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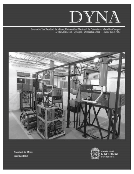

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Permeability measurement in porous media under unsaturated paths

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Abstract
Understanding the flow through porous media when it is part of geotechnical-hydraulic structures has been a scenario calculated from the most unfavorable situation. The passage of water through the porous skeleton of the soil is considered in a saturated condition. Few studies to date consider partially saturated trajectories regarding the influence on the stability of a dam, reservoir, embankment, among others. Estimating the speed with which the fluid under analysis flows through a partially saturated media is challenging to perform by conventional methods. By contrast, nowadays, it is easy to obtain for saturated soil. This study aimed to measure hydraulic conductivity (coefficient of permeability) in granular soils using easily accessible laboratory techniques. The permeability in unsaturated conditions will be measured, varying the suction in the sample, which is an essential requirement when there is a situation of partial saturation. The results provided data on the permeability values that allow to obtain a very evident difference between both proposed conditions.

Keywords: hydraulic conductivity; permeability; suction; unsaturated soils.

Medición de permeabilidad en medios porosos bajo trayectorias no saturadas

Resumen
El entendimiento del flujo a través de medios porosos cuando hace parte de estructuras geotécnico-hidráulicas, a través del tiempo ha sido un escenario calculado desde la situación más desfavorable. Es decir, el paso del agua por el tejido poroso del suelo siempre se considera en una condición saturada. Pocos estudios a la fecha, consideran trayectorias parcialmente saturadas, en cuanto a la influencia sobre la estabilidad de una presa, reservorio, terraplén, entre otros. La estimación de la velocidad con la que el fluido bajo análisis traspasa un medio parcialmente saturado, es difícil de realizar mediante métodos convencionales. Antagónicamente, hoy día es sencilla de obtener para un suelo saturado. El objetivo de este estudio consistió en intentar medir la conductividad hidráulica (coeficiente de permeabilidad), en suelos granulares usando técnicas de laboratorio de fácil acceso. La permeabilidad en condición no saturada fue medida, variando la succión en la muestra, lo cual es requisito esencial cuando existe una situación de saturación parcial. Los resultados arrojan datos sobre los valores de permeabilidad que permiten trazar una diferencia muy evidente entre ambas condiciones propuestas.

Palabras clave: conductividad hidráulica; permeabilidad; succión; suelos parcialmente saturados.

1. Introduction

Before contextualizing the topic, it is essential to clarify that the concept of permeability and hydraulic conductivity are not contradictory, nor do they mean different aspects. Simply the designation of permeability is associated with a global concept, while the hydraulic conductivity is the coefficient of permeability, the quantitative measure.

Flow in porous media is generally characterized by the passage of fluids such as water through a material with a certain level of voids. These voids allow the fluid to pass, either quickly or slowly, through the porous matrix. Within engineering, the

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study of this phenomenon can be applied to different types of knowledge. Most cases attempt to characterize this physical concept by measuring or quantifying the speed with which the water passes through the medium using a variable called the coefficient of permeability or hydraulic conductivity. In almost all the fields of this discipline, the engineering design exercise aims to predict the behavior of a particular structure using analysis parameters under very unfavorable conditions. Flow-through porous media is not contrary to this practice. Most studies include physical quantities related to permeability in a completely saturated condition, where the passage of water occurs under an effective connection, in which all pores of the material are filled with water.

However, in practice, the flow does not only exist in saturated conditions but in most cases, it is carried out in a partially saturated situation. Therefore, in geotechnical-hydraulic design, parameters in both conditions of the degree of saturation must be considered.

It is essential to understand that typically in the design or numerical predictions of geotechnical-hydraulic structures, the flow under or within the porous medium is represented by the saturated permeability value (k_s). However, part of this flow may be in partially saturated conditions. Therefore, a more suited variable is required for the analysis to design or simulate properly, such as permeability in unsaturated conditions.

Therefore, generating a parameter of unsaturated permeability will enable an additional tool for realistic analysis in hydraulic-geotechnical structures, where flow is a critical variable within the study, mainly in design or numerical prediction tasks. The evaluation of this problem will be carried out on fine granular soils. The samples will be part of the Guamo and Ottawa sands, widely used nationally and internationally.

Consequently, the main objective of the current research is to analyze the permeability in saturated and unsaturated conditions for granular soils. Measuring the hydraulic conductivity of a porous material in a partially saturated condition is complex, both in the laboratory and in the field. However, there is a technique to measure this parameter using a disk infiltrometer indirectly. It is crucial to consider that the partially (not) saturated condition is understood from the concept of suction. In other words, suction levels were incorporated into the sample to measure the permeability coefficient in this condition. This concept will be explained later. The saturated condition will be measured using a conventional up-flow permeameter.

2. Background

Since the dependence between suction and the degree of soil saturation has been shown, it is possible to identify that partially saturated hydraulic conductivity eventually maintains a correlation with these two variables [1-7]. From these studies, the concept is consolidated around the influence of the degree of saturation and suction on the soil's effective stresses.

The permeability of partially saturated soil is not a constant value during the flow through the porous medium; it also depends on elements such as suction that act within the microstructure. Experimentally, estimating the unsaturated permeability is not as easy as the saturated due to soil moisture conditions [8].

There are some techniques to obtain the hydraulic conductivity of unsaturated soils. They are directed towards stable and unstable state methodologies [7]. These two aspects of study have been studied over time [9-21]. In summary, unsaturated permeability can also be obtained through empirical formulations, macroscopic or statistical models, always including the water retention curve (WRC) [22,23].

High suction values make the permeability measurement more complicated; however, these high values generate beneficial effects on the soil in terms of its strength. Therefore, this is a challenge for today's researchers in this area. Suction can be imposed using techniques such as axis translation [24], vapor balance and osmotic techniques in stable states.

In unstable states, the suction in the system is continually modified, which influences the volumetric variability of the earth pack. Impact on quantities refers to humidity, degree of saturation, and specific volume. If the terrain also presents load stresses unrelated to the soil skeleton, measurement difficulties increase [7]. For this reason, the definitions of permeability without external loads are not realistic because slope failures of this style have been reported in relict slopes [25]. However, any study on the soil's unsaturated permeability can better understand this phenomenon, which has been little studied in the last 30 years.

Currently, the understanding of the flow phenomenon in partially saturated soils has not been thoroughly studied [26]. For a clear understanding of this mechanism, the permeability of the soil must be studied in these intermediate saturation conditions. This study deals precisely with this problem. It attempts to improve knowledge about the permeability in fine sands for different degrees of suction. The granular soils are widely used in the engineering area so that the result can be relatively quickly associated with known hydraulic behaviors.

In the study of permeability in saturated conditions (k_s), typically, the appraisals are developed regarding the void ratio. Since the degree of saturation is considered a constant parameter in any analysis. In contrast, partially saturated permeability must be evaluated considering the void ratio and the humidity. The hydraulic conductivity determines the influence of the void ratio, while another function defines the humidity. Direct and indirect techniques can be applied to obtain permeability in partially saturated soil [27]. The permeability measurement must be carried out both in the laboratory and in the field. Experimentally, it is possible to control more aspects that lead to the accuracy of the results [28]. Methods that allow the WRC to be traced indirectly estimate the unsaturated permeability.

The stable methods mentioned support obtaining the hydraulic conductivity by imposing a constant head on the sample [7]. When the water flows through the sample, the soil is left with a matric suction and controlled humidity. The unstable methods, such as variable head, penetration methodologies, and expedited techniques, can be performed in the laboratory or in-situ. The movement of the flow can be through wetting or drying, depending on the initial conditions of the test [7,29]. According to [30], it is difficult to maintain the state of stress in the sample during the test.

The trace and qualitative trends of the permeability function concerning humidity are similar to the water retention curve [31]. Multiple functions have been proposed to estimate

Table 1.
Equations for permeability functions.

Type	Permeability functions	Reference
$k = f(\theta_\omega)$	$k_\omega = a\theta_\omega^b$	[37-40]
	$k_\omega = k_s\left({}^{\theta_\omega}/_{\theta_s}\right)^b = \left({}^{\Delta \log \varphi}/_{\Delta \log \omega}\right)$	[41-44]
	$k_\omega = k_s e^{[b(\theta_\omega - \theta_s)]}$	[44,45]
$k = f(\psi)$	$k_\omega = a + b\varphi$	[46,47]
	$k_\omega = a\varphi^{-b}$	[46,37]
	$K_\omega = K_s\left\{\frac{(u_{a-}u_\omega)_b}{(u_{a-}u_\omega)}\right\}^\eta, \eta = 2 + 3\lambda$ $K_\omega = K_s \therefore u_{a-}u_\omega \leq (u_{a-}u_\omega)_b$	[6]
	$k_\omega = \frac{k_s}{1 + a\left(\frac{\varphi}{\rho_\omega g}\right)^b}$	[48]
	$k_\omega = ae^{(b\varphi)}$	[49]
	$k_\omega = k \therefore \varphi \leq \varphi_b$	[50]
	$k_\omega = k_s e^{[b(\varphi - \varphi_b)]} \therefore \varphi > \varphi_b$	[51]

Source: Adapted from [26]

permeability under partial saturation conditions [7,27,32-35]. The functions mostly show correlations between the WRC, permeability, and void ratio. The WRC shows concordance with the suction vs. permeability curve [22,27,36]. Table 1 shows some proposals for permeability functions using different geotechnical parameters.

Where a and b are constant scalars, k is the permeability coefficient, w and s indicate unsaturated and saturated condition, S denotes the degree of saturation, ψ is the matrix suction, θ_ω corresponds to the volumetric water content, and φ_b is the angle of friction due to increased suction.

In general, any water flow in saturated soil can be described by Darcy's law (1856). This law proposed that the flow that passes through a porous medium is proportional to the hydraulic gradient (eq. 1).

$$v_\omega = -k_\omega \frac{\delta h_\omega}{\delta y} \tag{1}$$

Where v_w is the flow rate, k_w is the permeability coefficient concerning the water phase, and the other term is the hydraulic gradient. The hydraulic conductivity that is presented as a constant value for saturated soils, after the mathematical integration process of the equation, which is called the coefficient of optionality between the flow rate and the hydraulic head, is perfectly applicable for partially saturated soils according to studies on the subject [31,52]. However, some adjustments must be made because the unsaturated hydraulic conductivity is not constant during the test since it depends on more variables, such as the matric suction.

It is logical to think that the flow will be faster in saturated soil because it encounters a continuous phase like water. However, in unsaturated soils, the presence of air in the pore will hinder the flow in the soil. Additionally, Darcy's law must be verified to monitor its application in unsaturated soils. Experimentally, in this kind of test, the humidity should always be kept constant as much as possible, while the hydraulic head is varied. Fig. 1 shows some empirical verifications of Darcy's law for flow through unsaturated soil [52].

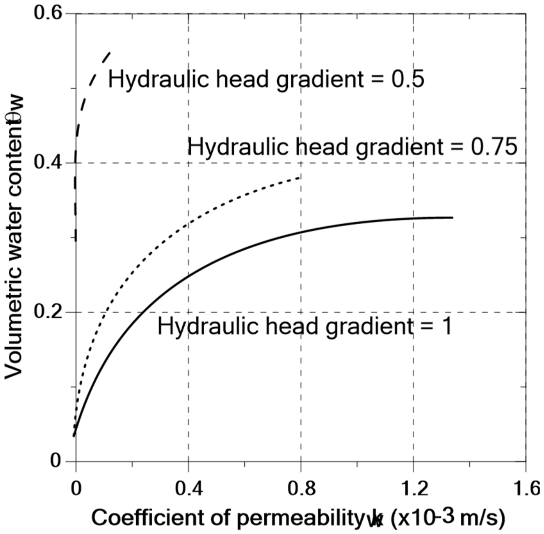

Figure 1. Experimental verification of Darcy's law for unsaturated soils.
Source: [52]

This study shows that, for a given humidity, kw is constant for various hydraulic gradients in different unsaturated simples. Then the flow rate is proportional to the pressure head with constant hydraulic conductivity, analogously to what happens in unsaturated soil, that is, endorsing Darcy's law.

In principle, the avant-garde of the subject is accompanied by the use of modern analytical methodologies such as fractal theory. Chen et al. [53] developed a model of multiphase flow through partially saturated porous media. The pore structure is modeled by a fractal scaling law, considering the water located in the pores. There is a correlation between permeability, capillary pressure, and degree of saturation. Fourteen sets of experimental data tests were used, demonstrating that the fractal model converges with the data obtained from the tests.

Other investigations study flow using large pressure heads as described by [54]. The infiltration was carried out for 62 days with a 4 m head. The results were validated by a 1D numerical study using an infiltration theory for unsaturated soils. The main contributions of this study show a relationship between hydraulic properties in the stable zone and the flow velocity, which is determined by the average infiltration rate. Regarding other types of porous media, such as solid waste, [55] determine WRC in the laboratory by analyzing the effect of aging and dry density on hydraulic parameters. The life cycle of leachates in the sanitary landfill was studied through saturated and unsaturated filtration analysis considering the precipitation.

[56] propose a model to reproduce the WRC using basic measurements of soil properties. Empirical equations were established to evaluate parameters of the reference model, saturated permeability, granulometry, and plasticity index. The model was verified by applying results from different WRCs found in the literature, which were not included in the calibration of the model. The proposed model presented better predictions than the existing models.

3. Methodology

A series of tests were proposed for essential characterization and the material's basic knowledge, such as permeability tests

Table 2.
Material permeability tests.

Model	Guamo Sand	Ottawa Sand
Saturated	Three replicates	Three replicates
Unsaturated suction 1 cm	Three replicates	Three replicates
Unsaturated suction 2 cm	Three replicates	Three replicates
Unsaturated suction 3 cm	Three replicates	Three replicates
Unsaturated suction 4 cm	Three replicates	Three replicates
Unsaturated suction 5 cm	Three replicates	Three replicates

Source: The authors

Table 3.
Gravity and loose unit weight of granular materials.

Material	Gs	Loose unit weight (g/cm3)
Guamo Sand	2.70	1.41
Ottawa Sand	2.67	1.47

Source: The authors

under full and partial saturation conditions. These will provide the necessary data to conclude about the essence of the project. Table 2 shows the permeability tests that were part of the research.

3.1 Basic characterization of the material

Before the main research tests, it was essential to understand the materials involved in the research. The specific gravity and loose unit weight of the sand from the Guamo and Ottawa rivers can be found below (Table 3). These were averaged from ten tests performed. It is essential to highlight that the specimens for the execution of the saturated permeability tests (Norm INV-E 130-13, Permeability of granular soils under constant head) and unsaturated permeability (mini-disk infiltrometer) were made using a loose condition of the sample, which was prepared by simple dipping on the container.

Particle size distribution is a factor that can indirectly provide information on the type of pores that the sample presents. Although to know the characterization of the pore, a mercury intrusion porosimetry test is required. However, it is not widely used in granular soils. The grain size of the Guamo sand is slightly more porous, translating into higher permeability coefficient values (Fig. 2).

3.2 Saturated and unsaturated permeability

The permeability tests, in the conditions previously mentioned, were conducted by a conventional permeameter, as illustrated in Fig. 3. Based on the recommendation of the norm INV-E-130-13 for saturated samples. As already mentioned, the sample was assembled using a maximum void ratio condition, that is, in a situation of loose unit weight. The permeability coefficient, in this case, is calculated as shown in eq. 1.

Regarding the partially saturated permeability tests, a mini-disk infiltrometer was used, consisting of a sintered steel disk, a suction regulation tube, a reservoir, and a Mariotte tube (Fig. 4).

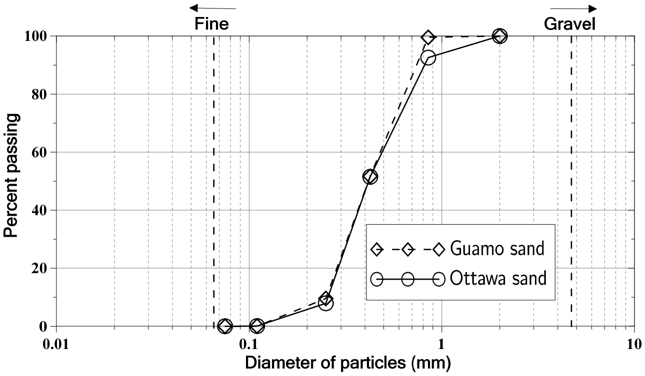

Figure 2. Particle size distribution of the materials.
Source: The authors.

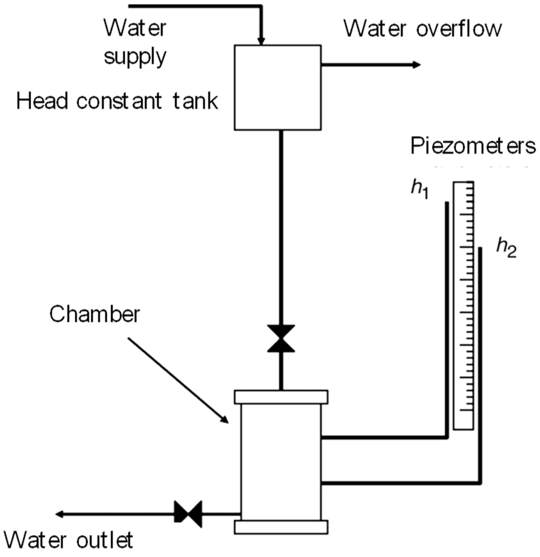

Figure 3. Constant head permeameter.
Source: The authors.

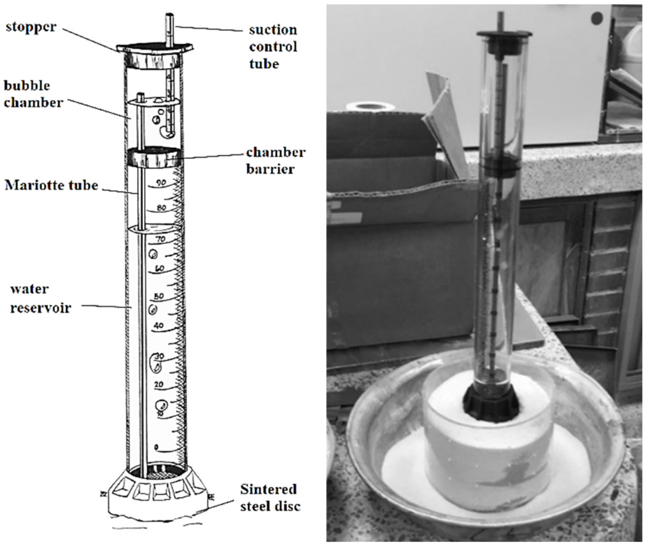

Figure 4. Mini-disk infiltrometer.
Source: The authors.

For suction measurement, both chambers must be filled with water. The 10.2 cm long upper chamber is responsible for maintaining constant suction during the test. According to the suction imposed on the upper chamber (bubble chamber), the 135 ml volume reservoir releases the water that will infiltrate the soil. The bottom of the device has a porous disk that will not allow water to seep into the open air but rather percolate directly to the ground. The reduced diameter of the disc makes it possible to measure without alterations on the surface level of soil samples.

When the device is placed in the soil sample, water begins to infiltrate the soil at a rate that depends on the suction and soil properties (in this case, the unit weight). As the water level drops, the volume is recorded at specific time intervals. It is vital to remember that the suction imposition is local, right in the place where the porous disc comes into contact with the ground.

The calculation of the unsaturated permeability coefficient (k_u) is estimated by the method of Zhang [57]. It requires the collection of water infiltration data vs. time, which are adjusted by eq. 2, where C_1 and C_2 are parameters related to the hydraulic conductivity and sorptivity of the soil.

$$I = C_1 t + C_2\sqrt{t} \tag{2}$$

The hydraulic conductivity of the soil is calculated from eq. 3. C_1 is the slope of the cumulative infiltration curve vs. the square root of time.

$$k_u = \frac{C_1}{A} \tag{3}$$

A is the value that articulates the Van Genuchten parameters for a given type of soil with the suction rate and the radius of the mini-disk infiltrometer. *A* is calculated from the following use eq. (4)-(5):

$$A = \frac{11.65(n^{0.1} - 1)\, e^{[2.92(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}} \quad \therefore n \geq 1.9 \tag{4}$$

$$A = \frac{11.65(n^{0.1} - 1)\, e^{[7.5(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}} \quad \therefore n < 1.9 \tag{5}$$

Where n and a. are the Van Genuchten parameters for the soil, previously calculated [58], r_o is the radius of the disk, and h_o is the suction on the surface of the porous disk. The device allows water to infiltrate when the suction values are between 0.5 and 6 cm, with a radius of 2.25 cm. From measured data, a cumulative infiltration curve vs. t½ is obtained. Using the coefficients of the quadratic equation, C_1 is calculated, which is necessary to obtain k_u (Fig. 5).

4. Results

Table 4 shows the results of the tests carried out on the saturated samples in loose conditions.

In this case, the permeability coefficient shows values comparable to those stated by [59] as a clean sand, and [60,61], who typify this value as a medium to high permeability. In the particle size distribution results, it could be inferred that the granulometry of the Guamo sand is slightly coarser, which means that its pores are also somewhat more significant. The above can be seen in the coefficient results, which are also slightly high.

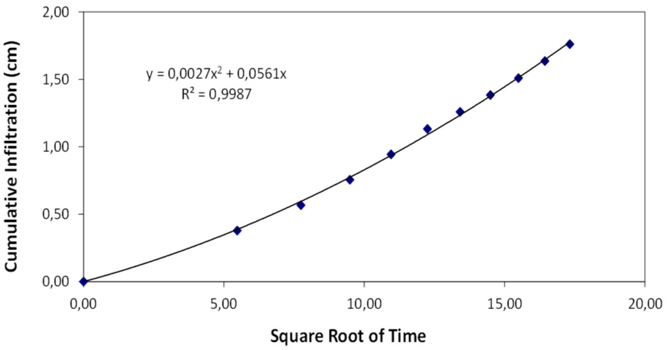

Figure 5. Graph to obtain the parameters of the van Genuchten equation.
Source: The authors.

Table 4.
Saturated permeability results.

Material	Sample	Time (s)	Initial Height (cm)	Final Height (cm)	k_s (cm/s)
Guamo Sand	1-G	4.37	160	50	0.0242
	2-G	4.47	160	50	0.0236
	3-G	3.86	160	50	0.0274
Ottawa Sand	1-O	4.86	160	50	0.0217
	2-O	5.03	160	50	0.0210
	3-O	4.92	160	50	0.0215

Source: The authors.

On the other hand, the unsaturated hydraulic conductivity will be calculated for five suction values imposed on the upper chamber of the device. According to the supplier's instructions, some parameters were previously estimated. The following values were taken for a clean sand sample, as is the case of both types of sand used in the tests (Table 5).

The results of the unsaturated permeability coefficients are shown in Table 6. A trend that is evident when reviewing the values is that the applied suction levels, although small, directly influence the unsaturated permeability.

Table 5.
Van Genuchten parameters and A value for unsaturated permeability tests.

Texture	α	n	Suction h_o (cm)				
			1	2	3	4	5
Clean Sand	0.145	2.68	2.40	1.73	1.24	0.89	0.64

Source: The authors

Table 6.
Saturated permeability results.

Material	Sample	Suction (cm)	k_s (cm/s)
Guamo Sand	1-G	1.0	0.0227
	2-G	2.0	0.0216
	3-G	3.0	0.0208
	4-G	4.0	0.0194
	5-G	5.0	0.0187
Ottawa Sand	1-O	1.0	0.0209
	2-O	2.0	0.0192
	3-O	3.0	0.0187
	4-O	4.0	0.0165
	5-O	5.0	0.0145

Source: The authors

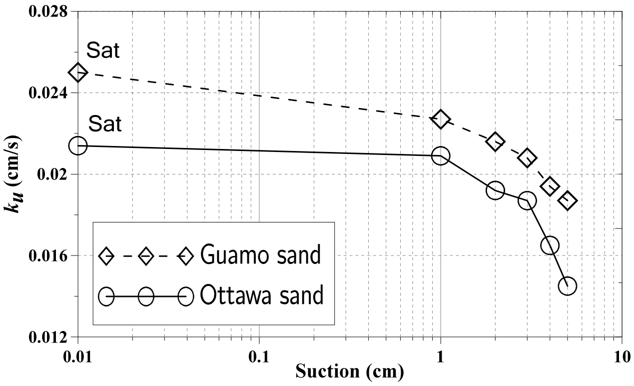

Figure 6. Suction curve vs. partially saturated permeability coefficient
Source: The authors.

Before measurements, it was suspected that the saturated permeability, in any case, would be higher than the partially saturated situation. This can be explained because the saturated medium is an effective flow channel for permeability, so the water has a continuous connection to permeate through the sand.

Although the sandy soil stiffens because it generates tension between the granular skeleton due to the surface tension in the pore meniscus, the permeability will be affected by increasing the suction. This phenomenon happens because the water that enters the sample for the first time adheres to the particles forming a meniscus due to the vacuum effect offered by suction. Of course, at higher suction values, the effect is increased, and the water entering the ground does not find an effective predecessor water connection. Instead, it has to traverse a dry path down the poral throat.

Fig. 6 shows the dependence between the suction and the permeability of the soils used in the study.

5. Conclusions

The permeability coefficients in saturated and partially saturated conditions were obtained effectively by using the proposed methodologies such as the constant head permeameter and the mini-disk infiltrometer with the imposition of matrix suction.

It is observed that the suction has a tension effect on the granular skeleton of the samples, which causes the water that enters the soil to adhere to the particles forming a meniscus in the pore due to the surface tension, among other physical effects. Namely, this means that the water does not find a continuous path to flow and must follow the advancing front towards dry poral throats. This effect is the opposite of the saturated scenario, where the water will always find a continuous phase in front, which facilitates the flow speed, increasing its permeability coefficient.

A clear dependence between suction and the unsaturated permeability coefficient was evidenced. This technique could be helpful to correlate this curve with the WRC, which in some techniques may have problems obtaining suction for low levels due to the technical limitations of some equipment.

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