Revista EIA, ISSN 1794-1237 / Year XIII / Volume 13 / Issue N.25 / January-June / pp. 53-68
Technical-scientifical biannual publication / Universidad EIA, Envigado (Colombia)

NUMERICAL ANALYSIS OF THE WATER INFILTRATION PROCESS AND STRAIN LOCALIZATION IN PARTIALLY SATURATED SOILS

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ABSTRACT

This paper presents one- and two-dimensional simulations of the water infiltration process on unsaturated soils by using a coupled infiltration-deformation model. Two examples are presented for the one-dimensional infiltration analysis. The first example simulates the infiltration process on a homogenous soil, and the second on a stratified soil composed of two different layers. For both cases, a one-meter column of soil was used to conduct a parametric study by assuming different values of rainfall intensity. It was found from this analysis that the one-dimensional infiltration process on the homogenous soil is highly dependent on the rainfall intensity (I) / permeability (k_s^W) ratio, and for the stratified soil, the infiltration process was controlled by the soil with less permeability. Finally, one example is presented to study the bi-dimensional infiltration process on a slope subjected to a high-intensity rainfall, where the localization of the failure surface is presented. The results of this analysis show the advantages of this methodology to study soil structures subjected to infiltration processes.

KEYWORDS: Unsaturated soils; Infiltration; Rainfall intensity; Strain localization; Numerical analysis.

ANÁLISIS NUMÉRICO DEL PROCESO DE INFILTRACIÓN DE AGUA Y LOCALIZACIÓN DE DEFORMACIÓN EN SUELOS PARCIALMENTE SATURADOS

RESUMEN

En este trabajo se presentan simulaciones del proceso de infiltración de agua en suelos parcialmente saturados en una y en dos dimensiones, haciendo uso de un método acoplado infiltración-deformación. El estudio de la infiltración unidimensional se realizó en dos partes: primero, considerando un suelo homogéneo y, posteriormente, un suelo estratificado compuesto de dos horizontes diferentes. Para ambos casos se modelaron columnas unidimensionales de un metro de espesor, con las que se realizó un estudio paramétrico tomando diferentes valores de Intensidad de lluvia. Del análisis se encontró que el fenómeno de infiltración unidimensional tiene una alta dependencia de la relación intensidad de lluvia (I)/Permeabilidad del suelo (k_s^W) y en el caso de los suelos estratificados se evidenció un control de la infiltración por parte del suelo de menor

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Paper history:
Paper received: 28-IV-2015 / Approved: 06-IV-2016
Available online: October 30 2016
Open discussion until October 2017

DOI: http:/dx.doi.org/10.14508/reia.2015.13.25.53-68

permeabilidad. Finalmente, se analizó el caso de infiltración bidimensional mediante la modelación de un talud sometido a lluvia de alta intensidad donde se pudo localizar la superficie de falla en el talud. Los resultados de este análisis muestran el potencial de esta metodología para el estudio de estructuras de suelo sometidas a procesos de infiltración.

PALABRAS CLAVE: suelos parcialmente saturados; infiltración; intensidad de lluvia; localización de deformación; análisis numérico.

ANÁLISE NUMÉRICA DO PROCESSO DE INFILTRAÇÃO DA AGUA E LOCALIZAÇÃO DE DEFORMAÇÃO EM SOLOS PARCIALMENTE SATURADOS

RESUMO

Neste trabalho apresentam-se simulações do processo de infiltração da agua em solos não saturados em uma e duas dimensões, mediante a utilização de um código acoplado infiltração-deformação. O estudo da infiltração unidimensional realizou-se em duas partes: primeira, considerando um solo homogêneo e, posteriormente, um solo estratificado com uma configuração de duas camadas diferentes. Em ambos os casos as simulações consideraram colunas unidimensionais de um metro de comprimento com as quais foram feitas análises paramétricas para diferentes valores de intensidade da precipitação. As análises mostraram que o processo de infiltração unidimensional é altamente dependente da relação Intensidade da precipitação (I) / Permeabilidade do solo (k_s^W) e, no caso do solo estratificado evidenciou-se que a infiltração está governada pela camada de menor permeabilidade. Finalmente, analisou-se o caso da infiltração bidimensional mediante a modelagem de um talude submetido a uma precipitação de alta intensidade sendo possível identificar a aparição da superfície de ruptura no talude. Os resultados desta análise mostraram o potencial desta metodologia para o estudo de estruturas geotécnicas submetidas a processos de infiltração.

PALAVRAS CHAVE: Solos parcialmente saturados; Infiltração; Intensidade de precipitação; Localização da superfície de ruptura; Análises numéricas.

1. INTRODUCTION

Currently, the numerous analyses gathered together for partially saturated soil are being utilized more and more to study problems related to the effect of water infiltration on the stability of slopes and embankments. Failures in these structures occur frequently due to different rain conditions involving periods of short and long duration. When water infiltrates partially saturated soil its moisture increases. Consequently, changes occur in pore pressures (suction reduction), reducing resistance to material cutting. For that reason, the study of water infiltration in partially saturated soil and its effect on deformation is a topic with a wide interest and a continued need for research in the field of geotechnics.

Many have conducted experimental research to study water infiltration in partially saturated soil (Liakopouthe, 1964; Yang et al., 2004; Bathurst et al., 2007).In that vein, Sryvastava & Yeh (1991) proposed analytical solutions for describing the infiltration process in one dimension in homogenous and stratified soils; their results were then utilized by Zhang & Ng (2004) to analyze the effect of hydraulic parameters and rain conditions on the infiltration process. The first people to obtain an analytical solution for the one-dimensional infiltration-deformation process were Wu & Zhang (2009), who used a constitutive model introduced by Fredlund (1993), and whose results demonstrated that the most important variables in the distribution of suction in a column of soil and its deformation are changes in volume due to changes in suction, and the relationship between the intensity of the rain and the saturation permeability of the soil (I/k_s^W). Recently, Wu et al. (2015) presented a combined analytical solution for a flow border variable demonstrating that the combination of infiltration and deformation has a significant effect on the distribution of pressure for a transitory flow in unsaturated soils. This shows that it is necessary to conduct a coupled infiltration-deformation analysis so that the problem of infiltration in partially saturated soils can be analyzed in a way that ensures the most accuracy.

Currently, numeric solutions have been converted into a potential analytic tool due to the ease of implementation with different types of borders and initial conditions (variety in stratified soils, intensity of variable rain, and complex geometries) which allow for an improved approach to the problems that occur in geotechnics engineering. In this way, various authors have developed numeric solutions for the study of water infiltration in porous mediums: Cai &Ugai (2004) researched the effects of hydraulic characteristics in the transition flow of water through saturated and partially saturated slopes and the involvement they have in their strength. Pinder & Gray (2008) studied the behavior of infiltration and drainage of air and water in homogenous and heterogeneous soils. Griffiths & Lu (2005) used Bishop's definition for the effective stress in partially saturated soils together with the theory of one-dimensional suction to analyze the stability of a slope as a result of water infiltration. Ehlers et al. (2004) used a coupled infiltration-deformation method that included the terms of effective pore pressure and effective stress to calculate deformations in partially saturated soils caused by water flow. Likewise, Cho & Lee (2001) utilized the same type of model to analyze stability in slopes, as well as Alonso et al. (2003) to calculate deformation and the safety factor of an unstable slope in an over consolidated clay profile. Oka et al. (2009), Kato et al. (2009) and Kimoto et al. (2013) investigated the characteristics of a coupled infiltration-deformation process in partially saturated dams and embankments. Wu & Selvadurai (2016) conducted research on the effect of variable infiltration border conditions on homogenous soil horizons, finding that the coupling has a significant influence on the position of accumulated water levels.

The advantage of coupled infiltration-deformation methodologies is they make it possible to keep in mind the changes in the conditions of the material's effective stress and deformation due to variations in the level of saturation produced by the water infiltration process. This allows for the study of deformation distribution and the location of the most likely failure surface, which is not possible when using classic analysis methodologies for slope stability.

This work presents a coupled infiltration-deformation model and, afterwards, using this methodology, examines the following case studies of interest in the engineering field: (1) one-dimensional infiltration process in homogenous soil, (2) one-dimensional infiltration process in stratified soils, and (3) distribution and location of the failure surface in a homogenous slope. The analyses presented attempt to examine the phenomenon of soil infiltration and deformation, showing the advantages provided by the coupled methods to investigate infiltration problems, easing observation at the time of the most important variables in operation there. The results are thus presented from a study on variation in saturation, suction, and deformation when materials are submitted to different infiltration scenarios.

Coupled infiltration-deformation model

Oka et al. (2006) formulated a coupled infiltration-deformation method based on finite elements and utilizing a viscoplastic model for the description of the behavior of partially saturated soils (Kimoto & Oka, 2005). This methodology is utilized for case analysis further on. The proposed methodology is based on the fundamental concepts of the Porous Medium Theory (e.g., Biot, 1962; Atkin &Craine,

1976; Boer, 1998; Ehlers, 2003). It is assumed that the soil is composed of three phases: solid, liquid, and gas, which are distributed in a continuous manner through space. During the analysis, water pressure, air pressure, and deformation are taken as independent variables. The following is a description of the components of the methodology and the equations employed:

Strength variables

The behavior of the material is described within the framework of continuum mechanics through use of the Porous Medium Theory. Terzaghi (1943) defined the concept of effective stress for saturated materials. However, the processes of infiltration occur for the most part in partially saturated soils; therefore, the concept of effective stress must be redefined with the aim of considering a gaseous phase included in the pores of the material.

With the objective of defining the stresses that occur in partially saturated soil, an effective stress is adopted for the granular structure σ'_{ij} (Oka *et al.* 2010), which is analogous to the effective stress of saturated soils. The total stress tensor, σ_{ij}, is obtained by adding the partial stresses accordingly:

$$\sum_{\alpha} \sigma^{\gamma}_{ij} = \sigma_{ij}\,(\gamma = \mathrm{S,W,G}) \tag{1}$$

$$\sigma^{s}_{ij} = \sigma'_{ij} + n^{s} P^{F} \delta_{ij} \tag{2}$$

$$\sigma^{W}_{ij} = n^{W} P^{W} \delta_{ij} \tag{3}$$

$$\sigma^{G}_{ij} = n^{G} P^{G} \delta_{ij} \tag{4}$$

Where P^W and P^G are water and air pressure, respectively; n is the porosity; n^γ is the volumetric fraction of the phase γ (γ=S: Solid, W: Water, G: Air); d_{ij} is the Kronecker delta function, and P^F is the average of the calculated pore pressures in accordance with saturation, s, as follows:

$$P^{F} = sP^{W} + (1 - s)\,P^{G} \tag{5}$$

From **Equations 1** through **5** the effective stress equation is derived for partially saturated soil,

$$\sigma'_{ij} = \sigma_{ij} - P^{F} \delta_{ij} \tag{6}$$

Conservation of mass

The conservation of mass is given by the following equation:

$$\frac{\partial}{\partial t}\,(n^{\gamma}\rho_{\gamma}) + (n^{\gamma}\rho_{\alpha} v^{\gamma}_{i})i=0 \tag{7}$$

Where ρ_γ is the density of the material, and v^γ_i is the velocity in phase γ. Supposing that the spatial derivatives of the volumetric fraction n^γ are negligible, and that the solid particles and water are incompressible, the laws of conservation for the water and air phases can be expressed in the function of s and n, as follows:

$$sD_{ii} + \dot{s}n - V^{W}_{i,i} \tag{8}$$

$$(1-s)D_{ii} - \dot{s}n + (1-s)n\,\frac{\dot{\rho}_G}{\rho_G} = - V^{G}_{i,i} \tag{9}$$

Where D_{ii} is the volumetric deformation and V^γ_i is the apparent velocity of the phase γ.

Balance equation

The variation of the balance equation can be expressed in the following way:

$$\int_{V} \dot{\hat{S}}_{ji,j}\, dV = 0 \tag{10}$$

Where $\hat{S}_{ij}$ is the nominal stress tensor.

Curva de retención de agua

The relationship between saturation and suction occurs by way of the equation proposed by Van Genuchten (1980), as follows:

$$S = S_{\mathrm{min}} + (S_{\mathrm{max}} - S_{\mathrm{min}}) \left\{ 1 + (\alpha P^{C})^{n'} \right\}^{-m} \tag{11}$$

in which P^C is suction; α, n', and m are the material parameters, where $m=1-1/n'$; and s_{max} and s_{min} are the maximum and minimum saturation limits, respectively. The effect of the degree of saturation on the permeability of the fluids is established in the following manner:

$$k^{W} = k_s^{W}\, s^{a} \left\{ 1 - \left(1 - s^{1/m} \right)^{n'} \right\} \qquad (12)$$

$$k^{G} = k_s^{G}\, (1 - s)^{b} \left\{ 1 - \left(s^{1/m} \right)^{n'} \right\} \qquad (13)$$

Where a and b *b*are the material parameters, k_s^{W} is the coefficient of permeability for water under saturated soil conditions and k_s^{G} is the coefficient of permeability for air under dry soil conditions.

Constitutive model for partially saturated soil

Kimoto & Oka (2005) formulated a constitutive viscoplastic model for the description of the behavior of partially saturated soils. In this model, it is assumed that an over consolidation surface exists (*fb*) which demarcates a normally consolidated region (NC) and another over consolidated region (OC), described with the following equations:

$$f_b = \bar{\eta}^{*}_{(0)} + M^{*}_{m} \ln(\sigma'_m / \sigma'_{mb}) = 0 \qquad (14)$$

$$\bar{\eta}^{*}_{(0)} = \left\{ \left(\eta^{*}_{ij} - \eta^{*}_{ij(0)} \right) \left(\eta^{*}_{ij} - \eta^{*}_{ij(0)} \right) \right\}^{1/2} \qquad (15)$$

Where $\eta^*_{ij}=S_{ij}/\sigma'_m$, S_{ij} is the stress deviator tensor, σ'_m is the effective medium force, and M_m^* is the value of $\eta^*=\sqrt{(\eta^*_{ij}\eta^*_{ij})}$ when the increment of the volumetric deformation changes from compression to dilation, which is equal to M_f^* in the critical state. σ'_{mb} is the hardening parameter of the material which controls the size of the border surface. The effect of the suction is shown in the model below:

$$\sigma'_{mb} = \sigma'_{ma} \exp\left(\frac{1+e_0}{\lambda - \kappa} \varepsilon^{vp}_{kk} \right) \left[1 + S_I \exp\left\{ -S_d \left(\frac{P^C_i}{P^C} - 1 \right) \right\} \right] \qquad (16)$$

Where ε^{vp}_{kk} is the volumetric viscoplastic deformation, λ and κ are the compression and expansion coefficients, respectively; and e_0 is the initial void ratio. P_i^C is the value of the initial suction, P^C is the value of the actual suction, S_I is the parameter that denotes the change in resistance of the material from its initial suction condition until it reaches saturation. S_d is the parameter that controls the change in the increase or decrease of the resistance with the change in suction. σ'_{ma} is the softening parameter used to describe the degradation of the material due to structural changes.

The yield function material is given by:

$$f_y = \bar{\eta}^{*}_{(0)} + M^{*} \ln(\sigma'_m / \sigma'^{(S)}_{my}) = 0 \qquad (17)$$

In this way, the effect of suction through the value of $\sigma'^{(s)}_{my}$ is introduced here as follows:

$$\sigma'^{(S)}_{my} = \frac{\sigma'^{(s)}_{myi}}{\sigma'_{mai}} \sigma'_{ma} \exp\left(\frac{1+e_0}{\lambda - \kappa} \varepsilon^{vp}_{kk} \right) \left[1 + S_I \exp\left\{ -S_d \left(\frac{P^C_i}{P^C} - 1 \right) \right\} \right] \qquad (18)$$

The volumetric deformation tensor is given by the following equations:

$$D^{vp}_{ij} = C_{ijkl} \left\langle \Phi_1 (f_y) \right\rangle \frac{\partial f_p}{\partial \sigma'_{kl}} \qquad (19)$$

$$C_{ijkl} = A\delta_{ij}\delta_{kl} + B(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) \qquad (20)$$

$$\mathrm{C}_1 = 2B, \quad \mathrm{C}_2 = 3A + 2B \qquad (21)$$

Where f_p is the viscoplastic potential surface, Φ_1 denotes a function of the effect of loading speed, A and B and *B*are material parameters which are related to the deviator component C_1 and the volumetric component C_2 of the viscoplastic parameters.

2. NUMERIC SIMULATIONS AND RESULTS

Case 1: One-dimensional infiltration in a homogenous column of soil

The simulation of the infiltration process was conducted on a column 1 meter thick composed of a homogenous layer of sand represented by a mesh composed of 20 square elements measuring 5 cm on each side, and which are horizontally restricted. The base of the column is restricted in both directions, allowing for only the vertical deformation of the elements. The column possesses impermeable lateral borders. The air is evacuated by the upper border at the same time as it receives water from rain that penetrates the column of soil, varying its moisture conditions via the water infiltration. The base of the column is a drained border which allows the passage of water from the interior of the column to the inferior strata. An initial groundwater level is supposed, located at the lower end of the column, and a distribution of linear suction through the partially saturated soil. The mesh of finite elements and the initial conditions for the simulation are represented in **Figure 1**.

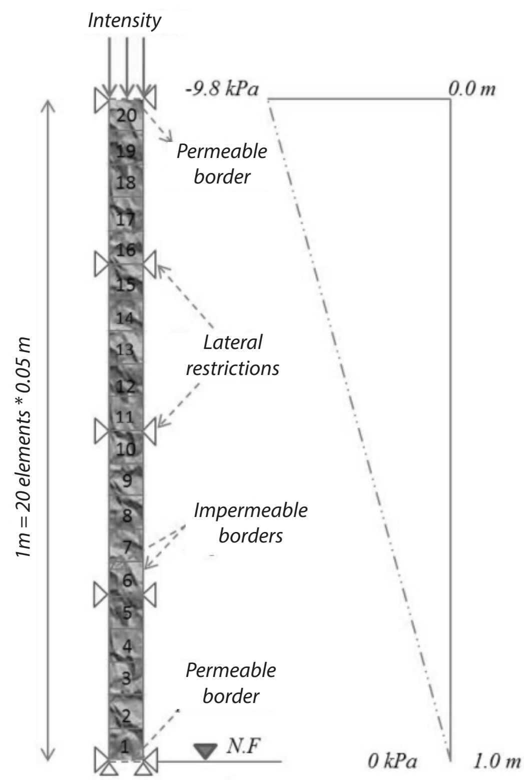
For the simulation, a constant-intensity rain less than or equal to the saturated permeability of the soil was generated, which guarantees that an accumulation of water will not occur on the surface and the entire volume of water will be introduced into the soil. The rain was applied to the surface of the column for a period of 30 h, which allowed it to show a tendency typical of the infiltration process for soil permeability. A parametric analysis was conducted of the sandy stratum, maintaining constant permeability for the water in a saturated state (k_s^W=1*10^{-6} m/s) and changing the intensity of the rain (I), which had the following values: I = 0.2k_s^W, 0.4k_s^W, 0.6k_s^W, 0.8k_s^W and k_s^W.

The parameters that define the characteristic water retention curve for the partially saturated soil can be seen in **Table 1**. α, n' and s_{max} correspond to the variables of the Van Genuchten (1980) equation utilized to link the saturation and suction of the soil, and a is an independent soil parameter that makes it possible to define the permeability variation for the water with the soil saturation. The parameters displayed in **Table 1** are typical parameters for sandy soil (Lu and Likos 2004).

TABLE1. HYDRAULIC VARIABLES UTILIZED IN THE SIMULATION WITH k_s^W CONSTANT

Parameter	Value
α (kPa^{-1})	0.1
n'	4.0
s_{max}	0.99
a	3.0
k_s^W (m/s)	10^{-6}

Figure1. Mesh and initial simulation conditions for the one-dimensional infiltration-deformation process



With the object of analyzing the response of the soil during the infiltration process, the comparative results of the suction and saturation profiles were graphed for a rain intensity of I = 0.2k_s^W. In **Figure 2(a)** it can be observed that the suction profiles for the times t=0, 1, 5, 10, 20 and 30 h showed little variation in soil suction. This is because the intensity of the rain is not high regarding the permeability of the soil (I = 0.2k_s^W), representing an infiltration capacity that sufficiently surpasses the intensity of the rain. The decrease in suction is higher on the surface and shows progress over time, indicating an increase in water contained in the soil. The previous results are verified in **Figure 2(b)** where the saturation profiles for the same rain intensity are shown. It can be observed that the saturation degree on the surface grows from the first hour of infiltration, making it higher as time progresses, followed by a decrease in depth.

To analyze the response to the rain intensity, **Figure 3(a)** shows the suction profiles corresponding to 30 h of rain at different intensities (i.e. $I = 0.2k_s^W$, $0.4k_s^W$, $0.6k_s^W$, $0.8k_s^W$ and k_s^W). The results show suction profiles with maximum values on the surface of the column that decrease as the depth increases until reaching values of zero at the base of the same, where the groundwater level is located. As the intensity of the rain grows, the suction values become smaller due to the higher water content in the soil. Likewise, **Figure 3(b)** shows how saturation varies with the rain intensity, indicating that the saturation of the soil grows with the intensity of the rain.

Finally, when the intensity of the rain gets close to the saturated permeability of the soil, suction goes to zero and saturation reaches the maximum along the length of the column for the duration of the simulation. This indicates that the higher the I/k_s^W ratio the faster the decrease in suction occurs, as well as the increase in soil saturation within the column. These results correspond with the experimental results obtained by Yang et al. (2006).

Figure 2. (a) suction profile and (b)saturation degree profile for the simulation in a homogenous column where $I = 0.2\ k_s^W$

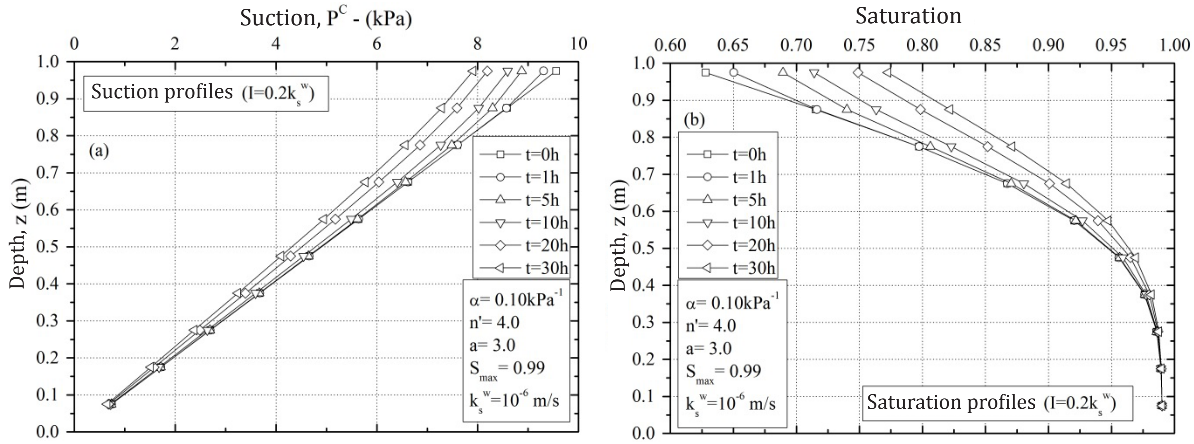


Figure 3. (a)suction profile and (b)saturation degree profilefor different rain intensitiesafter 30 h of infiltration

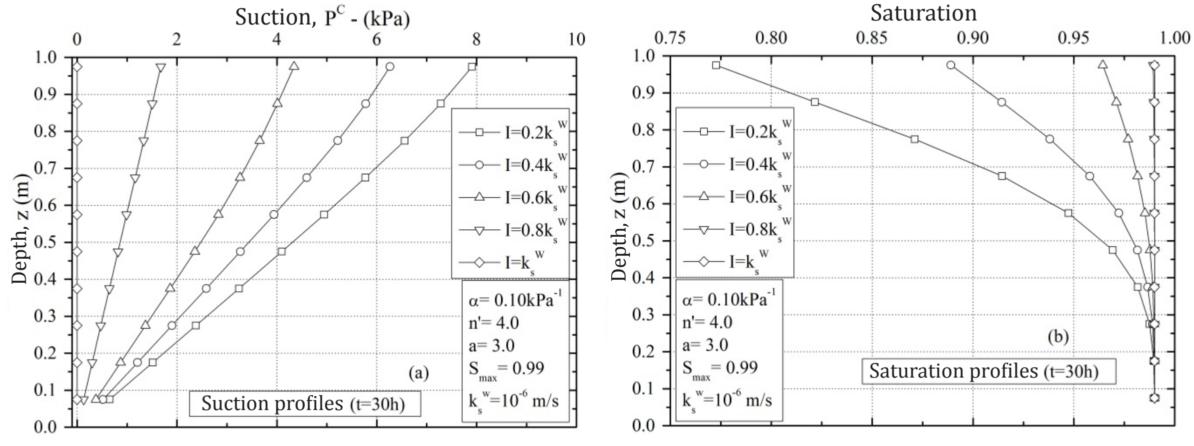
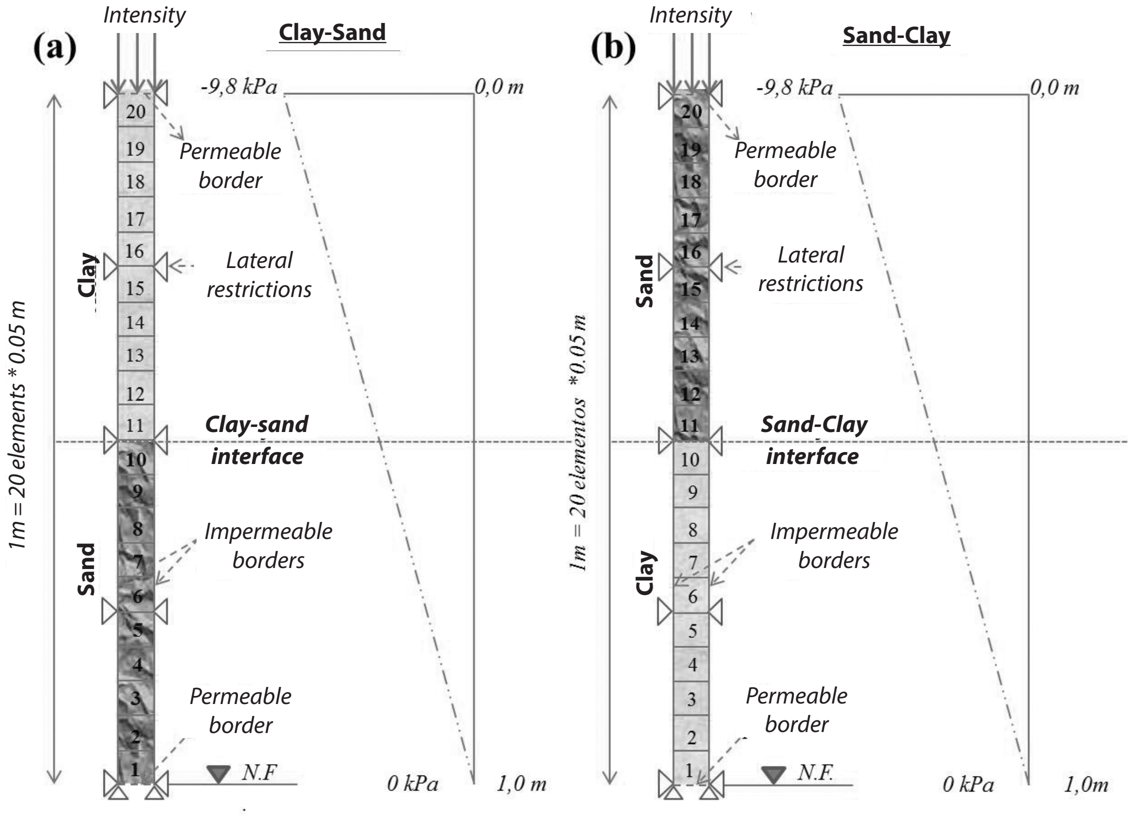


Figure 4. Initial conditions for (a) column of clay over sand and (b) column of sand over clay



Case 2: One-dimensional infiltration in a column of stratified soil

In this case the one-dimensional flow in a stratified soil was analyzed, where the hydraulic properties of the soil change for each material. For the simulation, a 1-meter-thick column was used, composed of a stratum of sandy soil and a stratum of clay soil. The position of the strata varied with the aim of studying the differences in the infiltration process (See **Figure 4**). The parameters that describe the characteristic water retention curve are, for the sand, $\alpha = 0.1$ kPa^{-1}, $n' = 4$ and $k_s^W = 10^{-6}$ m/s; and for the clay $\alpha = 0.071$ kPa^{-1}, $n' = 1.3$ and $k_s^W = 10^{-8}$ m/s (Lu & Likos, 2004).

Clay over sand

Figure 5(a) shows the suction profiles obtained for a column of soil comprised of a horizon of clay 0.5 m thick, which rests on top of a horizon of sand 0.5 m thick. The column of soil was submitted to a flooding process for a duration of 200 h with the aim of guaranteeing the entry of water throughout the entire column. In this Figure the suction values can be seen decreasing with the passage of time but only on the surface of the upper horizon (clay). In addition, a variation is not observed in the suction profiles of the sandy horizon, this being because the water that arrives at this horizon evacuates rapidly due to the higher permeability of the soil without significantly affecting its saturation conditions. This is confirmed by observing **Figure 5(b)**, in which the constant saturation profiles for the sandy stratum are shown, except that they increase for clay as the infiltration time progresses.

In this case, the behavior of a soil horizon that acts as a barrier and another horizon that acts as a filter is demonstrated. The upper stratum (fine soil) is relatively impermeable, as it retains the water, making passage to lower horizons difficult. The lower stratum (granular soil) functions as a filtering medium, easing the evacuation of the infiltrated water and impeding its accumulation.

Sand over clay

Figure 6(a) shows the suction profiles obtained for the case in which the clay horizon is below the sand horizon. The soil column was submitted to an inundation process for 10 h, which is sufficient to guarantee the entry of water throughout the entire column. In the Figure it can be observed that the decreases in suction during shorter times compares with the case of the clay-sand horizons (200 h); after 5 h the sandy stratum is saturated (**Figure 6(b)**) and the constant suction has a value of zero; however, the lower stratum (clay) still has suction; this is because the clay stratum is not saturated, being influenced by its incapacity to allow the passage of all of the water that arrives from the upper stratum due to lower permeability.

Figure 5. Suction profiles for the clay over sand simulation: (a) suction profile, and (b) saturation profile

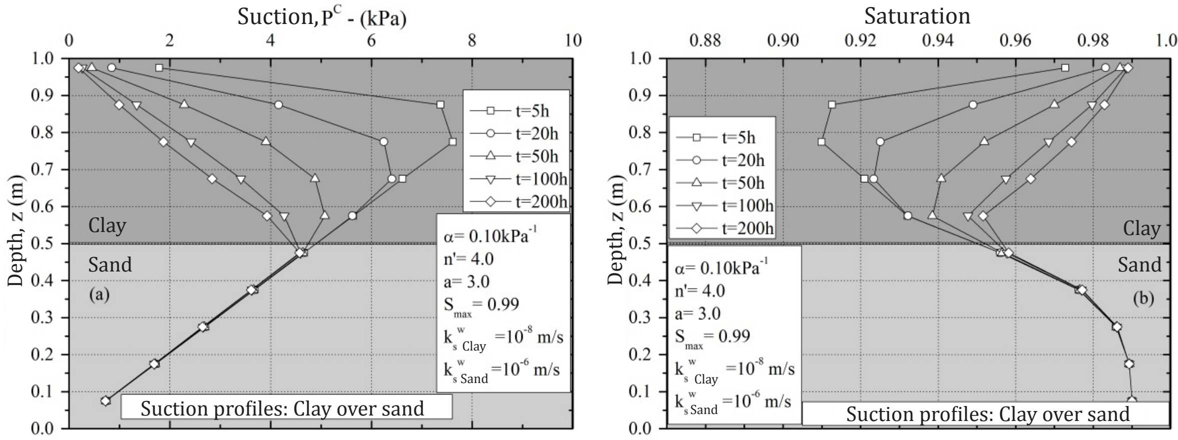
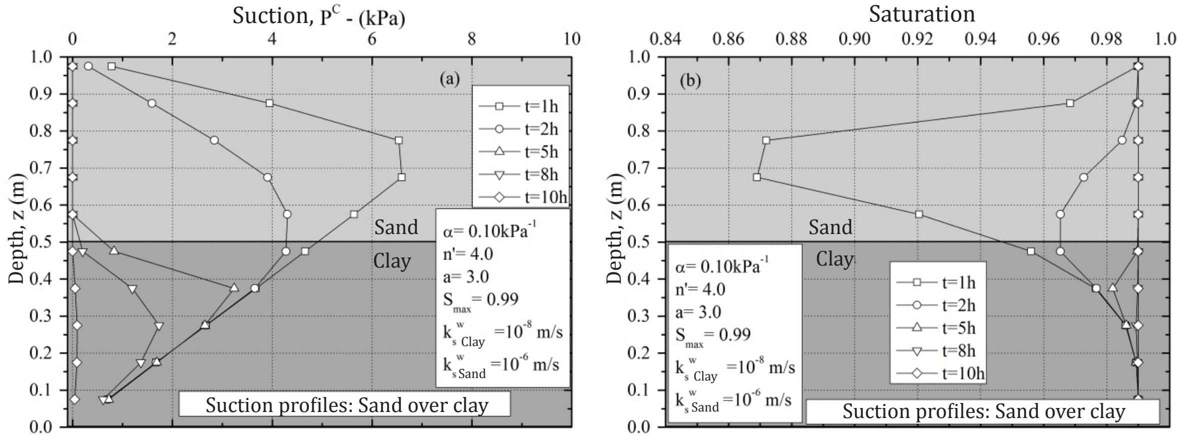


Figure 6. Profiles for (a) suction and (b) degree of saturation resulting from the simulation with sand over clay



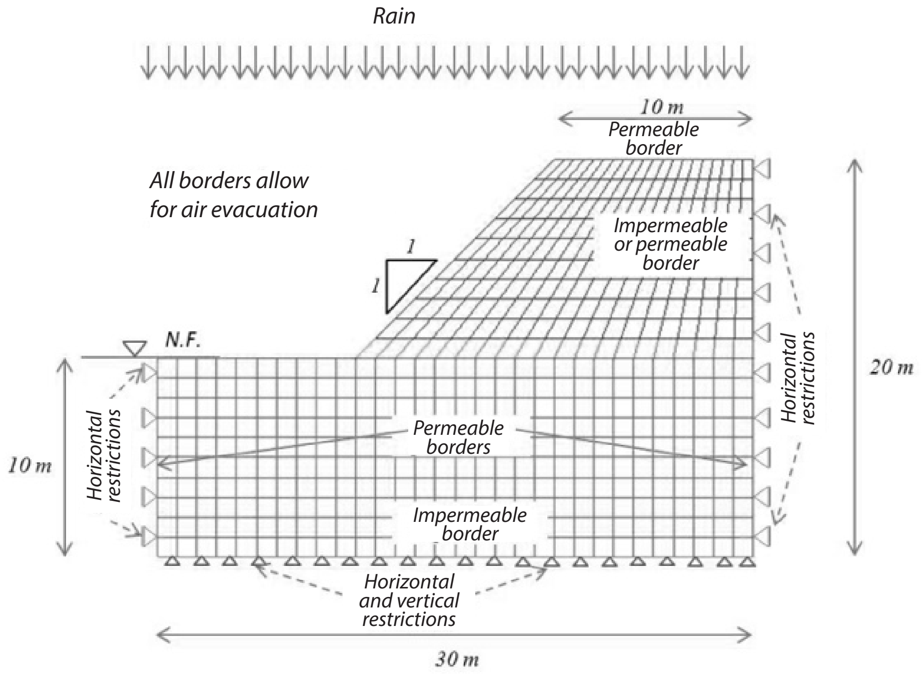
These types of profiles result in "suspended" groundwater levels, where the water that infiltrates through the surface meets with impermeable strata that impede its passage and cause an accumulation of water, saturating the upper strata; consequently, it is often confused with the real groundwater level of the soil. This type of accumulation causes superficial failures in slopes and embankments (Abramson et al. 2002).

Case 3: Two-dimensional infiltration in a homogenous slope

In this case the previously introduced coupled infiltration-deformation model was used to analyze the infiltration of rain in a homogenous slope. In **Figure 7**, the spatial zoning of the slope, the position of the groundwater level can be found in the lower part of the slope, and a lineal distribution is assumed for the initial suction up to a height of 1 m from the groundwater level, from which it is constant. The air pressure is assumed equal to the atmospheric pressure. The air can be drained at any of the borders that make up the slope. A rain with a known intensity is generated as a border condition on the surface of the slope, which permits the water to enter according to the intensity of the rain and the suction level of the material. The base of the slope is impermeable and is subject to lateral and vertical movement restriction. The lateral borders below the groundwater level are permeable and horizontally restricted.

The soil parameters utilized in the simulation can be seen in **Table 2**. These parameters represent a loamy soil. A rain with an intensity I = 30 mm/h ($8.33*10^{-6}$ m/s) was generated with a duration of 48 h. During this time, the groundwater level grew in the right border of the slope with the objective of simulating a lateral flow. From this infiltration process the behavior of the slope can be analyzed through the evolution of the accumulated viscoplastic saturation and deformation. It was considered a soil with a saturated permeability of $3*10^{-5}$ m/s.

Figure 7. Mesh zoning to model infiltration in a two-dimensional slope



The parameters shown in **Table 2**, were utilized in infiltration-deformation simulations in dams by Kimoto et al. (2013).

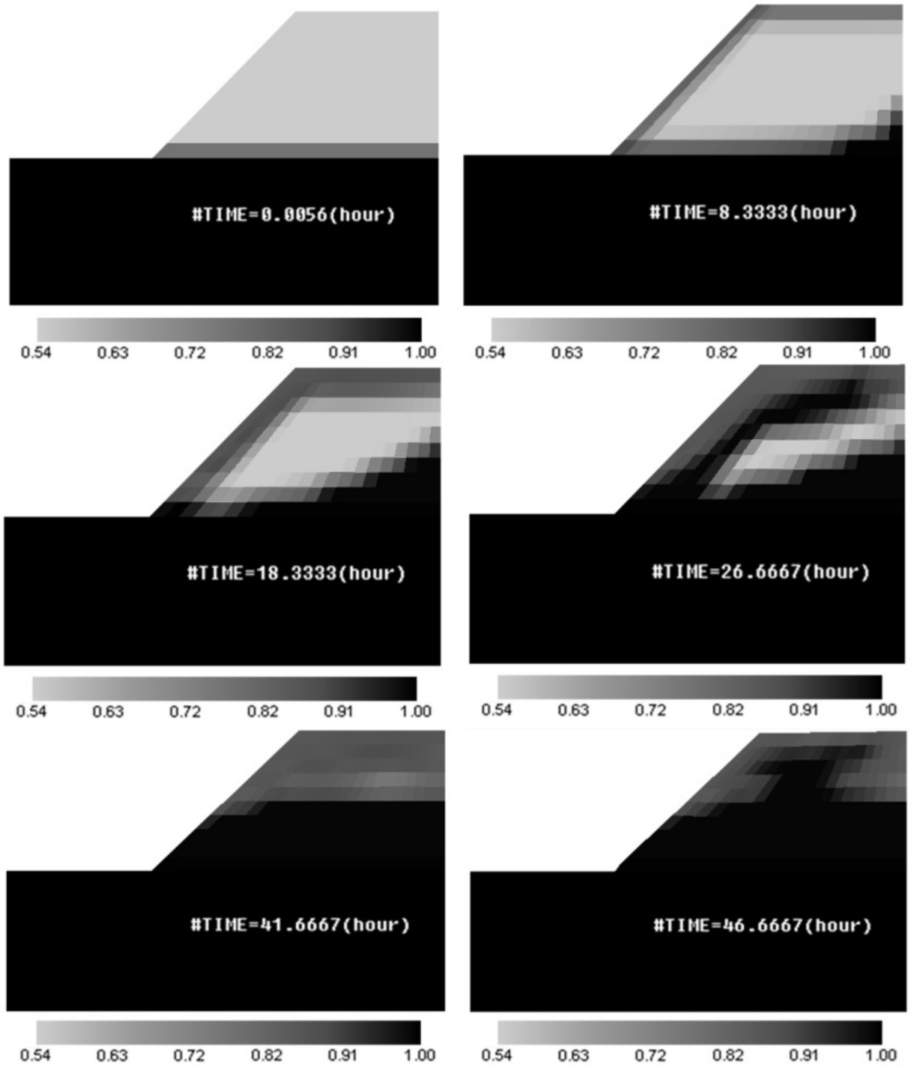
The parameters of the soil shown in **Table 2** are obtained from experimental trials of undrained compression, consolidation and permeability by the following means:

- The viscoplastic parameter m' is obtained through undrained triaxial compression trial sat different speeds of deformation.
- The viscoplastic parameters C_1 and C_2 are obtained based on **Equation 19**.
- The critical state stress ratio M^*_m is determined with the residual state stress ratio.
- The compression λ and expansion κ indices are obtained through consolidation trials.
- The elastic shear modulus G_0 is obtained from the initial slope of the triaxial compression trial ($G_0=\Delta q/(3\Delta\varepsilon_{11})$).
- The void ratio e_0 is determined from the physical properties trials.
- The structural parameter β is determined by adjusting the softening zone of the curve q-ε.
- The parameters S_I and S_d are obtained by adjusting the growth curve for resistance due to suction.
- Parameter b is obtained by adjusting the permeability curve for the air.
- **Figure 8** shows the progress of the saturation front for the analyzed slope from before the rain started (t = 0), in which only the soil below groundwater level is saturated. Above groundwater level the soil is partially saturated with degrees of saturation higher than 50%. of this Figure, it can be observed that as the rain's time period progresses, the saturation values increase, initially growing in the higher borders of the slope, due to the direct rain they receive, and on the right border due to the horizontal infiltration flow.

TABLE 2. PARAMETERS FOR THE SOIL CORRESPONDING TO THE SLOPE

Viscoplastic parameter	m'	23.0
Viscoplastic parameter (1/s)	C_1	1.0×10^{-8}
Viscoplastic parameter (1/s)	C_2	1.0×10^{-8}
Stress ratio in a critical state	M^*_m	0.947
Parameter for the rigid tangent line method	θ	0.50
Permeability coefficient for air at s=0 (m/s)	k_s^G	1.0×10^{-3}
Compression index	λ	0.03
Expansion index	κ	0.002
Initial elastic shear modulus (kPa)	G_0	25000
Initial void ratio	e_0	1.0
Structural parameter	β	216
Van Genuchten parameter (1/kPa)	α	2.0
Van Genuchten parameter	n'	1.2
Suction parameter	S_1	0.2
Suction parameter	S_d	5.0
Saturation minimum	s_{min}	0.0
Saturation maximum	s_{max}	0.99
Saturated permeability coefficient parameter for water	a	3.0
Permeability coefficient parameter for air	b	1.0

Figure 8. Changes in the degree of saturation for the two-dimensional slope model



At 27 h of rain an area appears at the interior of the slope that continues with the initial saturation values, because neither the moisture front, nor the lateral flow have come together. Given that a higher degree of saturation represents lower air permeability values, the advancement of water impedes the rapid exit of the same, which remains trapped in the soil, restricting the advancement of the moisture front. For the end of the simulation time period, a high degree of saturation can be observed in the material.

For the deformation analysis, a fault in the soil is considered to be effectively reached when its accumulated irrecoverable unit deformation surpasses a value of 5%. In **Figure 9**, deformation intervals were taken with this value as a maximum starting at 35 h of infiltration. The first appearances of viscoplastic deformation to surpass 1.5% occur at 40 h, at the base of the slope. From these small deformations a fault surface begins to form that ascends from the foot of the slope to its crest. At 47 h of simulation it is possible to see that major deformations occur in the fault surface for almost the entire longitude 5%.

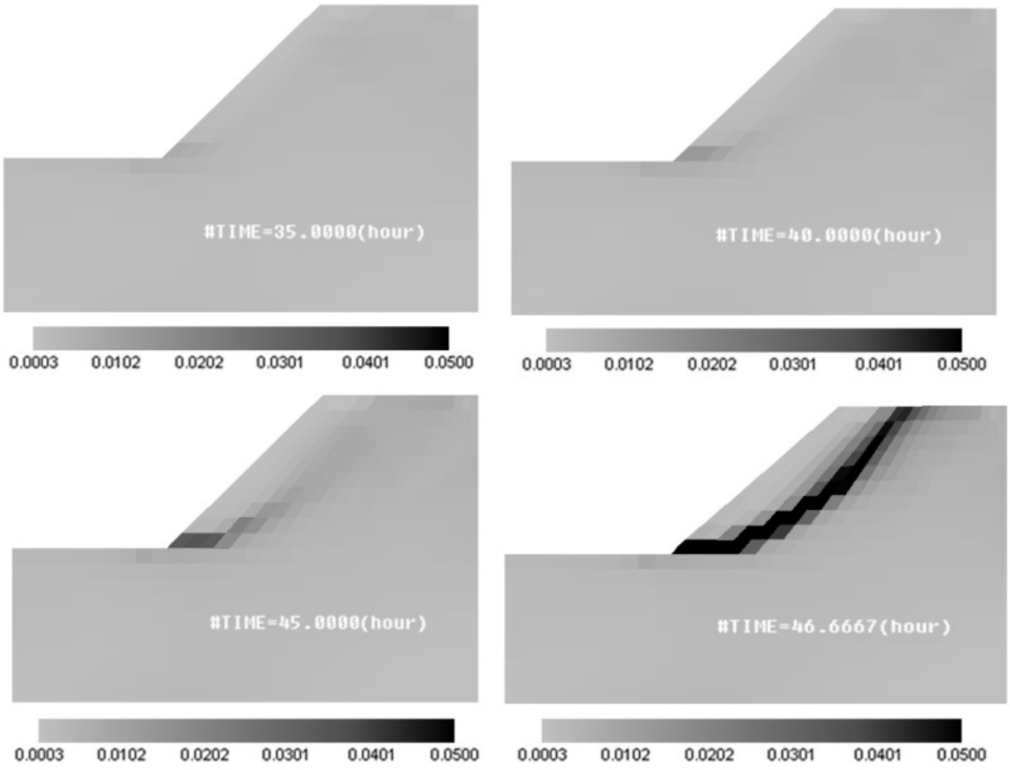
Analyzing the advancement of the viscoplastic deformation during the time period, a rotational fault can be seen in the slope. This localized surface appears through an increase in the weight of the soil's mass and a reduction in resistance to the cut by the rain water infiltration. The fault surface encountered via the simulation is a natural result of the infiltration process, which converts this analysis methodology into a potential tool for obtaining a more accurate stability analysis of slopes and embankments.

The coupled infiltration-deformation methodology employed for the analysis does not exhibit limitations for studying any type of geotechnical work. Due to its flexibility, it is possible to analyze the interaction of different types of materials (e.g. soils, concrete, drains, geosynthetics, etc.), with different types of borders (e.g. infiltration, evaporation, overload, load removal, deformation, etc.). However, the complexity of this methodology implies the collection of additional geotechnical and hydraulic parameters for determining stress-deformation ratios of materials at different degrees of saturation. These methodologies provide the advantage of a more accurate result for the analysis of a structure's behavior during a transitory event.

3. CONCLUSIONS

The problems regarding partially saturated soils are common in the engineering field; their study has been implemented using numerical simulations that allow for the introduction of different border conditions for real and hypothetical case studies related to water infiltration.

Figure 9. Changes in the viscoplastic deformation for the two-dimensional slope



The coupled infiltration-deformation model presented makes it possible to analyze water flow advancement processes in homogenous and stratified soils by tracking the changes in suction, saturation and deformation generated by the change ineffective stress.

The analysis of the one-dimensional infiltration process in homogenous soil exhibits the effect of the intensity of rain on soil, showing that the higher the ratio I/k_s^W the faster the decrease in suction and increase in saturation occur in the column of soil.

For the simulated cases in stratified soils, it is found that when clay horizons are localized above the sand horizon, the inflow of water is made more difficult; but once it reaches the sandy horizon it flows rapidly due to its higher permeability, playing the role of a filtration layer. When the sand is the upper horizon the water infiltrates rapidly and the clay controls its exit, causing suspended groundwater levels and the complete saturation of the upper horizon. In other words, the clay controls the infiltration process whether reducing the water infiltration when located on the surface or retaining it when encountered as an underlying horizon.

Finally, for the two-dimensional analysis of the infiltration process of a homogenous slope, it can be observed that when the rain is applied, the changes in saturation and suction initiate close to the surface and progress to greater depths as the duration of the rain increases. The process of infiltration brings with it changes in the material's effective stress conditions which make possible (by way of the stress-deformation ratios included in the model) the study of the most probable fault surface's deformation and localization distribution; which is not possible when classic analysis methodologies are used for slope stability.

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