Hysteresis phenomenon of a tropical soil profile observed by means of soil water characteristic curves obtained in laboratory and field

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ABSTRACT
This research presents the soil-water characteristic curves (SWCC) for a tropical soil profile from the region of Campinas, Brazil. This profile consists of colluvial, lateritic and collapsible silty clay about 6.5m thick. From this profile, soil samples were collected and submitted to geotechnical characterization and mineralogical tests. From the soil samples, specimens were made and used to determine the SWCC using the filter paper method with wetting and drying paths. In the field, matric suction was obtained by conventional tensiometers, installed in the soil profile during the period of one year. Impregnated thin-layer plates were prepared with undisturbed samples, to obtain their structures along the profile. The SWCCs were bimodal, typical of tropical soils with macro and micro-aggregated structures. The SWCCs obtained by wetting and drying evidenced the hysteresis phenomenon. In the field, several wetting and drying paths were obtained.

RÉSUMÉ
Cette recherche présente les courbes caractéristiques sol-eau (CCSE) pour le profil d'un sol tropical de la région de Campinas, Brésil. Ce profil se compose de l'argile silteuse, colluvial and ferralitique. De ce profil, les échantillons de sol ont été rassemblés et soumis à une caractérisation géotechnique et à des essais minéralogiques. Des spécimens ont été faits avec ces échantillons de sol et utilisés pour déterminer la CCSE par la méthode du papier filtre avec chemins de drainage et d'imbibition. Sur le terrain, la succion matricielle a été obtenue par des tensiomètres conventionnels. Des lames minces impregnées ont été preparées avec des échantillons non-remaniés pour obtenir leurs structures le long du profil. Les CCSEs ont été bimodales, typiques des sols tropicaux avec des structures macro et micro-agrégées. Les CCSEs obtenues par imbibition et drainage ont montré le phénomène d'hystérésis. Sur le terrain, plusieurs chemins de drainage et d'imbibition ont été obtenus.

1 INTRODUCTION

1.1 Lateritic Soils

Lateritic soils are tropical soils with certain peculiarities that make them present physical, mechanical and hydraulic behaviors that differ from the Classical Soil Mechanics models.

The formation of lateritic soils occurs through the pedological alteration processes that act later or together with the mechanisms of disaggregation and decay caused by physical and chemical weathering, with a more intense chemical action.

The pedological alteration process that contributes most significantly to lateritic soil formation is leaching, which is the intense migration of particles under the action of infiltration and evaporation, resulting in a layer of porous soil (high permeability), consisting of more stable minerals (quartz, kaolinite and magnetite) and a low degree of saturation. Since this process is very slow, it occurs in the well-drained superficial layers, located above the water level, therefore, not saturated. (Committee on Tropical Soils of ISSMFE, 1985; Gidigasu, 1976).

1.2 Soil-Water Characteristic Curves

The mechanics of unsaturated soils have a significant stress state variable in order to understand the behavior of the shearing, compressibility and permeability of these soils. This variable is called suction and can be matric or total. First, in order to evaluate changes in the suction of a stress state in an unsaturated soil, it is necessary to determine the soil-water characteristic curve (SWCC). This curve is a graphical representation of the suction (matric or total) and the quantity of water that can be represented by the gravimetric moisture content (w), volumetric moisture content (θ) or the degree of saturation (S_r).

1.3 Hysteresis Phenomenon

SWCC describes a different pathway in terms of soil drying or wetting. Because of this, the curves obtained by the drying or wetting paths do not coincide, giving rise to a phenomenon called curve hysteresis and which is a characteristic of soil suction (Bonder, 2008).

Hysteresis caused by drying and wetting paths can be attributed to non-uniformity of the voids, to the air bubbles captured by the voids of the soil during the wetting and structure alteration due to the expansion or contraction of the soil (Calle, 2000).

According to Rojas (2002), the real value of suction depends not only on the degree of saturation, but also on the initial state of the soil and the whole history of drying and wetting until that moment.

1.4 Methods of Measurements of Suction

There are several methods to determine soil suction, both in the field, as well as in the laboratory. According to Soto (2004), suction measurements in the laboratory and in the field, come up against a number of experimental problems and usually must resort to different methods in order to know if the suction, within a wide range, is sufficient for practical use.

1.5 Filter Paper Method

The filter paper method has been widely used to obtain SWCC as it is easy to use, inexpensive and covers a relatively large suction range. The disadvantage of the filter paper method is the need for extreme caution in its implementation. The advantage of this method is that the paper filter is adapted to the value of the soil suction, instead of the soil adjusting to the applied suction value.

The test consists of placing a filter paper with its known retention characteristics in a hermetic environment along with a soil sample. Due to the contact of the paper with the soil, which is able to retain moisture content, there is water migration until potential equilibrium is reached, thus obtaining matric suction (Gardner, 1937). If water in the soil is not in direct contact with the filter paper, total suction can be obtained after the potential equilibrium.

This equilibrium time is being studied by several authors. Feuerharmel et al. (2006) suggests a seven day equilibrium time for suction values above 10,000 kPa and four days for values lower than 10,000 kPa. Marinho (1997) argues that equilibrium time is related to the type and level of suction. This author suggests a seven day period when measuring matric suction, regardless of the level of suction. According to ASTM D 5298-03 (2004), the minimum equilibrium time between the filter paper and the soil is seven days. Equilibrium time is a very important factor to obtain the correct suction value.

The procedure of this method is quite simple; however, it requires great care in determining the filter paper moisture content. According to Chandler and Gutierrez (1986), filter paper weighing time should be approximately 30 seconds to prevent gains or losses of moisture to the atmosphere. According to Marinho (1994), the filter paper transfer time for a closed capsule or a zip lock plastic bag must be 5 seconds at most.

1.6 Tensiometers

The tensiometers are largely used in the agriculture where the maximum suction of interest is usually 1atm, with a few exceptions. The limiting of the maximum suction value that can be measured with a tensiometer is due to the occurring of a phenomenom called cavitation. Cavitation in the tensiometers is not a water exclusive phenomenon. The water itself can withstand the traction efforts of hundreds of megapascal (Marinho, 1997).

The presence of air in the system causes the instrument to give a slow response in relation to changes in soil water pressure. This fact happens because of the expansion and contraction of the air with the change of pressure (Cassel and Klute, 1986).

The porous element of the tensiometer is usually from a ceramic material (porous stone). This element is in the interface between the soil and the water of the measuring system. The porous stone keeps the hydraulic conductivity between the soil and the measuring system.

The water pressure of the tensiometer, introduced for the soil suction, can be measured by appropriated sensors. According to Stannard (1992), the vacuum gauges indicate suction between zero and 1atm. They are positioned a little below the end of the tensiometer pipe. The space above is reserved for the air inlet (Figure 1).

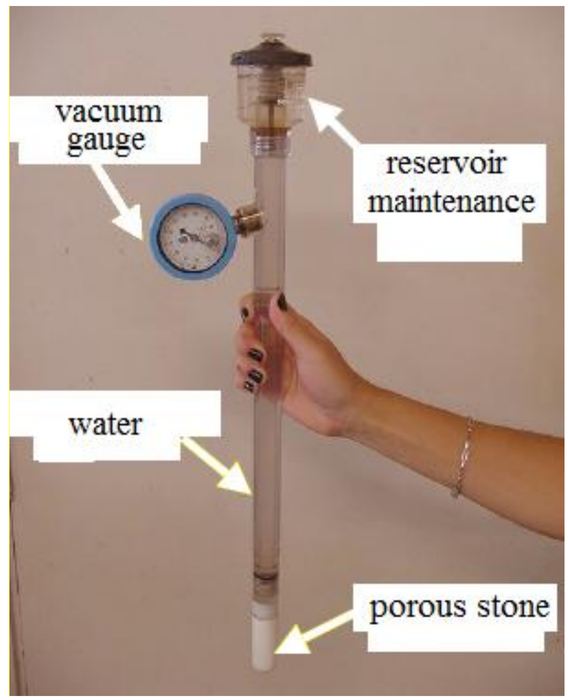

Figure 1 – Tensiometer with gauge vacuum

According to Vieira (1999), the elimination of the cavitation nucleos demands a special technique that the majority of the commercial tensiometers cannot withstand. To minimize the problem, distilled and de-aired water is used, when the tensiometer saturation is done.

Some procedures must be performed with care during the tensiometer saturation and calibration, according to Marinho (1997).

The saturation of the porous element can be done by simple immersion, when the porous stone used has capacity of the up to 100kPa of air-entry. However, caution must be taken due to the possibility of air bubbles forming on the walls of the pipe.

The contact of the porous stone with the soil must be such that it allows an optimum interaction with the interstitial water. For that, the installation of the porous stone must be done by immersing it in the mud (same soil where the tensiometer will be installed).

On the readings performed in the manometers, it must be taken into consideration that the water column is presented by the distance between the porous stone and the reading system. The equation [1] shows how the correction is done in relation to the length of the tensiometer.

$$\psi(kPa) = readings(kPa) - (h_c \times \gamma_w) \quad [1]$$

Where: ψ = matric suction
h_c = height of the water column (m)
γ_w = specific weight of the water (kN/m^3)

Some advantages of the conventional tensiometers are:

a) Direct readings
b) Continuous readings are allowed when associated with pressure transducers
c) Low cost
d) Field use

Some disadvantages are:

a) Limited use to suctions up to 100kPa
b) Need of appropriate contact between the water inside of the tensiometer and the water from the soil (if soil volume varies, the contact with the soil can be lost)
c) Need of permanent maintenance due to air diffusion to the inside of the tensiometer

The aim of this study was to determine SWCCs from a lateritic and colluvial surface layer soil up to a 2.5m depth, by filter paper method in the laboratory and by conventional tensiometers, installed in the soil profile during the period of one year. These curves were analyzed in terms of the chemical-mineralogical structure and composition, considering their formation processes by interpreting the thin and impregnated plates in order to better understand the behavior of unsaturated tropical soil.

2 MATERIALS AND METHODS

2.1 Soil Characterization

This study was carried out with soil from the Experimental Field Soil Mechanics and Foundations (EFSMF), the State University of Campinas. EFSMF is a geological-geotechnical profile which is typical of 14% of the region of Campinas, located in the central-east portion of the state of Sao Paulo in Brazil.

The subsoil is made up of a layer of approximately 6.5 m thick colluvial soil. This layer consists of a lateritic silty clay (Miguel et al., 2007). Below it, there is a layer of non-lateritic clayey-sandy silt up to a depth of 19 m. Between 6.5 and 7 m depth, the profile shows a layer of concretioned material, consisting of a little compact yellowish brown sandy silt. The water table is about 17 m. Several field tests were carried out at EFSMF such as SPT (Standard Penetration Test), CPTU (Cone penetration test), DMT (Dilatometer test) and others (Cavalcante et al., 2007).

The superficial layer of EFSMF consisting of lateritic clay has been the subject of research because of its geotechnical behavior peculiarities. X-ray diffraction tests carried out on samples collected throughout the profile indicated the presence of minerals such as kaolinite, gibbsite, hematite, goethite and quartz. Table 1 presents natural specific weight values (γ_{nat}), field moisture content of (w_{field}), void ratio (e) and degree of saturation (S_r) of this EFSMF layer for the depths studied (Miguel et al., 2007). Figure 2 shows the size-grain distribution curves for the same samples with and without the use of deflocculant (WD and ND, respectively) during the sedimentation and depth function phase (z) of the samples.

Table 1 - Physical Index values of undisturbed samples (Miguel et al., 2007).

Depth (m)	γ_{nat} (kN/m^3)	ω_{field} (%)	e (-)	S_r (%)
1.5	11.80	24.2	2.14	33.7
2.5	13.71	23.7	1.74	44.3
3.5	13.96	22.3	1.68	40.7
4.5	14.38	27.2	1.72	48.6
5.5	14.11	22.2	1.66	41.1
6.5	14.68	22.4	1.55	44.2

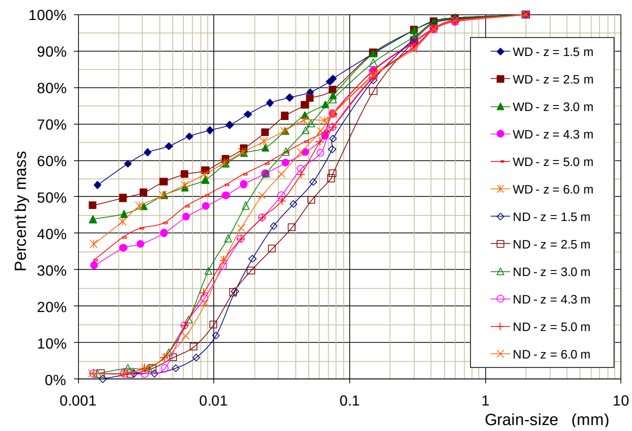

Figure 2 – Size-grain distribution curves with and without the use of deflocculant.

2.2 Soil Specimens

The soil samples studied were undisturbed and disturbed, and were taken from the colluvial and lateritic surface layer of the EFSMF profile at 1.5 m, 2.5 m, 3.5 m, 4.5 m depths, by excavating a 1m diameter pit.

2.3 Thin Plates

Thin plates were prepared and impregnated by means of undisturbed samples collected at 1.5m and 2.5m depths. The plates were impregnated with small quantities of acrylic resin (capillary impregnation), using a vacuum desiccators, and then with methylene blue in order to obtain pore distribution. After sample hardening, the samples were sliced to make the thin plates. The interpretation of these specimens was carried out using a petrographic microscope with 2.5X, 10.0X, 25.0X, 40.0X and 50.0X objective lenses, associated with data from X-ray Diffraction.

2.4 SWCCs by Filter Paper Method

To determine the soil water characteristic curve (SWCC) of the suction, many specimens were prepared from undisturbed samples. These specimens were trimmed into metal rings with height of 2cm and diameter of 5cm, through the samples collected at 1.5m and 2.5m depths.

The SWCCs were obtained from the wetting and drying paths. In the drying paths, the specimens were initially saturated by backpressure. The specimens were placed on a porous stone, previously saturated with distilled water, during a period of 48hrs. The porous stone and specimen were placed on a tray with distilled water. The water level of the tray reached half of the height of the porous stone, so that it would remain saturated and the samples would be able to saturate by backpressure. Between the specimen and the porous stone, there was a filter paper so that soil loss would not occur.

For the wetting path, the specimens were taken to the oven for 24 hours, so that the tests would start from a very low moisture content condition, between 0 and 1%.

Marinho (1994) suggests that the wetting and drying paths be performed from the natural moisture content from the field, but, in this study, it was preferred to begin it from the extreme moisture conditions to observe the hysteresis phenomenon.

The test was carried out in a temperature-controlled room at a temperature of 20°C. The filter papers used were Whatman No 42, taken out of the box and immediately placed in contact with the specimen. The specimens receive a PVC plastic film at the bottom of the metal ring, attached to the sides of the rings, to avoid material loss during the handling of the specimens. Thereafter, each set (specimen and filter paper) was protected by aluminum foil, as suggested by Feuerharmel et al. (2006), and an overload (aluminum capsule cap) was placed to ensure that there would be total contact between the paper and soil. The whole set was protected again, but now with the PVC film and placed inside a sealed plastic bag, which in turn was placed inside a plastic box which was also closed, to ensure that the variation in air moisture would not interfere in the equilibrium of the filter paper with soil. The entire procedure was done as quickly as possible to prevent the filter paper from reaching equilibrium with the air, that is, with relative air moisture.

The specimens were left in the plastic box for seven days so that the equilibrium time between the filter paper and soil would be reached. After seven days, the specimens were taken from the box and plastic bag, following the steps: the PVC film and aluminum protection was removed, along with the overload, and then after that the filter paper in contact with the soil. After that, the paper was placed inside an aluminum capsule, the weight of which was known, to be weighed on a scale with 0.1 mg resolution. This procedure, from the time of the removal of the protection layers until the placing of the filter paper inside the capsule was carried out in about 6 seconds, so as to prevent the filter paper losing or gaining water. After weighing the capsule and the paper filter set, the filter paper was taken to a furnace oven for 24 hours. To determine other values of the specimen's wetting paths moisture content equilibrium, a certain amount of distilled water was added uniformly with the help of a dropper on the surface of the specimen, waiting for two hours so that the water could infiltrate the specimen (equilibrium) and not accumulate on its surface. After that, the process described above was repeated.

During the drying path, the specimen had been drying in front of a window, so that the sun heat would evaporate the water from the soil. When the mass and the moisture content expected were reached, the process of placing the filter paper was repeated. From certain moisture content on, it was not possible to eliminate water by evaporation, with the specimen exposed to the air, because of that the samples were taken to an oven for some minutes to could eliminate more water.

In all the testing phases, the handling of the filter paper was carried out with a metal clamp to avoid altering the characteristics of the paper.

The moisture content equilibrium rates of the filter paper and soil were calculated, in which each gravimetric moisture content corresponds to a matric suction estimated from the moisture of the filter paper, using the calibration curve for Whatman paper No 42, obtained by Chandler et al. (1992). These suction and moisture content values correspond to a SWCC point.

2.5 Monitoring of the Matric Suction in the Field

The monitoring of the matric suction in field was performed using four tensiometers, two with 0.6m length and the other two with 1.2m length, installed inside of a trench of 1 meter in depth and placed 1m apart from each other. Thus, the analysis depths were at 1.6m and 2.2m.

This trench was dug one meter in depth, due to the fact that the first meter in the layer is a landfill and for the tensiometers to be supported on the depth values near the ones from the undisturbed samples collected.

The tensiometers were calibrated in the laboratory with upmost care so that the saturations were obtained without air (bubbles) inside of the tensiometer, specially, on their inside walls. This was carried out using water under high temperatures, around 50^{o}C, and with the vacuum application.

The tensiometers were installed in the EFSMF by means of a pre-hole. Before the installation, a paste was prepared with the soil removed from the site (soil with water, practically forming mud) and placed in contact with the porous stone. Frequently, the tensiometers were calibrated, putting more water without air in its interior and trying, to the maximum, to remove the air from inside of them, by using a vacuum extractor.

The conventional tensiometers have a limitation on its reading capability, because they can only measure suctions lower than 100kPa. This value can be even lower, due to the altitude of the site, the kind of equipment and length of the tensiometer, as it was stated by Vieira (1999). Table 2 presents the limit values of the tensiometer adopted in this study due to the influence of these factors.

Table 2 - Limits adopted for each tensiometer

Tensiometers (-)	Length (m)	Limits of Suction Values Adopted

		(kPa)
T1	0.6	76.7
T2	0.6	76.7
T3	1.2	72.0
T4	1.2	72.0

The monitoring period of the matric suction, together with the obtaining of the weather data (air moisture and rainfall), was from March of 2006 to March 2007. In the month of November, the tensiometers were removed from EFSMF and taken to the laboratory to be calibrated and saturated again because they had suffered cavitation due to the low contents of moisture content in the field, typical of this period of drought and, consequently, high matric suction values.

After a few weeks, they were reinstalled and demonstrated no problems. The gravimetric moisture content was obtained by means of undisturbed samples removed from the soil in distant points, approximately 0,5m of the tensiometers, and in depth similar to the support depth of the tensiometers (about 1.6 m and 2.2 m). The samples were collected with the help of an auger, and placed in capsules, which were weighed and taken to an oven in the laboratory.

The weather data were obtained from the CEPAGRI (Center of Meteorological and Climatic Research Applied to Agriculture) of State University of Campinas, located around 70m from EFSMF, allowing the consideration that these data are highly reliable.

3 PRESENTATION AND ANALYSYS

3.1 Structure and Mineralogical Composition

In the interpretation of the thin plates impregnated with undisturbed soil samples collected up to a 2.5m depth, one can note that they are made up of very angular quartz grains and, with undulating extinction, typical of sedimentary material. The grains were covered by ferruginous reddish material, made up of hematite and at times goethite. Some of these grains are fractured and filled with the same material that is around it.

In the thin plates with the 1.5m and 2.5m depth specimens, there is a predominance of interconnecting pores (Figures 3 and 4, respectively). In the 2.5m samples, non-connected pores were found, even though less expressive, due to the existence of cementing material (Bonder, 2008).

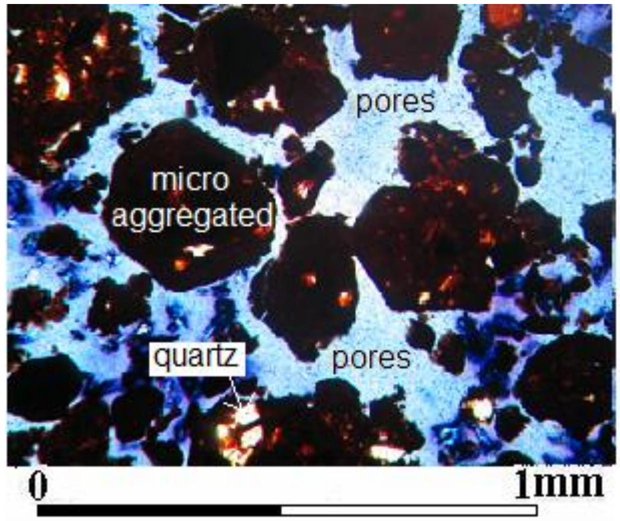

Figure 3. Thin plates impregnated for 1.5m (modified by Miguel and Vilar, 2009).

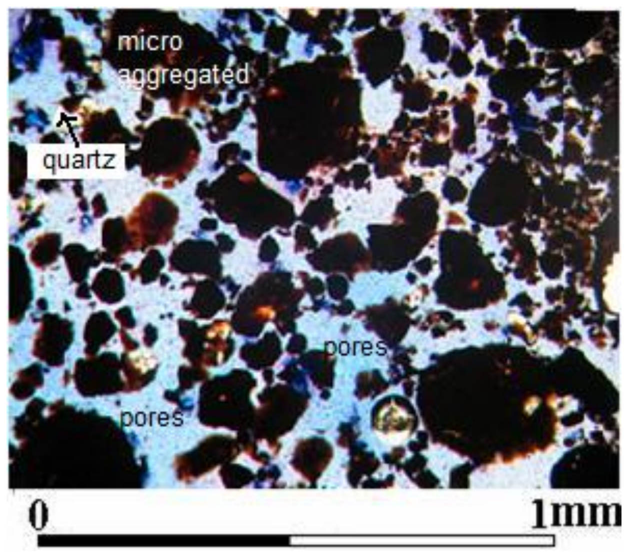

Figure 4. Thin plates impregnated for 2.5m (modified of Miguel and Vilar, 2009).

3.2 SWCC Obtained by the Filter Paper Method

The SWCCs obtained by the filter paper method, for the wetting path as well as the drying path, for depths of 1.5m and 2.5m. The SWCCs are shown on Figures 5 and 6.

The values of air-entry at both depths were which could be considered similar to all depths, around 3kPa.

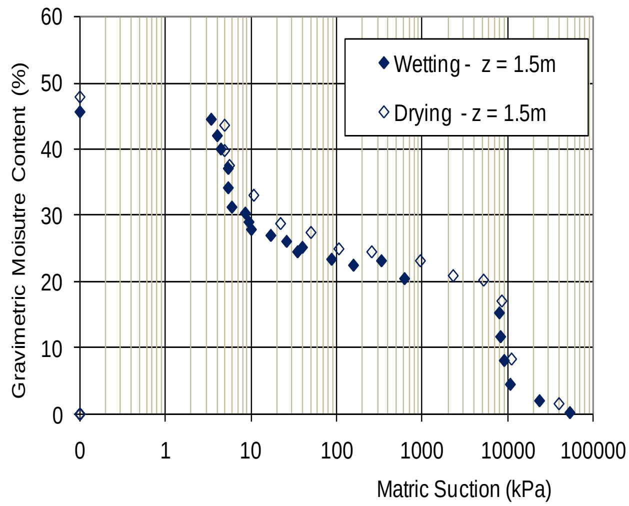

Figure 5. SWCCs obtained with the filter paper method for the 1.5m depth.

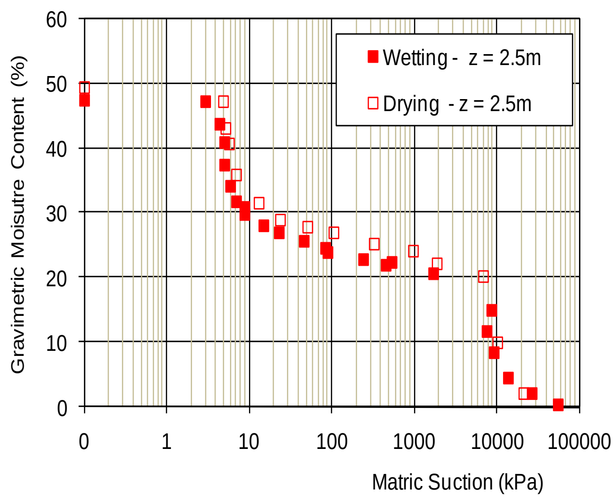

Figure 6. SWCCs obtained with the filter paper method for the 2.5m depth.

3.3 Field Monitoring

In the period of field monitoring, the rainy season (between November and April) was unusual, precipitating much more than the values from the annual averages registered in the field; and the drought season was also unusual, with a long period of drought and some very hot days.

The tensiometers installed at the same depth had similar behaviors, offering very proximate values. Therefore, the arithmetic average of the values obtained from the matric suction was calculated to each depth.

In Figure 7, the variations of the matric suction throughout one year are presented. During the drought period (between May and November), the tensiometers did not register the matric suction values, due to the cavitation, for this reason, the maximum values of the suction (Table 2) were considered as the ones that the tensiometers were capable of measuring, yet, these values, related to that period, are higher than the ones presented.

In Figure 8, the points of the retention curve, obtained with the tensiometers in drying and wetting paths, and the gravimetric moisture content values, obtained from the undisturbed samples, are presented.

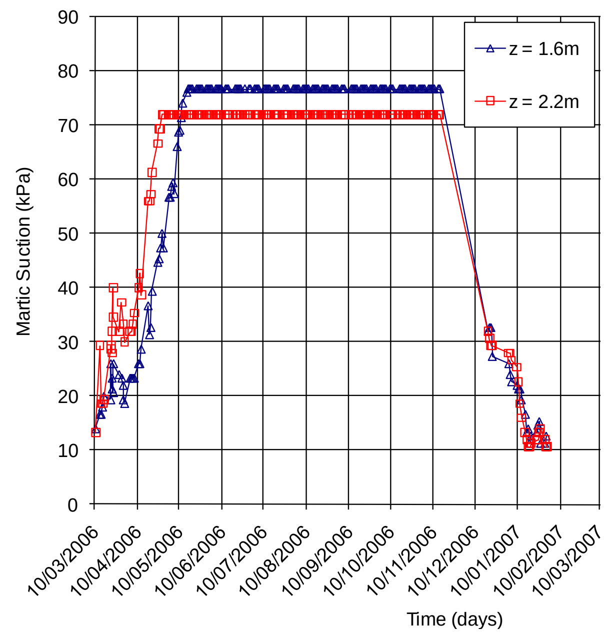

Figure 7. Matric suction throughout one year

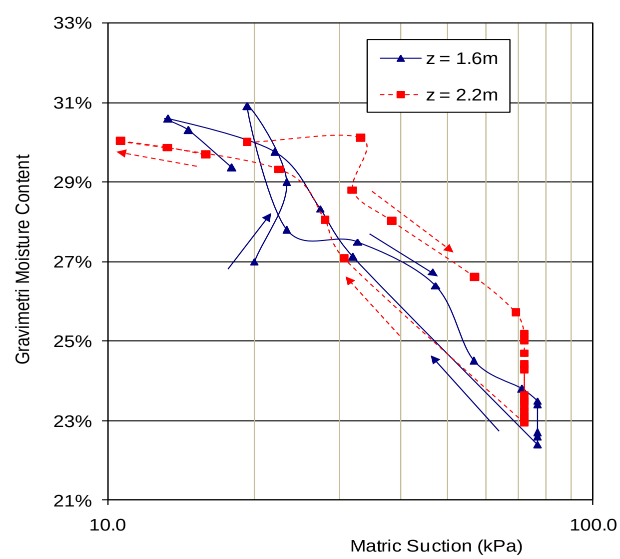

Figure 8. SWCC obtained in the field.

It is possible to observe that the curves obtained from the drying and wetting paths do not coincide (Figure 8). The difference among the points obtained in the drying and wetting paths, considering the same depth, is due to the hysteresis phenomenon.

The hysteresis phenomenon was observed more expressively in the samples from 2.2m depth in relation to the 1.6m ones (Figure 8), due to most likely the values of the void ratio of depth, 1.6m, so there were just a few air bubbles captured by these pores. Moreover, at the 2.2m depth, there are pores connected and non-connected, according to Figures 3 and 4.

In the field, the soil does not present the same behavior in relation to the laboratory because the soil in the field is not always submitted to the isolated paths of drying or wetting, but to the cycles of these paths, which, incidentally, can occur in the same day, for example.

3.4 Hysteresis Phenomenon

Putting it in the same graphic the SWCCs obtained through the drying and wetting path and the pairs: matric suction and moisture content, obtained by the field monitoring, it is possible to notice the difference between these curves, as indicated in Figures 9 and 10, for the 1.5m and 2.5m depths, respectively.

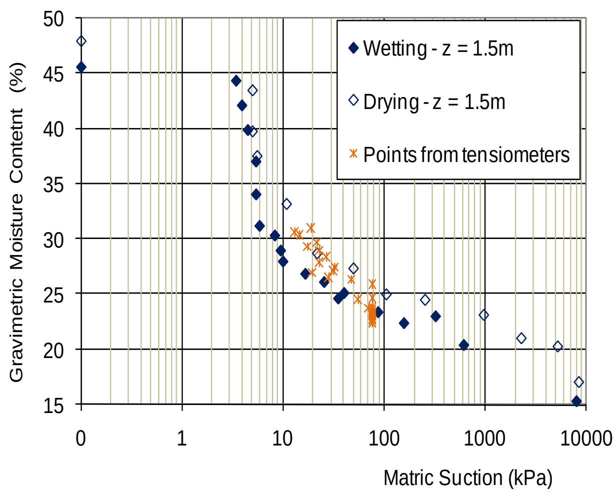

Figure 9. SWCCs and points obtained by the tensiometer (1.5m depth)

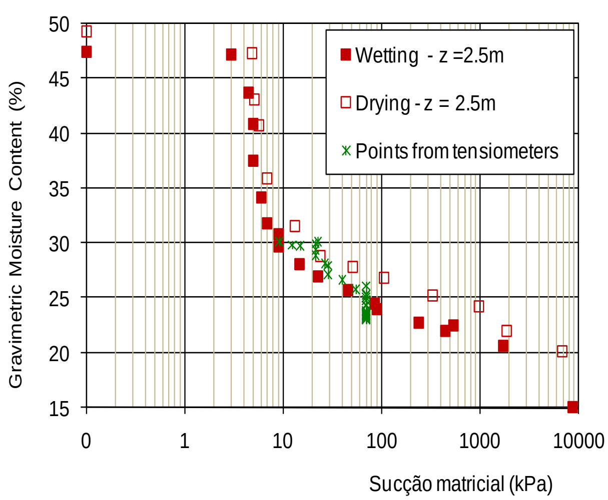

Figure 10. SWCCs and points obtained by the tensiometer (2.5m depth).

The hysteresis, more evident between the air-entry in the macropores up to the micropores, occurs due to, mainly, the existence of a great amount of connected pores, as seen on Figures 3 and 4.

The points obtained with the tensiometers were located below the SWCCs, determined by drying path, and above SWCCs, by wetting path. Probably, this approximation with the filter paper method is due to the fact that the soil getting wet in the field by the infiltration of the water from the rain, that means, the soil performs a passive work as well as the test of the filter paper carried out by drip.

While the soil samples have the same mineralogical composition, it is possible to notice that hysteresis phenomenon is related to the amount, grain-size, and specially, the distribution and geometry of the pores. Askarinejad et al. (2010) state that the SWCCs obtained from the laboratory originated from only one direction of the one-dimensional flow (in this case, vertical). However, in the field, the flow can take the three directions, becoming tridimensional. This fact can also explain the differences obtained between the SWCCs in the laboratory from the ones obtained in the field.

4 CONCLUSION

The curves of water retention of the soil for the colluvial soil profile, up to 2.5m of depth, obtained by the filter paper method, displayed themselves to be bimodal type, typical of tropical soils with macro and micro aggregated structures. The pressure values of air-entry are relatively low; likewise the values obtained for the sands, demonstrating that the behavior of this soil is similar in some aspects, for example, the permeability and size-grain distribution without the use of defloculant in the sedimentation phase, to the sands.

The conventional tensiometers have the porous stone cavitation as limiting, preventing the reading of matric suctions higher than 100kPa.

The hysteresis phenomenon was observed in the soil profile, being always more evident in soil samples with higher void ratio and with connection between the pores. The cementing material was very important to understand how the pores distribute, when the grains of clay-minerals and quartz are covered by the same material.

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