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Evaluation of Soil-Water Characteristic Curve Prediction Models with Emphasis on Tropical Soils

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Abstract – The main constitutive relationship for the characterization of unsaturated soils is the Soil-Water Characteristic Curve (SWCC). Several models of SWCC predictions have been proposed and studied in the literature, as an alternative source to obtain soil water retention properties. However, most of these models only consider physical aspects of the soil, such as granulometry. There are not many studies in the literature verifying the performance of these models for tropical soils. This paper aims to verify the application of four theoretical and semi-empirical models, which use soil granulometric properties to predict the SWCCs of a tropical and collapsible soil profile. Samples were collected in the Experimental Field of the University of Brasília, at depths of 4 and 12 m. The most superficial soil is highly weathered and the deeper soil is poorly weathered. The granulometry of the materials was determined using different methodologies to verify the material disaggregation and define which methodology could allow a better prediction of SWCC. The results show that the Arya and Paris [1] model had the best performance for the 12 m sample. Following the model by Aubertin *et al.* [3], when using the methodology for fine soils, had predictions with good and similar performances for both samples in studies, while the version of the same model, predicting for granular soils, had a weak performance. The Arya and Paris [1] and Arya and Dierolf [2] models, for a 4 m sample, predicted the SWCC reasonably well when using the methodology to determine the least disaggregating particle size possible of the sample. The model by Wang *et al.* [4] had similar predictions for both samples.

Keywords: Soil-Water Characteristic Curve, Granulometric Curve, Prediction Models, Tropical Soils

1. Introduction

Due to the relatively long time involved in determining the experimental SWCC and/or specific equipment requirements, there is a growing interest in models that estimate this property from soil textural data, such as granulometry and other basic properties like particle density, voids index, and Atterberg limits. It is worth remembering that the use of prediction models must be adopted in a preliminary or estimative nature, not discarding the need to determine the experimental SWCC for executive geotechnical projects. The use of these models may still be relevant when it is intended to estimate the impact of changing parameters such as porosity on the SWCC, which experimentally would generally require the performance of new tests or the adoption of other estimation models such as the one proposed by [5].

Most of the SWCC prediction models in the literature are based on the hypothesis that through the granulometric curve, the soil pore distribution is indirectly obtained, with an idealized arrangement of the particles. However, the validity of this hypothesis is questioned when dealing with structured soils, such as the collapsible porous soil of Brasília [6] or containing intervening lamellar particles in the form of pores and interaction between particles as proposed by [7].

According to [8], the soil profile of the Experimental Campus of the University of Brasília used in this study is up to 8 m deep, composed of a deeply weathered soil, called lateritic, with a bimodal pore distribution structure (macro and micropores). Underlying this soil, between 8 and 10 m deep, is a transition soil characterized by high heterogeneity of physicochemical and mineralogical properties, ie composed of heavily weathered portions, lightly weathered portions, and intermediate portions. Then, from 10 to 12 m deep, there is the saprolitic soil, in which less porosity is observed, with a structure marked by the rock of origin with the presence of neoformed and primary minerals and unimodal pores distribution.

One of the most used properties in the characterization of soils is granulometry curve. Brazilian norms follow the international ones, making use of techniques aimed at the deflocculation of particles, which often, especially in the case of deeply weathered tropical soils, takes away the results from the real situation in which the soil is or will be. When using different methodologies to determine the granulometry of the material under study, including the use of disaggregating or deflocculating techniques of the particles, as presented in [9], there is an instability of the aggregates present in the material, which depends on the technique used. It is recommended the use of techniques that approach the field situation and in certain cases the use of associated techniques to lead to the maximum individualization of the particles.

Thus, this paper aims to evaluate the effectiveness of four SWCC prediction models applied to the collapsible and tropical soil of Brasília. The models of Arya and Paris [1], Arya and Dierolf [2], Aubertin *et al.* [3], and Wang *et al.* [4] were analyzed. Granulometric curves determined conventionally were considered, via sieving and sedimentation with and without the presence of chemical action of deflocculant and through the laser granulometer with and without the physical action of ultrasound. The use of granulometries under different degrees of aggregation aimed to find out which methodology could allow a better representation of the pore distribution of the samples under analysis. It is worth remembering that the materials under study are different in terms of classification, structure, and mineralogy from those that were used in the original development of the models. Therefore, a critical analysis of the results found is of great importance for understanding the potential use of these models for soils of different characteristics and for establishing indications on how such models could be improved.

The results of the predictive models are expected to significantly deviate from the experimental results for the following reasons: first, none of the models studied takes into account all the inherent factors and changes the format of the SWCC, such as: stress history, sample preparation method , deformability, pre-consolidation effects, hysteresis effects, capillarity, adsorption, aggregation effects as determinants of material behavior. Therefore, for our tropical soils, possible combinations of the last four points listed in the SWCC predictions can lead to better predictions. However, SWCC prediction models that incorporate this information remain a major geotechnical challenge.

2. SWCC Prediction Models

.1. Arya and Paris [1]

The model proposed by Arya and Paris (AP) [1] uses the granulometric curve, soil density, and particle density as input parameters to predict the SWCC. According to the authors, the model was proposed based on the observation of the similarity between the granulometric distribution and the SWCC. The predictions of the proposed model were originally verified for five types of materials, demonstrating close agreement with the experimental data. The method considers that the granulometric curve can be divided into n arbitrary fractions. Each fraction has a certain average pore diameter and corresponds to a respective idealized SWCC, which is defined by its air entry value and by a total and abrupt drainage.

An important observation of the Arya and Paris model [1] is that the total length of the pores is equal to the number of particles arranged along the pore multiplied by the length contributed by each particle. As real soil particles are not spherical, the authors assume that the length of each particle is greater than the equivalent diameter of the sphere. Arya and Paris [1] assume that the number of particles needed to trace the actual length of the pores needs to include the empirical parameter α, to take into account the non-sphericity of the particles. The nature of the α parameter proposed by Arya and Paris [1] was tested by calculating the relationship between its value and the particle size. The authors found that the calculated value of α varies slightly within a given particle size range and that a value of $\alpha = 1.38$ for more granular soils, and $\alpha = 1.16$ for clayey soils, were assumed with better predictions.

The following simplifying assumptions are adopted by the Arya and Paris (AP) model [1]: a) the specific mass of solids is constant and the same for all n granulometric fractions; b) the particles of each granulometric fraction can be considered spherical and with a diameter equal to the average diameter of each fraction; c) the pore volume of each granulometric fraction can be idealized as a cylindrical capillary tube whose radius is associated with the average radius of the particles of the fraction; d) the Kelvin capillary equation can be applied to each fraction; e) hysteresis and its generating mechanisms are not considered.

2.2. Arya and Dierolf [2]

The prediction model proposed by Arya and Dierolf (AD) [2] reevaluated the original model by Arya and Paris [1], introducing the empirical parameter (α^*) seeking to improve the original equation of the model that relates the pore radius to the particle radius. According to Arya and Dierolf [2], the empirical parameter α^* represents the effective length of the pore associated with each particle size fraction. The parameter α^* removes the number of particles from the equation that relates the radius of the pores to the radius of the particles. The authors found that the model was less sensitive to α^* than the model using the α variable proposed by Arya and Paris [1]. The authors used the same materials as the Arya and Paris model [1] and showed that α^* varies over a relatively narrow range of values of 0.3 and 1.5 cm and that a value of 0.938 cm was assumed with better predictions.

2.3. Aubertin *et al.* [3]

Aubertin *et al.* (AU) [3] proposed a set of equations to predict SWCC. The model was developed only for isotropic and homogeneous materials, under a drying trajectory, and influencing factors such as internal microstructures, anisotropy, and volumetric variations were not taken into account.

In the model proposed by the authors, the degree of saturation (S_r) includes two components that act together: one is produced by capillarity (Sr_c – for granular materials), which is more important at relatively low suction, and the other is related to adhesion. (Sr_a – for fine materials) which mainly contributes to higher suctions, and both are expressed as functions of equivalent capillary rise in a porous medium (h_{co}) and matrix suction. In addition, both components can be evaluated from the basic properties (usually available) of the material, including void ratio (e), grain density (ρ_s), effective diameter (D_{10}), uniformity coefficient (C_u) for granular soils and the liquidi limit (w_L) for cohesive plastic soils. The two components act simultaneously and are therefore included in measurements made to determine the relationship $\theta - \psi$.

2.4. Wang *et al.* [4]

Using the SWCC fit model proposed by [10] as a basis, the authors proposed a model to estimate the SWCC (WA) of granular soils based on a semi-physical and semi-statistical approach. The equation of [10] was presented in terms of the effective saturation degree. The authors used dimensional analysis to propose the following equations for variables n and α (from [11]), which are related to C_U and D_{60}, through two adjustment parameters $C_1 \approx 1.07$ and $C_2 \approx 12.07$ obtained for a set of SWCCs extracted from the UNSODA database.

3. Materials and Methods

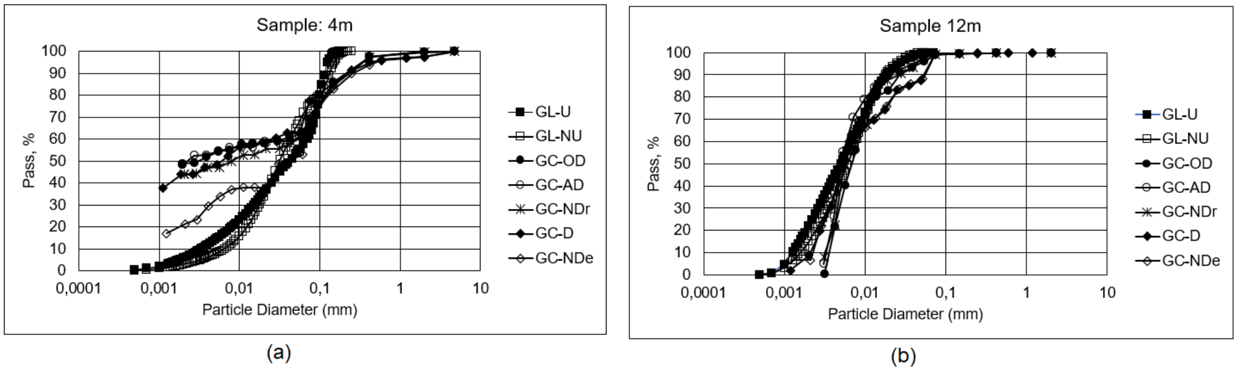
Undisturbed samples were collected in the Experimental Field of the Graduate Program in Geotechnics at the University of Brasília at depths of 4 and 12 m, which is located on the Darcy Ribeiro University Campus, coordinates 15º45'56" south latitude and 47º52'20' ' of west longitude. The site represents the typical profile of the porous layer of Brasília and is a residual soil from the domain of the slate unit of the Paranoá group. [8] and [11] present a detailed description of the samples collected at these depths. The values of the physical indices of the studied samples are presented in Table 1 and were used to predict the SWCC.

Table 1: Physical indices of the studied samples

Visual Tactile Classification	Depth (m)	Specific Weight of Solids (γ_s) (kN/m^3)	Void Index (e)	Porosity (n)	Liquid Limit (w_L)
Red clayey sand	4	27,10	1,227	55,1	48
Variegated silt	12	27,78	0,933	48,3	38

Deeply weathered tropical soil in its natural state is aggregated, and the aggregates are linked to each other by the presence of clay bridges and/or iron and aluminum oxyhydroxides [12]. Depending on the type of methodology used to determine the granulometric curve, there is a greater or lesser disaggregation of this material, modifying the granulometric distribution of these soils. In addition to the granulometric analysis of the fine fraction of the soil by the conventional method of sedimentation, it is possible to carry out this analysis employing the laser granulometer, which allows the execution of tests using in addition to the deflocculant, the ultrasound device, whose objective is to disaggregate/deflocculate the agglomerated particles by cementitious bonds or other binding mechanisms. Another aspect that influences the result of the granulometric analysis is the way of preparing the sample for the test. Examples that will be seen below, show that a sample with natural moisture has different results when it is air-dried or oven-dried.

The granulometric curves of the samples (Figure 1) were obtained using the following methodologies: laser granulometer with and without ultrasound (abbreviations: GL-U/GL-NU), conventional granulometry (sieving and sedimentation) with samples previously submitted to drying in oven – in air – and without drying (abbreviations: GC-OD/GC-AD/GC-NDr) and with and without the use of deflocculant (abbreviations: GC-D/GC-NDe). It can be observed in Figure 1(a) that in deeply weathered soils, the joint action of the chemical deflocculant and the ultrasound may be necessary to provide the complete disaggregation of the soil, and the use of only one of the techniques must be associated with the real situation of the soil in situ. Figure 1(b) obtained for the poorly weathered soil collected at 12 m depth indicates that in these soils it is unnecessary to use the two techniques together to promote the separation of particles. Table 2 presents a summary of the granulometric percentages of the samples under study.



(a) (b)

Fig. 1: Granulometric curves of the studied samples: a) Sample 4m; b) Sample 12m;

Table 2: Material Granulometric Percentages

Granulometry	Depth (m)	% Clay	% Silt	% Sand	% Gravel	Uniformity Coefficient (Cu)
GL-U	4m	5,8	51,9	42,3	0,0	21,4
GL-NU		3,0	69,1	27,9	0,0	6,4
GC-OD		48,8	14,3	36,7	0,2	-
GC-AD		48,4	13,2	38,2	0,2	-
GC-NDr		44,0	17,0	38,6	0,4	-
GC-D		39,2	26,3	33,7	0,8	-
GC-NDe		3,1	43,1	53,0	0,8	-

GL-U	12m	22,0	78,0	0,0	0,0	5,3
GL-NU		15,0	85,0	0,0	0,0	4,9
GC-OD		-	98,8	0,9	0,0	2,3
GC-AD		-	94,2	0,9	0,0	1,9
GC-NDr		-	90,9	0,9	0,0	2,1
GC-D		19,4	69,7	10,9	0,0	3,4
GC-NDe		6,5	82,8	10,7	0,0	4,2

The SWCC determined directly (Figure 2) of the materials were obtained by the techniques of the suction plate, filter paper, and dew point potentiometer, using the mixed trajectory. The detailed procedure of each methodology can be found in [11]. In the case of deeply weathered soils (4m sample), a bimodal SWCC with non-homogeneous pore distribution (macro and micropores) is observed. The 12 m deep sample corresponds to a poorly weathered soil, saprolitic soil with no aggregations, and therefore a unimodal SWCC is observed, with a homogeneous distribution of pores.

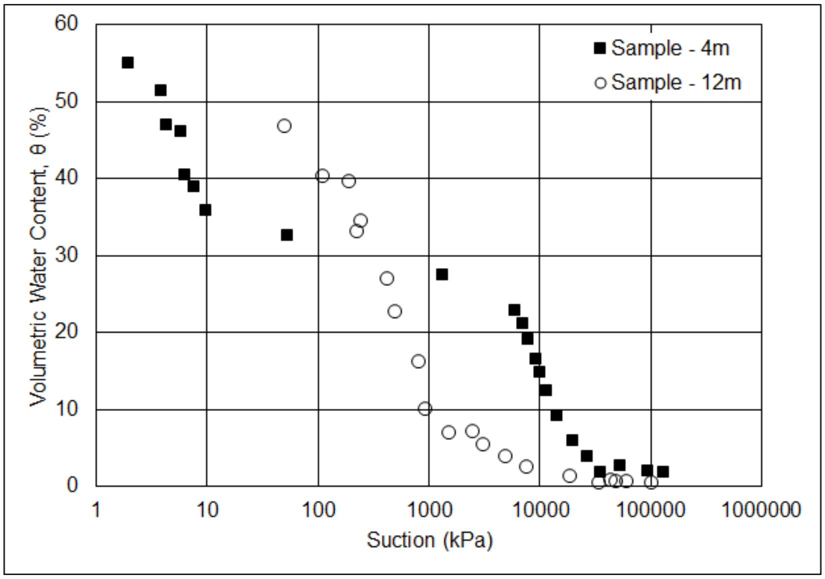


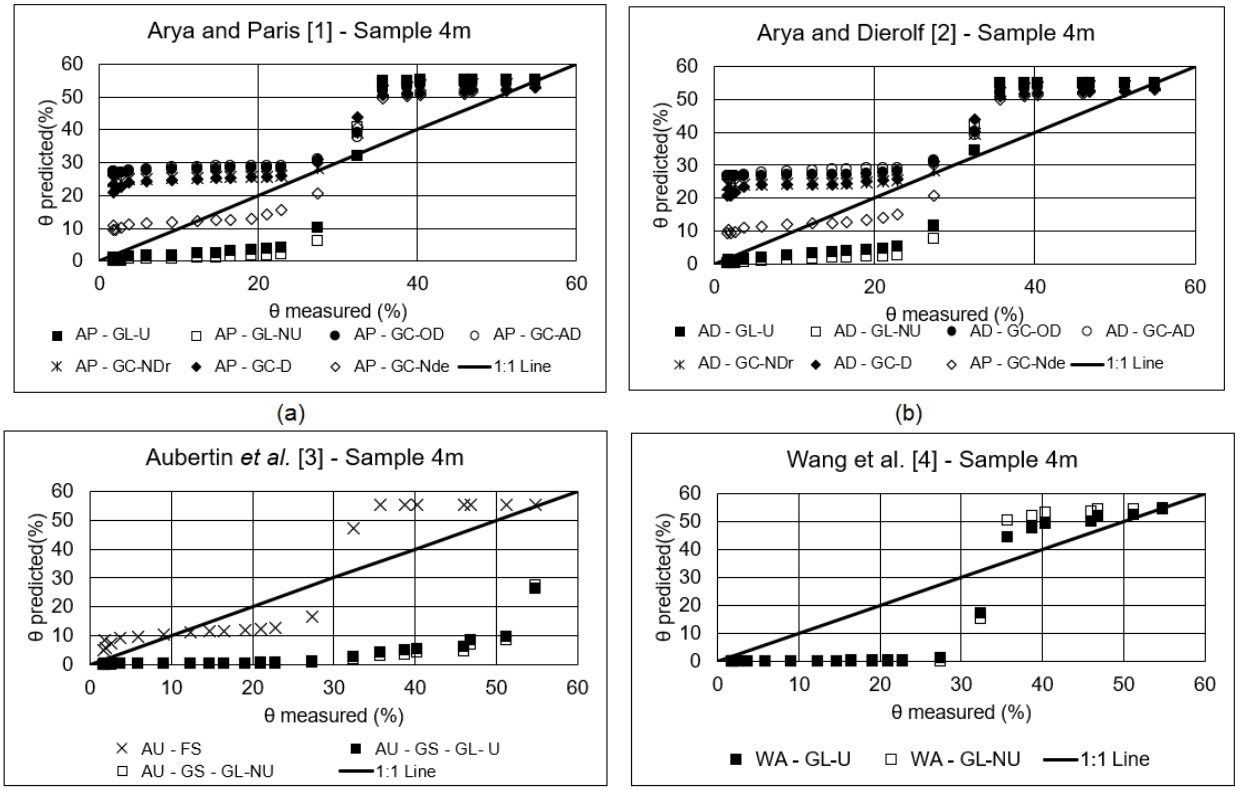
Fig. 2: SWCC of the studied samples.

3. Results and Discussions

Figures 3 and 4 present the results of the volumetric moisture prediction as a function of the experimental volumetric moisture obtained from the experimental SWCC, for both materials under study. To evaluate the prediction efficiency of the models studied in this work, as a function of the various analyzes of granulometry distribution for the studied samples, it was decided to use a 1:1 graphic relationship between the estimated and measured moisture content values in different matric potentials. In this type of relationship, the fewer points scattered in relation to the mainline, the greater the accuracy of the prediction, which represents a perfect fit of the model. It is necessary to carry out an interpolation of the measured and predicted data for a correct evaluation of the adherence meters (R^2, adjusted R^2, and RMSE), presented in Table 3, and the values presented represent the averages of all methodologies used. It is observed that in the model by Aubertin et al. [3] (Figure 3c) and Wang et al. [4] (Figure 3d), for the 4 m sample, not all granulometry methodologies were presented because it is possible to determine the material uniformity coefficient, which is an input parameter of these models.

Table 3. Mean values of adherence meters.

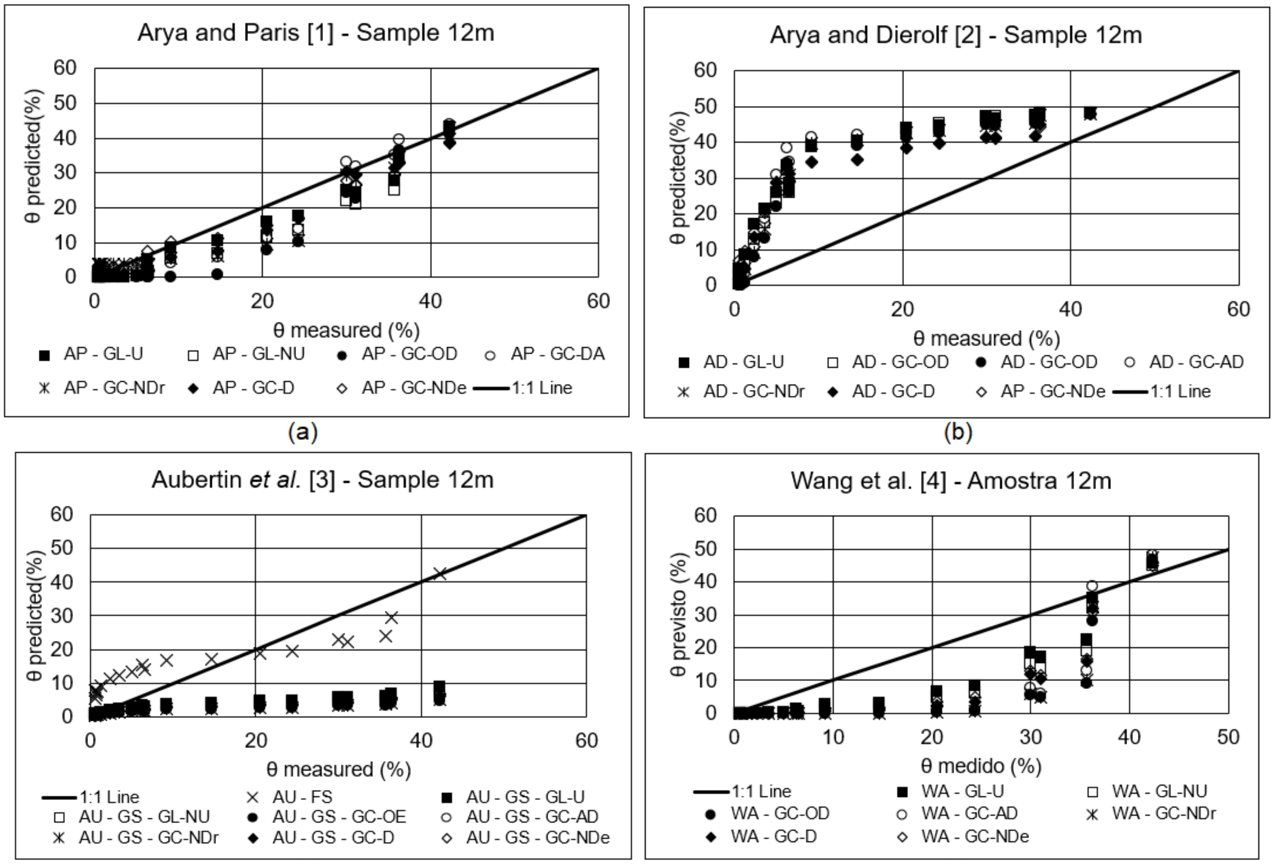
Prediction Model	Sample 4m			Sample 12m		
	R²	R² adjusted	RMSE	R²	R² adjusted	RMSE
Arya e Paris (1981)	0,435	0,375	0,127	**0,884**	**0,871**	**0,047**
Arya e Dierolf (1989)	0,453	0,396	0,125	-0,257	-0,405	0,158
Aubertin *et al.* [3] – Fine soils	**0,732**	**0,704**	**0,090**	**0,741**	**0,710**	**0,072**
Aubertin *et al.* [3] – Granular soils	-0,943	-1,148	0,241	-0,404	-0,570	0,167
Wang *et al.* [4]	0,464	0,407	0,127	0,382	0,310	0,109



(a) (b)

(c) (d)

Fig. 3: Relationship between measured volumetric moisture values (θmeasured) x predicted volumetric moisture (θpredicted) for 4m sample: a) Arya and Paris model [1]; b) Arya and Dierolf model [2]; c) Aubertin *et al*. model [3] and; d) Wang *et al.* model [4].



(a) (b)

(c) (d)

Fig. 4: Relationship between measured volumetric moisture values (θmeasured) x predicted volumetric moisture (θpredicted) for 12 m sample: a) Arya and Paris model [1]; b) Arya and Dierolf model [2]; c) Aubertin *et al*. model [3] and; d) Wang *et al.* model [4].

It can be seen in Figures 3a and 3b, for the 4m sample, that predictions using the models of Arya and Paris [1] and Arya and Dierolf [2]are quite similar and overestimate the volumetric moisture in the stretch of macropores of the material (zone more saturated), while in the driest range of the SWCC (micropore zone) there is both an overestimation and an underestimation of the volumetric moisture values in this stretch, depending on the granulometric curve used in the prediction. In addition, it is noted that the prediction of both models is quite similar through the adhesion meters defined in Table 3. It is also possible to observe a very interesting result when entering the model of Arya and Paris [1] and Arya and Dierolf [2]with data from the conventional granulometry methodology by sieving and sedimentation without deflocculant, that is, preserving the maximum of the sample's aggregates, an adhesion meter R^2 of 0.83 was obtained for both models. A value of 0.8 is quite high when dealing with SWCC prediction, due to the number of phenomena involved in determining this property.

In Figure 3c, it is observed that the model by Aubertin et al. [3] using the granular soils methodology had the worst performance, while when using the formulation for fine soils, it provided adjustments with R^2 slightly higher than 0.7. This model uses a greater number of input parameters, such as physical indices: void index, uniformity coefficient and sample liquid limit. Furthermore, the model is not based only on the geometry of soil particles and pores, as it includes empirical observations that allow considering the complexity of soil-water interactions. This is believed to justify the best SWCC predictions for the 4m sample. The model by Wang et al. [4] there are slightly better predictions than the models by Arya and Paris [1] and Arya and Dierolf [2].

In Figure 4a, for the sample collected at a depth of 12 m, the SWCC predictions using the Arya and Paris [1] model had the best performance of all the analyzes performed, R² greater than 0.85 regardless of the granulometry methodology used, thus showing that the predicted moisture values are close to the experimental values. The 12 m sample is a curve with a single pore distribution, that is, unimodal, and therefore it was very close to the characteristics of the materials used to develop the prediction model, and therefore, it had the best predictions of SWCC. Furthermore, it can be seen in Figures 4b and 4c that the models by Arya and Dierolf [2] and Aubertin et al. [3] for granular soils, were very precarious, all presenting a negative R², thus indicating that the predicted values are far from the experimental values, while the model of Aubertin et al. [3] for fine soils had slightly better predictions than the other models. While the model by Wang et al. [4], Figure 4d, had slightly higher predictions than the other models, but still underestimated the predicted values.

4. Conclusions

The main objective of the paper was to verify, for the application of four methods of prediction of SWCC, for a deeply weathered soil (4m sample) with bimodal pore structure, and a poorly weathered soil (12m sample) of the same profile under study, with a unimodal pore distribution. Granulometric curves determined by different methodologies were used to investigate the impact of the disaggregation of this material on the results obtained. Regression analyses using R², adjusted R², and RMSE were performed to measure the goodness of fit of the models when dealing with tropical soils.

The models tested are based on simplifications of the soil pore distribution geometry and were developed to predict only the drying curves of the materials. The Arya and Paris [1] model had the best performance in predicting the SWCC for the 12 m (lightly weathered) sample, but it was not good when used in the 4 m (weathered) sample. The model by Aubertin *et al.* [3] for fine soils, seems to be promising, as it had high and similar performances in the SWCC's predictions for both samples (4 and 12 m). Therefore, in general, the SWCC prediction models did not present satisfactory predictive capacity for the analyzed tropical soil profile, and their application to a broader dataset may be necessary. In this way, it will be possible to verify the need to develop more appropriate prediction models for unimodal and bimodal tropical soils with differentiated SWCC.

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