EFFECT OF INITIAL SUCTION ON STABILITY OF UNSATURATED SOIL SLOPES

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1. Abstract

The effect of suction is often ignored in slope stability studies in conventional soil mechanics. There is a perception among geotechnical engineers that suction cannot be relied upon in stability analysis of unsaturated soil slopes. Therefore, the objective of this paper is to demonstrate the importance of suction that should be taken into consideration in the stability of unsaturated soil slopes. A theoretical study using the SLOPE/W software has been presented to investigate the effect of initial suction on shear behavior and stability of unsaturated slopes. Two slope models were proposed in this study, the first model is a sandy soil of 10 m high with approximately 26^{o} inclination angle and the second model is a silty clay soil with a vertical cut of 8 m high. The results showed that the initial soil suction has a significant effect on the stability of unsaturated soil slopes. This result is considered crucial for geotechnical engineers, who should implement soil suction in the analysis of unsaturated soil slopes.

تأثير السحب الابتدائي على اتزان ميول التربة الغير مشبعة

ملخص البحث:-

تتجاهل معظم الدراسات الخاصة باتزان الميول مقدار السحب داخل التربة (ضغط المياه السالب)، حتى ساد تصور بين المهندسين الجيوتقنيين انه لا يمكن الاعتماد على مقدار السحب في حسابات اتزان الميول. لهذا كان من اهم اهداف هذه الدراسة توضيح دور السحب الابتدائي في الاتزان و اهمية اخذه في الاعتبار عند تصميم الميول في التربة الغير مشبعة. ويقدم هذا البحث نموذج نظري باستخدام برنامج SLOPE/W لتوضيح تأثير السحب الابتدائي على مقاومة القص للتربة وبالتالي مدى تأثيره على الاتزان الحدي لميول التربة الغير مشبعة. فتم عمل نموذجين: النموذج الاول يمثله ميل من التربة الرملية بزاوية ٢٦ درجة مع الافقي بارتفاع ١٠ م بينما النموذج الثاني عبارة عن قطع رأسي من الطين الطمي بارتفاع ٨ م. ولقد اوضحت النتائج ان للسحب الابتدائي تأثير جديرا بالاخذ في الاعتبار اثناء تصميم و دراسة ميول التربة الغير مشبعة. ولهذا يصبح تأثير السحب الابتدائي من العوامل الواجب دراستها لدى المهندسين الجيوتقنيين لما له من اهمية كبيرة عند دراسة اتزان ميول التربة الغير مشبعة.

2. Introduction

Fredlund, D.G. (1981, 1987) highlighted that the initial soil suction plays an important role in the stability of an unsaturated soil slopes especially in arid and semi-arid regions. Suction distribution in a soil usually depends on several factors such as soil type, ground water conditions and climatic conditions. Faroukm A., et al., (2004) and Estabragh, A.R., and Javadi, A. A. (2012) indicate that to include the effect of changing shear strength of a soil due to suction, the field soil suction profile of the soil must be known. Nevertheless, the suction profile can be determined directly using field measurements such as tensiometers. In this paper, an empirical conceptual is adopted for assessing the initial soil suction profile in slopes.

The stability analyses of unsaturated soil slopes in this work are mainly focusing on the effect of the suction shearing angle, ϕ_b, which is expressed as a fraction of the internal angle of friction. Fredlund and Rahardjo (1993) and Fredlund, D.G., and Vanapalli, S.K. (2002) summarized the results of ϕ_b measurements for a variety of soils and showed that ϕ_b indeed appears to be generally smaller than or equal to the internal friction angle, ϕ. In this research, the range of ϕ_b/ϕ was taken from zero to one. Therefore, the following sections present the effect of initial suction on the factor of safety of unsaturated soil slopes.

3. Shear strength of unsaturated soil

As shown in Figure (1), the shear strength of an unsaturated soil can be formulated in terms of independent stress state variables (Fredlund and Rahardjo, (1993)). The stress state variables, net normal stress and soil suction have been shown to be the most advantageous combination for practice. Using these stress variables, the shear strength equation could be written as follows (Fredlund and Rahardjo, (1993)):

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi_b \quad \text{.. (1)}$$

Where:

τ = the shear strength.

c' = the effective cohesion.

$(\sigma - u_a)$ = net normal stress.

$(u_a - u_w)$ = matric suction.

u_a = pore air pressure.

u_w = pore water pressure.

σ = normal total stress.

ϕ' = angle of internal friction associated with the net normal stress.

ϕ_b = the suction shearing angle associated with the soil suction.

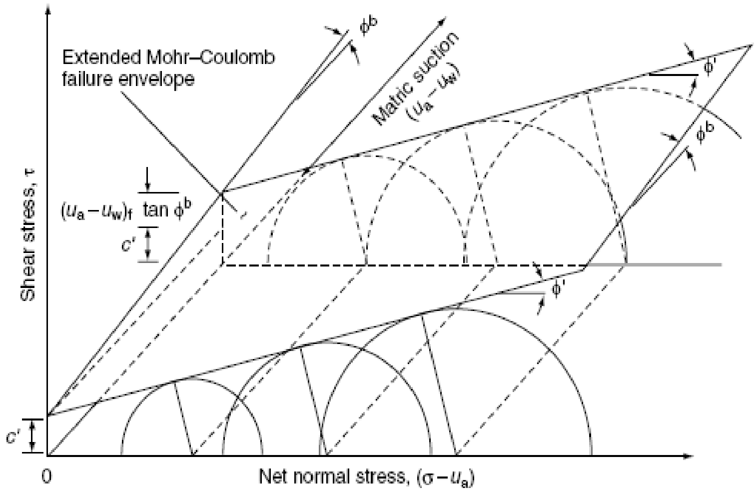

Figure (1) Extended Mohr–Coulomb failure envelope for unsaturated soils (after Fredlund and Rahardjo, 1993)

4. Model geometry and soil properties

The analysis was conducted for two slope models designated as Model (1) and Model (2). Model (1) is 10 m high with approximately 26^o inclination angle (approximately 2H: 1V). For Model (1), Ground water table, GWT, lies at 20 m under the ground surface as shown in Figure (2). The slope is formed of sandy soil. Model (2) is a vertical cut with 8 m high. The ground water table of Model (2) lies at 20 m under the ground surface as shown in Figure (3). The slope is formed of silty clay soil. Soil properties for the two models are presented in Table (1).

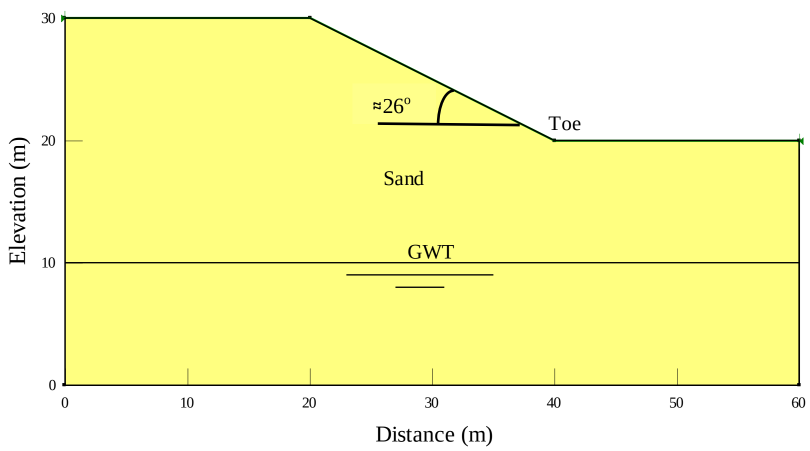

Figure (2) Geometry of Model (1)

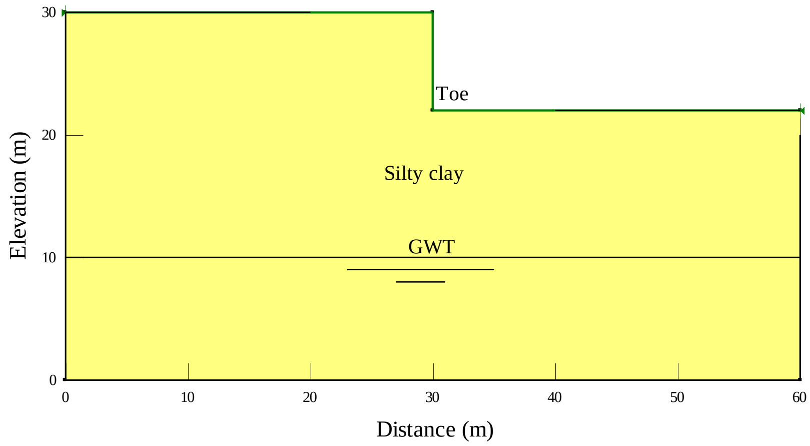

Figure (3) Geometry of Model (2)

Table (1) Soil properties for Model (1) and Model (2)

Soil property	Model (1)	Model (2)
γ = unit weight	17 kN/m^3	17.5 kN/m^3
ϕ = internal angle of friction	25^0 and 30^o	10^o : 25^o
ϕ_b = suction shearing angle	[0, 0.5, 1] ϕ	[0, 0.5, 1] ϕ
C = cohesion	0	5 kPa : 30 kPa
θ_s= saturated volumetric water content	0.3	0.45
k_s = saturated hydraulic conductivity	2.15*10^{-5} m/s	3.0*10^{-8} m/s

5. Effect of initial suction on stability of slopes

According to modified Mohr–Coulomb Failure Criterion, the suction shearing angle, ϕ_b, has a significant impact on shear strength of soil. Therefore, the main aim of this step is to investigate the effect of ratio ϕ_b/ϕ and variation of initial suction on the factor of safety of unsaturated soil slopes. Figure (4) depicts the analysis methodology adopted to investigate the effect of the initial suction on the safety of unsaturated soil slopes.

According to Ning Lu, (2004), the soil initial suction profile is assumed to be linearly increasing above ground water table up to a limiting value as shown in Figure (5). Mainly, the limiting values depend on soil type. The limiting values are 200 kPa in clay, 70 kPa in silt, and 10 kPa in sand.

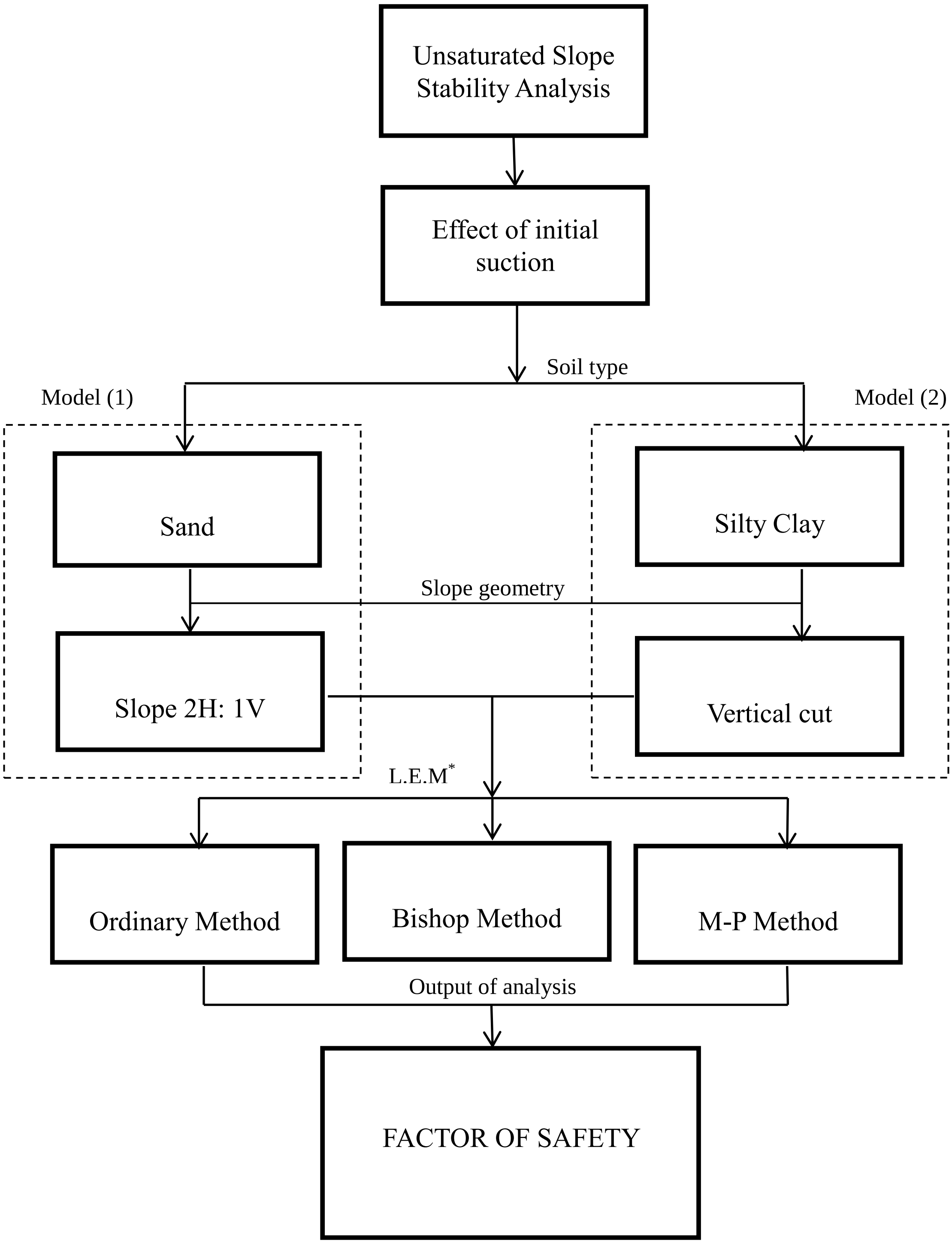

Figure (4) Adopted analysis methodology to investigate the effect of initial suction on stability of unsaturated soil slopes

(*L.E.M: Limit equilibrium method)

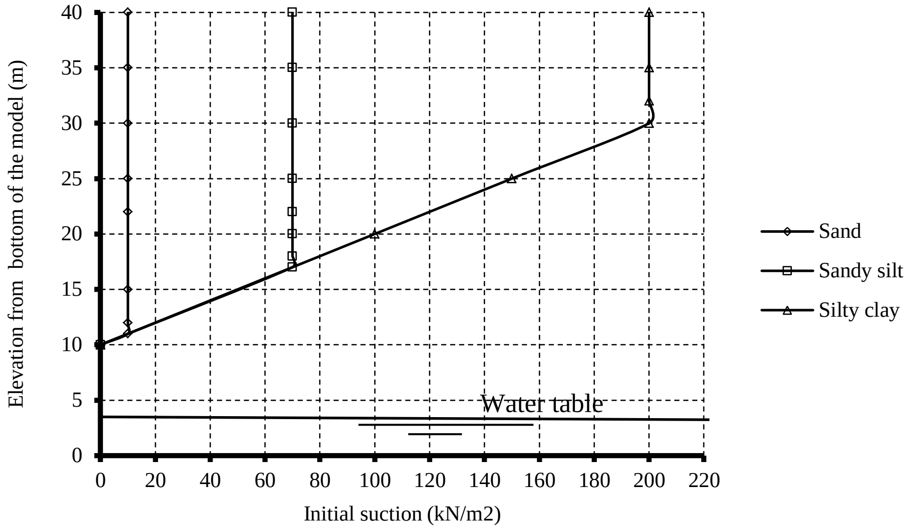

Figure (5) Initial soil suction distribution

5.1 Effect of Suction Shearing Angle on Factor of Safety

5.1.1 Model (1): Sandy Soil

Based on Mohr-Coulomb's modified criteria, the effect of initial suction on unsaturated soil slopes behavior can be expressed by the effect of suction shearing angle, ϕ_b. Therefore, this section investigates the effect of suction shearing angle which indicated by ratio ϕ_b/ϕ on safety factor of unsaturated soil slopes. Figures (6) and (7) illustrate the variation of the safety factor versus ϕ_b/ϕ for the cases of ϕ = 25^o and ϕ = 30^o, respectively. It can be noticed that the suction shearing angle has a significant effect on the factor of safety of unsaturated slopes. The factor of safety increases with the increase of suction shearing angle ϕ_b. Basically, this increase is attributed to the increase of soil shear strength. The increase in factor of safety by considering initial matric suction is changed by about 28% higher as compared to the conventional slope stability analysis at ϕ_b/ϕ= 0.5.The incorporation of suction effect in the analysis leads to change the stability of slope from failure state (i.e. FS<1.0) to stable state (i.e. FS>1.0) for ϕ = 25^0.

The results also indicate that soil shear strength increases as suction shearing angle increases, thus slope becomes more stable when initial suction is considered. It is noted that there is no obvious difference in the results of Bishop's method and Morgenstern-Price method (M-P), whose results are higher than the results of Ordinary method. This is regarded to the neglect of the interslice forces in analysis using

Ordinary method. For example, the factor of safety estimated using Bishop's method is 6% higher than estimated using Ordinary method.

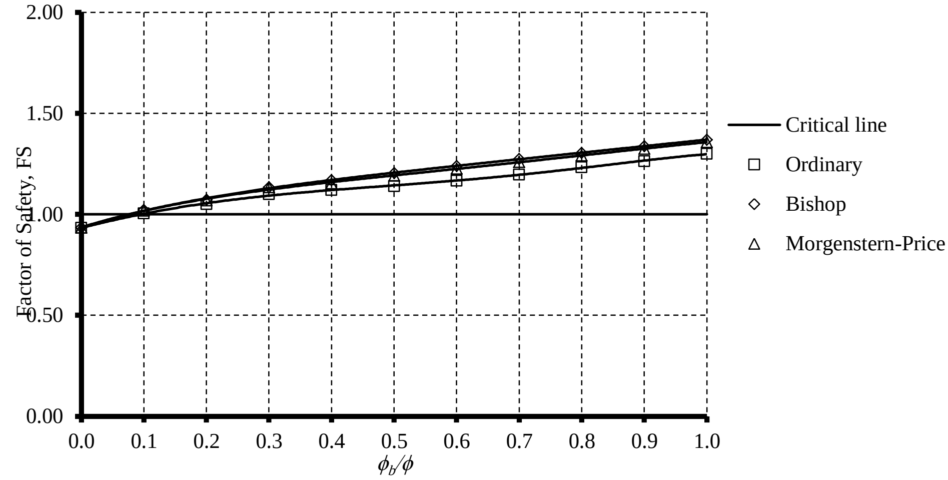

Figure (6) Variation of safety factor versus ϕ_b/ϕ, Model (1): sandy soil at ϕ =25^0

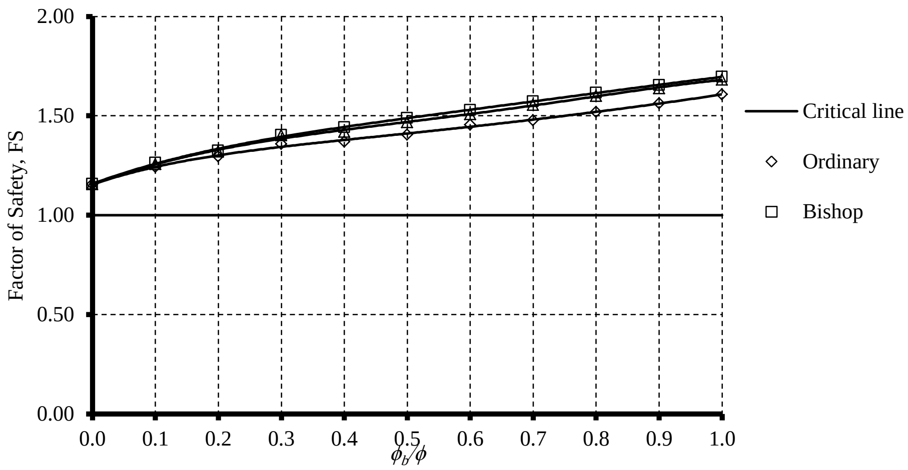

Figure (7) Variation of safety factor versus ϕ_b/ϕ, Model (1): sandy soil at ϕ = 30^0

Figure (8) presents the variation of the safety factor versus ϕ_b/ϕ for the cases of ϕ = 25^o and ϕ = 30^o. Internal angle of friction has a significant effect on the factor of safety of unsaturated soil slope. Magnitude of factor of safety increases by 23.5% when ϕ changed from 25^o to 30^o at ϕ_b/ϕ = 0.5. This observation is consistent with Mohr-Coulomb criterion. Therefore, the higher value angle of ϕ_b and ϕ, are the higher value of safety factor. The safety factor of soil slope reaches its minimum under saturated condition, which means that matric suction is zero. Under the saturated condition, the safety factors of soil for angle of internal friction ϕ = 25^o and ϕ = 30^o are 0.935 and 1.157 respectively. The slope becomes slightly unstable for 25^o angle of friction.

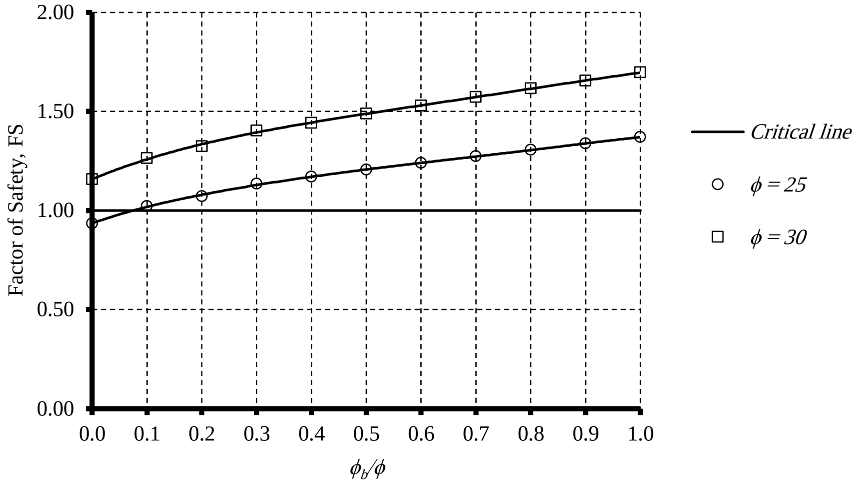

Figure (8) Variation of safety factor versus ϕ_b/ϕ, sandy soil, Model (1)

5.1.2 Model (2): Silty Clay Soil

Figure (9) illustrates the relationship between the internal angle of friction and the factor of safety. Furthermore, this figure takes into consideration the effect of ϕ_b/ϕ. Based on the pointing results of factor of safety, the relationship between the internal angle of friction and factor of safety looks almost linear. Moreover, internal angle of friction has a considerable effect on factor of safety for ϕ_b/ϕ = 0.5 and 1.0. However for ϕ_b/ϕ = 0.0, this effect becomes nominal. These conclusions come concerted with Mohr-Coulomb failure criteria. On the other hand, increasing of ϕ results in increasing of magnitude of safety factor, this is due to increase of soil shear strength. Factor of safety increases by 52% when ϕ varies from 10^o to 20^o at ϕ_b/ϕ = 0.5 as shown in Figure (9).

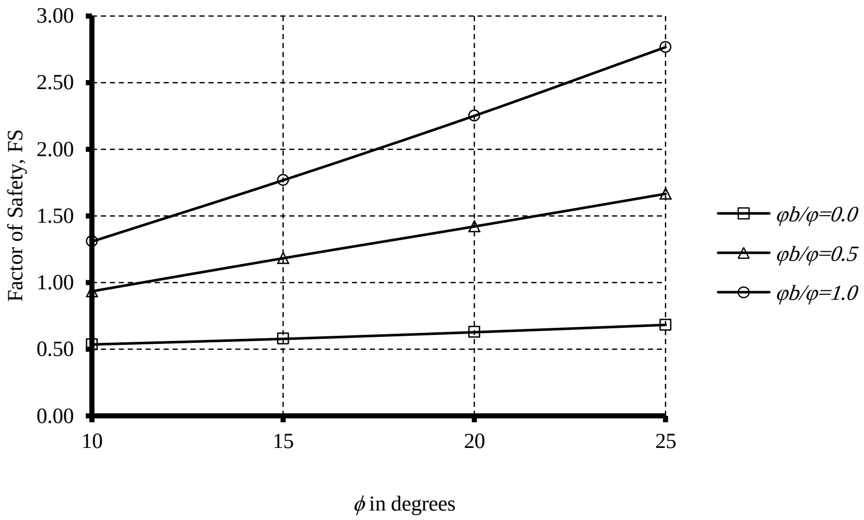

Figure (9) Safety factor versus angle of friction, Model (2), *C* = 15 kPa

Additionally, the effect of soil cohesion on the factor of safety is indicated in Figure (10). It is noted that the cohesion component significantly affects the factor of safety. The relationship between soil cohesion and the safety factor behaves linearly. Also, the higher value of soil cohesion is the higher magnitude of safety factor. With soil cohesion = 5 kPa, the factor of safety against failure along a slip surface as shown in Figure (10) is close to unity for ϕ_b/ϕ = 0.5. Adding a mere 5 kPa of cohesion increases the factor of safety from 1.105 to 1.262, this increase is about 14 % for ϕ_b/ϕ = 0.5.

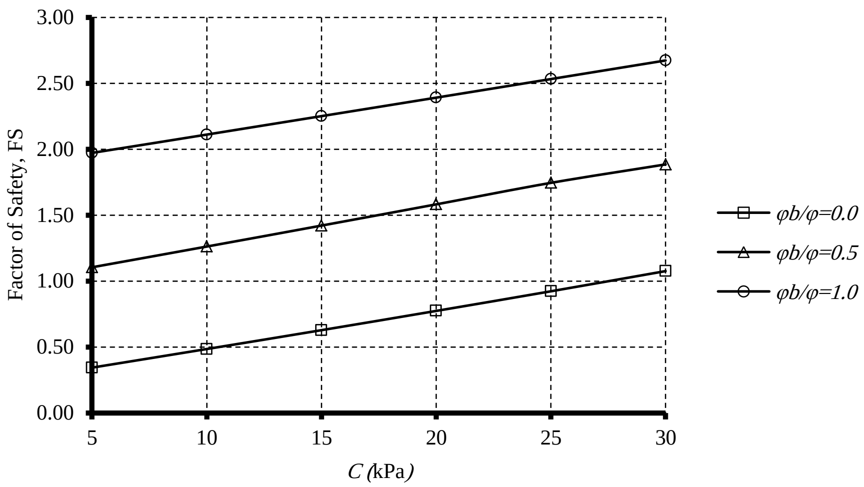

Figure (10) Safety factor versus cohesion, Model (2), ϕ = 20^o

5.2 Effect of Initial Suction Variation

5.2.1 Model (1): Sandy Soil

When the effect of matric suction is ignored (i.e., conventional soil mechanics), the factor of safety of unsaturated slopes is underestimated (Fredlund, D.G. (1981)). As shown in Figure (11) the increments of ϕ_b angle leads to the increase of the shear strength. Thus as soil suction increases, safety factor of unsaturated soil slope increases gradually. For example, the factor of safety increases by 5.6% when suction changes from 5 kPa to 10 kPa at ϕ_b = 15^o and it increases by 10.1% at ϕ_b = 30^o for the same variation of soil suction.

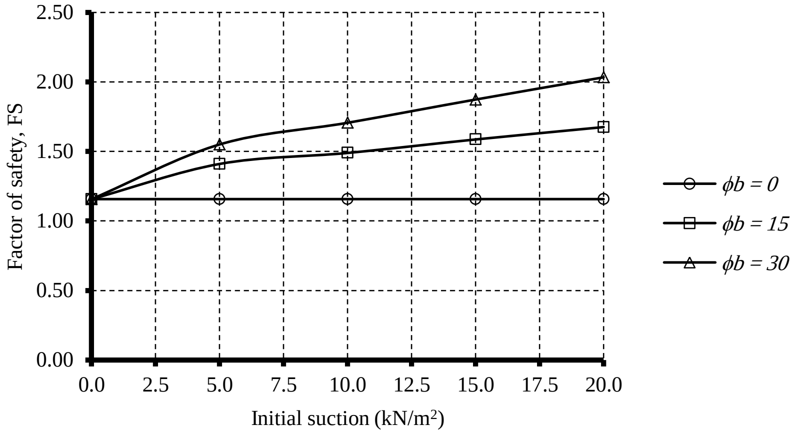

Figure (11) Effect of initial suction variation on factor of safety, Model (1): sandy soil, at $\phi = 30^0$

5.2.2 Model (2): Silty Clay Soil

For Model (2), a parametric type analyses were also performed using different values of initial suction. These analyses were conducted to study changes in the factor of safety in response to variation in the soil suction as shown in Figures (12). Indeed, the increase in initial soil suction has substantial effect on factor of safety due to increasing of soil shear strength. As matric suction increases, shear strength increases quite obviously. For instance, the safety factor increases by about 66.5 % for initial suction variations from 0 to 60 kPa at $\phi_b/\phi = 0.5$, as well, the equivalent to a cohesion of 16 kPa is attributed to this suction increase. Meanwhile, the factor of safety is noticeably influenced by alteration the values of ϕ_b/ϕ. Based on results illustrated in Figure (12), the factor of safety increases from 1.299 to 1.862 when ϕ_b/ϕ varies from 0.5 to 1.0.

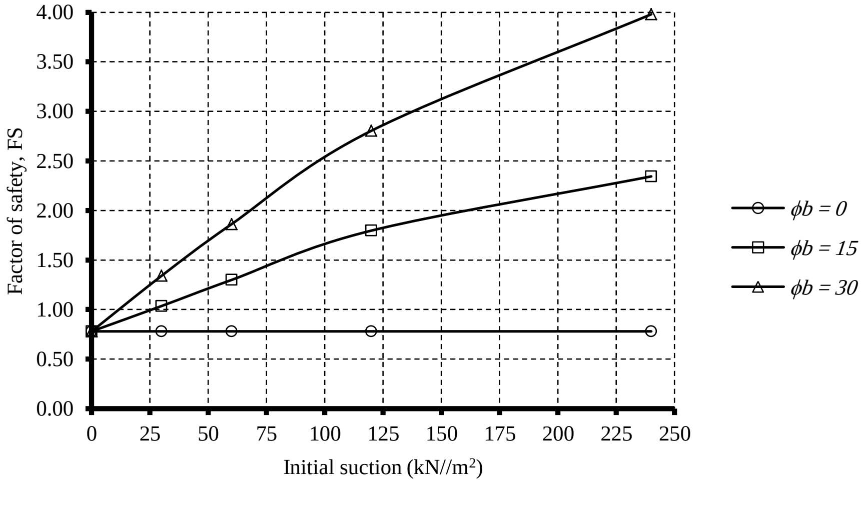

Figure (12) Effect of initial suction variation on factor of safety, silty clay soil, Model (2), $\phi = 30^0$, C = 15 kN/m^2

6. SUMMARY AND CONCLUSIONS

The most important parameter that affects the stability of unsaturated soil slopes is the shear strength of soils. For conventional soil mechanics, the shear strength of soil is a combination of cohesion, angle of friction and effective stress. In unsaturated soil, the suction shearing angle, ϕ_b, is considered as a part of cohesion and instead of positive pore-water pressure, suction is used as a component of unsaturated shear (Escario, V. and Juca. (1989)). Therefore, the suction is considered one of the main components in unsaturated shear strength. Understanding the effect of suction in unsaturated soils is important to relate the effect of soil suction to the factor of safety. Based on results, the following points can be drawn:

1. The suction is considered one of the main components in unsaturated shear strength. Understanding of soil suction distribution in unsaturated soil slopes is important to relate the effect of soil suction to the factor of safety.
2. It is important to take suction shearing angle, ϕ_b, into consideration, because it gives the rate of the suction influence on the shear strength increment.
3. The suction shearing angle, ϕ_b, has a significant effect on the factor of safety of unsaturated slopes. The factor of safety increases with increasing of suction shearing angle ϕ_b. Basically, this increase is attributed to the increase of soil shear strength based on Mohr-Coulomb's modified criteria.
4. The cohesion component significantly affects the factor of safety.
5. As soil suction increases, the soil strength increases as well. Thus unsaturated soil slopes become more stable, according to Mohr-Coulomb's modified criteria.
6. It is noted that there is no obvious difference in the results of Bishop's method and Morgenstern-Price method, whose results are higher than the results of Ordinary method. This is regarded to the neglect of the interslice forces in analysis using Ordinary method.

7. REFERENCES

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