Determination of soil-water retention curve for a young residual soil using a small centrifuge

Détermination de la courbe de rétention d’eau pour un sol résiduel jeune à l’aide d´une petite centrifugeuse

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ABSTRACT: The soil-water retention curve (SWRC) determination usually involves time-consuming conventional methodologies such as those based on soil-water plate extractors, tempe cells, suction plates and filter-paper method. In order to overcome the considerable large time lag necessary for SWRC evaluation, an alternative methodology for direct determination of the SWRC of the unsaturated soil was developed using a commercially available small centrifuge with a swinging type rotor assembly without in-flight instrumentation. The testing consists of spinning up four initially saturated soil specimens until constant water content is achieved for a given angular speed. The soil-suction relationship is determined by relating the respective water content to the suction magnitude induced by the ceramic plate at the specimen´s base. This methodology was applied for evaluating the SWRC of a young residual soil from gneiss using both, undisturbed and remolded soil specimens until 900 kPa matric suction magnitude. The testing results show good agreement to the similar SWRC obtained by conventional methods and depicted using the Van Genuchten (1980) mathematical model. Overall, it can be concluded that the methodology proposed ensures good agreement in determining the SWRC of studied soil.

RÉSUMÉ : Généralement on utilise, pour la détermination de la courbe de rétention du sol (SWRC), des méthodes classiques assez fastidieuses telles que celles basées sur des extracteurs de plaques sol-eau, des cellules Tempe, des plaques d'aspiration et du papier-filtre. Pour surmonter ces difficultés et réduire le temps nécessaire pour l'évaluation de la courbe de retention (SWRC), une autre méthodologie a été développée pour la détermination directe du SWRC de sol non saturé en utilisant une petite centrifugeuse disponible sur le marché, avec un assemblage de rotor de type oscillant sans instrumentation couplée. Le test consiste à faire tourner quatre échantillons de sol initialement saturés jusqu'à ce qu´une teneur en eau constante soit obtenue pour une vitesse angulaire donnée. La relation sol-aspiration est déterminée en fonction de la teneur en eau relative à la magnitude d'aspiration induite par la plaque de céramique à la base de l'éprouvette. Cette méthode a été appliquée pour évaluer le SWRC d'un sol résiduel jeune de gneiss en utilisant des échantillons de sol à la fois, non perturbés et reconstitués jusqu'à une magnitude d´aspiration matricielle de 900 kPa. Les résultats des essais sont pareils à ceux obtenus, pour la SWRC, par les méthodes conventionnelles et en utilisant le modèle mathématique de Genuchten Van (1980). Dans l'ensemble, on peut conclure que la méthode proposée montre une bonne concordance dans la détermination du SWRC du sol étudié.

KEYWORDS: unsaturated soil, soil-water retention curve, centrifuge technique, soil suction.

1 INTRODUCTION

The application of a centrifuge for inducing an unsaturated state within a soil sample is not new. Soil drainage tests using centrifugal flow have long been recognized as a valid and efficient way of determining the SWRC. Briggs and McLane (1907) and Russell and Richards (1938) have proposed methodologies for estimating the SWRC using a centrifuge. The proposed methodologies essentially consist in draining an initially saturated soil specimen under a certain induced gravity. Different lower values of water contents can be rapidly achieved by increasing the applied induced gravity. The decrease in soil moisture is then related to the corresponding increase in the soil suction magnitude. Gardner (1937), interested in evaluating the effect of the induced gravity over the matric potential of the soil, carried out several sets of filter paper tests within a centrifuge apparatus, with soil specimens placed over a free water surface. The matric potential of the soil was evaluated after achieving hydraulic equilibrium and related to the induced gravity applied. The work of Gardner (1937) showed clearly that a relationship exists between the soil matric potential and the induced gravity applied to the soil sample. Other researchers (e.g. Hassler and Brunner, 1945; Croney et al., 1952) have attempted inducing suction magnitudes at the soil specimen´s boundaries through use of ceramic disks or cylinders. Corey (1977), working with soil samples allowed to free drainage due to centrifugal flow, observed that the negative pressure gradient induced within the soil sample acts inward, once the centrifugal force induces water flow on the outward direction. Corey (1977) noted that the capillary pressure induced within the soil sample varies along the length of the sample, from zero magnitude at the outflow boundary (which is open to the atmosphere), to a maximum value at the top boundary of the sample. The author concluded that at each angular velocity, the sample drains until the capillary force equals the centrifugal force induced over the water molecules. Recently, Khanzode et al. (2002) attempted to determine the SWRC at a single induced gravity by simultaneously testing several soil specimens with different ceramic disks attached. The main idea was inducing different magnitudes of suction at each specimen simultaneously. The results, however, exhibit a pore matching when compared to the results obtained by using a pressure plate apparatus. Although the authors suggest the need of complementary studies for understanding the influence of the induced gravity over the soil´s suction, a careful analysis of the methodology applied by Khanzode et al. (2002) indicates that it was not ensured that the specimens tested in the centrifuge had identical initial densities and water contents as those tested in the pressure plate apparatus. These differences can lead to significantly different SWRC results as compared to the ones obtained with others methodologies**.**

Seeking the development of an accurate low cost alternative for direct evaluation of the SWRC and also in order to overcome the considerable large time lag necessary for SWRC evaluation by conventional methodologies, an alternative methodology is proposed in this manuscript for SWRC evaluation that uses a commercially available small centrifuge, without the need of in-flight instrumentation. Since there is no external invasive instrumentation (such as TDR probes, tensiometers, etc), the methodology allows evaluating the SWRC of undisturbed soils samples**.**

The methodology proposed was applied in determining the SWRC of a young residual soil using both, undisturbed and remolded soil specimens. The SWRC testing results show good agreement to the similar data obtained using filter-paper method, porous plate funnel and suction plate extractor.

2 TESTING SETUP AND THEORETICAL BACKGROUND

A schematic drawing of the testing setup developed is depicted in Figure 1.

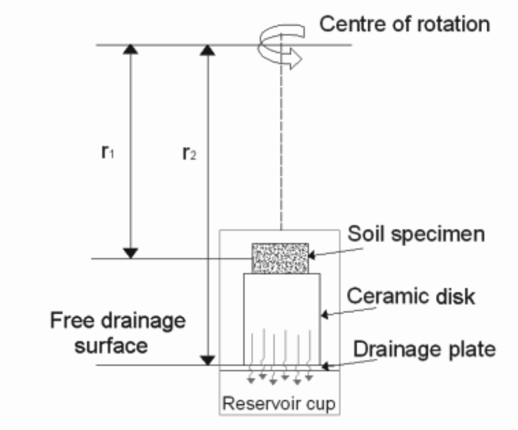

Figure 1. A schematic drawing of the centrifuge basic principle

Basically, the setup is composed by a water reservoir located underneath a drainage plate and a high flow ceramic disk fitted above this drainage plate. A 20 mm thick soil specimen, fitted into a stiff stainless steel cylinder, used to avoid any horizontal strains during testing, is placed above the ceramic disk. A saturated filter paper is placed between the soil specimen and the ceramic disk in order to prevent soil particles from migrating into the ceramic disk during testing. The entire setup is assembled into small centrifuge equipment specially modified for receiving four testing setups simultaneously. The drainage plate induces a free drainage surface at the bottom boundary of the ceramic disk in order that all water flow coming from the soil specimen is fully transmitted to the collection reservoir located underneath. The high flow ceramic disk has two important roles. First, it works by positioning the soil specimen at a given distance from the centrifuge axis of rotation. Second, it acts as a dripping surface at the specimen´s bottom boundary in order that the water outflow rate will be dictated by the saturated hydraulic conductivity of the soil specimen and by the induced gravity applied. High flow ceramic disks with 12 mm and 63 mm thick were specially manufactured using specific mixes of kaolin and water. The porosity of the ceramic disks after be placed in the oven was approximately 48% and the saturated hydraulic conductivity of the order of 10^{-4} cm/s. The suction at any point within the soil specimen is then evaluated using Eq. [1] proposed by Corey (1977). Mathematically, the suction is given by:

$$(= ((\rho\omega^{\uparrow}2)/(2g))(r_{\downarrow}2^{\uparrow}2) - r_{\downarrow}1^{\uparrow}2) \qquad (1)$$

where ψ is the suction magnitude within the soil specimen at a given distance r_1 measured from the center of rotation, r_2 is the distance from the center of rotation to the dripping surface, ρ is the fluid density, ω is the angular velocity (in radians per second) and g is the earth´s gravity. For suction estimate purpose, r_1 is set as the distance from the center of rotation to the middle height of the soil specimen. This distance can be changed by changing the ceramic disk thickness located underneath. The Eq. (1) defines a nonlinear relationship between the soil suction and the centripetal radius. The distance from the center of rotation to the dripping surface (r_2) is kept constant during testing. Analyzing Eq. (1) it can be noted that any change in the radial distance r_1 will give a different magnitude of suction within the soil specimen. Therefore, using ceramic disks with different thicknesses will induce different suction magnitudes applied to the soil specimen´s bottom boundary at a certain speed of rotation. The magnitude of the suction applied can also be increased simply by increasing the centrifuge angular velocity. Several centrifuge tests were carried out to verify the validity of Eq. [1] on estimating accurately the suction magnitude within the soil specimen. Basically, the procedure adopted consisted in comparing the soil moisture value reached after spinning and the correspondent suction magnitude estimated using Eq. [1] to the experimental data of the SWRC determined using conventional methods. In all tests carried out, Eq. [1] presented good agreement to the experimental data obtained by conventional methods. Table 1 summarizes the soil suction magnitudes at the center that a 20 mm thick soil specimen will be submitted under several angular speeds using the two different high flow ceramic disks. The testing procedure consists in assembling two soil specimens over two 63 mm thick ceramic disks and other two specimens over two 12 mm thick ceramic disks. Once the centrifuge equipment was modified to fit four soil specimens simultaneously, the identical ceramic disks thicknesses setups are displaced on swinging buckets located on opposite sides of the centrifuge center of rotation. This procedure allows submitting two sets of two soil specimens to different values of soil suction simultaneously at a given angular velocity.

Table 1. Suction magnitudes attained to different ceramic disks and angular velocity, ω.

ω (rpm)	*Suction* (kPa) (Corey 1977)	
	ceramic disks 12 mm	**ceramic disks 63 mm**
	central region	central region
300	2.8	9.3
500	7.9	25.9
1000	31.3	103.7
1500	70.4	233.3
2000	125.2	414.7
2500	195.7	647.9
3000	281,8	932,71

3 EXPERIMENTAL COMPONENT

The testing program was carried at the Civil Engineering Laboratory (LECIV) of the State University of Norte Fluminense Darcy Ribeiro (UENF). The centrifuge equipment used was a Cientec CT 6000 small-scale centrifuge specially adapted with four swinging buckets. The testing program consisted in evaluating the SWRC of a young residual soil from gneiss using both, undisturbed and remolded soil specimens. The soil is classified as clayey silt sand. The undisturbed soil specimens sets, identified herein as undisturbed young horizon (UY), were sampled with a 50mm diameter 20 mm height rings. The remolded samples sets, identified as remolded young horizon (RY), were obtained by handling undisturbed soil samples and re-compacting them statically in order to achieve same dry unit weight in all specimens of each set. This procedure was adopted in order to minimize potential heterogeneities usually present in undisturbed specimens allowing a better comparison among conventional methods and the alternative methodology using centrifuge. Table 2 presents some typical characteristics and index properties of the soils samples tested. As shown in Table 2, the void ratio of remolded specimens is greater than undisturbed specimens. This is justified in seeking to verify possible deformations in softer soils induced by high acceleration levels. Therefore, the mass of soil, at a specific remolding water content, for a known volume for each soil specimen was calculated. The mass of soil was placed in layers and a tiny compactor was used just to assent them until the complete volume was achieved.

Table 2 – Characteristics and index properties

	Sand (%)	Silt (%)	Clay (%)	LL (%)	LP (%)	IP (%)	W (%)	γ kN/m³	γs kN/m³	γd kN/m³	e	n (%)	Sr (%)	ASTM (2003)
RY	55.0	36.0	7.0	50.2	24.6	25.6	19.3	16.6	26.7	13.9	0.9	47.8	56.3	SC
UY	55.0	36.0	7.0	50.2	24.6	25.6	12.0	17.1	26.7	15.3	0.8	42.7	42.8	SC

Previously to the centrifuge testing, all soil specimens and all ceramic disks were soaked with distilled - deaired water. The soil specimens wetting procedure adopted consisted in gradually spraying the soil specimens with water until reaching a soaked state, characterized by a thin water layer formed above the top boundary of the specimen. The water content reached at the end of the soaking procedure was assumed to be correspondent to the saturation condition of each specimen. The ceramic disks saturation procedure consisted in submerging them during 48 hours into a recipient filled with distilled water and by spinning them up to 500 rpm in the centrifuge in order to flush air bubbles within them. Thereafter, two setups with 12 mm thick ceramic disks and two setups with 63mm ceramic disks were assembled as shown in Figure 2. Subsequently, the four testing setups were placed into the centrifuge buckets in a symmetric testing configuration with respect to the centrifuge axis of rotation in order to avoid in-flight unbalancing.

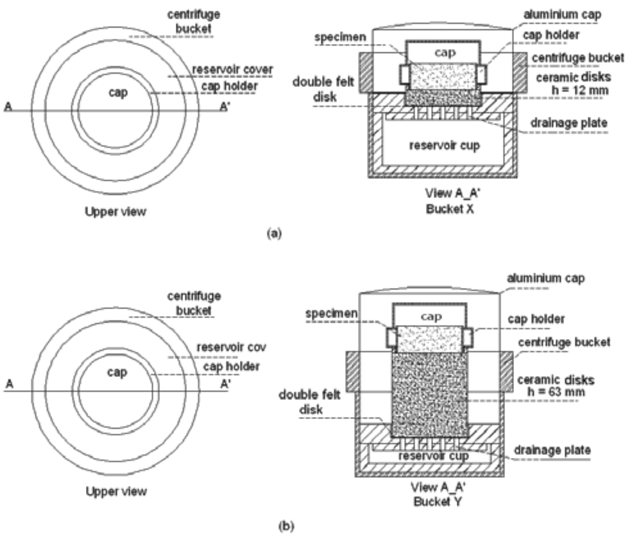

Figure 2. Setups Details (a) “Bucket X” (12 mm thick ceramic disks); (b) “Bucket Y” (63mm thick ceramic disks).

Figure 3 presents the general view of the centrifuge arrangement before starting the test. The soil specimens´ top boundary is protected with a PVC cap in order to prevent evaporation during testing. This cap is fitted over a stiff aluminum cap fixed in the centrifuge bucket (Figure 2). Subsequently, the soil specimens are subjected to angular velocities up to 3000 rpm. The tests were performed with initially soaked soil specimens displaced over an initially soaked high flow ceramic disk and submitted to successive increased gravities inducing successive unsaturated states without any external interference (even stopping the centrifuge).

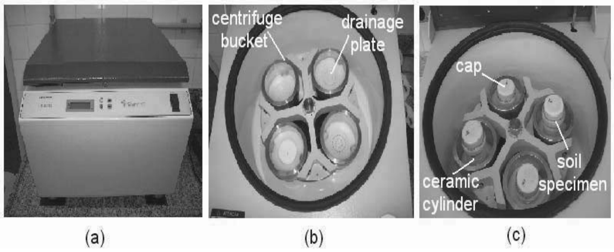

Figure 3. Views of Cientec CT 6000 small-scale centrifuge: (a) external view; (b), (c) internal view.

The methodology allows determining simultaneously two pairs of soil moisture – suction relationships at each induced gravity applied. Applying angular velocities of 300, 500, 1000, 1500, 2000, 2500 and 3000 rpm allows determining experimentally 14 soil moisture – suction relationships. The proposed setup configuration allows evaluating the data repeatability once the specimens with same ceramic disk thickness are subject to similar suction magnitudes and, therefore, they should have similar moisture changes in a specific testing step (denoted by similar changes in specimens´ weight). Due to the absence of in-flight instrumentation, the no-flow steady-state moisture profile condition was checked by stopping the centrifuge equipment and checking any change in each specimen´s weight. The equilibrium condition is yielded when a constant specimens´ weight is achieved. After reaching the no-flow steady-state moisture profile condition at the 3000 rpm run, all soil specimens were oven dried for final water content determination. The water content magnitudes of each intermediary testing step were then back calculated and the respective SWRC plotted.

In order to evaluate any potential effect of consolidation during centrifugal flow, it was evaluated the soil specimen´s height at each centrifuge monitoring stops. It was not observed any volume change for angular velocities lower than 1500 rpm. For angular velocities higher than 1500 rpm, it was observed changes in the specimen´s height of 0.8 mm, 0.4 mm for RY, UY, respectively. These height changes correspond to 4 %, 2 % of volume changes respectively. Once the volume changes observed were small, the corresponding volumetric water contents were evaluated considering the initial soil unit weight even for angular velocities higher than 1500 rpm. The corresponding suction magnitudes of the tests that underwent volume changes were evaluated considering the actual radius magnitude calculated at each testing step.

4 RESULTS AND DISCUSSION

Figures 4 and 5 present the comparison among the SWRC obtained by conventional methods and depicted using the van Genuchten (1980) mathematical model, and the experimental data obtained following the methodology proposed herein. Figure 4 shows the RY testing results while Figure 5 shows the UY testing results.

Analyzing the results in Figures 4 and 5 it can be observed that the experimental data obtained through the proposed methodology agrees with the experimental data obtained by conventional methods such as filter paper method, plate extractor and suction funnel. Concerning the SWRC mathematical description, it can be noted in Figures 4 and 5 that the van Genuchten (1980) model describes accurately the soil´s suction – moisture relationship observed experimentally.

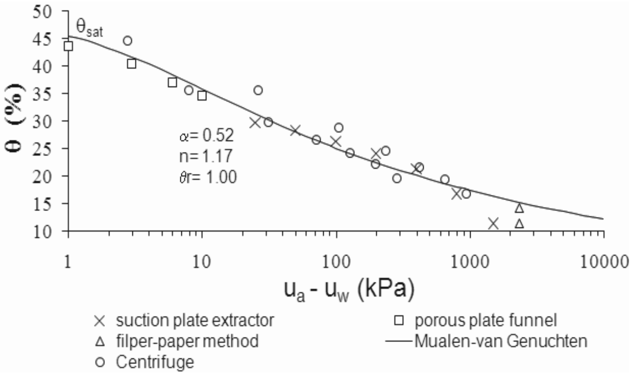

FIG 4. Comparison between SWRC from conventional methods fitted by the Mualem-van Genuchten model and the small-scale centrifuge method data for remolded young horizon (RY).

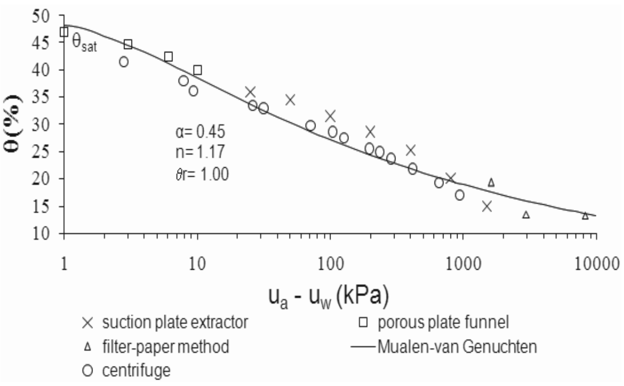

FIG 5 - Comparison between SWRC from conventional methods fitted by the Mualem-van Genuchten model and the small-scale centrifuge method data for undisturbed young horizon (UY).

5 CONCLUSIONS

From the research program involving evaluation of the SWRC of undisturbed and remolded specimens of a young residual soil from gneiss conducted it can be concluded that:

- The SWRC determined using the proposed methodology agreed well with the experimental data obtained using conventional methods such as paper filter method, suction plate extractor and porous plate funnel indicating the excellent potential use of the methodology for SWRC determination for studied soils in a reduced time-frame.
- The centrifuge methodology was able of determining the SWRC with good accuracy up to suction magnitudes of the order of 900 kPa.

6 ACKNOWLEDGMENTS

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