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Evaluation of unsaturated soil slope stability by incorporating soil-water characteristic curve

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Abstract. Loess soils are unsaturated and widely distributed in the northwest zone in China. Many steep slope of unsaturated are observed are observed to be naturally stable. However, a low factor of safety (FoS) for these slopes would be computed from the slope stability analysis following local code practices. It seems that the analyzed results following the local code practices do not agree with the real condition as observed in the field. It is commonly known that soil suction plays an important role in slope stability due to a higher shear strength of the unsaturated soil as compared with that of the saturated soil. In this paper, it is observed that the computed FoS can also be affected by unsaturated unit weight of the soil. However, the effect of unsaturated unit weight of the soil on the slope stability is commonly ignored in engineering practice. Therefore, both the effects of shear strength and unit weight of the unsaturated soil on the computed FoS of unsaturated soil slope are investigated in this study. It is observed that the unsaturated unit weight of soil on the computed FoS increases with increase in slope angle. It is also observed that the effects of the unsaturated shear strength and unsaturated unit weight on the computed FoS are more significant than the effect of 3D analyses compared to the 2D analyses on the FoS.

Keywords: shear strength; slope stability; soil-water characteristic curve; unit weight; unsaturated soil

1. Introduction

Loess soils are widely distributed in the northwest zone in China and many steep slopes of loess are observed to be naturally stable. However, the slope stability analyses using the classical saturated soil mechanics show the factors of safety (FoS) of these slopes may be less than 1 Azarafza *et al.* (2017); (Lizárraga and Buscarnera 2018). The design engineer always adopts a conservative method to design slopes and rarely considers the effects of suction on the slope stability. Sometimes, the engineers need to evaluate the slope stability of an existing slope near the construction site. In this case, the engineers cannot always choose the conservative methods because the existing slope may have been stable for a long time but has a very low FoS (i.e., less than 1) when analyzed using the conventional method. Therefore, it appears that the implementation of the unsaturated soil mechanics is imperative in the stability evaluation of an existing slope.

It is a common practice that a constant unit weight (either saturated unit weight or unsaturated unit weight) is adopted in the slope stability analysis(Gasmo *et al*. 2000, Ghadrdan *et al*. 2020, Hassanikhah and Drumm 2020, Peranic *et al*. 2021, Singh *et al*. 2018, Tran An *et al*. 2019, Zhao *et al*. 2017). It is known that unit weight of the unsaturated soil is a function of the degree of saturation (or a function of the soil suction) (Terzaghi *et al*. 1996, Tsai and Chenn 2010). As a result, the unit weight for the unsaturated soil near the crest of the slope may be different than that for the unsaturated soil near the toe of the slope. It is observed that considering the actual unit weight of the unsaturated soil (i.e., a function of the degree of saturation) may result in different FoS and critical slip surface than that using a constant unit weight.

In this paper, the slope stability analyses are carried out for different cases by using the commercial software Slope/W. Consequently, the effects of unit weight of the unsaturated soil on the computed FoS and determined critical slip surface are investigated and discussed.

2. Literature review

Both the limit equilibrium analysis and the finite element stress analysis methods are commonly used in the slope stability analysis(Mehdipour *et al*. 2017, Sengani *et*

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al. 2021, Sengani and Mulenga 2020). In the limit equilibrium analysis method, the computed FoS is same for each slice. In the finite element stress analysis method, the computed local FoS is different for each element. Fredlund and Fredlund (2020) indicated that the global FoS appears to be similar between the limit equilibrium analysis method and the finite element stress analysis method. As the principles in the limit equilibrium analysis method are straightforward, this method is adopted for the slope stability analysis presented in this paper.

Fellenius (1936) was the first researcher who adopted the method of slices in the slope stability analysis by assuming a circular slip surface. Bishop (1955) considered the interslice forces between slices and proposed a new method for the slope stability analysis by improving the original Fellenius (1936)'s method. Janbu (1954) proposed a method which is similar to the Bishop (1955)'s method and computed the FoS based on force equilibrium while Bishop (1955)'s method is based on moment equilibrium. With the advent of high speed computers, Morgenstern and Price (1965) proposed a more rigorous method and computed the FoS by satisfying both moment and force equilibriums.

The forces acting on a vertical slice are illustrated in Fig. 1. Morgenstern and Price (1965) considered the correlation between the horizontal interslice force (E) and the vertical interslice force (X) can be defined by Eq. (1).

$$X = E\lambda f(x) \tag{1}$$

where, X is the vertical interslice force, E is the horizontal interslice force, λ is the correlation parameter, $f(x)$ is the interslice force function.

By satisfying the moment equilibrium corresponding to the rotation point O, the FoS can be obtained by using Eq. (2).

$$F_m = \frac{\sum \left\{ c'lR + \left(P - u_w l \frac{\tan\phi^b}{\tan\phi'} \right) R\tan\phi' \right\}}{\sum Wx - \sum Pf} \tag{2}$$

where, F_m is the factor of safety obtained by satisfying the moment equilibrium; c' is the effective cohesion of soil; ϕ' is the effective angle of internal friction; ϕ^b is the angle indicating the rate of change in shear strength relative to the matric suction; u_w is pore-water pressure at the base of a slice; R is the radius of slip surface; l is the length along the base of a slice; W is the total weight of the slice of soil; P is the normal force; x is the horizontal distance of the slice from the center of rotation; f is the distance of the P from the center of rotation.

By satisfying the force equilibrium for all the slices in the horizontal direction, the FoS can also be obtained by using Eq. (3).

$$F_f = \frac{\sum \left\{ c'l\cos\alpha + \left(P - u_w l \frac{\tan\phi^b}{\tan\phi'} \right) \tan\phi'\cos\alpha \right\}}{\sum P\sin\alpha} \tag{3}$$

where, F_f is the factor of safety obtained by satisfying the force equilibrium; α is the inclination of the base of the slice with respect to the horizontal.

In Morgenstern and Price (1965) method, the FoS is obtained by solving both Eqs. (2) and (3) simultaneously by adjusting the value of correlation parameter (λ). In this paper, Morgenstern and Price (1965) method which has been programmed in Slope/W is adopted for the slope stability analysis.

Leong and Rahardjo (2012) conducted both 2D and 3D analyses for the slopes using Morgenstern and Price (1965)'s method and the computed FoS is illustrated in Table 1. As shown in Table 1, the absolute values of the difference between the FoS from 2D and 3D are within the range of [4.2%, 8.1%]. In addition, Arief *et al.* (2020) investigated the effect of 2D and 3D analysis slope on the computed FoS and observed the difference is within the range of [0.7%, 8.3%]. However, in their studies the unit weight of soil is assumed to remain constant under saturated and unsaturated conditions.

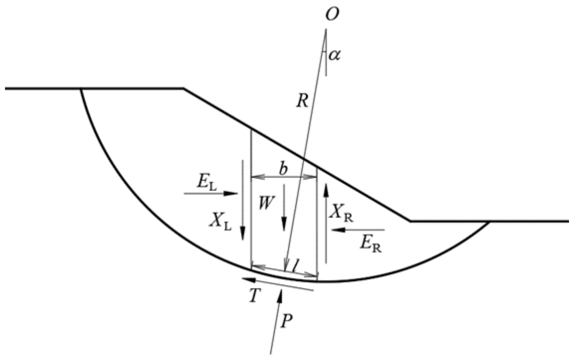


Fig. 1 Illustration of the slice in the Morgenstern and Price (1965) method

3. Effects of the soil suction on the slope stability

The shear strength of unsaturated soil increases with an increase in soil suction while the unit weight of the unsaturated soil decreases with an increase in soil suction. It is expected that either the increase in shear strength or the reduction in unit weight may affect the value of FoS.

Table 1 Computed FoS from 2D and 3D analyses from Leong and Rahardjo (2012)

ϕ' (°)	c'(kPa)	2D FoS	3D FoS	The difference between the 2D and 3D
32	2	0.595	0.566	4.9%
	6	0.708	0.748	5.6%
	10.6	0.84	0.908	8.1%
36.4	2	0.692	0.649	6.2%
	6	0.804	0.838	4.2%
	10.6	0.936	1.006	7.5%

3.1 Unsaturated shear strength

Fredlund *et al.* (1978) introduced the equation of shear strength for unsaturated soil using two independent stress variables. The shear strength equation for unsaturated soil is illustrated as follows

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{4}$$

where, τ is the shear strength of unsaturated soil; c' is the effective cohesion of soil; σ is the total normal stress; u_a is the the pore-air pressure; u_w is the the pore-water pressure; ϕ' is the effective angle of internal friction; ϕ^b is the angle indicating the rate of increase in shear strength relative to the matric suction.

The value of ϕ^b is commonly determined by best fitting the experimental data with Eq. (4). In other words, Eq. (4) cannot be used to predict the shear strength of unsaturated soil. To predict the shear strength of unsaturated soil from the soil-water characteristic curve, Vanapalli *et al.* (1996) modified Fredlund *et al.* (1978)'s equation as follows

$$\tau = c' + \left[(\sigma_n - u_a) + \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)(u_a - u_w)\right]\tan\phi' \tag{5}$$

where, θ is the volumetric water content, θ_s is the saturated volumetric water content, and θ_r is the residual volumetric water content.

Zhai *et al.* (2019) indicated that the prediction results from Eq. (5) are sensitive to the value of θ_r. By conducting the elemental stress analysis on the air-water interface between the soil particles, Zhai *et al.* (2019) concluded that curved air-water interface results in additional compression stress to the soil structure and additional capillary bonding between soil particles. Consequently, Zhai *et al.* (2019) proposed Eq. (6) for the estimation of the shear strength of unsaturated soil from SWCC as follows

$$\begin{aligned}\tau &= c' + (\sigma - u_a)\tan\phi' + \frac{S - S'}{1 - S'}(u_a - u_w)\tan\phi' \\ &+ \sum_{i=m}^{N}\frac{1}{\pi}\left[\left(\frac{\psi_i}{\psi_m}\right)^2\alpha_i - \sqrt{\left(\frac{\psi_i}{\psi_m}\right)^2 - 1}\right] \\ &(u_a - u_w)\left[S(\psi_i + 1) - S(\psi_i)\right]\end{aligned} \tag{6}$$

where, S is the degree of saturation, S' is the degree of saturation corresponding to the suction of 3100 kPa, $S(\psi_i)$ is the degree of saturation corresponding to the suction of ψ_i, α_i defines the relationship between the radius of the curved air-water interface and the radius of the capillary tube with radius of r_i, ψ_m is the suction level in soil specimen prepared for the shearing test.

The last term in Eq. (6) has insignificant effect on the estimated shear strength of unsaturated soil. In this case, Eq. (6) can be simplified as Eq. (7) as follows:

$$\tau = c' + (\sigma - u_a)\tan\phi' + \frac{S - S'}{1 - S'}(u_a - u_w)\tan\phi' \tag{7}$$

Eq. (7) was adopted for computing the shear strength on the base of each slice.

By comparing Eqs. (4) and (7), ϕ^b in Eq. (4) can be obtained as follows

$$\phi^b = \arctan\left[\frac{S - S'}{1 - S'}\tan\phi'\right] \tag{8}$$

3.2 Unit weight of unsaturated soil

Fredlund and Xing (1994)'s equation, as shown in Eq. (9) is commonly used to compute the degree of saturation for the unsaturated soil from soil suction.

$$\begin{aligned}S &= C(\psi)\frac{1}{\left\{\ln[e + (\frac{\psi}{a_f})^{n_f}]\right\}^{m_f}} \\ &= \left[1 - \frac{\ln(1 + \frac{\psi}{C_r})}{\ln(1 + \frac{10^6}{C_r})}\right]\frac{1}{\left\{\ln[e + (\frac{\psi}{a_f})^{n_f}]\right\}^{m_f}}\end{aligned} \tag{9}$$

where a_f, n_f, and m_f are SWCC fitting parameters, C_r is the input value.

The unit weight of the unsaturated soil can be obtained by using following equation.

$$\gamma = \gamma_d(1 + w) = \gamma_w\frac{G_s(1 + w)}{1 + e} = \gamma_w\frac{G_s + Se}{1 + e} \tag{10}$$

where, γ is the unit weight of the unsaturated soil, γ_d is the dry unit weight of soil; w is the water content; γ_w is the unit weight of water; G_s is the specific gravity; S is the degree of saturation; and e is the void ratio.

Substituting Eq. (9) into Eq. (10) gives

$$\gamma = \frac{\gamma_w G_s}{1 + e} + \frac{\gamma_w e}{1 + e}C(\psi)\frac{1}{\left\{\ln[e + (\frac{\psi}{a_f})^{n_f}]\right\}^{m_f}} \tag{11}$$

As a result, the unit weight of an unsaturated soil can be computed directly from the soil suction by using Eq. (11).

3.3 Numerical analyses on the effect of the soil suction on the slope stability

A typical slope geometry with a slope height of 5 m and a slope angle of 55 degrees, as shown in Fig. 2, was adopted for the slope stability analysis using Slope/W. The effective cohesion c' and the friction angle ϕ' of soil are defined to be 10 kPa and 25°, respectively. The water table is located 2 m deep below the toe of the slope and inclined 7 degrees.

There are four cases considered for the slope stability analysis as listed in Table 2. Case 1 is based on the classical soil mechanics (i.e., suction above the ground water table is ignored) and constant unit weight; Case 2 is based on the

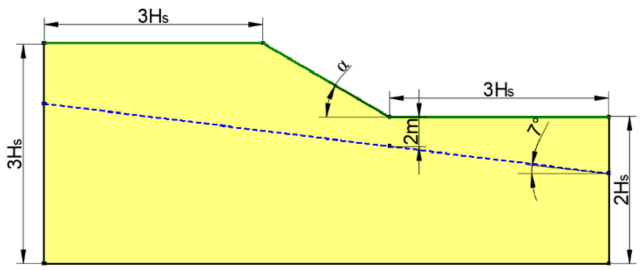


Fig. 2 Illustration of the geometry of the typical slope

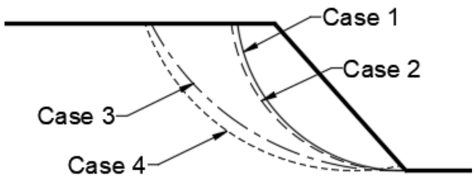


Fig. 3 Illustration of the critical slip surfaces for four cases

Table 2 The cases available in analyses

Four cases	Suction effect on shear strength	Suction effect on unit weight
Case 1	Not considered	Not considered
Case 2	Not considered	Considering
Case 3	Considering	Not considered
Case 4	Considering	Considering

classical soil mechanics and the unit weight of the unsaturated soil to be a function of soil suction; Case 3 is based on the use of the unsaturated soil mechanics and constant unit weight; Case 4 is based on the use of the unsaturated soil mechanics and the unit weight of the unsaturated soil to be a function of soil suction. The computed FoS for those four cases are 1.26, 1.30, 2.16 and 2.29 for Case 1, Case 2, Case 3 and Case 4, respectively. The critical slip surfaces for those four cases are illustrated in Fig. 3.

Fig. 3 indicates that considering unsaturated unit weight makes the slip surface to be deeper (i.e., Case 2 has a deeper slip surface than Case 1and Case 4 also has a deeper slip surface than Case 3). On the other hand, the contribution of suction on the shear strength makes the slip surface to be significantly deeper (i.e., Case 3 has a much deeper slip surface than Case 1 and Case 4 also has a much deeper slip surface than Case 2).

4. Simulation for slope stability analyses

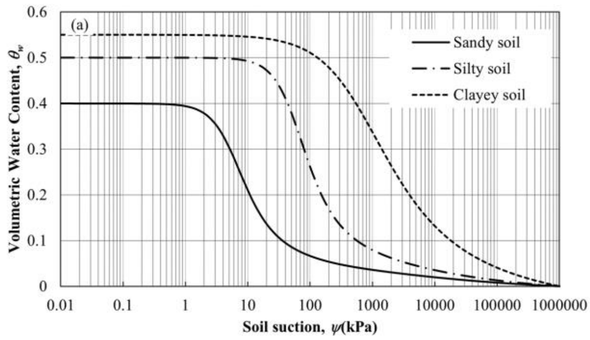
The results presented in Fig. 3 are only for a typical slope. To investigate the suction effect (including the unsaturated shear strength and unsaturated unit weight) on the computed FoS, a parametric study was carried out by varying the slope height, H_s, to be 5, 10 and 15 meters, the slope angle, α, to be 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 and 80 degrees. Three types of typical soils named sandy soil, silty soil and clayey soil are adopted for the slope stability analyses. Both the effective cohesion c' and the friction angle ϕ' for those three types of soils are illustrated in Table 3. The SWCC fitting parameters using Fredlund and Xing (1994)'s equation for those three types of soil are illustrated in Table 4. The SWCCs and the variations of ϕ^b with the change of soil suction for three types of soil are shown in Fig. 4.

Table 3 Summary of soil properties for three typical soil types

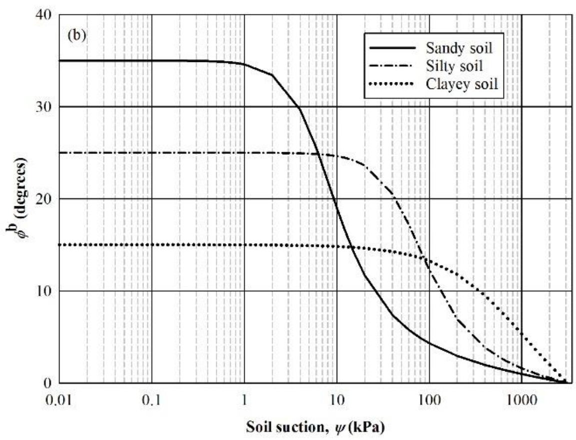
Property	Sandy soil	Silty soil	Clayey soil
Unit weight, γ (kN/m³)	19	19	19
Effective cohesion, c' (kPa)	1	10	20
Effective angle of friction, ϕ' (°)	35	25	15

Table 4 Fredlund and Xing parameter for three typical soil types

Property	Sandy soil	Silty soil	Clayey soil
Fitting parameter a, (kPa)	5	50	500
Fitting parameter n	2	2	1
Fitting parameter m	1	1	1
Saturated volumetric water content, θ_s	40%	50%	55%



(a) SWCCs for the soils



(b) Variations of ϕ^b for the soils

Fig. 4 SWCCs and variations of ϕ^b for three types of soil

5. Results and discussions

The computed FoSs for those three types of soil slope by considering different cases are illustrated in Figure 5 to 7. Figs. 5 to 7 indicate that the FoS decreases with increase in slope angle and slope height. The FoSs computed for Case 1, which is commonly adopted by the practical engineers, are consistently the lowest, followed by Case 2, Case 3 and Case 4. The magnitude of the differences between the FoSs for Case 2 and that for Case 1 increases with increase in the slope angle, and the same trend can be observed between Case 3 and Case 4. In addition, it is observed that the differences between the FoS for the Case 4 and Case 3 are larger than those for Case 2 and Case 1. As a result, it indicates that the effect of unit weight of unsaturated soil on the computed FoS can be amplified if the effect of the unsaturated shear strength on the FoS is considered simultaneously.

To quantify the effect of soil suction (i.e., both unit weight and shear strength of unsaturated soil), the

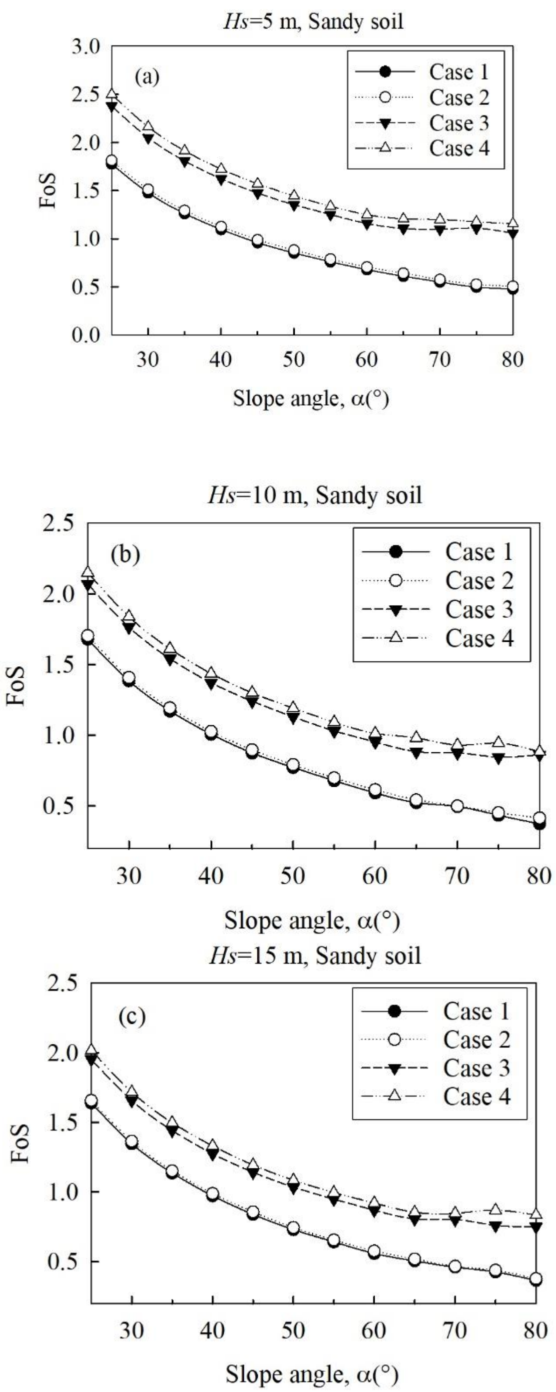


Fig. 5 FoS for sandy soil slopes, (a) H_s is 5 m, (b) H_s is 10 m and (c) H_s is 15 m

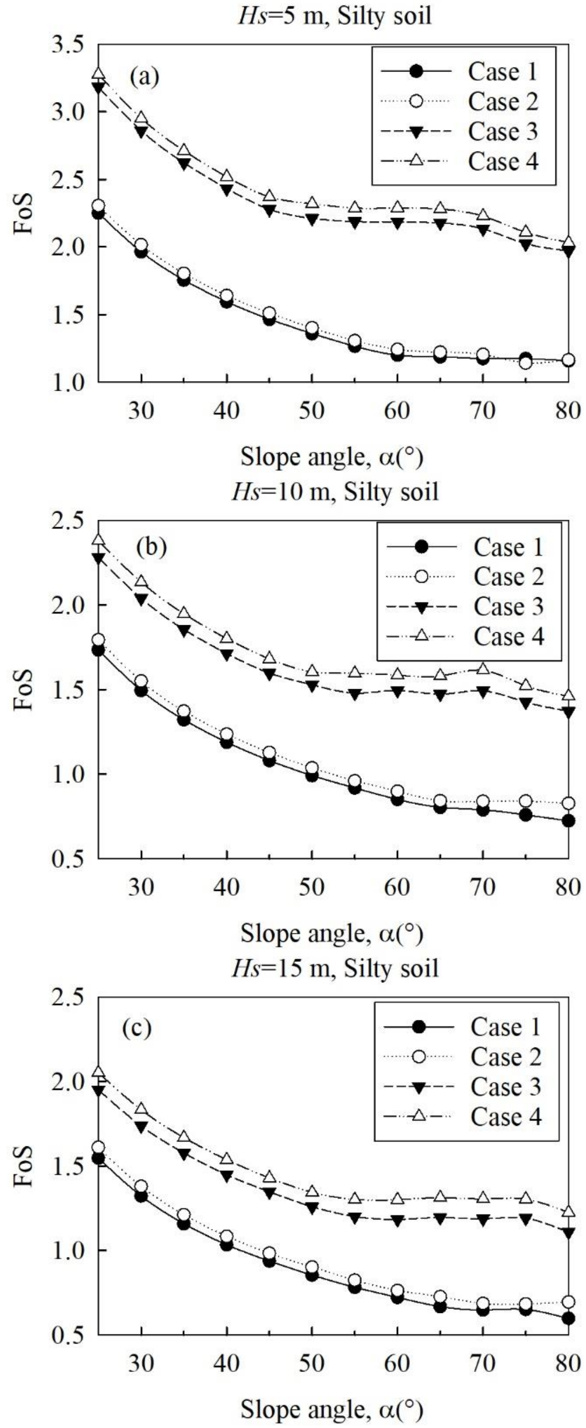


Fig. 6 FoS for silty soil slope, (a) H_s is 5 m, (b) H_s is 10 m and (c) H_s is 15 m

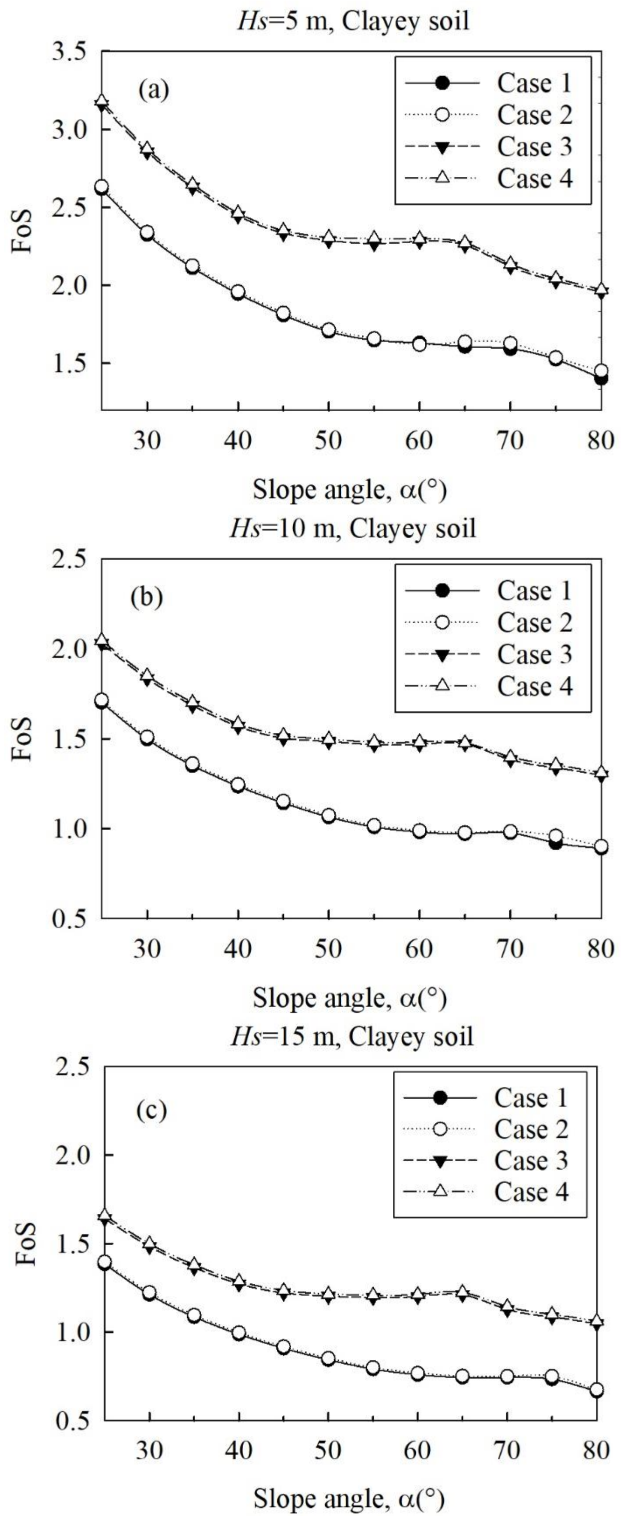


Fig. 7 FoS for clayey soil slope, (a) H_s is 5 m, (b) H_s is 10 m and (c) H_s is 15 m

differences between the FoS for the sandy soil slope is illustrated in Fig. 8. The difference in FoS is defined by the equation as follows

$$\Delta = \frac{y_i - y_1}{y_1} \times 100\% \tag{12}$$

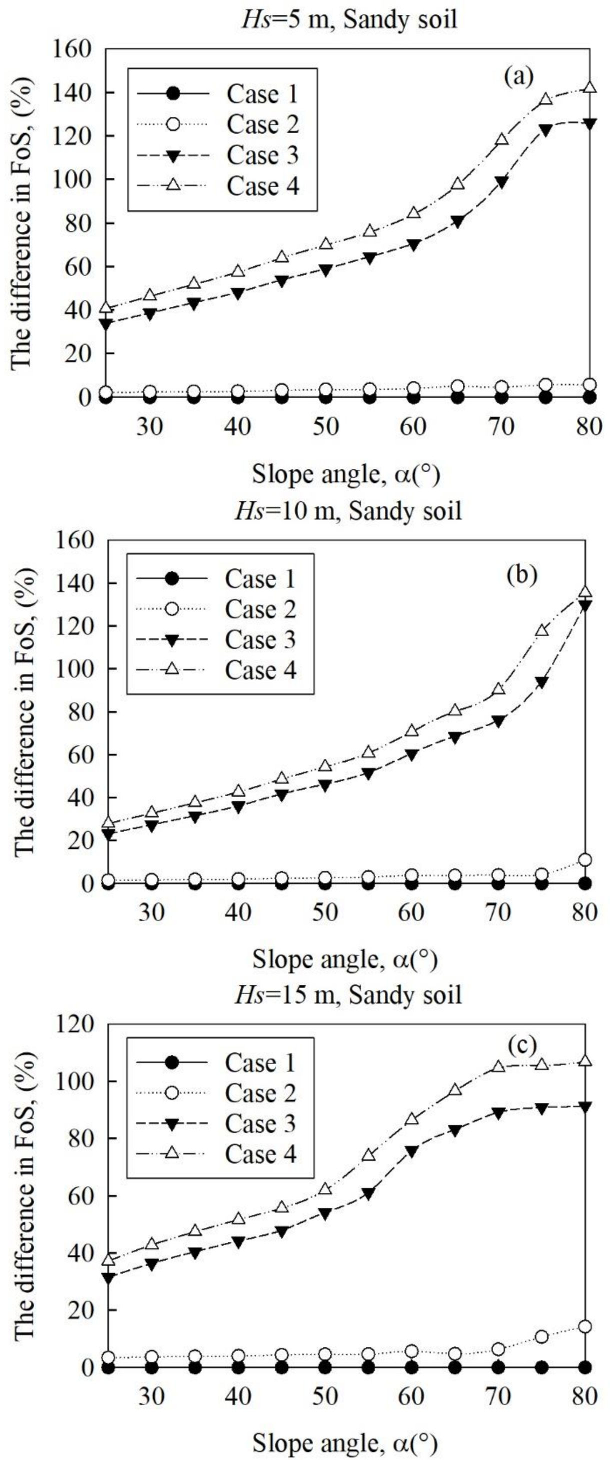


Fig. 8 The difference in FoS for sandy soil slope, (a) H_s is 5 m, (b) H_s is 10 m and (c) H_s is 15 m

where, Δ is the difference between the computed FoSs, y_1 is the computed FoS for Case 1, y_i is the computed FoS for Case i (i =2, 3, and 4).

Fig. 8 indicates, when the slope angle is greater than 60 degrees, considering the unsaturated shear strength in the analysis results in a higher FoS (i.e., more than 60%) than that obtained from the conventional method such as Case 1. If both the unsaturated shear strength and unsaturated unit weight are considered in the analysis, then the computed

FoS can increase by another 10% from that of the conventional method such as Case 1. The differences in the computed FoS considering unsaturated shear strength and unsaturated unit weight are larger than the differences between FoS from 2D and 3D analyses as reported by Leong and Rahardjo (2012). Therefore, the effect of unsaturated shear strength and unsaturated unit weight should be considered in the evaluation of slope stability.

6. Conclusions

Both the effects of shear strength and unit weight of the unsaturated soil on the computed FoS for the soil slopes are investigated by considering different typical cases for the analyses. It is observed that considering the unsaturated shear strength and unsaturated unit weight results in a deeper slip surface. In addition, considering the unsaturated shear strength and unsaturated unit weight leads to a larger FoS, especially for the slope with a slope angle greater than 60 degrees. It is also observed that the effect of the unsaturated shear strength and unsaturated unit weight on the computed FoS is more significant than the effect of 3D analyses compared to the 2D analyses on the FoS.

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