Hysteresis in Soil Water Characteristic Curve of Unsaturated Soil and its Influence on Slope Stability

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ABSTRACT
This paper presents a numerical modelling exercise that investigates the effect of hysteresis of the soil water characteristic curve (SWCC) on an unsaturated slope. Multi-year climate data is applied as a soil-atmosphere boundary condition on a two-dimensional finite element unsaturated slope model. The results obtained for hysteretic and non-hysteretic simulations are analyzed in terms of water balance at ground surface and temporal storage. Detailed slope stability analysis is performed considering the porewater pressures that are obtained from the hysteretic and non-hysteretic simulations. The research will contribute to existing literature and provide a better understanding of the impact of hysteresis in the SWCC on slope stability under an atmospheric boundary condition.

RÉSUMÉ
Cet article présente un exercice de modélisation numérique qui étudie l'effet de l'hystérésis de la courbe caractéristique de l'eau du sol (SWCC) sur une pente non saturée. Les données climatiques pluriannuelles sont appliquées en tant que condition aux limites sol-atmosphère sur un modèle de pente insaturée à éléments finis à deux dimensions. Les résultats obtenus pour les simulations hystérétiques et non-hystérétiques sont analysés en termes de bilan hydrique à la surface du sol et de stockage temporel. Une analyse détaillée de la stabilité des pentes est réalisée en considérant les pressions d'eau interstitielle obtenues à partir des simulations hystérétiques et non-hystérétiques. La recherche contribuera à la littérature existante et fournira une meilleure compréhension de l'impact de l'hystérésis dans le SWCC sur la stabilité de la pente dans une condition aux limites atmosphériques.

1 INTRODUCTION

1.1 Hysteresis of the SWCC

Soil water characteristic curves (SWCCs) and unsaturated hydraulic conductivity functions are two vital hydraulic parameters for soil that are required to perform numerical analysis of water flow in unsaturated soils. The soil water characteristic curve is the relationship between water content and suction and is hysteretic in nature. Hysteresis in the SWCC refers to a non-unique relationship between the soil's matric suction and water content, whereby soil can have different water contents at the same matric suction depending on whether the water content is achieved through the drying or wetting curve. Thus, the quantity of water that soil can retain at a particular suction is a function of drying and wetting history of the soil (Or and Tuller, 2005). Hysteresis of the SWCC occurs due to variable and irregular layout of pores, liquid-solid contact angles, air entrapment, swelling/shrinking of soil under wetting and drying events, and thermal effects (Selher et al., 1999). Hysteresis can have significant effects on soil water movement including infiltration (Tami et al., 2004), drainage (Dane and Wierenga, 1975), and redistribution (Philip, 1991).

Hysteretic behaviour of soil is observed in unsaturated flow systems caused by intermittent boundary conditions such as non-monotonic flow conditions resulting from precipitation events followed by periods of drainage and redistribution with surface evaporation. It is common practice to consider the SWCC to be non-hysteretic in numerical analysis of unsaturated flow. Hysteresis is routinely ignored due to a lack of measured SWCCs which can be time consuming and expensive to measure (Pham et al., 2005). Hysteresis is also ignored in numerical simulations due to additional computation time and numerical instabilities. Many studies have shown that in unsaturated flow systems, when water flow is non-monotonic, hysteresis in the SWCC needs be considered (Bashir et al., 2016).

An unsaturated soil hydraulic conductivity function could also exhibit hysteretic behavior (van Dam et al., 1996). However, when hydraulic conductivity is expressed as a function of water content instead of suction, the hysteresis effect disappears (i.e. same hydraulic conductivity for the same water content for both wetting and drying curves). On the other hand, the hydraulic conductivity varies for changing values of suction. There is little evidence that hysteresis in the unsaturated hydraulic conductivity function is of any practical significance and is often ignored (Stephens, 1996).

1.2 Slope Failures

Slope failures are one of the deadliest and most destructive natural hazards present around the world. Different phenomena influence the stability of slopes including rainfall, snow melt, earthquakes, loss of vegetation, volcanic eruptions, and human activities etc. However, rainfall induced slope failures are fairly common (Tsaparas et al., 2003; Rahimi et al., 2010). Factor of safety (FOS) is the primary design criteria for slope stability and is defined as the ratio of the ultimate shear strength and mobilized shear stress incipient at failure (Cheng and Lau, 2014). If the factor of safety is less than 1.0, the slope is considered unstable.

Slope failures could be triggered by the increase in positive pore water pressure and/or loss of unsaturated shear strength due to dissipation of matric suction (Tsai and Chen, 2009; Ma et al., 2011). For an unsaturated slope, at the onset of an infiltration event, near surface stratigraphy begins to saturate resulting in a reduction of matric suction. As the water penetrates deeper under the influence of gravity, it contributes to the development of positive pore water pressure or reduction of matric suction in deeper stratigraphy. Since hysteresis in SWCC is a natural phenomenon, its inclusion in seepage analysis will result in more realistic pore pressure distribution and better assessments of slope stability.

1.3 Current Literature

Most of the currently published literature studied the effect of hysteresis on slope stability, either based on simplified infiltration events (Tami et al., 2004; Ebel et al., 2010, Ma et al., 2011; Chen et al., 2017) or cyclic/variable head boundary conditions (Liu et al., 2017). None of the studies reported in the peer review literature have considered the soil-atmosphere boundary involving a historical multi-year climate dataset.

The soil-atmosphere boundary is a system dependent boundary condition where direction and magnitude of the flux at the soil surface is estimated using climate data and transient soil water conditions (Bashir et al., 2016). The common measures of flux estimated at the soil-atmosphere interface are infiltration, evaporation, and transpiration. The current study will focus on understanding and quantifying the hysteresis effects of the SWCC on slope stability subject to multi-year climate data for Toronto, Ontario, Canada.

2 METHODOLOGY

The study was successfully completed by performing hydrological and slope stability analysis. The hydrological analysis was performed using Hydrus 2D (Šimůnek et al., 2016) with consideration of hysteresis in SWCCs. The porewater pressure profiles obtained at different time steps from hydrological analysis were used in slope stability assessments. Slope/W (GeoSlope International Ltd., 2016), a limit equilibrium-based software package, was used for slope stability assessments.

2.1 Hydrological Analysis

To perform hydrological analysis, the finite element software HYDRUS-2D version 2.x (2.05.0200) (Šimůnek et al., 2016) was used. HYDRUS-2D is computer software widely used for simulating water, heat, and solute transport in two-dimensional variably saturated domains. It numerically solves the Richards equation for unsaturated water flow for a variety of initial and boundary conditions. The Richards equation can be expressed as (Šimŭnek et al., 2006):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iz}^A\right)\right] - S \qquad [1]$$

In the equation, θ is the volumetric water content [L^3L^{-3}], h is the pressure head [L], S is a sink term [T^{-1}], x_i (i=1,2) are the spatial coordinates [L], t is time [T], K_{ij}^A are components of a dimensionless anisotropy tensor K^A, and K is the unsaturated hydraulic conductivity function [LT^{-1}]. The anisotropy tensor K_{ij}^A in Equation 1 is used to consider the anisotropy in the medium. The diagonal entries of K_{ij}^A equal one and the off-diagonal entries are zero for an isotropic medium. For a vertical cross section within a two-dimensional domain, x is considered as the horizontal axis and z is considered as the vertical axis.

To numerically solve the Richards equation, two sets of hydraulic properties; namely the soil water characteristic curve and the unsaturated hydraulic conductivity function are required. The water content and hydraulic conductivity are highly nonlinear functions of suction and are frequently represented by functions proposed by van Genuchten (1980) and Mualem (1976). The van Genuchten function for SWCC is given as:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \qquad [2]$$

where, θ_s is saturated water content [L^3L^{-3}], θ_r is residual water content [L^3L^{-3}] and α (alpha) [L^{-1}], n and m are empirical fitting parameters. Alpha (α) is related to the inverse of air entry value, n is related to pore size distribution and m is a curve fitting parameter. Also, m = 1-1/n and n >1.

The Mualem (1976) model to obtain unsaturated hydraulic conductivity function in terms of soil water retention parameters of van Genuchten (1980) is given as:

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad [3]$$

In Equation 3, K_s is the saturated hydraulic conductivity [LT^{-1}] and S_e is effective saturation [L^3L^{-3}] while the rest of the variables were defined previously.

In order to account for the hysteresis in SWCCs, a number of hysteresis models have been proposed (Pham et al., 2005). For this research, the hysteresis model of Kool and Parker (1987) was used. This model is empirical in nature and is implemented in Hydrus 2D. The model predicts the drying and wetting scanning curves by scaling the main drying and wetting curves.

2.2 Slope Stability Analysis

To perform slope stability analysis, Slope/W from GeoSlope International was selected (GeoSlope International Ltd., 2016). Slope/W uses the limit equilibrium method for slope stability assessments. The results of seepage analysis performed using Hydrus 2D were imported to Slope/W.

For unsaturated soils, the shear strength envelope is nonlinear. The contribution of soil suction to shear strength can cause a significant increase in the FOS (Fredlund et al., 2012). Numerous empirical equations have been proposed for describing the shear strength of unsaturated soils. As the shear strength of an unsaturated soil is related to soil suction, most methods of shear strength estimation have been related to the SWCC.

Vanapalli et al. (1996) suggested an empirical analytical model to estimate unsaturated shear strength. The model involves a normalization of the SWCC between the saturated and residual water content states expressed as follows:

$$s = c' + (\sigma - u_a)\tan\emptyset' + (u_a - u_w)\left[\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\emptyset'\right] \quad [4]$$

where c' is effective cohesion (kPa), u_a is pore air pressure (kPa), u_w is porewater pressure (kPa), $\emptyset'$ is effective angle of internal friction for unsaturated soil (º), $(\sigma - u_a)$ is net normal stress on the failure plane (kPa) and $(u_a - u_w)$ is matric suction (kPa). The rest of the variables have been defined previously. Equation 4 has been implemented in Slope/W and is used in current research to calculate the unsaturated shear strength of soil.

3 NUMERICAL MODELLING

For this study, a two-slope model, 35 m wide and 10 m high was considered. A slope angle of 1:2 was used in the upper 5 m and 1:3 in the lower 5 m (Figure 1). The slope was assumed to consist of a homogeneous soil with no erosion at the toe of the slope. The initial groundwater table was initialized at 3 m from the bottom boundary.

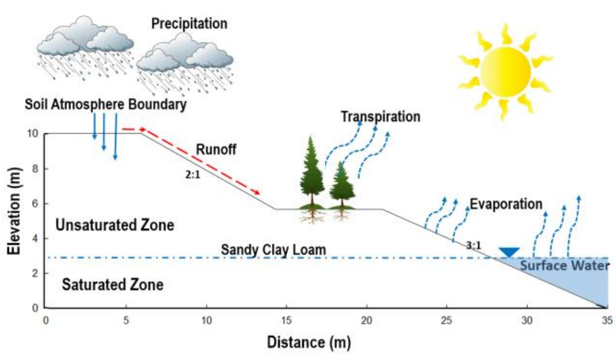

Figure 1. Homogeneous slope with climatic parameters and initial groundwater table

The slope was comprised of a sandy clay loam, whose hydraulic properties are reported by Warrick et al. (1971). Table 1 shows the hydraulic and strength properties of the assumed sandy clay loam. The hydraulic properties are presented for the hysteresis model of Kool and Parker (1987) and the hysteretic SWCCs are shown in Figure 2.

For this study the soil-atmosphere boundary detailed 15 years (1995-2010) of Toronto climate data. The climate data contained daily records of precipitation and potential evaporation and is shown in Figure 3. A zero flux boundary was placed at the bottom and left boundary of the domain. The effects of transpiration were not taken into consideration.

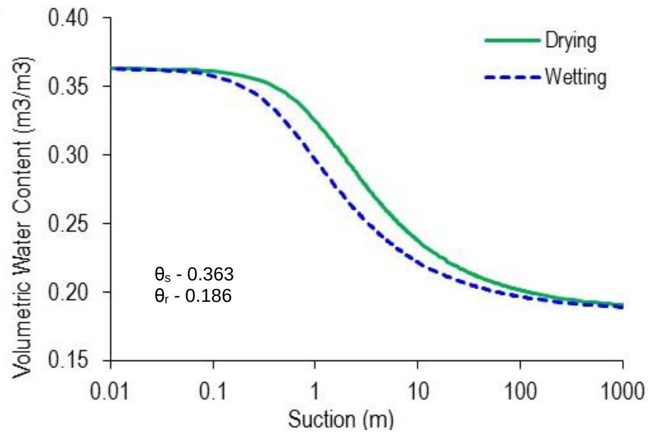

Figure 2. Hysteretic soil water characteristic curve (SWCC) of sandy clay loam

Several different methods based on the limit equilibrium concept are available in GeoSlope software. The Morgenstern-Price method (Morgenstern and Price, 1967) was used in this research to perform slope stability assessments. The Morgenstern-Price method is widely used because it considers both shear and normal interslice forces and satisfies both moment and force equilibrium. It is a rigorous method of analysis with the advantage that it allows for a variety of user-selected interslice force functions (GeoSlope International Ltd., 2016).

Table 1. Soil properties of sandy clay loam

Parameter	Values	Units
Saturated Water Content (θ_s)	0.363	m^3/m^3
Residual Water Content (θ_r)	0.186	m^3/m^3
Van Genuchten Parameter (n)	1.53	-
Saturated Hydraulic Conductivity K_s	1×10^{-6}	m/s
Van Genuchten Parameter for drying curve (α^d)	1	(1/m)
Van Genuchten Parameter for wetting curve(α^w)	2	(1/m)
Saturated Unit Weight (Υ_{sat})	20	(KN/m^3)
Cohesion (c')	0	(KPa)
Angle of Friction ($\emptyset'$)	20	(º)

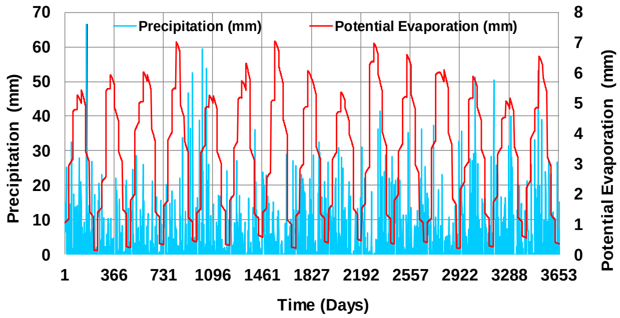

Figure 3. Precipitation and potential evaporation for Toronto, Ontario – (1995-2010)

4 RESULTS AND DISCUSSION

The hydrological model was analyzed using 15-year climate data with hysteretic and non-hysteretic soil properties. The results from the simulation can be presented in many ways. Figure 4 shows the water balance at the ground surface for the 15-year climate dataset assuming hysteretic and non-hysteretic simulations.

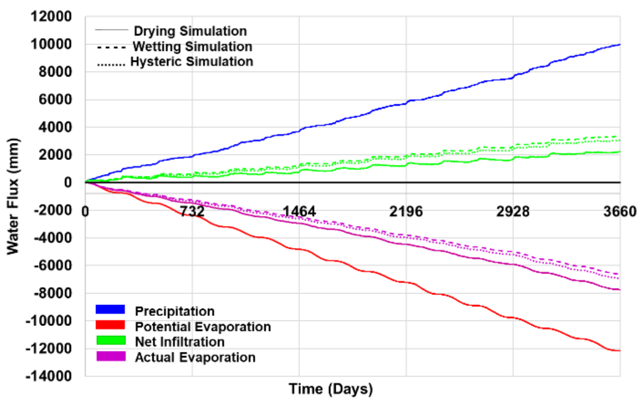

Figure 4. Water balance at the ground surface for 15-year Toronto climate dataset for hysteretic and non-hysteretic simulations

In Figure 4, quantities that leave the system, such as potential and actual evaporation, are expressed as negative, while quantities that enter the system, such as precipitation, are expressed as positive quantities. The only exception is runoff, which is always expressed as a positive quantity. Net Infiltration is the amount of water that enters the soil matrix and is estimated by:

$$NI = P - AE - RO \qquad [5]$$

where *NI* is net infiltration [L], *P* is precipitation [L], *AE* is actual evaporation [L] and *RO* is runoff [L]. A positive value of *NI* implies conditions of net water gain while a negative value for *NI* would imply a net water loss condition.

In Figure 4, it can be observed that the 15-year cumulative precipitation is 9983 mm and cumulative potential evaporation is 12,153 mm. The simulation results show that the cumulative *AE* values are lower than the *PE*. This is because of the soil–atmosphere boundary, which reduces evaporation from the potential value depending on the availability of water in the soil stratigraphy near the ground surface. It can also be observed that the *AE* for the wetting simulation is lowest when compared to hysteretic and drying simulations. The lower *AE* value for the wetting simulation suggests that less water is retained in the soil stratigraphy near the ground surface when compared to hysteretic and drying simulations, resulting in less evaporation. This observation is consistent with the hydraulic properties used in the simulations. The water entry value for the wetting SWCC is considerably lower than the air entry value of the drying SWCC in terms of matric suction. A higher air entry value is indicative of more water retention in the upper soil stratigraphy leading to higher *AE* values.

The *NI* and *AE* for wet, dry and average year climates from the 15-year climate dataset are shown in Figure 5. These years were identified by estimating the annual moisture index (I_m) as follows (Thornthwaite and Hare, 1955):

$$I_m = 1 - \frac{P}{PE} \qquad [6]$$

where all the variables are as previously defined. A higher value of I_m indicates more water availability at the ground surface which is indicative of a wetter climate. Presentation of the data for dry, wet and average year climates highlights the importance of running multi-year simulations to capture year to year variation in climatic conditions. It can be observed in Figure 5 that the water balance follows the trend predicted from the annual moisture. The *NI* value for the wet year is higher than that for a dry or average year, with the dry year having the least amount of *NI*. It is interesting to note that *AE* values for the wet, dry, and average years follow the same trend. This might seem counter intuitive as a lower *AE* value would be expected for a wetter climate owing to lower *PE* values. However, this is merely the result of higher moisture availability in upper soil stratigraphy for wetter climate due to higher precipitation quantity and intensity.

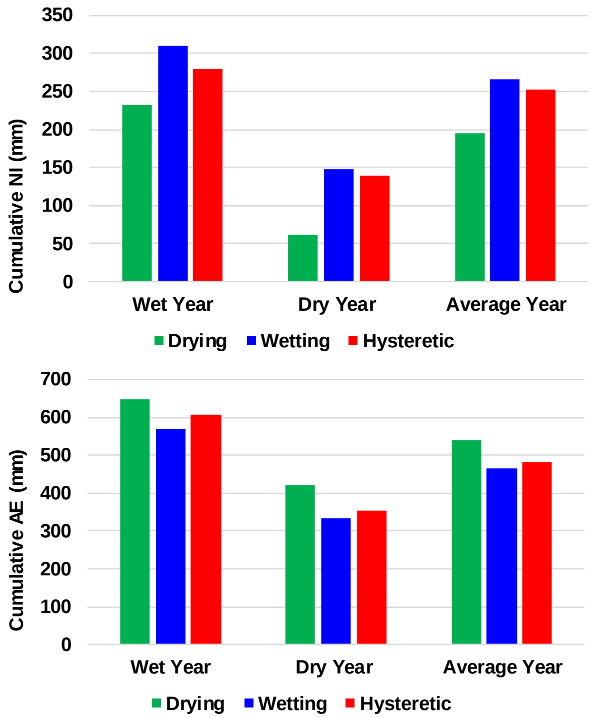

Figure 5. Comparison of NI and AE for hysteretic and non-hysteretic simulations for dry, wet and average years

Figure 5 also supports the earlier observation that the quantity of water entering the system is dependent on the retention characteristics of the soil. It can be observed that for all instances, the *NI* values are lower and the *AE* values are higher for simulations run with the drying SWCC. As explained earlier, this is an artifact of the higher air entry value which retains more water in the upper soil stratigraphy, resulting in higher *AE* values. The results also suggest that the effect of hysteresis is more pronounced for dryer climates whereas the quantity of water entering the system could be under predicted by approximately one third if the drying SWCC is used in the simulations.

To conduct slope stability assessments, porewater pressure data from select days using dry, wet, and average year climates was used for hysteretic and non-hysteretic simulations. The days were selected based on the total water storage in the domain. The days with the highest water storage in the domain were selected based on the observation that they represented porewater pressure profiles representative of lower suction values in the unsaturated regions of the slope. The results of the slope stability assessments are presented in Figure 6.

Figure 6 indicates that a significant difference in FOS between hysteretic and non-hysteretic simulations exists for dry, wet, and average year climates. FOS values for drying simulations are always higher than wetting and hysteretic simulations, irrespective of the climate. Similarly, the lowest FOS values were predicted for simulations conducted with the wetting SWCC. These observations are consistent with the water balance at the ground surface which indicated that larger quantities of water would enter the system if the wetting SWCC is used. It is also worth noting that for hysteretic simulations, FOS values are higher than those for wetting simulations but less than those for the drying simulation. Based on these results, it can be concluded that using the drying SWCC might result in over estimation of the FOS. Similarly, use of the wetting SWCC curve might result in underestimation of the FOS.

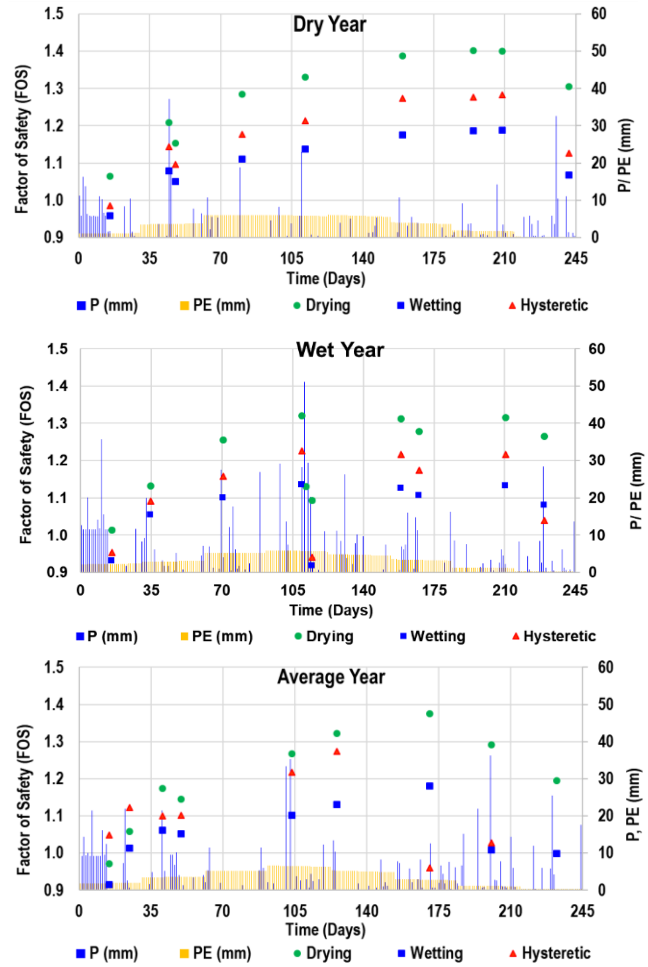

Figure 6. FOS values obtained for hysteretic and non-hysteretic simulations for dry, wet, and average years.

Several other observations can be made from Figure 6. It can be observed that the lowest FOS is associated with the spring freshet period, irrespective of the climate type and hydraulic properties. It is also shown that the FOS correlates well with the intensity of precipitation events, where a lower FOS follows higher intensity events. The results also reveal that that the highest FOS was observed during the dry year and the lowest FOS was observed in the average year climate. This result might be a little surprising because the quantity of the water that enters the slope is larger for a wet year climate. However, the maximum difference between the two is merely 15%.

Moreover, it should be noted that the pore pressure distribution in the slope is not only a function of total quantity of water that enters the slope, but also its temporal distribution within the domain which is a function of precipitation frequency. This observation once again highlights the importance of multi-year climate data sets to be used in conjunction with slope stability assessments as the lowest FOS might not occur in the wet year.

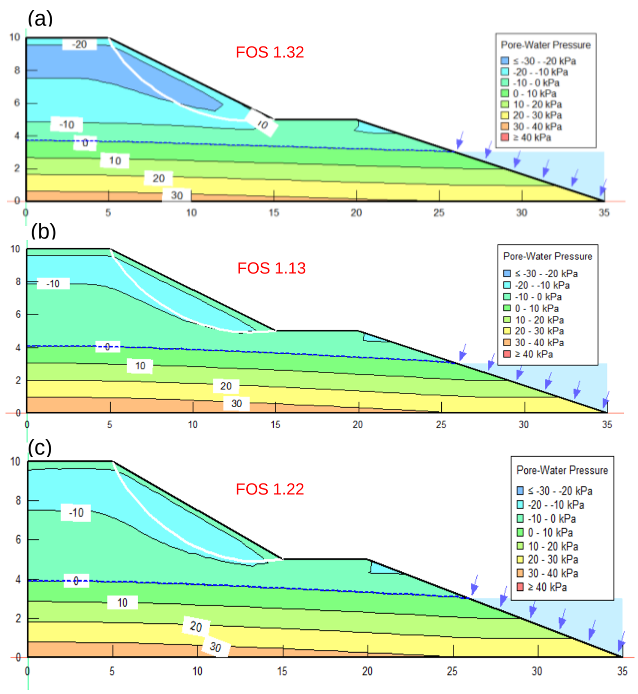

Figure 7. Critical slip circle and pore water pressure profiles for (a) drying (b) wetting and (c) hysteretic simulations

To quantify the effect of hysteresis on suction strength, the hysteretic and non-hysteretic porewater pressure profiles along with critical slip surfaces for day 158 of the wet year are shown in Figure 7. It can be observed that the hysteretic and non-hysteric properties of the soil affect the porewater distribution in the soil and impact slope stability. The difference between the pore pressure distribution for simulations run with drying and wetting SWCCs is very clear. The porewater pressure profile for the simulation run with the drying SWCC clearly shows a higher suction region near the ground surface when compared to simulations run with either the wetting or hysteretic SWCCs. The difference between the pore pressure distributions for wetting and hysteretic simulations is not as clear.

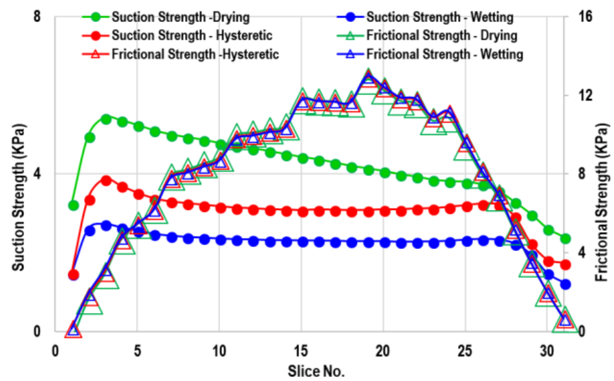

Figure 8. Frictional and suction components of shear strength along the slip circle

Figure 8 shows the frictional and suction components of shear strength along the failure surface. It can be observed that the frictional strength for the hysteretic and non-hysteretic simulations is similar, while the contribution of suction strength is different. This profile clearly shows that the suction contribution is highest for a drying simulation and lowest for a wetting simulation. This correlates well with the FOS values presented in Figure 6.

5 CONCLUDING REMARKS

This study presents the results of a numerical modelling exercise to investigate the impact of hysteresis of SWCC on the slope stability under a soil-atmospheric boundary condition. A two-dimensional finite element unsaturated flow model was used to simulate the infiltration and redistribution of water for hysteretic and non-hysteretic SWCCs. Results of the simulations are analyzed in terms of water balance at the ground surface. Porewater distribution profiles obtained from hydrological analysis were integrated into the slope stability models to estimate the FOS. The results presented in this paper indicate that consideration of hysteresis in the SWCC, results in prediction of significantly different infiltration characteristics than those predicted using a non-hysteretic SWCC. Use of the wetting SWCC results in an estimation of increased infiltration and movement of water compared with analysis using the drying or hysteretic SWCC. This increased infiltration and water movement results in a lower FOS owing to the diminished suction. The results of the study also highlight the importance of using multi-year climate data for slope stability assessments.

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