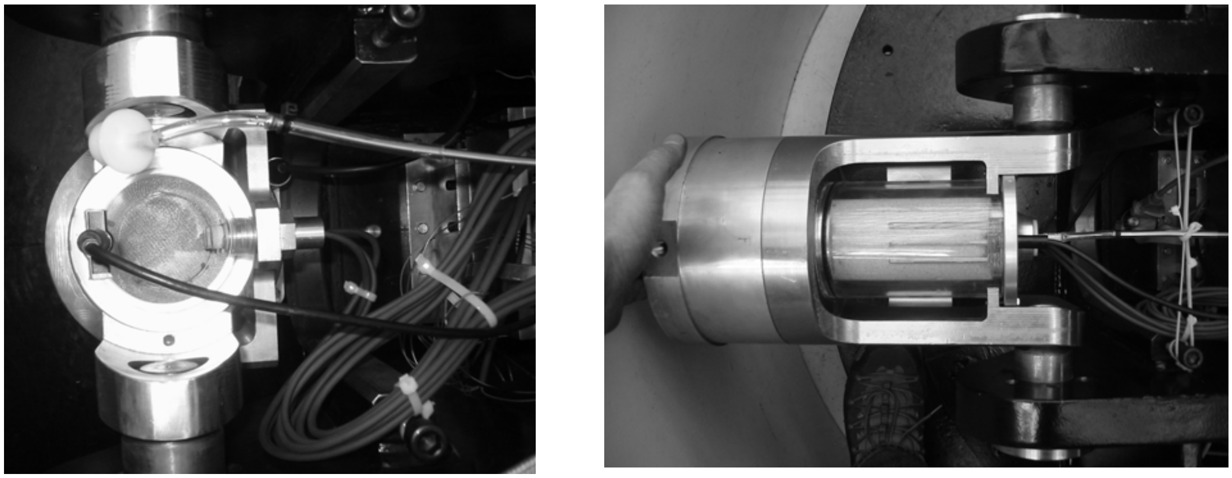


Figure 3: (a) Cable tester containment unit; (b) Cross section of the containment unit

A vertical TDR waveguide is partially embedded within the wall of the acrylic permeameter, as shown in Figures 4(a) and 4(b). The outer shielding probes are fully embedded within the acrylic, while the inner transmission probe is half-embedded within the wall of the permeameter. Use of acrylic prevents electrical interaction with the TDR waveguide. The motivation behind using a vertical TDR was due to space constraints and the fact that intrusions into the specimen may affect the flow behavior under investigation. Intrusions into the soil specimen may cause significant disturbance of the soil (or rock) structure during insertion, and may cause or prevent settlement of the soil during centrifugation. The increase in flow path tortuosity for a specimen with several inclusions may affect the measurement of the soil's hydraulic conductivity, particularly under increased gravity. Use of the permeameter itself as the shield for a central coaxial conductor was also considered, but a central waveguide would have to be pushed through the soil sample, causing a preferential flow path and potential changes in density.



(a) (b)

Figure 4: (a) Top view of permeameter before soil placement; (b) Permeameter ready for a test

There are several issues related to using the TDR in the centrifuge. The cabling has a tendency to move outward in the centrifuge. The cables were affixed using plastic stays in such a way as to permit free motion of the permeameter during swinging, but to prevent the cable from moving outward. Visualization of the cables during centrifugation using a strobe light indicates that the cables did not creep. The rotating centrifuge has been known to generate electrical fields due to the induction motor. This has the greatest impact on data that is transmitted from the moving centrifuge to the stationary environment through slip rings. The TDR data will be stored onboard the centrifuge during testing. The centrifuge tests using the TDR system have been preliminary at this point, but the results have been similar at 1-gravity and N-gravity. The electrical fields are not expected to impact the measurement process in the permeameter itself.

The permeameter also includes a profile of three suction sensors, shown in Figure 3(a), which are used to measure the suction profile with specimen height. The motivation behind measuring the suction profile is to determine if the suction gradient is negligible for a certain combination of fluid discharge velocity and g-level, which will allow use of Equation (3) to determine the K-function and SWRC. In other words, the average moisture content inferred using TDR would correspond with the particular values of hydraulic conductivity and suction measured in the specimen. If the suction gradient is not negligible, then numerical analyses are required to associate the average moisture content with the hydraulic conductivity and suction. The ranges of suction expected during testing will vary between positive pressures and 1000 kPa, depending on the soil type and flow rates. Heat dissipation units (HDUs) are used to measure suctions between 20 kPa and 1000 kPa and tensiometers are used to measure suctions less than 80 kPa.

Typical TDR Waveforms

Typical TDR waveforms for waveguides in air, water, and partially embedded within the acrylic wall are shown in Figure 5. The apparent dielectric permittivity, K_a, is calculated from a waveform using the time difference between the reflections at the beginning and end of the probe, Δt, as follows:

$$K_a = \left(\frac{c\Delta t}{2L} \right)^2 \tag{4}$$

where c is the speed of light, and L is the length of the probe. The values of K_a calculated for the different materials are 1.2 for air, 78 for water, and 2.5 for partial embedment in the acrylic. The first reflection observed on the waveforms does not signify the beginning of the waveguide. The beginning of the mini-buriable waveguides is offset by 0.12 ns from the initial reflection, which helps the WinTrase® waveform analysis software identify the travel times consistently. The end reflections were defined as the intersection between the tangent lines drawn to the second dip in the waveform. The end reflections are marked with arrows.

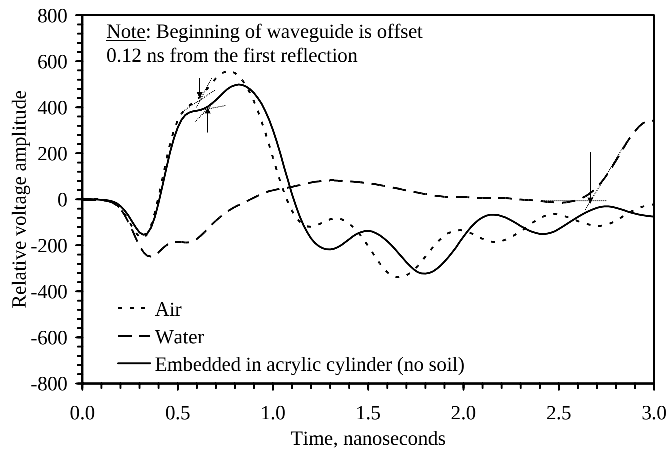


Figure 5: Typical waveforms for waveguides in air, water, and partially embedded in acrylic (arrows mark the reflection from the end of the waveguide)

Calibration Testing Program

A low-plasticity clay (CL) was used in the TDR calibration and infiltration programs. The calibration program included correlation of the apparent dielectric permittivity values calculated from the TDR waveforms with different soil compaction moisture contents. The TDR system was calibrated for waveguides embedded in the wall of the permeameter as well as for waveguides fully buried in the soil (in a separate mold). The soil was placed in the permeameter in four lifts, and a Bellofram® piston compactor was used to densify the soil. The soil was placed in the permeameter at a relative compaction of 70% (with respect to the maximum Standard Proctor dry density of 1920 kg/m^3) with a range of gravimetric moisture contents. The volumetric moisture content for the soil was calculated from the soil dry density, the density of water, and the compaction gravimetric moisture content as $\theta = (\rho_d w)/\rho_w$. Waveforms measured from a waveguide embedded in the permeameter wall, at different compaction moisture contents, are shown in Figure 6(a). The travel time was observed to increase with increasing moisture content, although the changes were not significant (an increase in travel time from 0.70 to 0.77) for changes in gravimetric moisture content of 4.5%. A comparison between the waveforms for waveguides embedded in the permeameter wall and buried in the soil is shown in Figure 6(b).

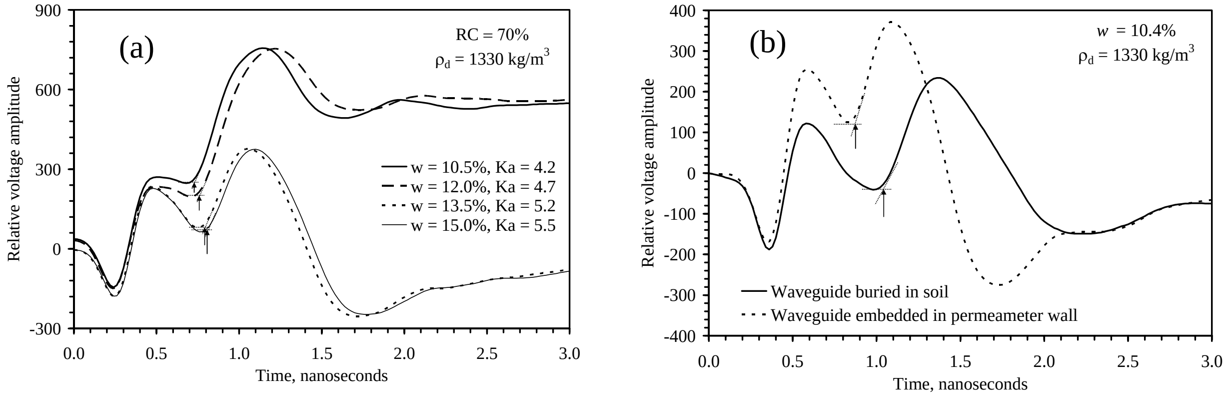


Figure 6: (a) Waveguide embedded in permeameter with different moisture contents; (b) Effect of embedment on waveforms (arrows mark the reflection from the end of the waveguide)

The calibration curves for waveguides buried in the low-plasticity clay and for waveguides embedded within the wall of the permeameter are shown in Figure 6. This figure indicates that the calibration curve for the waveguide embedded in the permeameter is steeper than that for the waveguide buried in the soil, which implies a decrease in sensitivity of approximately 2 times.

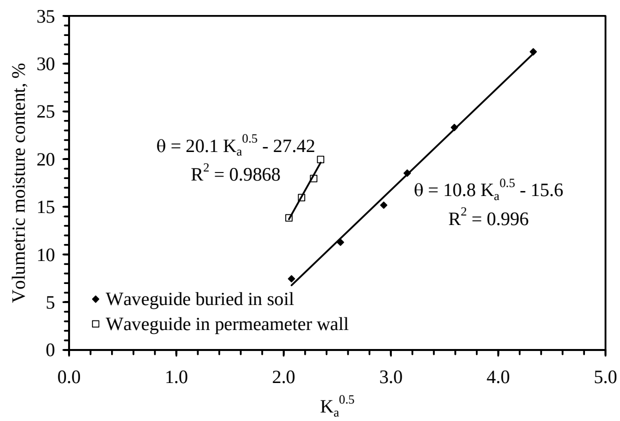


Figure 7: TDR calibration curves for a low-plasticity clay (plotted with square of K_a)

Infiltration Testing Program

The main problems anticipated with using a vertical TDR waveguide to monitor infiltration processes are the lower sensitivity of the TDR waveform to changes in water content in the specimen, preferential flow (or lack of flow) of water near the permeameter boundaries, difficulties in the interpretation of transient water flow processes (*i.e.*, wetting fronts), and bottom boundary effects on the moisture profile in the specimen. For the waveguide used in this study, TDR infers the average dielectric permittivity of material in a zone along the length of the vertical waveguide approximately 20 mm perpendicular from the plane of the waveguide. This implies that the measurement volume is less than ½ of that for a TDR fully embedded in soil. If the moisture distribution is not uniform in this zone (i.e., during transient flow, or if flow is not uniform with the area), the vertical TDR may also yield unreliable readings. The steady-state moisture profile is not expected to change except during minor variations in the centrifuge speed.

A flow boundary condition is desired for the base of the permeameter (*i.e.*, open flow conditions), so an outflow plate with similar hydraulic properties to the soil being tested is required. Steel mesh with similar porosity to the soil is used to limit the impedance to flow of the bottom boundary. McCartney *et al.* (2005[4]) observed that ponding of water occurred within a soil profile when a 6-oz/yd^2 nonwoven geotextile was used as a bottom boundary condition, which would be a worst-case scenario. It is anticipated that the height of ponding will likely be smaller under an increased g-level. Interpretation of the TDR waveform is difficult for near-saturated soil specimens, but the moisture content of the soil is expected to be less than saturation during centrifugation except for combinations of low g-levels and high inflow rates.

A 1-gravity permeameter with the same height, but larger radius, was developed to investigate the analysis of results from the vertical waveguide (outside of the centrifuge permeameter). Elevation and plan cross-section views of the permeameter are shown in Figure 8(a) and 8(b). This permeameter allows the use of multiple horizontal waveguides, which can be used to interpret the measurements obtained from the horizontal waveguides. Water was supplied to the permeameter from an infusion pump, but was distributed over the surface of the specimen using a set of cotton fiber wicks. The tubing from the infusion pump drips into a small cup, from which the fiber wicks draw water across the surface of the soil. The horizontal TDR waveguides are fully embedded within the soil, and are arrayed at the same spacing as the suction sensors in the centrifuge permeameter. The acrylic wall of the permeameter is thinner than that of the centrifuge permeameter, but this was assumed not to affect the calibration. The top surface of the permeameter was covered in plastic wrap to minimize evaporation.

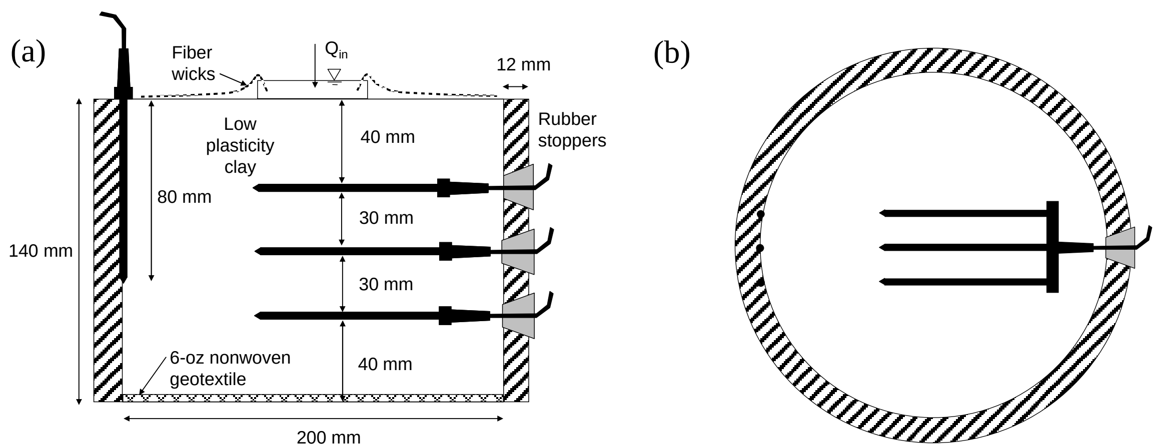


Figure 8: Permeameter for vertical TDR waveguide investigation: (a) Elevation cross section; (b) Plan cross section (at 100 mm from base)

A steady fluid discharge velocity of 3.8x10^{-8} m/s was applied to the top surface of the permeameter. Flow was stopped shortly after the wetting front reached the base of the profile to avoid the effects of the bottom boundary condition (*e.g.*, ponding) in the calculations, as shown in Figure 9(a). The apparent dielectric permittivity values measured by the four waveguides are shown in Figure 9(b). The horizontal TDR waveguides show a sharp increase in apparent dielectric permittivity as the wetting front passes each depth. The vertical TDR waveguide shows an increase in apparent dielectric permittivity immediately after infiltration started, from 4.2 at 18 hs to 5.4 at 38 hs. After this time, the reading from the vertical waveguide is constant.

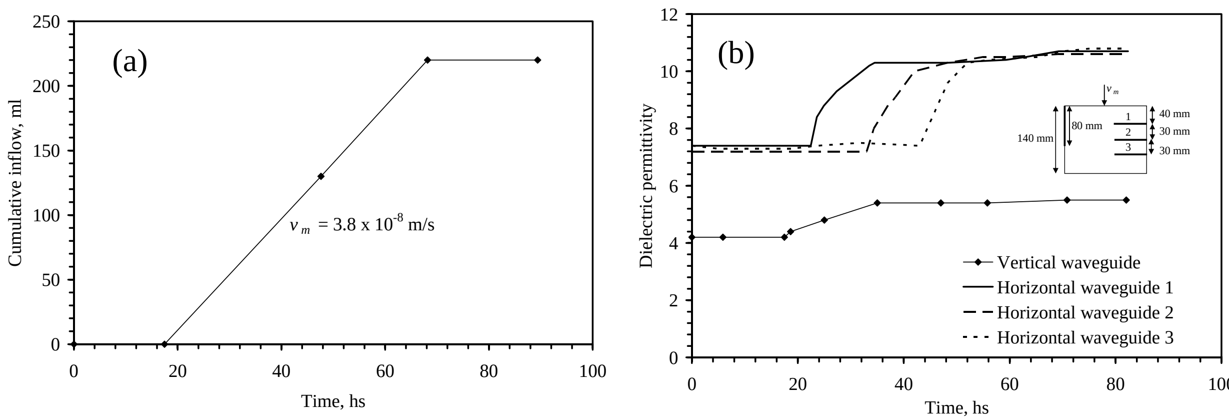


Figure 9: (a) Cumulative inflow; (b) Dielectric permittivity values from the different waveguides

Analysis of Vertical Transient and Steady-State Fluid Flow

Based on the concerns listed in the previous section, it is intended that the main application of the TDR system will be to infer the average moisture content within the top 80 mm of the specimen. The results shown in Figure 9(b) indicate that the apparent dielectric permittivity at steady-state for this inflow rate would be 5.4. This corresponds to a volumetric moisture content of 20%. Assuming a unit gradient, this test would define a point on the K-function with a moisture content of 20% and a hydraulic conductivity of 3.8×10^{-8} m/s. However, a unit gradient assumption for this particular test is not representative because steady-state conditions were not attained (flow was stopped after the wetting front reached the base of the permeameter). For steady-state conditions to occur, the moisture content in the soil profile would have to increase even further until reaching the breakthrough suction of the bottom boundary. McCartney *et al.* (2005[4]) observed that the soil would have to reach a moisture content of 38% up to a depth of 30 cm to have capillary breakthrough. This situation would present difficulties in analysis.

The results shown in Figure 9(b) can also be used to interpret the transient movement of moisture through the top 80 mm of soil. Topp *et al.* (1982[7]) developed a model to analyze the flow of water past a vertically-oriented TDR waveguide, as follows:

$$\sqrt{K_a} = \frac{z_{wf}\sqrt{K_{wf}} + \left(L_{probe} - z_{wf}\right)\sqrt{K_{initial}}}{L_{probe}} \tag{5}$$

where K_a is the apparent dielectric permittivity measured at any point in time by the TDR waveguide, $K_{initial}$ is the initial apparent dielectric permittivity, K_{wf} is the apparent dielectric permittivity of the soil in the wetted zone (which has a length of z_{wf}), and L_{probe} is the length of the waveguide. K_{wf} can be determined as the "steady-state" dielectric permittivity from the time series for a vertical TDR. The depth of the wetting front is obtained as:

$$z_{wf} = \frac{L_{probe}\left(\sqrt{K_a} - \sqrt{K_{initial}}\right)}{\sqrt{K_{wf}} - \sqrt{K_{initial}}} \tag{6}$$

This approach assumes that the wetting front has a sharp change in moisture content from the initial moisture content to the moisture content of the wetting front, and assumes that the TDR waveform will change in a linear fashion as the wetting front progresses. The results from the horizontal TDR waveguides indicate that the sharp wetting front is not a perfect assumption, as they approximately 5 to 10 hours were required for an increase in moisture content from the initial to steady-state values to occur. Other studies indicate that the use of a weighted average like Equation (5) is not particularly accurate (Schaap *et al.* 2003[6]). This study observed that the wavelength of the electromagnetic pulse ($\lambda = c/f$) and the thickness of the layer will change the propagation velocity, and provided more sophisticated averaging schemes.

The volumetric moisture content values calculated from the calibration equation for the vertical and horizontal waveguides are shown in Figure 10(a). This figure is used to determine the timing of the wetting front as it passed through the permeameter. The model in Equation (6) was used to predict the passage of the wetting front through the top 80 mm of the permeameter, as shown in Figure 10(b). The model shows a reasonable prediction of the wetting front progression. Although useful, this approach suffers from the same shortcoming as the steady-state approach, where the bottom boundary may influence the moisture content profile during flow. It may be difficult to obtain the value of K_{wf} from such a vertical waveguide time-series.

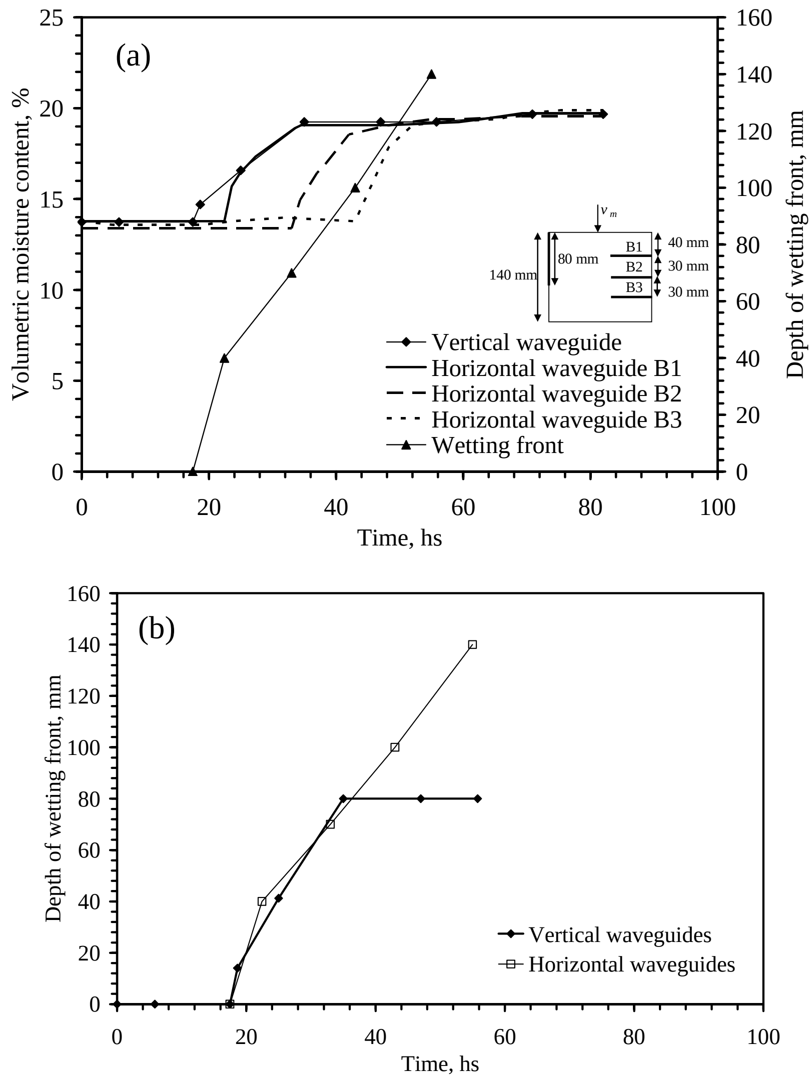


Figure 10: (a) Volumetric moisture content; (b) Wetting front calculated using Equation 6

Conclusions

An approach to measure the moisture content of a soil during infiltration under a centrifuge field was presented in this paper. A TDR system with a vertical waveguide partially embedded in an acrylic permeameter was found to be most suitable for monitoring of the average volumetric moisture content during steady-state water flow through the permeameter. If it is assumed (or experimentally determined using suction sensors) that the suction profile does not vary significantly with the specimen height, the average moisture content measured by the vertical TDR waveguide allows simple correlation between the hydraulic conductivity, suction, and moisture content to define the K-function. An approach was also presented that indicates that the vertical waveguide can be used to accurately interpret the movement of transient moisture flow past the waveguide. Several shortcomings of this approach were discussed, most important of which are a decrease in sensitivity of the TDR calibration due to the low dielectric permittivity of the acrylic, and the potential effects of the bottom boundary condition on the moisture content profile in the permeameter. New miniature dielectric sensors such as the ECH_20-TE probes, developed by Decagon, Inc. will also be investigated for the centrifuge permeameter, as they occupy less space and do not require a cable tester. These sensors may provide additional discretization of the moisture profile through the specimen and simplify the data acquisition system for the centrifuge. Future studies will investigate the effects of centrifugation on the SWRC and K-function, as centrifugation may cause changes to the air-water menisci and imposes high body forces on the soil, which may change the soil hydraulic behavior.

Acknowledgemen

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