The Capillary Rise in Fine and Coarse-Grained Soils Considering the Matric Suction

Jair de Jesus Arrieta Baldovino, Ronaldo Luis dos Santos Izzo, and Carlos Millan-Paramo

Abstract— **Few pieces of research have been conducted on the phenomenon of capillary rise in the field of soil for agriculture and geotechnical engineering. The rate of capillary rise of water in fine and granular soil is one of the major challenges for rising experiments in vertical open-tubes, as the time required for the water to reach the maximum height of capillary rise (h_c) can vary from 50 to 400 days. The control variables during the capillary experiment are mainly: saturated and unsaturated hydraulic conductivity, soil density, water content, soil column height, and velocity of capillary rise. Thus, this paper presents theoretical and experimental studies of capillary rise in several soils based on matric suction models. Results were gathered by comparing the behavior of capillary rise using the analytical solutions developed by Lu [1], Lu and Likos [2], and by Terzaghi [3]. On analysis of the results, it was concluded that the equation proposed by Lu and Likos [2] is the most suitable to predict the capillary rise velocity for the fine-coarse soils and the equation proposed by Lu [1] is more suitable to predict the matric suction. Other mathematical model developed by Liu et al. [4] is also suitable to estimate the h_c but do not consider the velocity of the water. The capillary rise method to measure the matric suction must be more applicable in sandy soil than clayey soils.**

Index Terms— **Capillary rise, matric suction, analytical models.**

NOTATION LIST

h_c= maximum height of capillary rise
ψ= matric suction
$\theta_a(\psi)$= adsorption water
$\theta_c(\psi)$= capillary water
θ_s= the saturated volumetric water content
θ_{max}= the maximum adsorption water content
ψ_{max}= maximum matric suction
m= fitting parameter controlling the overall shape
η= soil porosity
h_a= the saturation height
k_s= saturated permeability coefficient.

I. INTRODUCTION

THE soil stores water and makes it available to plants depending on the soil water content and suction. Water deficit decreases plant growth, reduces leaf size, and photosynthesis is also affected as a result of direct effects on enzymatic processes, electrolytes transport, and chlorophyll content [5]. Also, the capillary phenomenon and suction influence soil mechanic behavior. So, it is very important in engineering, agriculture, and biology to study water by capillary ascension with which plants can count in their growth.

Capillarity (or capillary rise) is a phenomenon that describes the movement of pore water from lower elevation to higher elevation, driven by the hydraulic head gradient and across the air/water interface [2]. Capillary rise can cause the liquid to flow towards the pull of the magnetic field, even against gravity.

Capillarity is a consequence of the surface tension between the liquid film and the wall of the capillary tube. The height reached by the liquid depends on the surface tension of the liquid and the radius of the capillary tube. This phenomenon occurs in several circumstances: in the movement of water through the soil pores, especially in fine granular soils, and is essential for the circulation of sap by plant stems, for example.

Several studies have been conducted to demonstrate, understand, and analyze the phenomenon of capillarity in soils. For instance, Lane et al. [6] used a capillarimeter and an open tube to analyze capillary rise. Natural sandy gravel was used and mixed in desired portions to create 8 soil classes, representing a wide range of grain size and distribution. Liu et al. [4] developed an approximation for capillary rise using only four parameters that apply to various soil types: the contact angle, the air entry height, porosity, and saturated hydraulic conductivity. Terzaghi [3] proposed an analytical solution demonstrating the capillary rise of any type of soil. Based on the solution developed by Terzaghi [3], Lu and Likos [2] also proposed an analytical solution, but unlike Terzaghi [3], they considered the permeability coefficient as nonlinear.

A. *Lu's equation for capillary regime*

Capillarity occurs due to the presence of a curved air-water interface in soil pores, whereas adsorption of water on or within soil particles occurs due to the presence of exchangeable cation hydration, mineral surface, or crystal interlayer surface hydration. Matric potential, therefore, reflects the energy equilibrium among mineral, water, and air in the soil [1].

Based on the local thermodynamic equilibrium principle, soil water content at any given matric suction ψ can be divided into two components: adsorption water $\theta_a(\psi)$ and capillary water $\theta_c(\psi)$, along with the two-physical water-retention mechanisms. Lu [1] proposed the following capillary water model:

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$$\theta_c(\psi) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\sqrt{2}\,\frac{\psi - \psi_{cav}}{\psi_{cav}}\right)\right][\theta_s - \theta_a(\psi)][1 + (\alpha\psi)^n]^{1/n-1} \qquad (1)$$

Where ψ is the matric suction, erf () is an error function, ψ_{cav} in the mean cavitation suction, θ_s is the saturated volumetric water content, n is an empirical fitted hydrological parameter with α (kPa^{-1}) being related to the inverse of the air entry suction and n being related to the pore size distribution. The adsorption water $\theta_a(\psi)$ is expressed by the following equation:

$$\theta_a(\psi) = \theta_{max}\left\{1 - \left[\exp\left(\frac{\psi - \psi_{max}}{\psi}\right)\right]^m\right\} \qquad (2)$$

Where ψ_{max} is maximum matric suction and varies 200-1200 MPa, θ_{max} is the maximum adsorption water content and m is a fitting parameter controlling the overall shape of the SWRC (Soil water retention curve) or SWCC (Soil water characteristic curve).

B. *Terzaghi's analytical solution*

Terzaghi [3] calculated the rate of capillary rise based on Darcy's law and as a function of the height of one column and the saturated hydraulic conductivity of the soil. Figure 1 conducts the conceptual model for the capillary rise in soils, defining the phenomenon as a direct relation between suction and degree of saturation, that is, the capillary rise is directly related to the characteristic curve of soil suction.

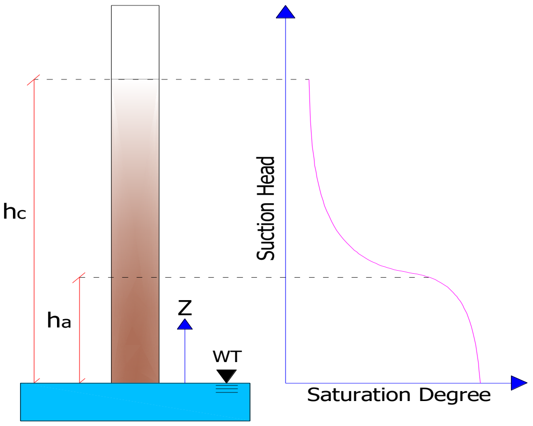


Fig. 1. The conceptual model for the capillary rise in soils.

In his study, Terzaghi made two assumptions: that Darcy's law for saturated soil is also applicable to unsaturated soil, and that the hydraulic gradient (i), responsible for capillary ascension, can be described as follows:

$$i = \frac{h_c - z}{z} \qquad (3)$$

Where h_c is the ultimate height of capillary rise; and z is the distance upwards of water above the water table. Applying Darcy's law in Equation 3, the function of saturation velocity that is derived, and can be expressed as follows:

$$\eta\frac{dz}{dt} = k_s\frac{(h_c - z)}{z} \qquad (4)$$

Where η is soil porosity, dt, and dz are the time and height differences, respectively, and k_s is the permeability coefficient of the saturated soil. Considering the boundary condition z equal to zero, when T is also zero, the solution of Equation 4 results in:

$$t = \frac{\eta h_c}{k_s}\left(\ln\frac{h_c}{h_c - z} - \frac{z}{h_c}\right) \qquad (5)$$

C. *Lu and Likos' analytical solution*

Lu and Likos [2] developed a solution for the rate of capillary rise based on the equation put forward by Terzaghi [3]. The authors considered the permeability coefficient to be nonlinear from the point where the soil ceases to be saturated and enters the wetting front. The nonlinear permeability coefficient (k) was described by Gardner [9] as a function dependent on k_s, the suction height (h), and the rate of decrease in hydraulic conductivity with decreasing suction head (α) (Equation 6 and Equation 7):

$$k = k_s \exp(-\alpha h) \qquad (6)$$

$$\frac{dz}{dt} = \frac{k_s}{\eta}\exp(-\alpha h)\frac{h_c}{h_c - z} \qquad (7)$$

The parameter α is proportional to pore size distribution. It is defined as the inverse of the saturation height (h_a), or air-entry head ($\alpha = 1/h_a$) and is between 1 cm^{-1} and 0.001 cm^{-1}. Considering Equations 6 and 7, the equation of the capillary rise defined by Lu and Likos [2] is (Equation 8):

$$t = \frac{\eta}{k_s}\sum_{j=0}^{m=\infty}\frac{\alpha^j}{j!}\left(h_c^{j+1}\ln\frac{h_c}{h_c - z} - \sum_{S=0}^{j}\frac{h_c^S z^{j+1-S}}{j+1-S}\right) \qquad (8)$$

The solution of Equation 8 is proposed to determine the rate of capillary rise (Equation 6). If linearity is considered in Equation 6, then m will be zero, and the equation reduces to Equation 5. However, if the nonlinearity is considered, m is equal to 10 for a wide range of soils.

D. *Liu et al. Model*

Liu et al. [4] developed an analytical solution to easily and quickly calculate the maximum height of capillary rise (h_c) in soils (mainly sandy soils). The solution was compared with a series of capillary rise tests of various types of soil in open tubes. The unsaturated permeability coefficient (k*) was considered as a function of the saturated permeability coefficient (k_s) and the capillary rise height:

$$k = k_s f(z) \qquad (9)$$

Where z is the height of the water above the water level (negative water height) and f is the proposed mathematical model. If Equation 9 is substituted in Equation 3, it has

(Equation 10):

$$\frac{dz}{dt}=\frac{k_s\, f(z)}{\eta}\frac{(h_C-z)}{z} \qquad (10)$$

Liu et al. [4] solved Equation 10 considering the water flow in the soil and assuming that: the fluid is incompressible and Newtonian, the flow is laminar through a tube, whose length is greater than the diameter, the acceleration in the fluid is zero. Using Poiseuille's law, the analytical solution for Equation 10 was (Equation 11):

$$h_C=\frac{\sigma\eta}{\sqrt{2n*\rho_{\omega} g k_S}}\cos\alpha+(1-\eta)h_a \qquad (11)$$

Where h_c and h_a are the maximum capillary rise height and air entry height, respectively, σ is the surface tension of water, α is the contact angle of the water-soil phase, ρ_w is water density, g is the acceleration of gravity, and n^* is the viscosity of the water. The value of $\sigma/\sqrt{(2n\rho_w g)}$ can be calculated as 0.164 ($m^{3/2}\ s^{-1/2}$) at a temperature of 20℃.

II. MATERIALS AND METHODOLOGY

A. Soils database

Several soils from current literature were used in the present study. For fine-grained soil database, soils studied by Pereira [10] from the Guabirotuba Formation, located in the city of Curitiba, Brazil were used. The geotechnical properties of Guabirotuba´s soils are exhibited in Table I.

TABLE I
GEOTECHNICAL PROPERTIES OF SOILS IN CONCORDANCE TO PEREIRA [10]

Geotechnical Property	Soil 1	Soil 2	Soil 3	Soil 4
Sand (%)	15.3	1.4	2.4	35.4
Silt (%)	26.7	23.6	19.6	34.6
Clay (%)	58	75	67	30
Specific gravity (Gs)	2.682	2.676	2.699	2.653
SUCS	CH*	MH**	MH**	CL***
Plastic Limit (%)	31.5	44.5	41.6	23.9
Plastic Index (%)	54.5	55.5	39.4	18.1
Porosity (η) in %	53.4	56.3	54.8	53.5

*CH=clay with high plasticity**MH=Silt with high plasticity***CL= clay with low plasticity

Sandy soil from Guabirotuba was employed to evaluate capillary rise. Sandy soil was previously characterized by Baldovino et al. [7]. The fraction of sand passed through sieve No. 40 and retained in sieve No. 100, where the sifting was carried out with washing and then the sand was dried in an oven at 100± 5℃ for 24 hours. The specific mass of grains (Gs) of the sand was tested, according to the D854 standard [11]. The permeability test was carried out with a constant load on the sand to obtain the saturated hydraulic conductivity coefficient (k_s). The procedure was performed according to the standard D2434-68 [12]. A specimen was molded within a 5 cm diameter and 10 cm high permeate so that the sand was as homogeneous as possible and ensuring a porosity η = 40%. The results of the sand characterization tests were: specific gravity Gs=2.688; k_s=2.959x10^{-2} cm/s for a porosity η=38.4%; k_s = 1.53x10^{-2} cm/s for η=39.9% and k_s=1.286x10^{-2} cm/s for η=45.9%. Sand compacted in different porosities is denominated as Sand 1, Sand 2, and Sand 3 for η=45.9%, 39.9%, and 38.4%, respectively.

Finally, soils denominated as Soil 5, Soil 6, and Soil 7 were used to model Terzaghi´s and Lu and Likos´s equations. Soil 5 was studied and characterized previously by Lane et al. [6] (1946) and it is a poorly graded coarse sand with k_s = 1.6x10^{-2} cm/s, h_c=28.4 cm and η=31%. Soil 5 was studied by Lane et al. [6] (1946) too. Soil 5 is sandy silt with fines and have a k_s=6.2x10^{-5} cm/s, h_c=239.6 cm and η=40%. Soil 7 were characterized as sand (namely Rewalwas sand) by Malik et al. [13] with k_s=4.4x10^{-3} cm/s, h_c=40 cm, and η=45%. Besides, Sand 3 [7] was also modeling using Terzaghi´s and Lu and Likos´s analytical solutions.

B. Suction measurements

The soils from the database were placed in an oven at a constant temperature. The dry soils were compacted in a transparent acrylic cylindrical tube (with different heights) in continuous layers and then the tube was placed on a tray with distilled water at constant height and temperature for the duration of the experiment. The exact mass and porosity of the compacted soil are calculated before the start of the experiment. Readings of the height of capillary rise were taken periodically, more frequently in the beginning, and then at greater intervals. The experiment was finalized when the water reached a maximum height (h_c).

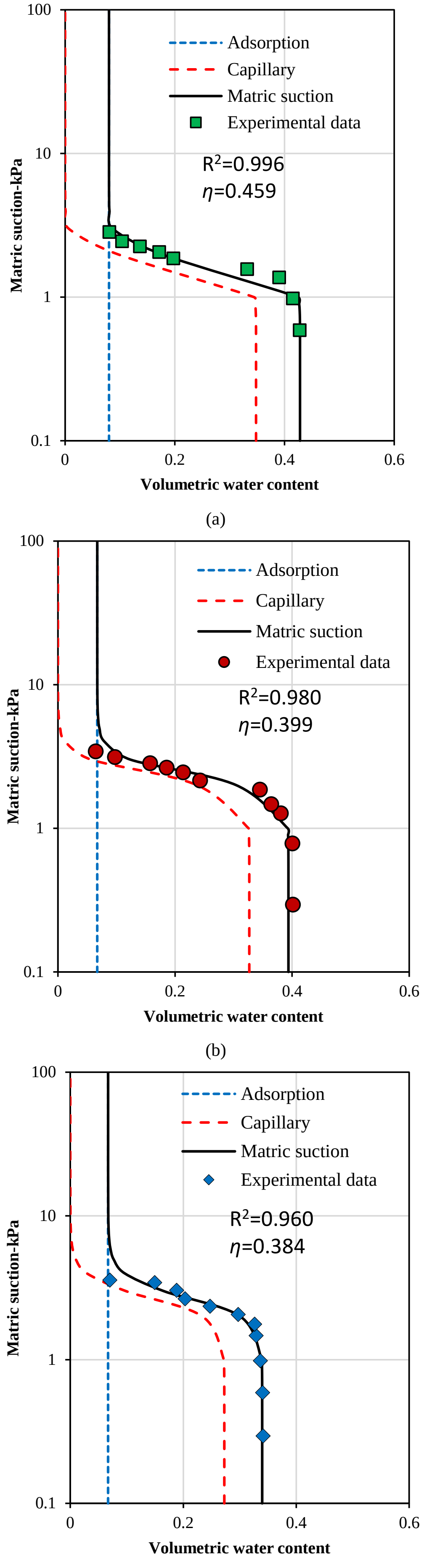
After the capillary rise readings are completed, the soils are extracted from the tube and a sample was collected to determine the water content throughout the tube. The volumetric water content of the soil can be computed. The height of a soil specimen above the water table is assumed to be equal to the capillary head (or negative pore-water pressure head) at that point. The magnitude of the negative porewater pressure head is equal to the matric suction head, as the air pressure in the tube is atmospheric (u_a= 0). The plot of volumetric water content versus matric suction gives the wetting SWCC of the soil [14].

III. RESULTS AND DISCUSSIONS

A. Lu’s Model

Figure 2 shows the soil-water characteristic curve for the sandy soil compacted in different porosities. Figure 2 demonstrates the decreasing porosity of sand the air-entry point increases. Because this value increases, the parameter α decrease too. Adsorption and capillary suction regimes are represented together matric suction. Adsorption suction is constant for small matric suctions and increases above 10 MPa. Suction is well-fit represented by Lu 2016 model. Excellent coefficients of determinations are obtained from the model with values above 0.98 (R^2>0.98).

Parameters controlling each curve are reported in Table 2. Parameters depending on soil classification: grain size distribution, density, plasticity, minerals, mainly. It is obvious in Table 2 volumetric water content to saturated fully the sand decrease when porosity is reduced. Because the voids between sand grains are reduced the matric potential increases and capillary water reaches higher heights. Thus, the forces acting on soil moisture in the unsaturated zone are attributable to the molecular attraction



(a)

(b)

(c)

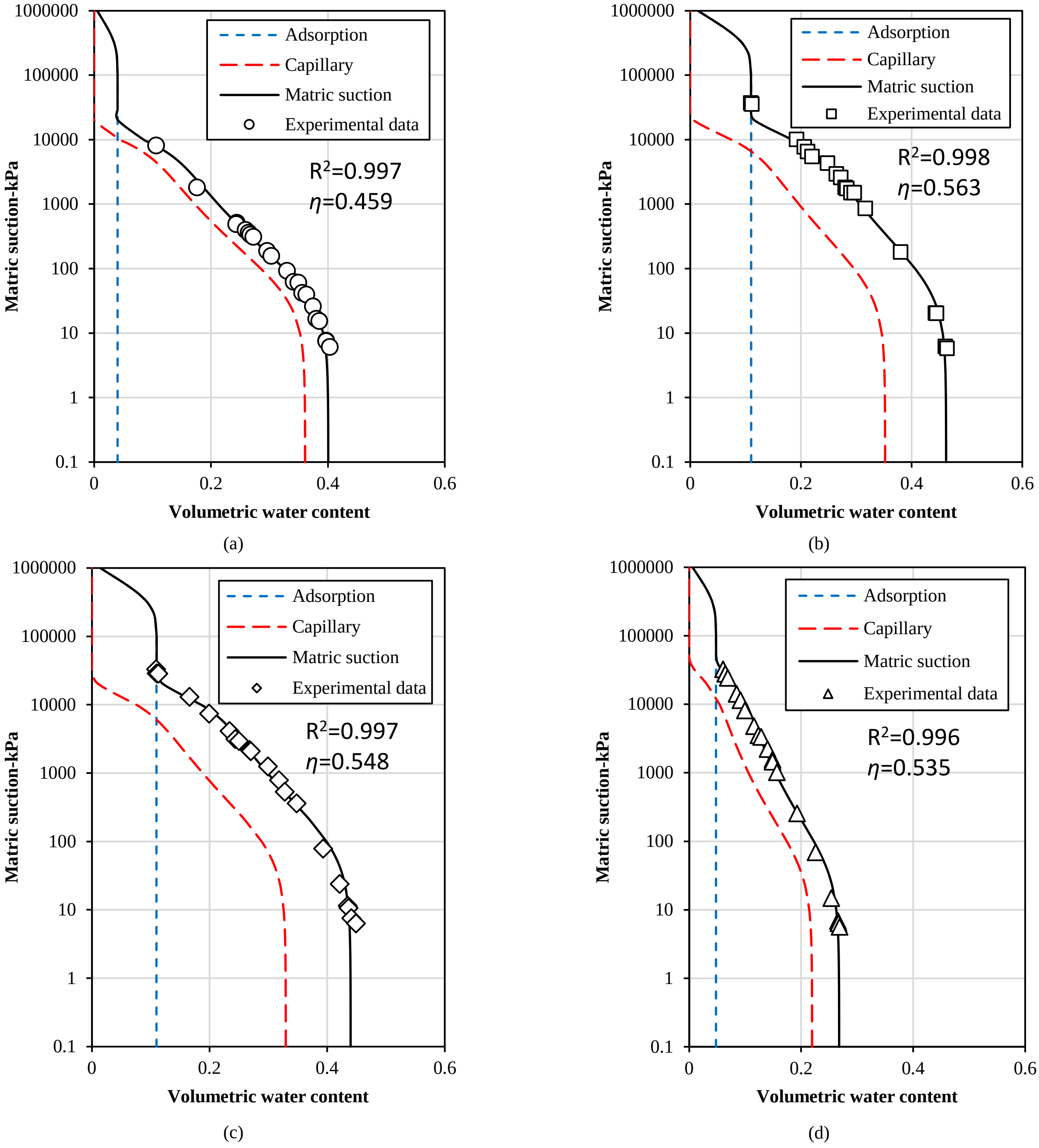
Fig. 2. Soil-water characteristic curves for the sandy soil compacted in different porosities: (a) Compacted in η=0.459. (b) Compacted in η=0.399. (c) Compacted in η=0.384.

TABLE II
PARAMETERS CONTROLLING THE LU [1] MODEL FOR THE SANDY SOIL STUDIED BY BALDOVINO ET AL. [7]

Parameter	**Soils**		
	Sand 1 (*η*=0.459)	**Sand 2 (*η*=0.399)**	**Sand 3 (*η*=0.384)**
θ_s	0.436	0.401	0.346
m	0.686	0.686	0.686
n	8.129	6.636	6.089
ψ_{max} (MPa)	1200	1200	1200
α	0.582	0.445	0.384
ψ_{cav} (MPa)	21.3	21.3	21.3
θ_{max}	0.080	0.067	0.067

between soil particles and water. By analysis from Figure 2, considering the high final saturation of soil column it can conclude the influence of suction was possibly reduced but not completely removed as explained by Baldovino et al. [15]. Figure 3 presents the SWCC of four fine soils from Guabirotuba studied by Pereira [10]. Pereira employed the filter paper technique to measure the matric suction under several states of volumetric water content. By applying Lu [1] model into Guabirotuba´s fine soils are obtained excellent correlations between volumetric water and matric suction. By comparing the SWCC curves, the slope of the SWCC curves for the portion between ψ_a (matric suction at which air first enters the largest pores of the soil during a drying process) and ψ_r (residual soil suction) is related to the parameter *n* observed in Table 3. As an example, the estimated SWCC for fine soils is shown in Figure 3, which shows close agreement with the test data of the wetting SWCC. These observations suggest that the wetting SWCC of the soil can be estimated directly from the grain-size distribution of the soil, particularly for silty-clayey soils. The results show that the shapes of the SWCCs of the soils, as determined by the soil parameters, bear a consistent relationship to the grain-size distribution of the soils (see Table 1). The effect of the porosity of the soil on the SWCC was demonstrated in concordance to Figure 2 and Figure 3. This indicates that a soil with a smaller porosity has a higher ψ_a because of the smaller pore sizes in the soil. Guabirotuba´s clays have high levels of matric suction, which directly interferes with effective tensions and soil behavior concerning erosion [7].

Coarse-grained soils have a lower air-entry value, lower residual soil suction, and lower water-entry value than a fine-grained soil. A uniform, coarse-grained soils have a smaller total hysteresis than a less uniform, fine-grained soil. Hysteresis between the drying and wetting process is approximately 0.2–1.1 logarithm cycles of suction for the SWCCs of the soils investigated by Yang et al. [14]. In the case of the present study, the drying process did not carry out and these properties cannot explain. In addition, the SWCC of uniform soils has a steeper slope than that of a less uniform soil. Soils with a large porosity have a lower air-entry value than soil with a small porosity.



(a) (b)

(c) (d)

Fig. 3. Soil-water characteristic curves of soils studied by Pereira [10] compared to absorption and capillary regimes: (a) Soil 1. (b) Soil 2. (c) Soil 3, and (d) Soil 4.

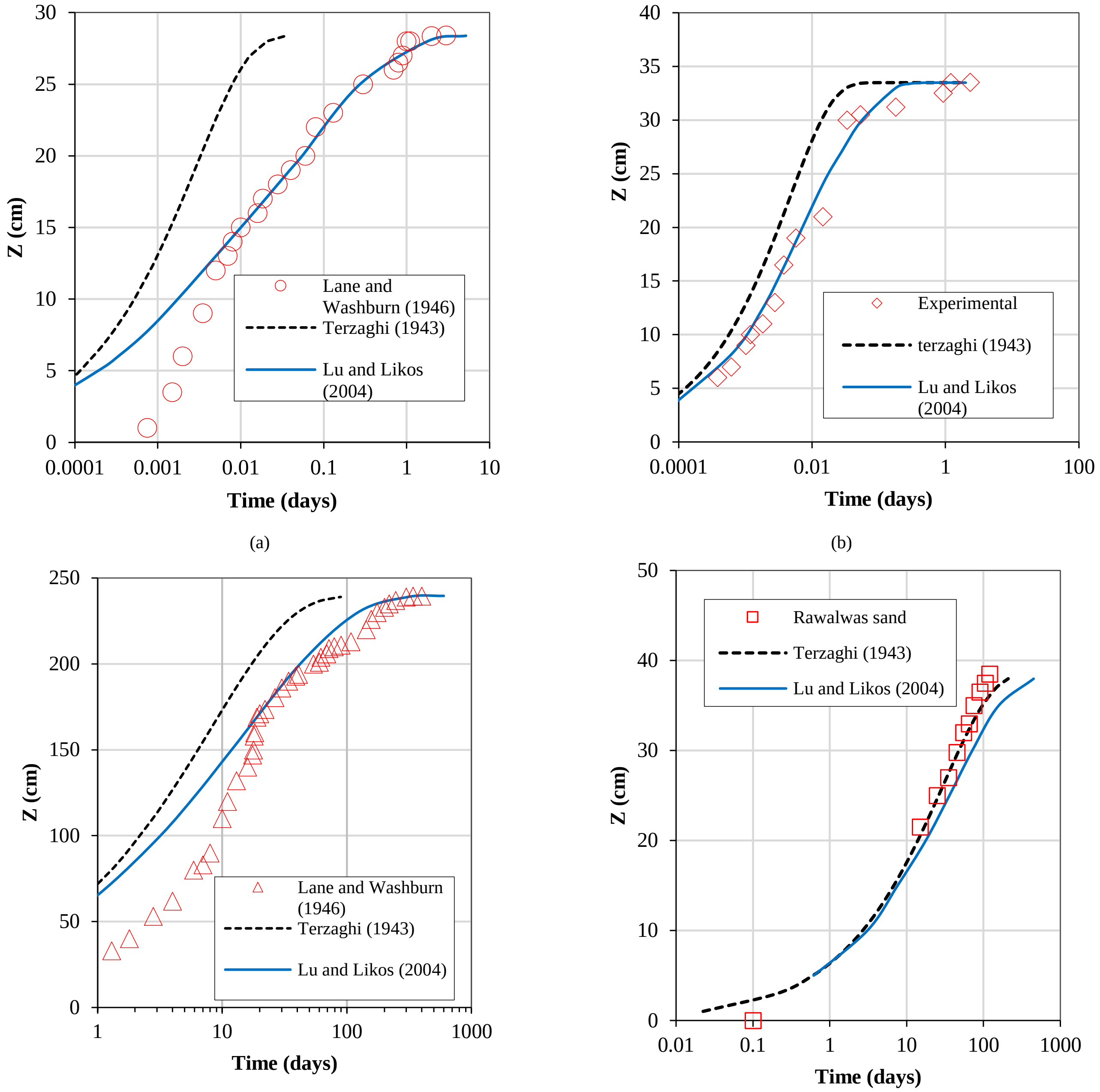
TABLE III
PARAMETERS CONTROLLING THE LU [1] MODEL FOR THE FINE SOILS FROM GUABIROTUBA FORMATION STUDIED BY PEREIRA [10]

	Soils			
Parameter	**Soil 1**	**Soil 2**	**Soil 3**	**Soil 4**
θ_s	0.409	0.470	0.448	0.273
m	0.686	0.686	0.686	0.686
n	1.240	1.204	1.232	1.243
ψ_{max} (MPa)	1200	1200	1200	1200
α	0.020	0.016	0.010	0.019
ψ_{cav} (MPa)	9.2	11.1	12.5	22.5
θ_{max}	0.040	0.110	0.110	0.048

B. Terzaghi´s and Lu and Likos Models application

Lu and Likos [2] analyzed the experimental values of capillary rise time observed by Lane et al. [6] compared with Terzaghi's [3] analytical solution and model. The calculation of the capillary rise time with Equation (5) can be obtained without the value of the height of the air-entry point. Thus, for the Lane´s soils, the Terzaghi curve can be drawn, but for soils two sandy soils, Lu and Likos [2] found the αh_c index value that best fit the experimental points. The value found for sandy soil was αh_c=5 and for soil other sandy soil the value ranges from 4 to 5. This means that, according to Lu and Likos [2], the theoretical value of h_a is between the fourth or the fifth part the maximum height of ascent.

Figure 4 shows the experimental values of the capillary rise in 4 soils used Lane et al. [6]-Soil 5 and 7, by Malik et al. [13]-Soil 6, Baldovino et al. [7]-Sand 3.



(a) (b) (c) (d)

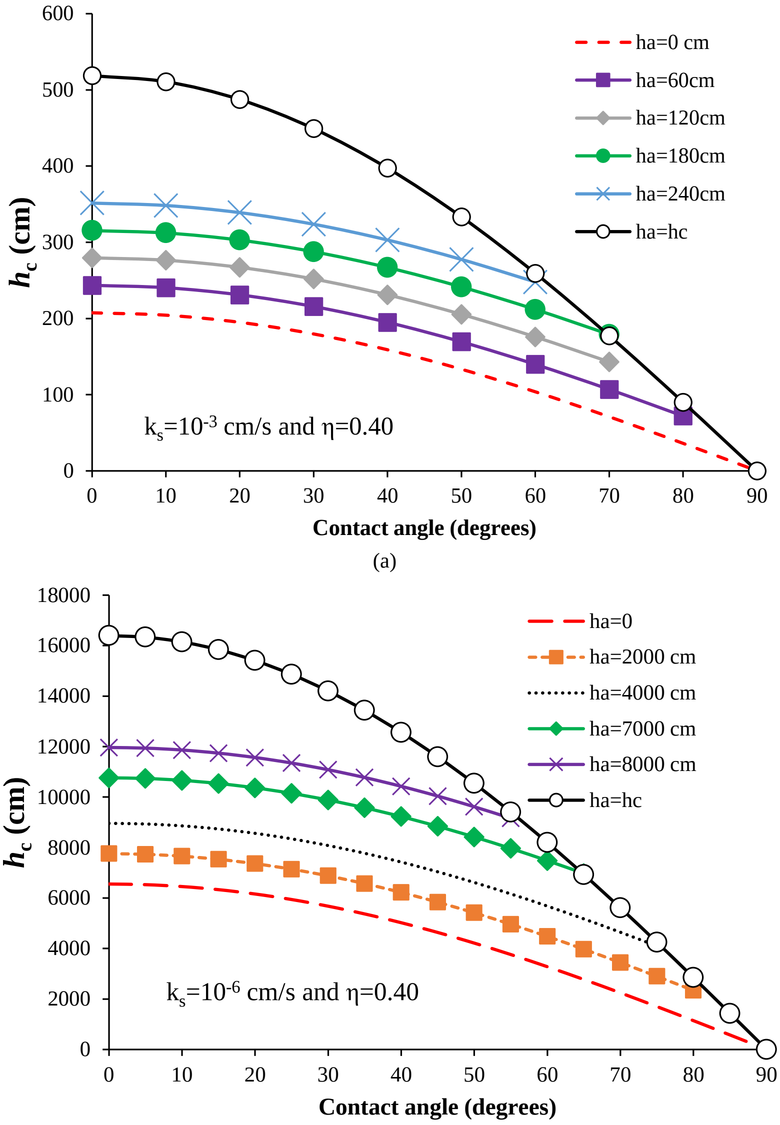
Fig. 4. Capillary rise experimental points compared to Terzaghi´s and Lu and Liko´s analytical solutions: (a) Soil 5. (b) Sand 3. (c) Soil 6, and (d) Soil 7.

The capillary rise experimental behavior was compared with the models by Terzaghi and Lu and Likos. Note that the theoretical Terzaghi curve for all soils shown in Figure 4d has a better fit with the experimental points of capillary rise compared to the rising curve of Lu and Likos. But in Soil 5, Sand 3, and soil 6, the Terzaghi curve has a better fit with the experimental points compared to Lu and Likos' analytical solution. The Rewalwas sand had a capillary rise height of 40 cm. This height is similar to Sand 3 compacted under porosity of 38%. Because more fine grains are common in clay and sands and causes more suction values, Soil 6 registers capillary height near 2.5 m in 400 days. The long term is the problem to measure suction in fine soils using the capillary rise method. Thus, the capillary rise is more appropriate for coarse materials.

C. Liu et al. [4] Model resolution

The value of k_s=10^{-3} cm/s is typical of sandy soils and sandy-silty soils, so the curves shown in Figure 5 are approximations of the maximum capillary height that could reach this type of soil.

The contact angle value of the liquid-solid phase for different soil types can vary from 0° to 90° and, according to Lu and Likos [2], the h_c/h_a ratio can vary up to 5. Thus, for the values shown in Figure 5a, the capillary rise height h_c can vary from approximately 200 cm to 520 cm. Also, h_a increases for when the contact angle decreases, and when ha increases.



(c)

Fig. 5. Variation in capillary rise height h_c for different contact angles, soil saturation heights, porosity of (a) 40% and $k_s=10^{-3}$ cm/s, and (b) porosity=40% and $k_s=10^{-6}$ cm/s [4,8].

Figure 5b shows the variation in capillary rise height (h_c) for different values of h_a and contact angles. The value of the saturated permeability coefficient remains constant at 10^{-6} cm/s, and a porosity of 40%. The value of $k_s=10^{-6}$ cm/s is typical of silty and clay soils, so the curves shown in Figure 3 are approximations of the maximum capillary height that could reach this type of soil. Thus, according to Figure 5b, soil for these porosity and permeability values can reach h_c values from 60 m to 160 m in height.

Liu et al. [4] showed the variation in the relationship between the maximum height of capillary rise (h_c) and the saturation height (h_a) depending on porosities, 40%, and 50%, and saturated permeability coefficients, 10^{-3} cm/s to 10^{-4} cm/s, thus showing different values for h_c/h_a that increase if the contact angle decreases. Lu and Likos [2] reported a maximum h_c/h_a ratio of 5, but Liu et al. [4] concluded that variations greater than 5 can be observed

The methodology by Liu et al. [4] is a clear and simple solution to calculate the maximum height of capillary rise using parameters and properties of the soil that can be easily obtained in the laboratory (apparent dry specific weight of the soil, the specific mass of the grains, permeability coefficient saturated and air inlet height). But the contact angle is more difficult to measure. Besides, Liu et al. [14] obtained an adjustment of 79% in the application of Equation 12 in experimental values of capillary rise of soils by other authors.

IV. CONCLUSION

– Two analytical solutions were used to predict the rate of capillary rise of fine/coarse-grained soils. Comparing the analytical solutions with the results obtained in the laboratory it can be said that the solution proposed by Lu and Likos [2] had a better fit, with porosity and the saturated permeability coefficient being the main control parameters.

– The Lu [1] model is suitable to measure and calculated the SWCC of soils using the height and volumetric water content measured after capillary rise experiments. The parameter αh_c is a better fit. The height of capillary rise as a function of time can be calculated using the specific gravity of the soil, the dry unit weight, the saturated hydraulic conductivity, and the air-entry head.

– All variables (from the soil) are easy to calculate and determine in a laboratory. An equation describing the capillary suction behavior of the studied soils was proposed as a function of parameters as θ_s, m, n, α, $\psi_{\max}$, ψ_{cav}, and θ_{max}, mainly.

– The use of the analytical solutions can be used to predict the rate of capillary rise of a soil which has the same characteristics of the studied soil. The solution of Lu and Likos [2] tends to predict a longer time due to the unsaturated behavior of the soil column. Besides, these solutions can be used to analyze geotechnical problems where capillary rise influences the behavior of structures, such as surface foundations and pavements, in the same way in the area of the soils in agriculture.

– The model developed by Liu et al. [4] is also suitable to estimate the h_c but do not consider the velocity of the water. Finally, the capillary rise method to measure the matric suction must be more applicable in sandy soil than clayey-silty soils.

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