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Measurement of soil-water characteristic curves of quasi-saturated soils

Mesure de courbes de retention d'eau des sols quasi-saturés

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ABSTRACT
Important geotechnical structures involve cohesive soil compacted either around or on the wet side of optimum water content. In general, at the corresponding saturation values, water component in soil voids is continuous but the air phase is not. The soil with entrapped air may be assumed to be in a state termed as "quasi-saturated". The soil-water characteristic curve is often used to estimate unsaturated soil property functions. Since the measurement of pore air pressure in an occluded sample is extremely difficult, the data for the soil-water characteristic curve of quasi-saturated soils is not well defined. A simple experimental procedure for rapid measurement of continuous soil-water characteristics curves of quasi-saturated soils is described in this paper. The apparatus, testing procedures and results are presented and discussed. Data from the test results are used to validate a theoretical soil-water characteristic function involving discontinuous air phase derived by using the occluded state theory proposed by Schuurman (1966).

RÉSUMÉ
Les structures géotechniques importantes utilise les sols non saturés compactés à teneur en eau optimum ou supérieur. En général, à ces valeurs de saturation, les sols contennent bulles de gaz incluses dans l'eau interstitielle. On peut assumer que le sol qui contenne des bulles de gaz incluses dans l'eau interstitielle est dans un état nommé comme "quasi-saturé". La courbe de retention d'eau des sols est souvent employée pour estimer paramètres non saturés de sol. La courbe de retention d'eau des sols quasi-saturés ne sont pas définis. Cet exposé presente une technique très simple pour la mesure rapide des courbes de retention d'eau des sols qui contiennent des bulles de gaz incluses dans l'eau interstitielle. Le appareil, les méthodes d'essai et les résultats sont présentés et discutés. Les resultats des expériences avec cette méthode s'accordent avec le modèle conceptual pour les sols qui contennent bulles de gaz incluses dans l'eau interstitielle proposée par Schuurman (1966).

1 INTRODUCTION

Compacted soils are widely used for the construction of earth embankments or earth fills in general, and engineers often specify that cohesive soils be compacted near optimum water content. In general, at the corresponding saturation values, the soil will be unsaturated with air component in soil voids no longer connected to the atmosphere. The soil with entrapped air may be assumed to be in a state termed as "quasi-saturated" (Faybishenko, 1995; Shahu et al., 1999), and the influence of pore air and water pressures on the change of the saturation must be taken to account in the investigation of such quasi-saturated compacted soils.

The graphical representation of the relationship between the amount of water in the soil and the capillary pressure (i.e., the pressure difference between air and water components in soil voids) is known as the soil-water characteristic curve (SWCC) for the soil. The SWCC for a particular soil is directly relates to the hydraulic conductivity, shear strength and volume change of the unsaturated soil. Thus, the knowledge of the SWCC and its changes within the domain of interest are an essential prerequisite for the solution of any engineering problem in unsaturated soil. Several techniques have been proposed over the years to measure the SWCC data of a soil. Most of the available methods used to measure the SWCC data of a soil sample are time consuming and expensive for routine applications where many samples may have to be analyzed for complete site characterization. Zapata et al. (2000) show that even some of the most experienced researches have difficulties in getting a unique SWCC for a soil. Also, the existing methods for the measurement of the SWCC data do so by actually measuring the difference between the ambient air pressure and the soil pore water pressure and the corresponding water content of the soil.

Since the measurement of pore air pressure in an occluded sample is extremely difficult, if not impossible, the part of the SWCC with entrapped air is not well defined (Corey, 1994). Thus, it is necessary that the SWCC data for quasi-saturated soils be properly measured and interpreted. This paper presents a testing technique for rapid measurement of continuous soil-water characteristics curves of quasi-saturated soils. The apparatus, testing procedures, experimental results and difficulties and advantages found on using this technique to obtain the SWCC data are presented and discussed here. Data from the test results are used to validate a theoretical soil-water characteristic function involving discontinuous air phase derived by using the occluded state theory proposed by Schuurman (1966). The theoretical soil-water characteristic function is derived elsewhere (Bicalho, 1999; Bicalho et al., 2002).

2 THEORY

The SWCC is highly hysteretic with respect to the wetting and drying processes. A curve is obtained starting with a completely saturated condition. This is called a primary boundary SWCC on drying condition. A different curve is obtained by starting with a sample containing only the nonwetting phase (i.e., completely dry) and allowing it to imbibe the wetting phase. The latter curve is called a primary boundary SWCC on wetting condition. These two boundary curves belong to an infinite family of curves that might be obtained by starting at any particular saturation and either increasing or decreasing saturation.

For soils with a high degree of saturation the water is continuous but the air phase is discontinuous with isolated air pockets within the pore space, which have no connection over macroscopic distances (occluded air bubbles or entrapped air). The value of the degree of saturation where the air starts to be entrapped, S_m, is considered the maximum field saturation (Corey 1994, Chiu and Shackelford, 1998). Corey (1994) indicates that $0.80 \le S_m \le 0.92$ for infiltration (wetting processes), which is consistent with the range of S_m values reported by Chiu and Shackelford (1998), i.e., $0.84 \le S_m \le 0.90$. However, the porous medium will eventually become fully saturated by imbibition even in the cases where there is no liquid flowing through the porous material (Bloomsburg and Corey, 1964). Moreover, compacted soils at great depths below the phreatic surface (i.e. subjected to higher pressures) may have the saturation in the occluded zone increased to full saturation. Therefore, it is necessary to define the SWCC data in the occluded zone (i.e., $S \ge S_m$).

The authors (Bicalho, 1999; Bicalho et al., 2002), assuming that the volume of the air-water mixture is compensated by adding water (i. e., there is no variation in the volume of void space), have proposed a theoretical relationship between pore water pressure, u_w, and saturation, S, considering occluded air bubbles. The relationship, derived using the theory proposed by Schuurman (1966), is given by:

$$u_w = u_a - (u_{a0} - u_{w0})\left[\frac{(1-S_0)}{(1-S)}\right]^{1/3}, \quad S \ge S_m \tag{1a}$$

$$u_a = \frac{[1 + S_0(H-1)]u_{a0}}{S(H-1)+1} \tag{1b}$$

u_w and S are the variables in Eq. (1) while u_{w0}, u_{a0} and S_0 are the initial values of water pressure, air pressure and degree of saturation, respectively, and H is the dimensionless coefficient of solubility or Henry's constant (equals 0.02 at 20 ^{0}C). The equations parameters are physically meaningful and can be easily determined (Bicalho, 1999). The initial air pressure is assumed to be the atmospheric pressure. A compacted cohesive soil contains air that may initially be under higher pressure due to the compaction process. However, if the soil is not immediately sealed, the air pressure will soon become atmospheric (Hilf, 1956). Thus, from a practical point of view, only two parameters (u_{w0} and S_0) need to be measured. The value of u_{w0} can be determined by using a tensiometer, details on the experimental procedure and initial results are presented in Bicalho (1999). The value of S_0 can be determined by using the specific gravity of the particles, initial water content and initial dry unit weight. The effect of u_{w0} on Eq.1 is small for the initial degree of saturation range used in the tests (Bicalho, 1999).

This relationship is determined using Boyle's law and Henry's law of solubility, and the Kelvin equation for pressure difference across the interface between the air and water phases. Schuurman (1966) also assumes that all spherical air bubbles are of the same size and the number of air bubbles within the pore space is constant. According to Henry's law the amount of dissolved air only depends on the air pressure in the bubbles. Hilf (1956) concluded that a uniform distribution of dissolved air requires an identical air pressure in all the bubbles. Since the interfacial tension is assumed constant, the equilibrium condition demands that free air bubbles in a uniform fluid have the same radius.

Equation 1 is in terms of absolute pressures. For the fully saturated state (S = 1) the function has a singularity with water pressure tending towards - ∞. This indicates that prior to their disappearance, the bubbles become unstable, collapsing due to the capillary effect. This phenomenon has yet to be explored experimentally. While this effect may be important at the microscopic scale for individual air bubbles, it is unlikely that would have a major effect on the macroscopic behavior of soils. Not all air bubbles would collapse at the same time, so the singularity will be smoothed out. Once the bubbles disappear, the difference between the air pressure and the water pressure no longer exists.

Based on Eq. (1), the P_c – S relationship at higher degrees of saturation on the wetting cycle is given by:

$$P_{c2}(S) = (u_{a0} - u_{w0})\left[\frac{(1-S_0)}{(1-S)}\right]^{1/3}, \quad S \ge S_m \tag{2}$$

where P_{c2} (S) is the relationship between P_c and S considering discontinuous air phase.

It must be emphasized that whereas an increase in the capillary values decreases the saturation values in the existing models for continuous air phase, in the occluded zone the saturation increase is associated with an increase in the pressure difference between pore air and pore water. Therefore, the values of P_c at $S \ge S_m$ can not be replaced simply by decreasing P_c. Considering that the measurement of pore-air pressure in an occluded sample is extremely difficult, Schuurman's theory is an attractive tool for defining the SWCC for quasi-saturated soils. It should also be stated that the predictive models for unsaturated hydraulic conductivity based on drying SWCC are based on the fact that the soil-water characteristic function reflects the pore size distribution of the soil. It is then logical for the function to be used as the basis for predicting the hydraulic conductivity function. However, in the occluded zone the capillary values and pore water pressure values contain no information on the pore sizes or their distribution. The pore water pressure controls only the volume change of the air water mixture and as such should not be used as the basis for predicting the hydraulic conductivity function.

The proposed equations only apply to higher degrees of saturation on the wetting cycle where the air is assumed to be present in the form of bubbles (i.e. $S \ge S_m$). Olson (1963) and Barden and Sides (1970) have shown that the optimum water content marks the change in the condition of the pore fluid (occlusion). The degree of saturation at the optimum water content may be used for defining the value of S_m, without the complete knowledge of the SWCC. Still, there is some doubt about the exact value of S_m and more studies are needed in order to precisely define the state of transition.

Fredlund (1976) recommended not to apply Kelvin's equation to the relationship between the pore-air and pore-water pressures in the occluded zone due to conceptual difficulties of Kelvin's equation (i.e. a slight increase in total stress could cause a progressive process which would reduce the air bubbles to an infinitesimal size while the capillary pressure goes to infinity). It is suggested that the pore-air and pore-water pressures be assumed to be equal in the occluded zone (i.e. disregarding surface tension, Bishop and Eldin, 1950). The effect of the Kelvin's equation on Schuurman's theory is very small (Bicalho, 1999). Of course, because the air-water interface is curved, the air pressure inside the bubble will be larger than that of the surrounding water. Therefore, it is necessary to take into account the surface tension at the interface between air and water. This effect should not be dismissed in a proper description of the behavior of unsaturated soil (Barends, 1980). If the Kelvin's equation is omitted from the model, and the air and water pressures are assumed to be equal, the suction at the moment of occlusion cannot be properly taken into consideration.

3 LABORATORY TESTING

3.1 *Equipment description*

The measurements were accomplished by using a modified triaxial cell connected to a flow pump. The system includes pore-water back pressure facilities, a differential pressure transducer, a differential mercury manometer and a data acquisition system.

Details on the experimental apparatus are presented in Bicalho (1999).

The standard triaxial cell was designed to accept a high air entry value porous stone at the bottom platen of the triaxial cell below the soil specimen. The fine porous stone is slight larger than the bottom platen and the soil specimen. The bigger diameter of the fine porous stone provides a perfect seal even without being permanently glued to the base. The confining cell pressure assures an intimate contact between the latex rubber membrane and the porous stone. The coarse porous stone is installed between the soil specimen and the top platen of the triaxial cell in order to prevent migration of soil particles into the back pressure chamber.

The flow pump enables a precise control of water flow in and out of the soil sample. The flow pump forces water through the soil sample at a constant predetermined rate and creates a pressure difference across the sample that is continuously recorded with a precision differential pressure transducer connected to a PC-based data acquisition system. The flow pump consists of two major components: a driving mechanism system and stainless steel syringe. The driving mechanism system is the model 901 Single Syringe Infusion-Withdrawal Pump manufactured by Harvard Apparatus Company. The speed of the flow pump can be selected depending on the test being performed. The flow pump can be operated in the infusion mode for measuring the SWCC data on wetting condition and a withdrawal model for measuring the SWCC data on drying condition.

The differential pressure transducer, model DP-15, is manufactured by Validyne Engineering Corporation. A membrane that is installed in the transducer can be changed in order to change the measurement range so that the transducer precision can be adjusted for the expected pressure range in the test. The transducer is connected to a data acquisition system and a personal computer. The transducer is connected to the bottom of the sample and to the top of the sample in order to measure the pressure difference across the sample.

3.2 *Test procedure*

A simple testing technique for rapid measurement of the continuous SWCC data has been developed at University of Colorado at Boulder. This technique has been used successfully on several soils (Znidarcic at al., 1991; Bicalho,1999; Hwang, 2002). The technique is able to obtain SWCC data using one test specimen, and is faster than almost all of the conventional methods. Control and data acquisition with a computer allow automation of the test procedure with minimal operator interference. Furthermore, it obtains continuous SWCC data, which is beyond the capabilities of almost all traditional techniques.

The experimental procedure proposed by Znidarcic et al. (1991) was used to obtain the SWCC involving continuous air phase. Once water appeared at the top of the sample in the wetting cycle, an impervious top boundary was created in order to measure the wetting SWCC involving discontinuous air phase. The pore-water pressures versus saturation (or volumetric water content) were obtained from the pressure-time data recorded. The assumption is made that the degree of saturation is uniform within the sample for the total duration of the experiment. This is a reasonable assumption since small samples were used (diameter = 71 mm and thickness ≤ 30 mm) and a very low Darcian water velocity was applied in the tests ($V_w = 3.3 \times 10^{-8}$ m/s). The validity of this assumption was further verified by numerical analysis in Bicalho (1999). It is noted that the selected flow rate determines how appropriate are the stated assumptions in the data interpretation. Znidarcic et al. (2002) show that performing the tests at a higher rate allows us to obtain both the SWCC data and permeability relationships from a single test in an inverse problem solution approach.

At the end of the tests, the total mass, the dry mass, the height and the diameter of the samples were measured, and negligible changes in the total volume of the tested samples were observed. There is a need for improved the testing equipment when measuring the SWCC data for high volume change soils.

4 EXPERIMENTAL RESULTS

Figure 1 presents the results of four pore water pressure-saturation tests conducted on 4 compacted samples (B_1, B_2, B_3 and B_4) of Bonny Silt with the porosity ranging from 36 % to 40 %. This silt is from a sedimentary formation at the Bonny Dam Site, in eastern Colorado. The liquid limit of the soil is 25%, the plastic limit is 21%, clay fraction 12%, Casagrande classification CL-ML, specific gravity 2.63, Proctor optimum water content 14.5% and the corresponding dry density 17.5 kN/m^3. The Bonny Silt was chosen because it combines the hydraulic conductivity of a clay with moderate suction values that allow better control during testing. The samples were compacted at their molding water content in a two-part split metal mold using a static compaction press, with S_0 ranging from 63 % to 79 %.

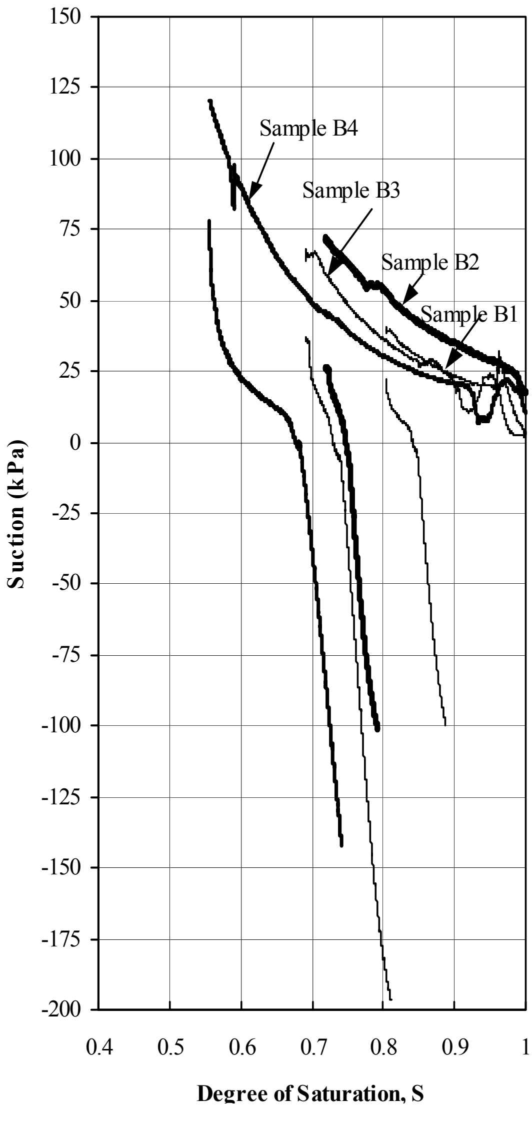

Figure 1. Soil-water characteristics curves (Bonny Silt) (Drying and wetting curves)

The experiments conducted indicate that silt has an air entry value of about 20 kPa and the value of S_m is around 70 % for the soil investigated. The term suction is used to indicate the negative pressure of water relative to atmospheric air pressure, i.e. - (u_w - u_{atm}). The drying curves show some differences that might be caused by different soil structure in different samples.

It is clear that different molding water contents could result in different soil structures. Topp and Miller (1966) and Vachaud and Thony (1971) have shown that a series of non-fully developed SWCC data may develop within the range of hysteresis, depending on the initial saturation at which soil begins to become wet or to dry. Therefore, different initial degrees of saturation resulted in different wetting curves during the infiltration sequence. As shown in Fig. 1, the wetting curves have similar slopes at higher degrees of saturation (positive water pressures). There is a discontinuity in the slope for the gauge pressure close to zero in the wetting curve. This might be partially caused by the change of the top boundary condition at this stage to an impervious boundary condition. The sample might also be in a transitional stage between the continuous air channels and the discontinuous air phase that is difficult to determine precisely.

The measured data of the pore-water pressure relative to atmospheric air pressure (gauge pressure) at $S \geq S_m$ on the wetting curve are used for verifying Eq. (1). The results of the experimental investigation indicated that the theory is in reasonable agreement with experiment for the soil tested as presented in Fig. 2. This provides encouraging evidence of the validity of the theoretical relationship between air and water pressures considering a porous medium containing occluded air bubbles proposed by Schuurman (1966). Moreover, Bicalho et al. (2003) show that the hydraulic constitutive functions derived from the occluded theory proposed by Schuurman (1966) are capable of producing simulations of the measurements of the unsaturated flow that are both qualitatively and quantitatively realistic.

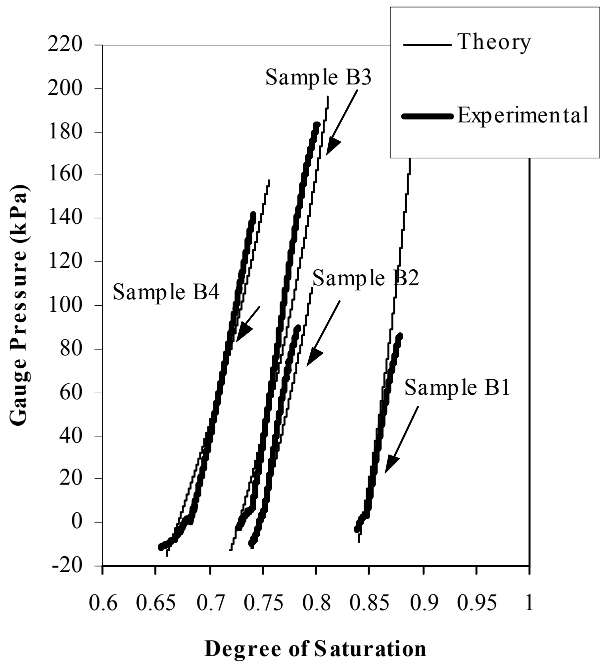

Figure 2. Water pressure measured and predicted from theory (Bonny Silt)

5 CONCLUSIONS

A simple testing technique is described in the paper to provide reliable data of the SWCC involving continuous and discontinuous air phase. The measurements were accomplished by using a modified triaxial cell connected to a flow pump. Only one test is required to describe drying and wetting cycles of the SWCC data for a particular soil. It obtains continuous SWCC data, which is beyond the capabilities of almost all traditional techniques. Control and data acquisition with a computer allow automation of the test procedure with minimal operator interference. Data from the test results provide encouraging evidence of the validity of the occluded state theory proposed by Schuurman (1966). The testing technique proposed is based on the assumption that the overall volume of the soil remains constant. It is recommended to investigate the effect of void ratio changes on the SWCC data for quasi-saturated soils. We leave it for future work.

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REFERENCES

Barden, L. & Sides, G. R. 1970, Engineering behavior and structure of compacted clay. *Journal of Soil Mechanics and Foundation Engineering,* ASCE, 96 (7), 1171-1200.

Barends, F. B. J. 1980. Nonlinearity in groundwater flow." Ph. D. Dissertation, Delft, Holland.

Bloomsburg, G.L., & Corey A. T. 1964. Diffusion of entrapped air from porous media. Colorado State University, *Hydrology papers*, No. 5, 1-27.

Bicalho, K. V. 1999. Modeling water flow in an unsaturated compacted soil. Ph.D. dissertation, University of Colorado, Boulder, Co, USA.

Bicalho, K. V., Znidarcic D. & Ko H.-Y. 2000. Air Entrapment Effects on Hydraulic Properties. ASCE, *Geotechnical Special Publication*, 99, 517-528.

Bicalho, K V., Znidarcic D. & Ko, H.-Y. 2002. Soil-Water Characteristic Curve of a Quasi-saturated Compacted Soil. *Unsaturated Soils*, Jucá, de Campos & Marinho (eds), Sweets & Zeitlinger, Lisse, 1, 277-281.

Bicalho, K V., Znidarcic D. & Ko, H.-Y. 2003. Influence of air entrapment on the unsaturated hydraulic conductivity functions. *12 Panamerican Conf. on Soil Mech. and Geotech. Engrg*, Culligan, Einstein & Whittle (eds), Cambridge, Ma, USA, 2, 1597-1602.

Bishop, A.W. & Eldin, A. K. G. 1950. Undrained triaxial tests on saturated sands and their significance in the general theory of shear strength. *Geotechnique*, 2, 13-32.

Chiu, T.-F. & Shackelford, C. D. 1998. Unsaturated hydraulic conductivity of compacted Sand-Kaolin mixtures. *J. Geotech. Engrg, ASCE*, 124(2), 160-170.

Corey, A.T. 1994. *Mechanics of immiscible fluids in porous media*. 3rd Ed., Water Resources Publications, Highlands Ranch, Co.

Faybishenko, B. A. 1995. Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: laboratory experiments. *Water Resources Research*, 31(10), 2421-2435.

Fredlund D. G. 1976. Density and compressibility characteristics of air-water mixtures. *Can. Geotech. J.*, 13, 386-396.

Hilf, J. W. 1956. An investigation of pore-water pressure in compacted cohesive soils. Ph.D. dissertation, University of Colorado, Boulder, Co, USA.

Hwang, C. 2002. Determination of materials functions for unsaturated flow. Ph.D. dissertation, University of Colorado, Boulder, Co,USA.

Olson, R E 1963. Effective stress theory of soil compaction, ASCE, 89 (SM2), Proc Paper 3457, 27-47.

Schuurman, E. 1966. The compressibility of an air/water mixture. *Geotechnique*, 16 (4), 269-281.

Shahu, J.T., Yudhbir, & Kameswara Rao N. S. V. 1999. Effective stress behavior of quasi-saturated compacted cohesive soils. *J. Geotech. Engrg, ASCE*, 125(4), 322-329.

Topp, G. C. & Miller, E.E. 1966. Hysteretic moisture characteristics and hydraulic conductivities for glass beads media. *Soil Sci. Soc. Amer. Proc.*, 30, 156-162.

Vachaud, G. & Thony, J. 1971. Hysteresis during infiltration and redistribution in a soil columm at different initial water contents. *Water Resources Research*, 1(1), 111-127.

Zapata C. E, Houston W. N., Houston S. L. & Wash K. D. 2000. Soil-Water Characteristic Curve Variability. ASCE, *Geotechnical Special Publication, 99,* 84-124.

Znidarcic D., Illangasekare T. & Manna M. 1991. Laboratory testing and parameter estimation for two-phase flow problems. *ASCE, Geotechnical Special Publication, 27*, 1089-1099.

Znidarcic D., Hwang C. & Bicalho K V. 2002. Experimental determination of hydraulic characteristics for unsaturated soils. *Unsaturated Soils,* Jucá, de Campos & Marinho (eds), Sweets & Zeitlinger, Lisse, 3, 1137-1141.