Effect of Drying and Wetting SWCCs on Unsaturated Soil Slopes

Ammavajjala Sesha Sai Raghuram[1*][0000-0002-0284-5619] and B. Munwar Basha[2] [0000-0003-1417-3650]

[1]Research Scholar, Department of Civil Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy – 502 285
raghuram.ammavajjala@gmail.com
[2]Associate Professor, Department of Civil Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy – 502 285
basha@iith.ac.in

Abstract. The soil water characteristic curve (SWCC) exhibits hysteresis. It is the relation between soil water and soil suction. Desorption (drying) and sorption (wetting) can be used to obtain SWCC. The suction is different in drying and wetting SWCC paths. The slope failures generally take place in wetting SWCC. Therefore, a few efforts have been made in this direction to investigate the effect of drying and wetting SWCCs on slope stability. In this study, the change in factor of safety (FoS) considering drying and wetting SWCCs of unsaturated infinite slope is presented. It is noted that there is a substantial change in the FoS during drying and wetting cycles. A significant difference in the fitting parameters of SWCC for drying and wetting cycles can be observed. In addition, a notable change can be observed in the suction stress of the unsaturated soil slope obtained using both drying and wetting SWCCs. Additionally, the FoS values obtained from experimental data are compared with the correlations available for wetting SWCC in the literature. The correlations available in the literature are in good agreement with the experimental data. The present study highlights the importance of wetting SWCC on the stability analysis of unsaturated soil slopes.

Keywords: Infinite slope, Unsaturated soils, Hysteresis, SWCC.

1 Introduction

Seasonal variations change the depth of slip surface in soil slopes. Many of the slope failures take place in the unsaturated zone, where the slip surface lies above the water table. The suction that exists in unsaturated soil increases the stability of slopes in dry conditions and decreases the stability in wet conditions. Until recently, conventional soil mechanics has been used for most of the slope stability analysis in which soil suction is neglected. In conventional soil mechanics, pore water pressure is assumed to be either zero or positive along the failure surface. However, in real field conditions, pore water pressures within the slope could be highly variable and it could be negative due to which slope failures occur in the unsaturated zone [29]. Therefore, it is of great importance to consider the soil suction in the slope stability analysis. The infinite slope analysis is conducted that accounts for the unsaturated soil shear strength.

Soil water characteristic curve (SWCC) relates soil water to the soil suction, which is a key element to model the unsaturated soil properties like shear strength. There are two possible ways to obtain SWCC namely desorption (drying) and sorption (wetting). It is well recognized that for a given constant suction, soil water contents are not unique. Therefore, soil exhibits different SWCCs during drying and wetting cycles and is termed as hysteresis. The soil water content in the drying SWCC is greater than the soil water content in wetting SWCC for a constant value of suction. Drying SWCC can be obtained by considering a completely saturated soil sample and thereby drying the soil sample by applying suction in increments while measuring the corresponding soil water content and suction. Wetting SWCC can be obtained by considering the completely dried soil sample and thereby wetting the soil sample by decreasing the suction. Though both of these methods yields continuous SWCC's which are not the same. The direction of the process (drying or wetting) and dependency of soil water content leads to hysteresis [9]. The following are the reasons for the hysteretic behavior of SWCC:

1. Inkbottle effect.
2. Contact angle effect.
3. Entrapped air.
4. Ageing of soil.

Fig. 1 shows the typical hysteresis of SWCC. Drying SWCC (initial drying curve) is the SWCC from complete saturation to residual state. Upon wetting, SWCC starts from residual state to saturated state on the drying path, which is referred to as wetting SWCC (main wetting curve).

2 Studies Related to Hysteresis of SWCC

Several studies are reported to evaluate the SWCC by using various techniques like filter paper method [2, 16], Tensiometers [21], pressure plate apparatus [10, 19], axis translational technique [25], and dew point potentiometer [11, 23]. The hysteretic SWCCs of sands and loams are found by using the pressure plate apparatus [15]. The author proposed a simple method to estimate the scanning curves of SWCC. Tempe pressure cell and hanging column techniques are used to find the hysteresis of sands [27]. Similar work was done using dew point potentiometer to find the hysteresis of clayey silts and clays [3]. Pressure plate apparatus and dew point potentiometers are used to find the hysteresis of highly expansive clays [14]. The influence of relative density on the hysteretic SWCC of sand was presented using automated SWCC apparatus [20]. A simple method was proposed to predict the collapse behavior of soil in wetting [12]. The hysteretic SWCC behavior of bentonites was investigated and proposed a model to predict the boundary wetting SWCC [6]. Natural deposited soils and fine soils, when compacted at the dry of optimum, are subject to collapse upon wetting [22]. It was reported that most of the slope failures take place in wetting SWCC [26].

The previously published studies highlight the significance of hysteretic SWCC behavior of soils. However, no attempt has been made to evaluate the influence of hysteresis of SWCC on the infinite slopes. Therefore, a few efforts have been made to investigate the effect of hysteretic SWCC on slope stability.

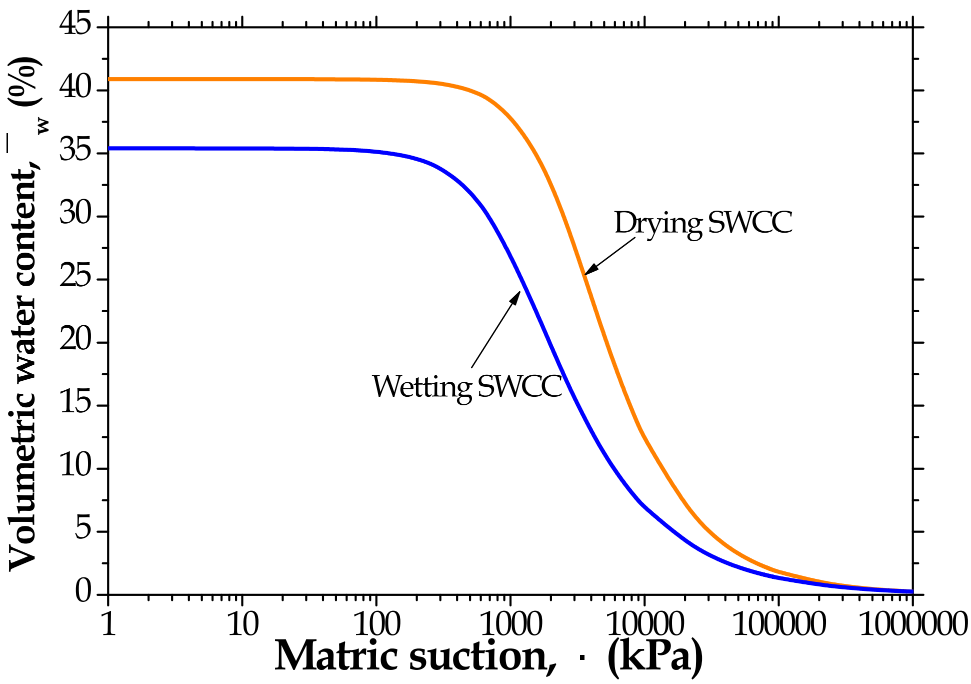

Fig. 1. Hysteresis of soil water characteristic curve.

3 Unsaturated Soil Slope Stability

Consider an infinite slope, which makes an angle 'β' with the ground surface as shown in **Fig. 2**. Assume the depth of the slip surface is at H = 1 m in the present study below the ground surface. Let 'H_w' represents the depth of the water table (H_w is varied from 1.5 m to 10 m in this study). The study proposed by [4] reported the factor of safety (FoS) for unsaturated soil slope by extending the Mohr-Coulomb failure criteria and is given as follows [17]:

$$FoS = \frac{c'}{\gamma H \sin\beta \cos\beta} + \frac{\tan\phi'}{\tan\beta} + \frac{¡(\psi)}{\gamma H \sin\beta \cos\beta} \quad (1)$$

where c' and ¤$'$ are the effective cohesion and effective internal friction angle, ¥ is the unit weight of soil, ¡ depends upon the degree of saturation, · $=(u_a - u_w)$ is the matric suction, u_w and u_a are the pore water and pore air pressures.

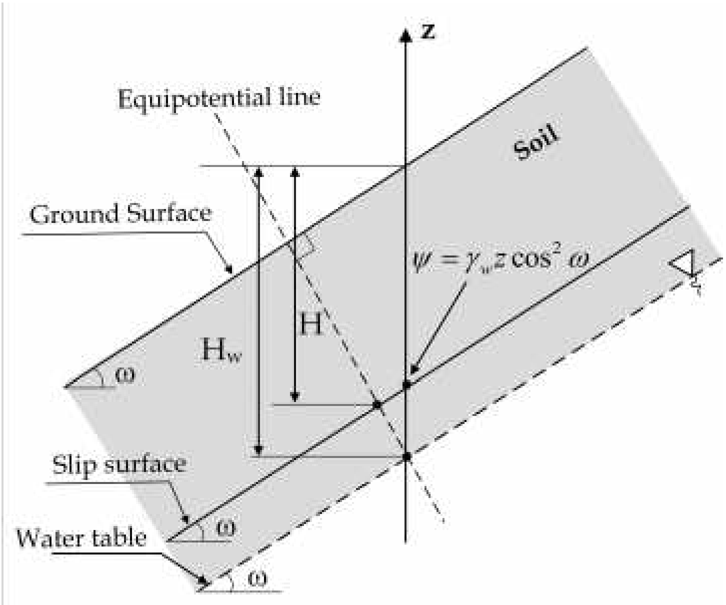

Fig. 2. Infinite slope considered in the study.

The parameter ¡ as shown in Eq. 1 varies with shear strength models for unsaturated soils. In the present study, non-linear shear strength model proposed by Fredlund et al. [5] is assumed. Therefore, Eq. 1 becomes

$$F = \frac{c'}{¥ H \sin µ \cos µ} + \frac{\tan ¤'}{\tan µ} + \frac{\left(\frac{¯_w}{¯_s}\right)^{©} \tan ¤' (u_a - u_w)}{¥ H \sin µ \cos µ} \tag{2}$$

where © is the fitting parameter which depends upon the type of soil, $¯_w$ is the volumetric water content, and $¯_s$ is the saturated water content. In atmospheric conditions, u_a = 0. Therefore, Eq. 2 becomes,

$$F = \frac{c'}{¥ H \sin µ \cos µ} + \frac{\tan ¤'}{\tan µ} + \frac{\left(\frac{¯_w}{¯_s}\right)^{©} \tan ¤' (-u_w)}{¥ H \sin µ \cos µ} \tag{3}$$

The matric suction along the slip surface is given by

$$\cdot = -u_w = -\left[¥_w \left(-H_w \right) \cos^2 µ \right] = ¥_w H_w \cos^2 µ \quad (4)$$

The study presented by Garven and Vanapalli [7] suggested an equation to find the fitting parameter © which is based on plasticity index (I_p) of the soil and is given as

$$© = -0.0016 I_p{}^2 + 0.0975 I_p + 1 \quad (5)$$

Eq. 5 is used in this study to find the fitting parameter © . In the literature, several equations are available to find the SWCC. In this study, van Genuchten (VG) model is considered [24]. The VG model represents the SWCC precisely. The dimensional less water content (Θ) is given by

$$\Theta = \frac{—_w}{—_s} = \frac{1}{\left[1 + \left(\sim \cdot \right)^n \right]^m} \quad (6)$$

where ~ is the fitting parameter of SWCC and is related to the inverse of air entry value (AEV), n is the fitting parameter of SWCC and is related to the slope of SWCC, m is fitting parameter related to the symmetry of SWCC. The fitting parameter m as shown in Eq. 6 is directly related to the fitting parameter n as shown below.

$$m = \left(1 - \frac{1}{n} \right) \quad (7)$$

By imposing this relation in Eq. 6 it becomes

$$—_w = \frac{—_s}{\left[1 + \left(\sim \cdot \right)^n \right]^{\left(1 - \frac{1}{n} \right)}} \quad (8)$$

The FoS of the unsaturated infinite slope can be found by using Eqs. 3, 4, 5 and 8.

Three different soils are considered in the present study from the literature. Goh et al. [8] reported the shear strength of three different types of unsaturated soils considering the hysteresis of SWCC. The three soils have sand : kaolin ratios of 15 : 85 (Inorganic silt), 35 : 65 (Inorganic clay), and 55 : 45 (clayey sand). The same soils are considered in the present study to evaluate the effect of hysteretic SWCC on slope stability. Table 1 summarizes the soil properties for three soils. The SWCC fitting parameters for the VG model are presented in Table 2.

4 Results and Discussions

Fig. 1 shows the hysteretic SWCC of soil. The saturated water content in drying SWCC is greater than the wetting SWCC. This is due to the entrapped air in the soil.

Table 1. Basic and engineering properties of the soils considered.

Property	Inorganic silt	Inorganic clay	Clayey sand
Specific gravity	2.66	2.67	2.66
Maximum dry density	15	16.7	18.6
Plasticity index	19.9	18.6	13.1
Grain size distribution			
Sand (%)	15.0	35.0	55.0
Silt (%)	73.6	44.5	39.0
Clay (%)	11.4	20.5	6.0
Unified soil classification system, USCS	MH	CL	SC
Effective cohesion, c' (kPa)	29.5	8.5	8.2
Effective friction angle, ϕ' (deg.)	26.8	26.9	33.2

Table 2. SWCC fitting parameters for three soils.

Property	Inorganic silt	Inorganic clay	Clayey sand
Drying saturated water content, θ_{sd}	0.503	0.466	0.359
Wetting saturated water content, θ_{sw}	0.441	0.452	0.325
VG fitting parameters			
α_d (kPa^{-1})	0.016811	0.010746	0.016118
α_d (kPa^{-1})	0.054752	0.057118	0.085011
n_d	1.40	1.23	1.38
n_w	1.24	1.12	1.21

In general, the drying process initiates from the micro pores of the soil at a higher suction range. On the other hand, the wetting process initiates from macro pores in the soil at lower suction [6]. **Figs. 3** to **5** represents the drying and wetting SWCC of inorganic silt, inorganic clay and clayey sand for VG model. It can be noticed from **Figs 3** to **5** that, there is a significant difference in between the drying and wetting SWCCs. Furthermore, the hysteresis is more in case of clayey sand followed by inorganic silt and inorganic clay.

In addition to the experimental data for wetting SWCC, correlations available in the literature are used to compare the suction stress and FoS values for different water table positions. Likos et al. [13] proposed correlations based on the type of soil (cohesive or cohesionless). **Figs. 6** to **8** shows the influence of water table position and hysteretic SWCC on the suction stress and FoS for both experimental data and correlations proposed by Likos et al. [13]. **Fig. 6** represents the change in suction stress and FoS with the depth of the water table for inorganic silt in drying and wetting cases. It can be observed from **Fig. 6** that there is a noticeable change in the suction stress and FoS for drying and wetting SWCCs. As an illustration (compare drying and wetting experimental data fits), the suction stress and FoS values are reduced from 0.9 kPa to 0.79 kPa and 6.24 to 6.02 when the water table is at 10 m below the ground surface.

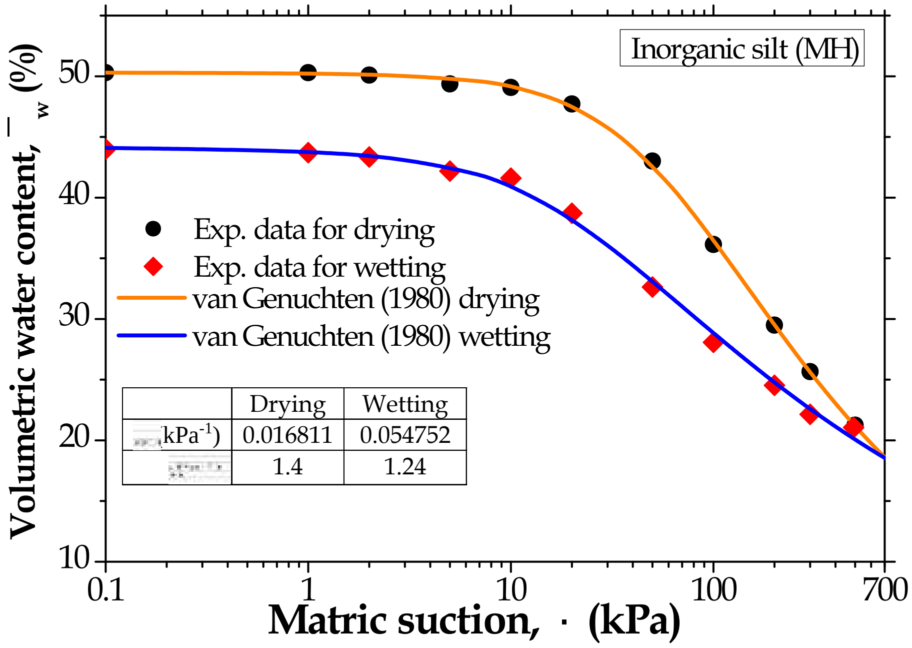

Fig. 3. Hysteresis of inorganic silt for the VG model.

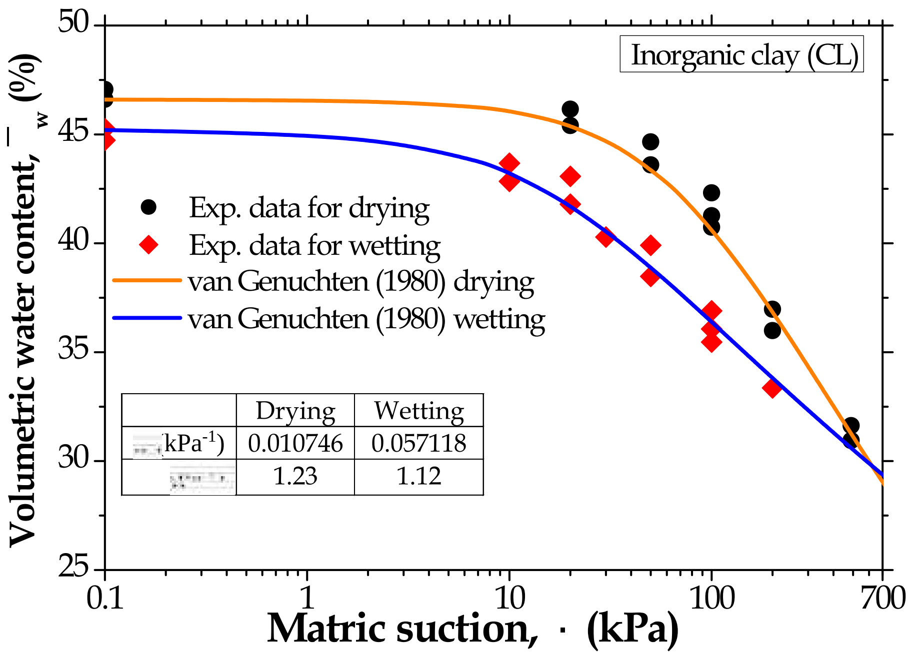

Fig. 4. Hysteresis of inorganic clay for the VG model.

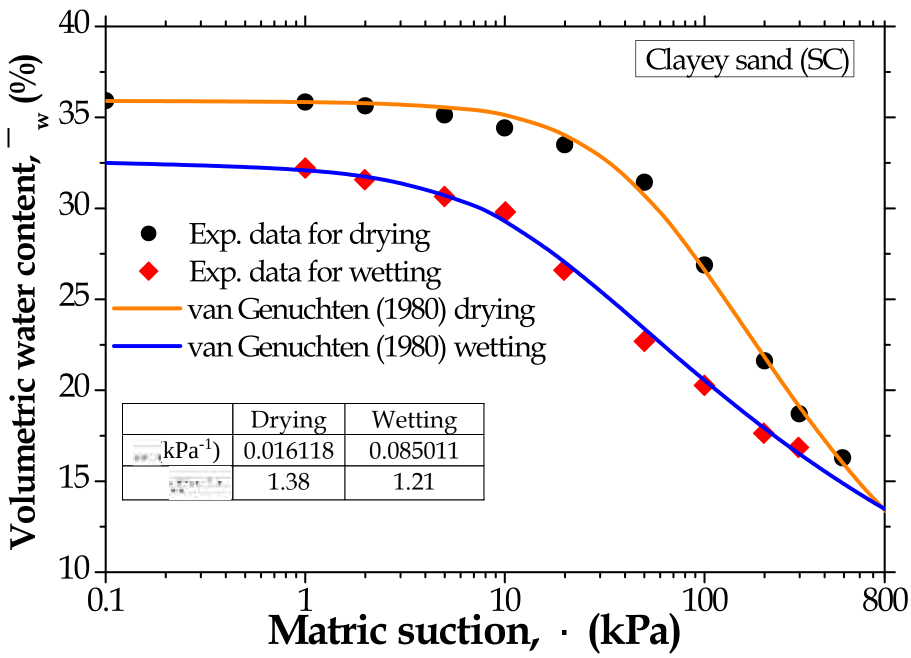

Fig. 5. Hysteresis of silty sand for the VG model.

In addition, it can be observed that the hysteresis of SWCC does not show any impact when the water table is below 4 m from the ground level. This might be due to insufficient suction head. The suction stress and FoS values obtained from the experimental data lies within the ranges proposed by Likos et al. [13]. The difference in suction stress and FoS values are very high for $\alpha_w = 2.67\alpha_d$ and $n_w = 1.05n_d$ correlations.

The effect of water table position on the suction stress and FoS of inorganic clay is presented in **Fig. 7**. **Fig. 7** shows that the suction stress and FoS values are reduced from 1.1 kPa to 0.97 kPa and 3.73 to 3.48 for a given water table position if 10 m below the ground level (compare drying and wetting experimental data fits). Though the suction stress reduction is negligible (0.13 kPa), the reduction in the FoS is significant. **Fig. 8** shows the variation of suction stress and FoS along with the depth of the water table for clayey sand. It can be observed from **Fig. 8** that the effect of hysteretic SWCC and water table position on suction stress and FoS is very high. As an example, suction stress and FoS values are reduced from 1.06 to 0.86 and 3.66 to 3.26 respectively.

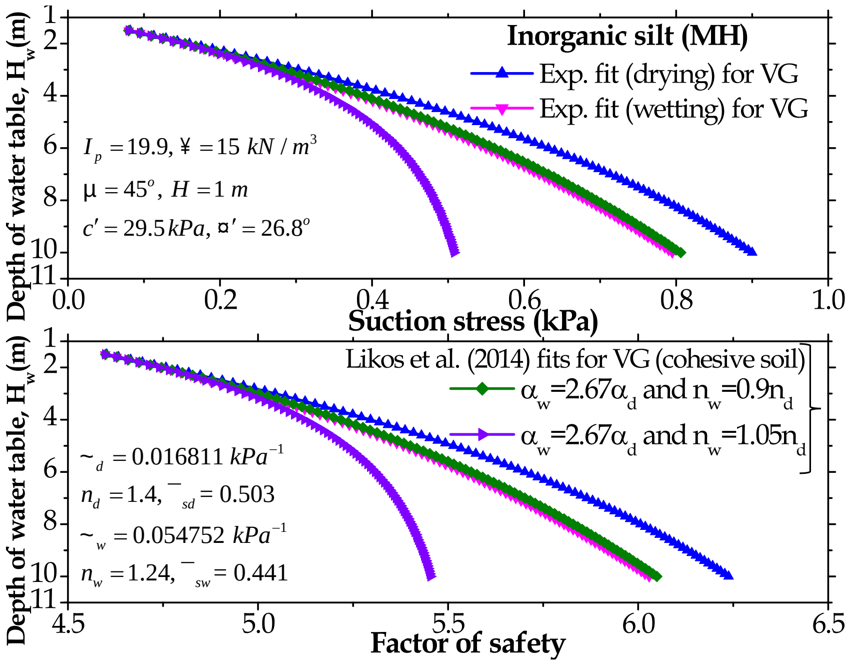

Fig. 6. Effect of water table position on suction stress and FoS for Inorganic silt.

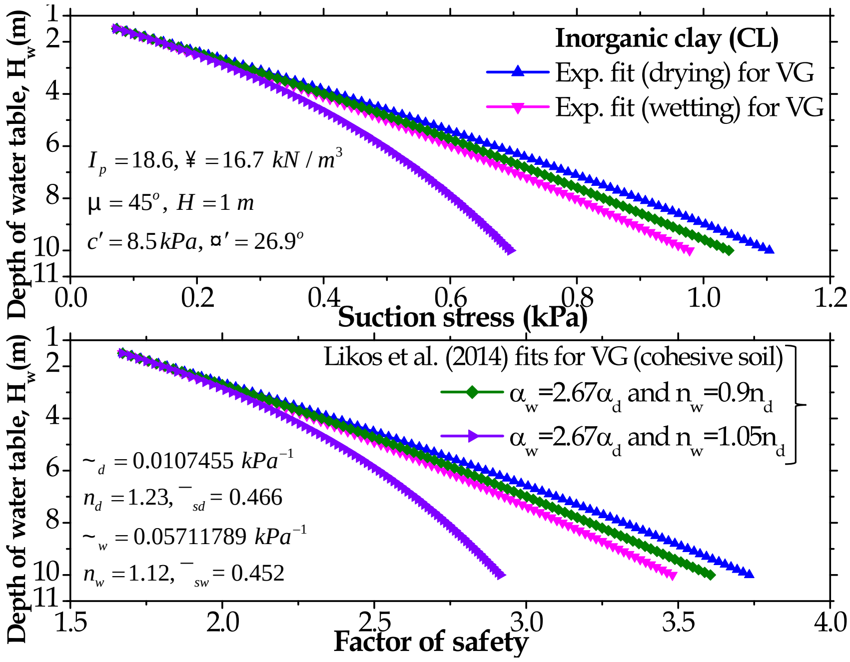

Fig. 7. Effect of water table position on suction stress and FoS for Inorganic clay.

Figs. 6 to **8** depicts the fact that, as the depth of the water table increases, the suction stress and FoS increases. This could be attributed to the increase in the suction head which increases the suction stress and FoS. A similar trend was noticed by Raghuram and Basha [18]. In addition, the FoS and suction stress is greater in drying SWCC when compared to wetting SWCC. This is due to the fitting parameters of SWCC. As mentioned in the earlier sections, the fitting parameter ~ is related to the inverse of AEV. As, the AEV increases, the slope stability increases [28]. Furthermore, the maximum decrease in the FoS due to hysteretic SWCC follows the order clayey sand > inorganic silt > inorganic clay. This is due to the fact that the increase in wet to dry ratio of AEV increases the hysteresis [1]. Therefore, as the hysteresis increases, the difference in suction stress and FoS between drying and wetting increases. In the present study, the hysteresis is more in clayey sand followed by inorganic silt and inorganic clay. The suction stress and FoS values for all the three soils overestimate FoS when the drying SWCCs are considered. However, wetting SWCCs results underestimate the FoS.

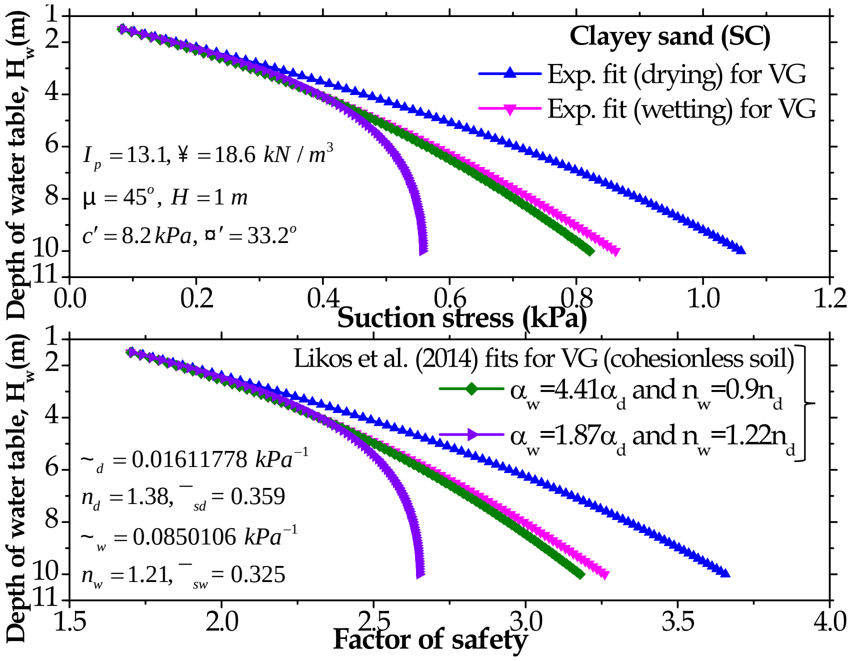

Fig. 8. Effect of water table position on suction stress and FoS for clayey sand.

5 Conclusions

The effect of hysteretic SWCC on the slope stability is carried out by considering three different soils from the literature. The following are the major findings from the study:

1. The current study highlights the importance of hysteresis of SWCC on slope stability.
2. It can be observed that there is a significant difference in the suction stress and factor of safety due to drying and wetting SWCCs.
3. The difference in the suction stress and FoS between drying and wetting SWCC depends upon the wet to dry ratio of the AEV value, which intern depends upon the type of soil. In this study, it was observed that the maximum decrease in the FoS due to hysteretic SWCC follows the order clayey sand > inorganic silt > inorganic clay.
4. The correlations proposed by Likos et al. (2014) gives good estimates of the wetting SWCC's.

It is shown that neglecting the hysteresis of SWCC overestimates the suction stress and FoS. Therefore, due consideration must be paid to wetting SWCCs for slope stability analysis for safe and reliable designs.

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