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Assessment of Shear Strength and Vertical Stress Variations in Cohesive-Frictional Soil Slopes

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Abstract: In this study, based on limit equilibrium principles and using horizontal slices, a simple solution is presented to calculate normal stress in the slopes. Using γH relationship is suitable in vertical slopes but in non-vertical slopes, using γH relationship is associated with a lot of errors. Previous researchers have presented a complex relationship, the use of which is only use fulinn on-cohesives oils. In this method which is derived from the horizontal slices method, primarily, the horizontal slices above the rupture line are divided in to a number of horizontal slices. In each system, four equations and four unknowns are formed; solving the so called equations system, horizontal shear force between the slices and the vertical force between the slices asre obtained for each slice. Dividing the vertical force between the slices by the surface, the average normal stress value is obtained. Specific in no vation of this study is to present normal stress for cohesive-frictional soil slopes. In addition, the current study set to present charts to state the shear strength and normal stress relationship, the values of which can be calculated with no need for calculations.

Key words: Shear strength, normal stress, soil slopes, cohesive-frictional, soil internal friction angle

INTRODUCTION

Research on stability of soil slopes can be classified in to three categories: laboratory, numerical and analytical methods. Among the technical literature, there area limited number of analytical solutions for the analysis of slopes; however, even in these limited researches in which of ten soil type is cohesive-frictional have beenless attended to. Among the methods available to analyze slopes, limit equilibrium method, accounted as a subset of plasticity theories has attracted the attention of many researchers. Limit equilibrium approach examines several mechanisms of rupture surface and obtains the minimum factor of safety using force equilibrium and moment equations forwedge slip. This approach which designs reinforced soil structures using the vertical slices was applied by Ling *et al*. (1997b) and by adding earth quakeloads has extended the seismic analysis (Ling *et al*., 1997a). In recent years, to study the effect of horizontal rein forcements, a method called horizontal slices was presented by researchers of Tehran University. The ideaw as first suggested by Shahgholi *et al*. (2001) and then people like Nouri *et al*. (2008), Azad *et al*. (2008) and Reddy *et al*. (2008) continued the work.

Based on this methodology, extensive research has been done including research carried out under the supervision of Dr. Ali Ghanbari and the students of Technical Faculty of Khwarizmi University (Shekarian *et al*., 2008; Ahmadabadi and Ghanbari, 2009; Ghanbari and Ahmadabadi, 2010a; Ghanbari *et al*., 2013). In all the introduced methods, normal stress in soil mass was calculated from γH relationship and in methods by Shekarian *et al*. (2008), Ahmadabadi and Ghanbari (2009) and Ghanbari and Ahmadabadi (2010b), normal stress was calculated by the complex relationship of Segrestin. Using γH relationship is suitable in vertical slopes but in non-vertical slopes, use of γH relationship is associated with a great deal of error and Segrestin relationship should be used. Using Segrestin relationship is useful only in non-cohesive and in cohesive soils no relationship has been provided. In this study, based on limit equilibrium principles and using horizontal slices method, a simple solution is presented to calculate the normal stress in slopes. The current study has been carried out following the mentioned studies and it is hoped the results will be useful for the scientific community of geotechnical engineering. The main purpose of research is to provide a mechanism for the

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expression of normal stressin cohesive-frictional soil slopes and the effort is based on a simple analytical method according to limit equilibrium. Specific innovation of this study is to provide a normal stress for cohesive-frictional soil slopes. In addition, the study provides charts to express the relationship between shear strength and normal stress with no need to formula for calculations.

MATERIALS AND METHODS

Normal stress orvertical forces between V_i and V_{i+1} slices in horizontal slices method from Segrest in relationship is obtained as follows (Fig. 1):

$$V_i = \left[\gamma \sum_{j=1}^{i-1} h_j\right] \times \tanh(aU_i + b) \quad (1)$$

In the Eq. 1:

$$k_a = \left[\frac{\sin\left(\frac{\pi}{2}-\phi\right)}{\sin\left(\frac{\pi}{2}\right)+\sqrt{\sin\left(\frac{\pi}{2}\right)\cos\left(\frac{\pi}{2}-\phi\right)\sin\phi}}\right]^2 \quad (2)$$

$$k_a = \tan^2\left(\frac{\pi}{2}-\frac{\phi}{2}\right) \quad (3)$$

$$b = \frac{\log\frac{k_a-k_a}{k_a-k_a}}{2} \quad (4)$$

$$U_i = \frac{X_{V_i}}{\sum_{j=1}^{i-j} h_j} \quad (5)$$

$$U_{i+1} = \frac{X_{V_{i+1}}}{\sum_{j=1}^{i} h_j} \quad (6)$$

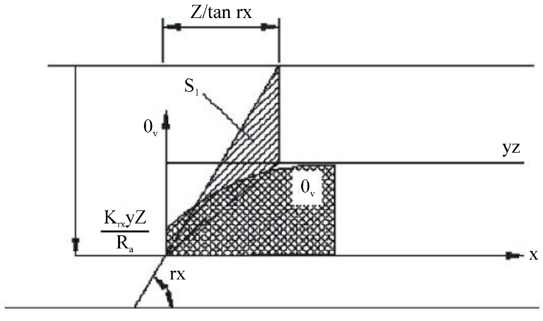

Fig. 1: Normal stress by Segrestin

$$a = 2\ \text{tanalog}\left(\frac{2k_a}{k_a+k_a}\right) \quad (7)$$

Using the above equation is beneficial in non-cohesive soils as the formula specify, the relationships proposed by Segrestin lack cohesion. In this method which is derived from the horizontal slices method for calculating normal stress, a new relationship in cohesive-frictional soils is presented. Firstly, horizontal slices of top surfaces of fracture lineare divided in to a number of horizontal slices; the assumptions are as follows:

- The rupture surface is considered as plane
- The analysis is based on limit equilibrium
- The rupture surface passes the slope base
- The force N is from the bottom of the slice
- The soil mass is considered homogeneous

The slope is considered according to Fig. 2 where θ is the angle of slope versus vertical axis. It is assumed that hypothetical rupture wedge surface angle makes β angle with the horizontal axis. In Fig. 2, for a slope, rupture wedge is divided in to horizontal slices. If the number of slices equals, η then:

$$h_i = \frac{H}{n} \quad (8)$$

Based on trigonometric relationships, distances shown in Fig. 3 are obtained from the following relationship:

$$X_{1i} = \frac{\sum_{j=1}^{n} h_j}{\tan(B)} \quad (9)$$

$$X_{2i} = \left[\sum_{j=i}^{n} hj\right]\tan(\theta) \quad (10)$$

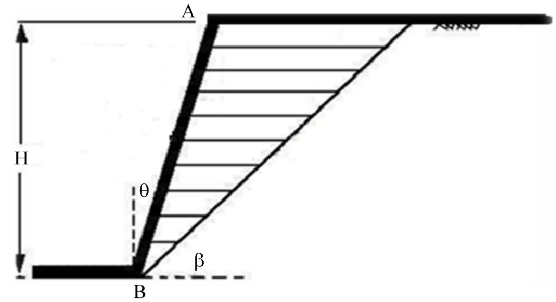

Fig. 2: Division of rupture wedge into horizontal slices in the soil slope

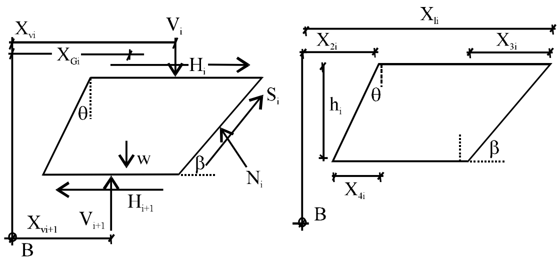

Fig. 3: The equilibrium of forces at slice i

Table 1: The number of equations and unknowns of horizontal slices method

Unknowns	No.	Equations	No.
H_i	n	$\Sigma F_x = 0$	n
N_i	n	$\Sigma F_y = 0$	n
S_i	n	$\Sigma M_0 = 0$	n
V_i	n	$S_i = N_i \tan\phi\ C_i$	n
-	4n	-	4n

$$X1_{i+1} = \frac{\sum_{j=i+1}^{n} hj}{\tan(\beta)} \quad (11)$$

$$X_{3i} = \frac{h(i)}{\tan\beta} \quad (12)$$

$$X_{4i} = h(i)\tan\theta \quad (13)$$

Also, X_{gi} distance and the weight of each slice are obtained from the following relationship:

$$X_{G_i} = \frac{x1_i}{2} + \frac{x2_i}{2} - \frac{x3_i}{4} - \frac{x4_i}{4} \quad (14)$$

$$W_i = \{(X_{1i}-X_{2i}-X_{3i}) + 0.5(X_{3i}+X_{4i})\}h_i\gamma_i \quad (15)$$

In the above equations, W_i is the weight of each slice. The fourth equation of Table 1 is in fact the Mohr Coulomb yield criterion, applicable for the points on the rupture wedge. Writing the equations of forces' equilibrium, moment and shear strength for each slice, four unknowns of the equation are obtained. Table 1 summarizes the equations and unknowns of the related formulation. The equationsare as follows:

$$\sum F_x = 0 \longrightarrow H_i - H_{i+1} + S_i\cos\beta - N_i\sin\beta = 0 \quad (16)$$

$$\sum F_y = 0 \longrightarrow -V_i + V_{i+} - W_i + S_i\sin\beta + N_i\cos\beta = 0 \quad (17)$$

$$\sum M_o = 0 \longrightarrow -V_iX_{V_i} + V_{i+1}X_{V_{i+1}} - W_iX_{G_i} + \left[\frac{N_i}{\sin\beta_i}\right] \times \left[\sum_{j=i+1}^{n} hj + \frac{h_i}{2}\right] + H_{i+1}\sum_{j=i+1}^{n} h_j - H_i\sum_{j=i}^{n} h_j = 0 \quad (18)$$

$$S_i = [N_i\tan\phi + Cl_i] \quad (19)$$

$$l_i = h_i/\sin\beta \quad (20)$$

Solving these equations, horizontal shear force between the slices (H_i) and the vertical force between the slices (V_i) are obtained for each slice. Dividing the horizontal shear force between the slices by surface, the average value of shear stress between the slices is obtained; dividing vertical force between the slices (V_i) by surface, the average value of vertical stressis obtained.

Calculating shear stress between the slices and the vertical force between the slices, the variations of these two variables are investigated. For this purpose, it is assumed that the average shear stress along each slice is a factor of shear strength in yield condition. This factor for slice i is shown by. Thus, we have:

$$H_i = [V_i\tan\phi + c]\lambda_i$$

The charts given in addition to showing the variations trend with increase of cohesion, internal frictional angle, slope tilt and slope height, it suggests that for cohesive-frictional soils, the shear stress coefficient at different heights and in the pressure zone increases by height increase on shear stresses values. Accordingly, ignoring the shears between the slices conducted by previous researchers on non-cohesivesoils is not acceptable in some cases.

To investigate λ variations in height, some graphs are presented that is the selected percentage of for different heights or indeed for different horizontal slices. In Fig. 4-6, λ variations versus the slope height for 10-30 internal friction angles, cohesion coefficient of 5-15 kN/m^{-2} and 0-20° slopetilt are shown. The curve forms are all the same and by variation of c and θ only the slope and x-intercept change. For precise relationships, variations are drawn for 1000 slices at the slope height. Variations are drawn versus slope height, comparing slope in cohesive-frictional soils (Fig. 4) by increasing the slope tilt, the curve slopedecreases and the diagram will have two main components including negative and positive factors. Also, by increasing the slope tilt, coefficient increases in value in the negative part.

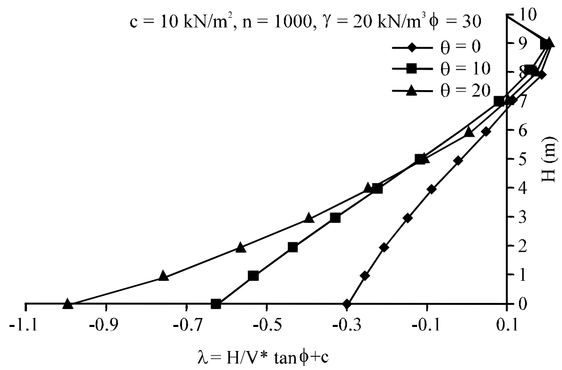

Fig. 4: γ variations versus slope height, comparing slope in cohesive-frictional soils

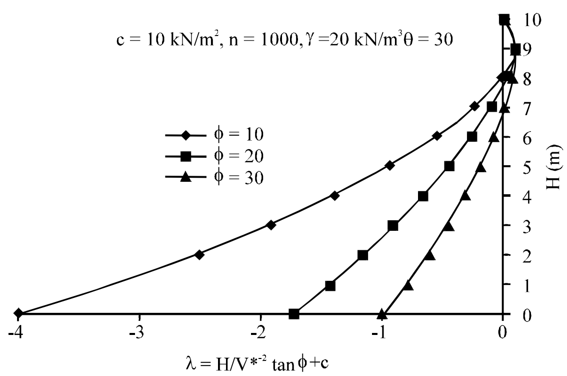

Fig. 5: γ variations versus slope height, comparing internal friction angle in cohesive-frictional soils

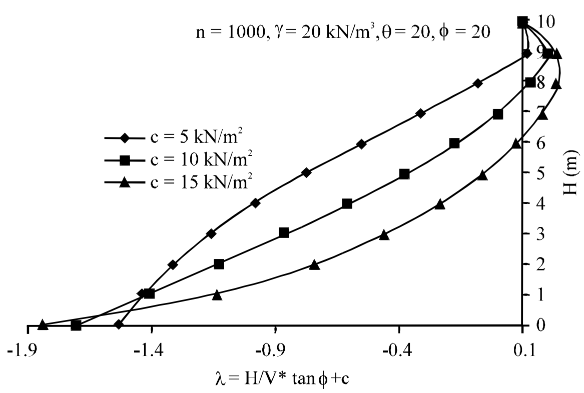

Fig. 6: γ variations versus slope height, comparing soil cohesion in cohesive-frictional soils

Increase of the internal friction angle increases the slope of the curve. Also increase of theinternal friction angle of soilreduces λ value. Changing the internal friction angleof the curve, the value is still made of both positive and negative coefficients that by increasing the soil internal friction angle, the negative coefficients increase. In addition to the impact of the slope tilt and soil internal friction angle, cohesionisal so effective in λ value; all previous researchers have ignoredit. Increase of cohesion increases the λ-value and in zero cohesion, λ coefficient is always negative. With increase in cohesion, positive coefficients increase and in turn, the value of negative coefficients decreases (Fig. 6).

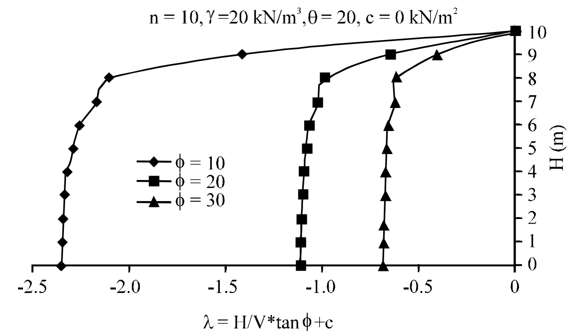

Fig. 7: γ variations versus slope height, comparing the internal friction angle in non-cohesive soils

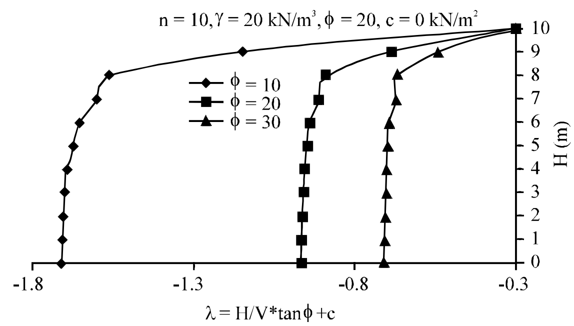

Fig. 8: γ variations versus slope height, comparing the slope of the wallinnon-cohesive soils

According to Fig. 7 and 8, λ variations are presented for non-cohesivesoils. The results suggest that increasing of internal friction angle and slope tilt increases λ factor. Also in non-cohesivesoils, λ coefficients will be no more positive and all are negative. In Fig. 7, λ variations versus slope height are drawn comparing internal friction angle and in Fig. 8 comparing the wall slope.

RESULTS AND DISCUSION

γH relationship has been used to determine vertical stress of soil structures so far. However, this method is also non-vertical slopes have limitations and errors. However, this method has had limitations and error on the non-vertical slopes. Therefore, Segrestin method has been usually used in recent years in inclined walls and slopes

Table 2: Comparison of the proposed method with results of other studies

$\gamma = 20$ kN/m^3, $\phi = 30°$, c = 0 kN/m^2, $\theta = 20°$

H (m)	Segrestin (1992) (V_i)	Proposed method (V_i)	γH (V_i)
2	38.82710	37.8371	40
3	57.02140	54.6702	60
4	73.94341	69.7155	80
5	89.03161	82.5140	100
6	101.59270	92.3614	120

to calculate vertical stress. This method is effective only in non-cohesive soils. In this study, a new method in cohesive-fictional soil was provided using limit equilibrium principles and assumptions of horizontal slices. In this study, the proposed method was compared with results of previous studies in the equal conditions. Results of this comparison are shown in Table 2.

CONCLUSION

Based on the studies presented in this study, the following results are obtained:

- For soil slope, a new formulation was presented that contains 4n equations and 4n unknown. Applying the formulation, the shear force between the slices (H_i) and the vertical force between the slices (V_i) are obtained for cohesive-frictional soils, values that we reignored by most scholar sorused common as sumptions to calculate them
- The proposed method has the advantage that considers soilas cohesive-frictional and also gives the normal stressand shear strength. The proposed method can also calculate the variations of these two variables and draw the relevant diagrams
- In addition to the formulation, graphs are provided to calculate λ values with noneed to calculations. λ Variations are drawn comparing cohesion, internal friction angle and slopetilt and slopeheight. The graphs are drawn forinternal friction angles of 10-30, cohesion of 5-15 kN/m^{-2} and the slopetilt of 0-20°. And in other cases, values can be obtained by reference to a formula or by interpolation

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