Influence of Fines Content on Stability of Unsaturated Soil Slopes

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1 Introduction

Natural sands usually consist of considerable fines content (FC), the presence of which severely affects its structure and unsaturated behavior [1–4]. Various proportions of clay and/or silt exist along with the natural sands, which significantly changes the shape of the soil–water characteristic curve (SWCC) or water retention characteristic curve (WRCC) [4]. SWCC or WRCC relates to soil water and soil suction. "Though the usage of locally available soil is economical many a times, it may not be appropriate for satisfactory execution. Therefore, it is necessary to opt for reconstitution of the soil. However, the capability of reconstituted soil would be significantly influenced by the level of reconstitution with the FC". Hence, it is highly necessary to understand the unsaturated behavior of reconstituted soils (sand and fines). WRCC is one of the key tools to address the unsaturated behavior of the soil in terms of shear strength and hydraulic coefficient. WRCC can be obtained in two ways namely desorption and sorption. However, both methods yield continuous WRCCs but are not identical. It is well accepted that, for a given constant water content, soil suction is not unique. This is termed as hysteresis. Hence, soil exhibits different WRCC during the desorption and sorption process. Hysteresis is due to the dependency of soil water content and desorption or sorption process. Ink bottle effect, contact angle effect, entrapped air, and aging of soil are responsible for hysteresis. The hysteresis of WRCC is illustrated in Fig. 1. The WRCC from full saturation to

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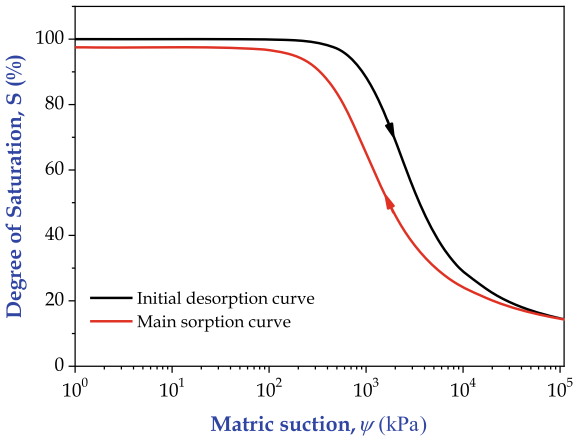

Fig. 1 Hysteretic water retention characteristic curve

residual zone represents the initial desorption curve. The main sorption curve is the WRCC from the residual zone to the completely saturated zone.

The change in depth of slip surface is very common in the natural and man-made slope due to seasonal variations. Most of the time, the failure slip surface lies in the unsaturated zone (i.e., above the water table). The change in soil suction in the unsaturated zone highly influences the stability of the slopes [5]. The assumption made in traditional soil mechanics is that the pore water pressures are either positive or zero along the failure plane. However, in the real field conditions, the pore pressures within the slope could be negative and even may change significantly. The earlier wealth of published research showed that there has been a clear understanding of the suction role in augmenting the shear strength and stability of the slopes. Recent developments have led to several devices that measure the soil suction accurately. Hence, it is highly appropriate to consider the effect of soil suction and hysteretic WRCC in the slope stability analysis. A simple procedure to obtain desorption and sorption WRCCs is presented by Raghuram et al. [6].

2 Literature on Hysteretic SWCC

Many researchers reported various techniques to predict the SWCC using a filter paper method [6–9], pressure plate apparatus [9–12], axis translation method [13], and dew point potentiometer [14]. Pham [15] used a pressure plate apparatus to find the hysteretic behavior of sands and loams and developed a simple method to estimate the SWCC scanning curves. Yang et al. [16] illustrated various parameters affecting the hysteretic SWCC of the sandy soil. A similar study was conducted by Ebrahimi-Birang et al. [17] to estimate the hysteretic SWCC at the high suction range. Li and Vanapalli [18] adopted an easy method to estimate the collapse behavior of soil under wet conditions. Recently Gapak and Tadikonda [19] investigated the influence of desorption and sorption SWCCs of bentonites and developed a simple model to predict the boundary sorption SWCC. A study by Sun et al. [20] found that naturally deposited soils and most of the fine soils when compacted at the dry of optimum are prone to failure under wetting conditions. Xie and Chi [21] concluded that many slopes collapse under wetting conditions. A recent study by Raghuram et al. [6] demonstrated the effect of FC on the desorption and sorption of WRCC and concluded that the shape of WRCC changes significantly with change in FC. Likos et al. [22] and Raghuram and Basha [23] carried out the unsaturated slope stability analysis for three different soils and found that the factor of safety of the slope is significantly affected by the hysteretic SWCC.

The published studies highlight the importance of the influence of FC and hysteretic behavior of SWCC on unsaturated soils. However, to date, no studies are reported on the influence of FC and hysteresis of SWCC on the infinite slope stability and it has been undertaken in this work.

3 Soils Considered

Three different sand and red soil fines mixtures are used in this study from the Raghuram et al. [6]. Ennore sand of Grade—II quality was considered in this study. The specific gravity of the Ennore sand is 2.64. Ennore sand was reconstituted with 30, 40, and 50% red soil fines to obtain a desirable mixture of sand to fines ratio as 70: 30, 60: 40, and 50: 50, respectively. The basic and engineering soil properties of the three reconstituted samples are presented in Table. 1. The particle size distribution for Ennore sand and red soil fines is presented in Fig. 2. The shear strength parameters (cohesion and friction angle) and unit weight of the soil are maintained constant for all the three reconstituted soils to evaluate the effect of WRCC fitting parameters on the factor of safety (FS) of the unsaturated infinite slope.

Several models are available to estimate the WRCC. In the present study, the van Genuchten (VG) model is considered [24]. The VG model is popularly used and predicts the WRCC accurately and precisely. The VG WRCC model is given by

$$S = \frac{\theta_w}{\theta_s} = \frac{1}{\left[1 + (\alpha\psi)^n\right]^m} \tag{1}$$

where α is the fitting parameter of WRCC related to the inverse of air entry value (AEV), n is the fitting parameter of WRCC related to the slope of WRCC, and m is the fitting parameter of WRCC related to the symmetry of WRCC. The WRCC parameter m is directly related to the fitting parameter n as shown below.

$$m = \left(1 - \frac{1}{n}\right) \tag{2}$$

Table 1 Engineering properties of the reconstituted soils

Property	30% fines	40% fines	50% fines
Specific gravity	2.649	2.652	2.655
Maximum dry density	19.08	18.61	18.10
Plasticity index	–	7.78	11.01
Grain size distribution			
Sand (%)	70	60	50
Fines (%)	30	40	50
Unified soil classification system, USCS	SM	SC	SC-CL
Effective cohesion, c' (kPa)	10	10	10
Effective friction angle, ϕ' (deg.)	27	27	27
Drying saturated water content, θ_{sd}	0.266	0.285	0.306
Wetting saturated water content, θ_{sw}	0.262	0.281	0.302
VG fitting parameters			
α_d (kPa^{-1})	0.04292	0.02311	0.00484
α_w (kPa^{-1})	0.08145	0.04449	0.00937
n_d	12.74	10.19	5.76
n_w	10.99	10.04	5.32

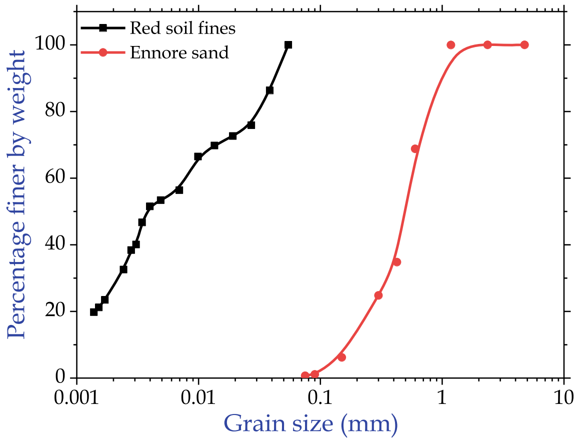

Fig. 2 Particle size distribution for Ennore sand and red soil fines

Substituting Eq. 2 into Eq. 1, it becomes

$$\theta_w = \frac{\theta_s}{\left[1 + (\alpha\psi)^n\right]^{\left(1-\frac{1}{n}\right)}} \tag{3}$$

4 Unsaturated Infinite Slope Stability

As shown in Fig. 3, an infinite slope with a slope angle "ω" is considered. The unsaturated shear strength (USS) model proposed by Fredlund et al. [25] is considered. The FS of the unsaturated slope is given in Eq. (4).

$$F = \frac{c'}{\gamma H \sin\omega\cos\omega} + \frac{\tan\phi'}{\tan\omega} + \frac{(\theta_w/\theta_s)^{\kappa}\tan\phi'(u_a - u_w)}{\gamma H \sin\omega\cos\omega} \tag{4}$$

where c' and ϕ' are the effective cohesion and effective internal friction angle, H = represents the depth of slip surface, γ is the unit weight of soil, $\psi = (u_a - u_w)$ is the matric suction, u_w and u_a are the pore water and pore air pressures, θ_w is the volumetric water content, and θ_s is the saturated water content. In atmospheric conditions, $u_a = 0$. Therefore, Eq. 4 becomes

$$F = \frac{c'}{\gamma H \sin\omega\cos\omega} + \frac{\tan\phi'}{\tan\omega} + \frac{(\theta_w/\theta_s)^{\kappa}\tan\phi'(-u_w)}{\gamma H \sin\omega\cos\omega} \tag{5}$$

Along the failure slip surface, the matric suction can be given as follows:

$$\psi = -u_w = -\left[\gamma_w(-H_w)\cos^2\omega\right] = \gamma_w H_w \cos^2\omega \tag{6}$$

where H_w represents the depth of the water table from the ground surface. The FS of the unsaturated infinite slope can be estimated using Eqs. 3, 5, and 6.

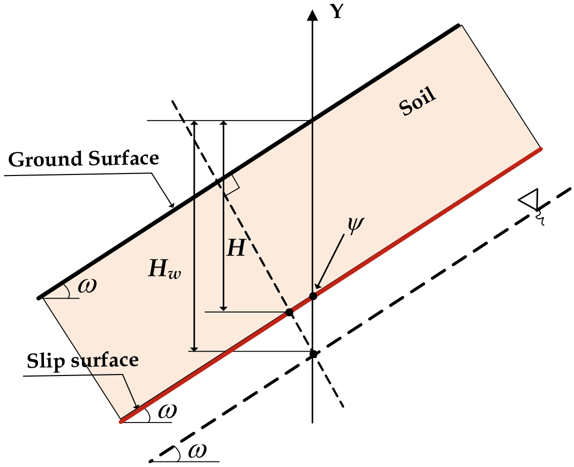

Fig. 3 The geometry of the unsaturated infinite slope

5 Results and Discussion

Figure 4a, b and c shows the hysteresis of WRCC for the three reconstituted soils with 30, 40, and 50% FC. It can be observed from Fig. 4a that the suction associated with desorption WRCC is greater than the suction associated with sorption WRCC because of hysteresis. The entrapped air in the soil is responsible for the higher degree of saturation for desorption WRCC when compared to sorption WRCC. Similarly, for given constant water content, the suction in desorption WRCC is greater than sorption WRCC. This could be attributed to the ink-bottle effect [1]. An interesting finding is that with an increase in the percentage of fines in the soil, the shape of WRCC significantly changes and shifts toward the higher suction range. This is because, as the FC increases, the macropores in the soil reduce, and therefore air requires more suction to enter the soil. Figure 4d shows the shift in WRRCs with respect to FC in the soil.

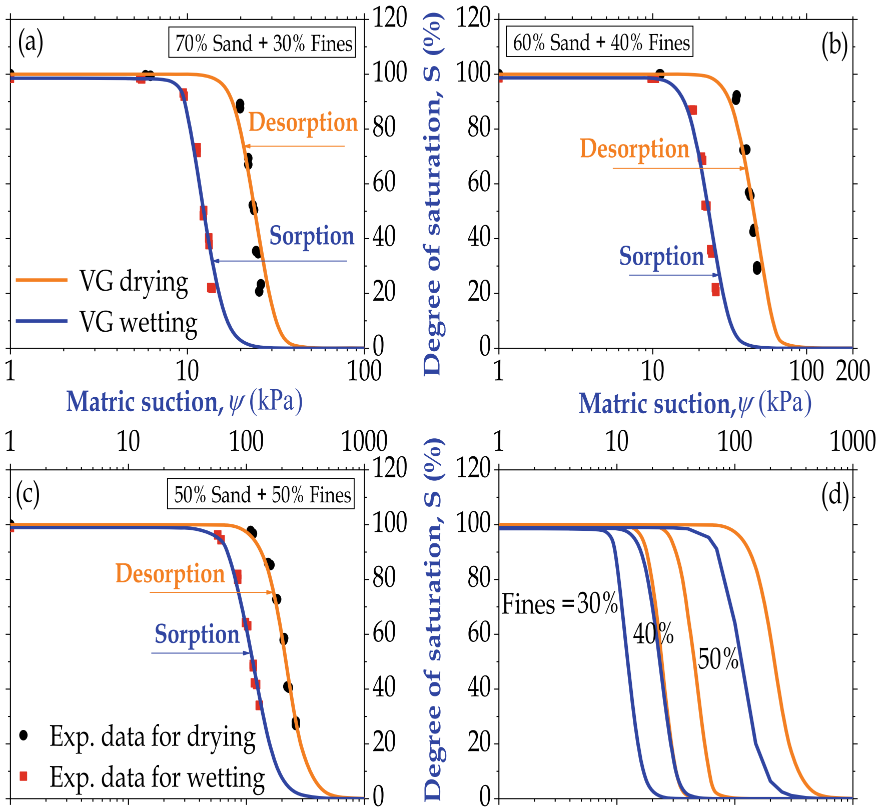

Fig. 4 Influence of FC on hysteretic WRCC, (**a**) 30% fines, (**b**) 40% fines, (**c**) 50% fines, (**d**) 30%, 40, and 50% together

The influence of FC and hysteretic WRCC on the factor of safety is shown in Fig. 5a, b and c. It can be noted from Fig. 5a that the effect of hysteresis on FS is insignificant for 30% fines. This is because suction in coarse-grained soil is less when compared to fine-grained soil. As the majority of the proportion is sand, the shear strength contribution by the suction is less. However, the difference in FS between desorption and sorption WRCC increases with an increase in depth of water table for 40 and 50% fines. As an example, the maximum difference in FS for desorption and sorption WRRC is 0.08 and 0.15 for 30 and 50%, respectively (Figs. 5a and c).

Additionally, it can be observed from Fig. 5a, b and c that the FS increases with an increase in the FC for both desorption and sorption cycles. This could be attributed to an increase in the shear strength due to matric suction with an increase in the FC. Furthermore, it can be observed that for a given depth of water table, the difference in FS between desorption and sorption WRCC follows the order for 30% fines > 40% fines > 50% fines. As an illustration for a given depth of water table at 7 m, the difference in FS between desorption and sorption WRCC is 0.08, 0.05, 0.03 for 30% fines, 40% fines, and 50% fines, respectively. The difference in FS between the desorption and sorption WRCC depends on the degree of hysteresis. As the degree of hysteresis is more, the more is the difference in FS between desorption and sorption WRCC.

5.1 Degree of Hysteresis

Lu and Khorshidi [26] and Raghuram et al. [6] proposed simple equations to estimate the degree of hysteresis. Figure 6a demonstrates the procedure to estimate the degree of hysteresis. The required number of slices to compute the D_h for the three reconstituted soils is shown in Fig. 6b. The difference between maximum and minimum suctions divided by the total number of slices gives the spacing between the slices ($\Delta\psi$). The suction value at the i$^{\text{th}}$ slice is given by

$$\psi_i = \psi_{\min} + (\Delta\psi \times i) \text{ Where } i = 1 \text{ to } N \tag{4}$$

The corresponding degree of saturation (S) can be estimated using the VG WRCC model. The local degree of hysteresis ($D_{h\_\psi_i}$) is given as

$$D_{h\_\psi_i} = \frac{S_{d\_\psi_i} - S_{w\_\psi_i}}{S_{m\_\psi_i}} \tag{3}$$

where $S_{d\_\psi_i}$ and $S_{w\_\psi_i}$ = degree of saturation on desorption and sorption WRCCs at the ith slice, and $S_{m\_\psi_i}$ = mean value of $S_{d\_\psi_i}$ and $S_{w\_\psi_i}$. The total degree of hysteresis (D_h) for the complete hysteresis is given by

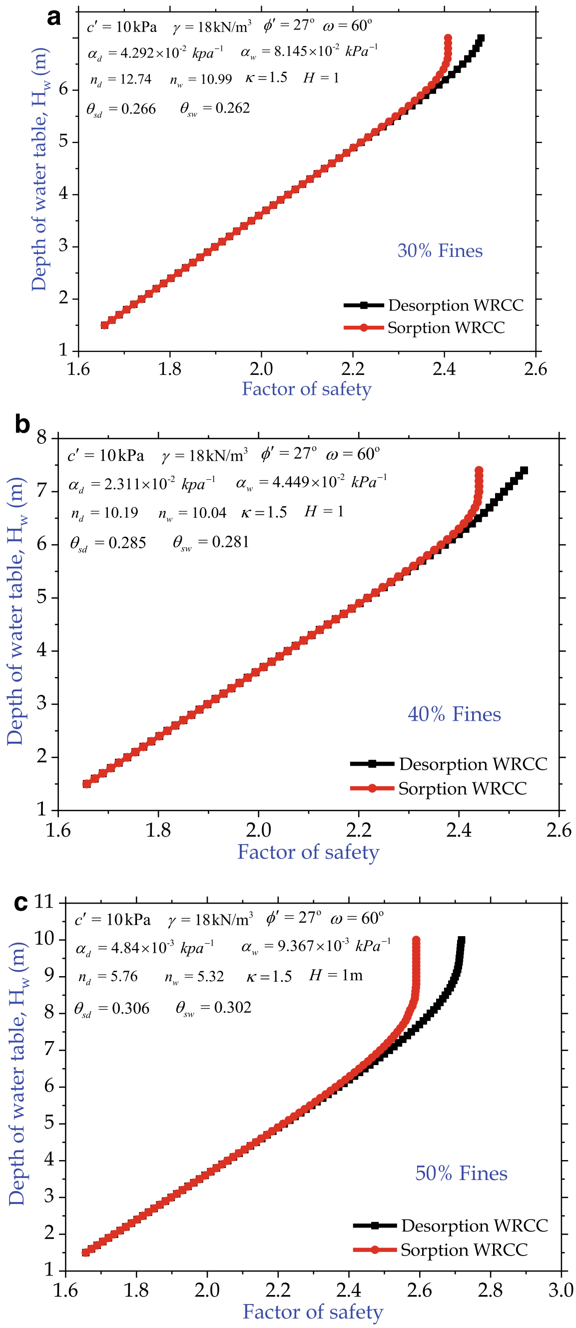

Fig. 5 (**a**) Effect of hysteresis on the FS for 30% fines in the soil. (**b**) Effect of hysteresis on the FS for 40% fines in the soil. (**c**). Effect of hysteresis on the FS for 50% fines in the soil

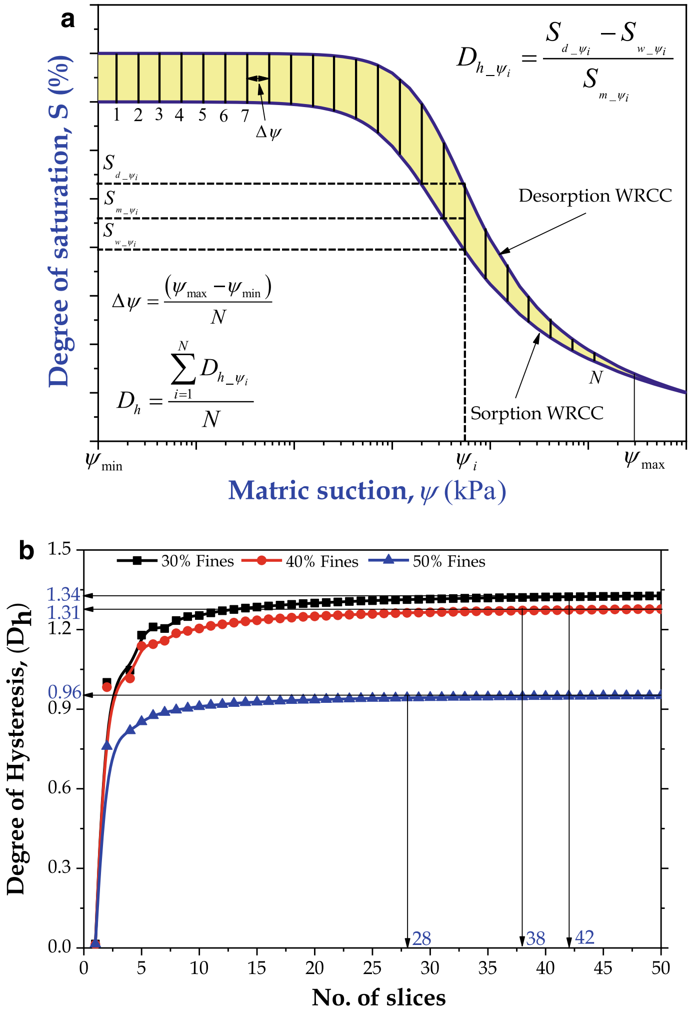

Fig. 6 (**a**) Degree of hysteresis for the WRCC and (**b**) Effect of FC and slice number on the degree of hysteresis

$$D_h = \frac{\sum_{i=1}^{N} D_{h\_\psi_i}}{N} \tag{4}$$

A D_h value of 0.4 represents the degree of saturation of 40% to its mean degree of saturation. Figure 6b shows that the required number of slices to compute the converged value of D_h reduces as the FC in the soil increases.

As an illustration, the number of slices decreases from 42 to 28 as the FC increases from 30 to 50%. This is because of the decrease in D_h from 1.34 to 0.96 as the FC increase from 30 to 50%. The decrease in the degree of hysteresis with an increase in FC in the soil depends on the wet to dry ratio of the AEV value, which is highest for 30% fines.

6 Conclusions

The influence of fines content and hysteretic WRCC on the infinite slope stability is carried out at three different fines contents. The key findings from the study are:

1. The present study emphasizes the importance of the effect of fines content and hysteresis of WRCC on the infinite slope stability.
2. A considerable difference in the WRCC fitting parameters and FS is observed due to desorption and sorption WRCC.
3. The difference in FS between desorption and sorption WRCC depends on the degree of hysteresis which in turn depends on wet to dry ratio of the AEV value.
4. The difference in FS between desorption and sorption WRCC is maximum for 30% fines and minimum for 50% fines.

The results revealed that neglecting the effect of hysteretic WRCC overestimates the FS. The effect of FC has a substantial influence on the hysteretic WRCC and thereby on the FS of the slope. Therefore, due consideration must be given to sorption WRCC and FC to obtain realistic values of the FS of the unsaturated soil slope.

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