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NUMERICAL STUDYING THE EFFECTS OF GRADIENT DEGREE ON SLOPE STABILITY ANALYSIS USING LIMIT EQUILIBRIUM AND FINITE ELEMENT METHODS

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ABSTRACT

Limit equilibrium and finite elements methods are among the most popular methods of slope analysis. Using software such as Geostudio-slope/W and PLAXIS, these two analysis methods have widely become common among Geotechnical engineers. One of the most important challenges of these software users in Geotechnical engineering is the presence of differences in results from estimation and evaluation of a project regarding the different modeling ways. In this research results from modeling in FLAC and PLAXIS software were compared with results from studying Bishop and Janbu methods in Geostudio-Slope/W software. Results from the present research show that compared to limit equilibrium method, finite elements method, gives less safety factors against increase in slope gradient. Also, in regard with these results it is seen that together with increase in underground water level, this difference will considerably be more in slope.

Key words: limit equilibrium, finite elements, slope stability, safety factors, failure surface

1. INTRODUCTION:

Slope stability analysis is one of the most important parts of design in projects in which there is slide potential probability on slope. Since the presentation of the first slopes stability analysis method by Fellenius [2] more researches have been done in this field. Currently, slope analysis methods are as follows: small elements limit equilibrium methods, boundary methods [3], finite elements methods [4] and neural methods [5, 6]. Compared to other methods, small elements limit equilibrium methods are more commonly used because of their ease and feasibility in use [7]. In limit equilibrium method, Fellenius [2], Taylor [8], Bishop [9], Junbu [10-12], Spencer [13-14], Morgencstern-Price etc. methods can be used. The first three cases can only be used in circular failure surfaces, while the fourth case is usable in non-linear and the fifth and sixth for failure surfaces with any forms [16].

Because of increase in probable failure surfaces, computer has been used for analyzing stability using small elements limit equilibrium. According to previous studies, safety factors obtained from methods that satisfy all equilibrium condition, have about 7% difference with each other [17]. These methods include frictional circular methods, logarithmic spiral methods, strong limit equilibrium methods and finite element methods.

This paper studies and compares safety factors resulting from limit equilibrium and finite elements methods in slopes with 45-90 degrees in both dried and fully saturated forms and results from the discussion have been offered graphically, as well as in tables. In order to analyze with the help of limit equilibrium, Geostudio-Slope/w software and Janbu and Bishop methods, and in order to analyze with the help of finite elements methods the two advanced PLAXIS [18] and FLAC [19] software have been used, respectively.

2. ANALYZING THE SLOPE ANALYSIS USING LIMIT EQUILIBRIUM METHOD

Substantial steps in limit equilibrium method are as follows [16]:

A. Selecting acceptable failure or failure surface mechanisms
B. Determining the forces on failure surface
C. Using equilibrium equations (from static) in order to determine failure load

So, force equilibrium with mass moment from soil on a potential failure surface is studied. The soil on this rigid failure surface (that is, shear can only happen on this surface) is considered and it is assumed that soil shear resistance on this surface is developed with the same speed on all points and consequently, safety factor on all of failure surface points will be constant [20].

The main difference between different limit equilibrium methods is in made assumptions in case of failure surface shape (circular, logarithmic spiral, non-circular etc.) as well as in using statics in evaluation of equilibrium and stability (using sum of the forces, sum of the moments, etc.) [7].

Bishop is one of the very accurate methods of limit equilibrium that, on the basis of soil mass division on failure surface into several slices, studies the static equilibrium of forces on these slices. Safety factor determination in this method is as the following equations:

$$FS = \frac{\sum_{n=1}^{n=p} (cb_n + W_n \tan\phi) \frac{1}{m_{\alpha(n)}}}{\sum_{n=1}^{n=p} W_n \sin\alpha_n} \tag{1}$$

$$FS = \cos\alpha_n + \frac{\tan\phi \sin\alpha_n}{FS} \tag{2}$$

Where W_n is the slice weight and b_n is the slice width.

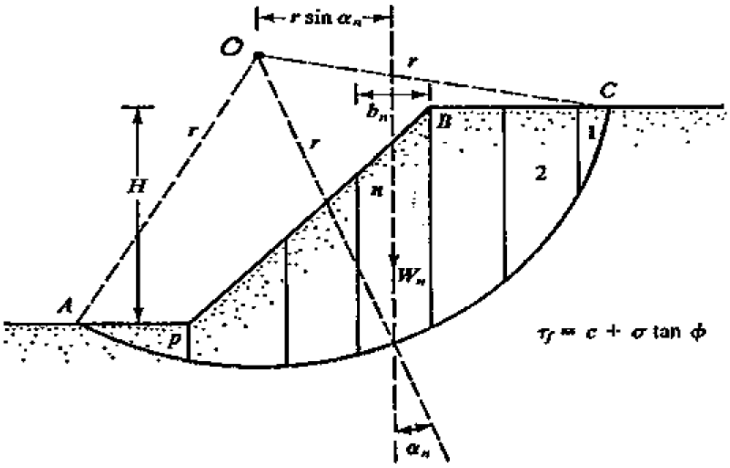

Fig. 1. *Dividing the Failure Mass into Several Vertical Slices*

Janbu method is also an appropriate method for safety factor calculation and like Bishop method, it divides the soil over failure surface into several slices and then studies the static equilibrium of forces on these slices; the difference is that in Bishop method the failure surface is circular and the moment equilibrium equation is satisfied and shear forces among the slices have been ignored (they neutralize each other), while in Janbu method failure surface is non-linear and equilibrium equation is established for horizontal forces and no forces among the slices neutralize each other. Determining the safety factor in Janbu method takes place as follows:

$$FS = \frac{\sum (S_u)_j b_j}{\sum W_j \tan\theta_j} \tag{3}$$

3. ANALYZING THE SLOPE STABILITIES USING STRESS-DEFORMATION

In stress-deformation method, stress and strain distribution in different parts of the slope is analyzed and safety factor on the most susceptible failure surface is determined by comparing the developable shear resistance on the mention surface with the sum of active forces on that surface. The mentioned method requires applying elasticity or plasticity and solving the obtained equations on the basis of these theories. One of the modern methods for solving these equations is using finite elements method and in this method, elements stiffness matrix, which relates the force on each node to that node's displacement, is determined on the basis of minimizing the total potential energy. Figure 2 shows a meshed slope in finite elements method that has been meshed regarding the importance of different parts. If an assumed failure surface is considered, the stress amounts, i.e. σ_x , σ_y , σ_z , on a random point on the failure surface that is under θ gradient and can be calculated using the finite elements method. In this case, according to figure 3, the amounts of normal stresses and shear on failure surface can be determined using (4) and (5) relations [7].

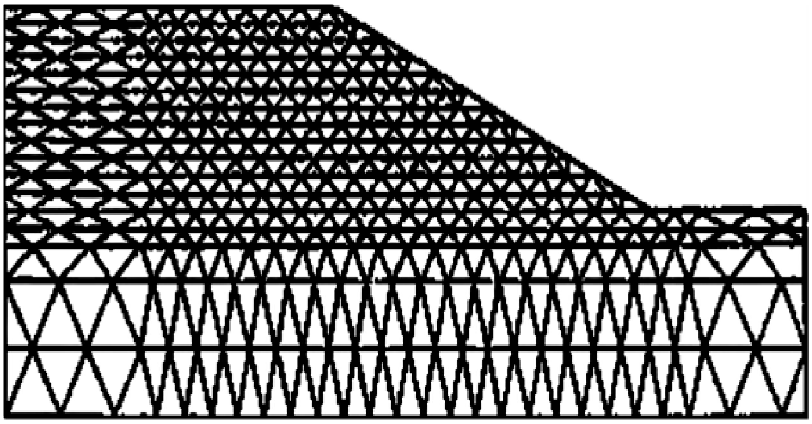

Fig. 2. *Slope meshing in finite elements method*

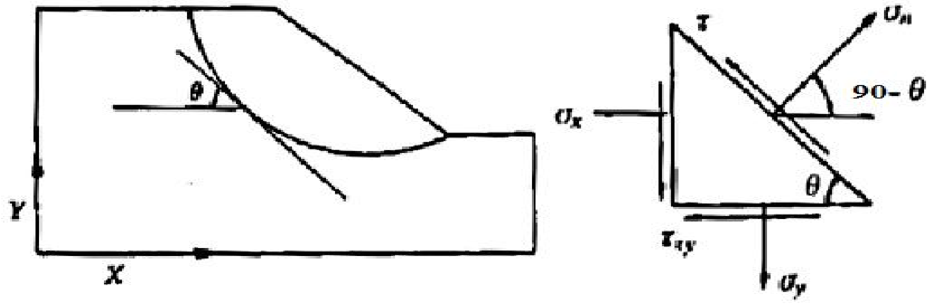

Fig. 3. *Stress components on each point on failure surface*

$$\sigma_n = \frac{1}{2}(\sigma_x + \sigma_y) - \frac{1}{2}(\sigma_x - \sigma_y)\cos 2\theta + \tau_{xy}\sin 2\theta \tag{4}$$

$$\tau = -\tau_{xy}\cos 2\theta - \frac{1}{2}(\sigma_x - \sigma_y)\sin 2\theta \tag{5}$$

Now, considering a behavioral model, such as Mohr-Coulomb's model according to the equation (6), stability of slope safety factor can be studied [22].

$$FS = \frac{I_1}{3}\sin\phi + \sqrt{J_2}[\cos\theta - \frac{1}{3}\sin\theta\sin\phi] - C\cos\phi \tag{6}$$

Where σ_n, τ and θ are normal stress, shear stress and the angle between tangent on failure surface and along the horizon, respectively.

In order to analyze using the finite elements method the two PLAXIS and FLAC software will be used and obtained results will be compared with each other [21]. It should be noted that in numerical methods, resistance reduction method is used to determine the safety factor and some information on failure mechanism, slope displacement pattern and stress counters is obtained. Shear resistance reduction technique used here bears two advantages compared with limit equilibrium method. Firstly, critical failure surface is obtained directly and accurately and there is no need for determining the failure surface (circular, linear, etc.). Secondly, numerical methods directly satisfy rotational and translational equilibrium, while limit equilibrium does not enjoy such a capability. Thus, shear resistance reduction technique gives less safety factors compared with other methods and this is a reliable amount [22].

Finally, using Bishop and Janbu methods and with the help of Geostudio – Slope/w software and finite elements method and taking the advantage of the two advanced PLAXIS and FLAC software, safety factor resulted from these two analysis types in 45-90 gradients will be compared in both dry and saturated states and graphically will be judged on.

4. GEOMECHANICAL CHARACTERISTICS OF THE MODEL

In order to make the ground ready for comparing the present study and the previous one in this field that has been done using FLAC software [21], geomechanical characteristics of modeled slop has been considered in the form of the following table. It should be noted that slope materials have been considered homogeneous and have statically been analyzed.

Table 1. Geomechanical characteristics of the model

Tensional Resistance (MPa)	Internal friction angle (Degree)	Cohesion (MPa)	Poisson's Ratio	Elasticity Module (Gpa)	Density (kg/m^3)
0.014	28	0.124	0.25	1.575	1900

5. FACTORS EFFECTIVE IN SLOPE STABILITY

From among the most important factors effective in stability of slopes are angle and the elevation of the slope, materials' geomechanical characteristics and underground water level. The best modeling method for slopes in software based on finite elements method is using a medium meshing for the entire model zone and changing the sizes of elements into fine elements within the adjacent range of the slope oblique (transverse part). Because, if the total zone of the model is considered as very fine elements, the time needed for calculations will abnormally be increased[7].

Figures 4 and 5 show work environment in Geostudio – Slope/w and PLAXIS software, and the most probable failure surface for gradient 80 degrees.

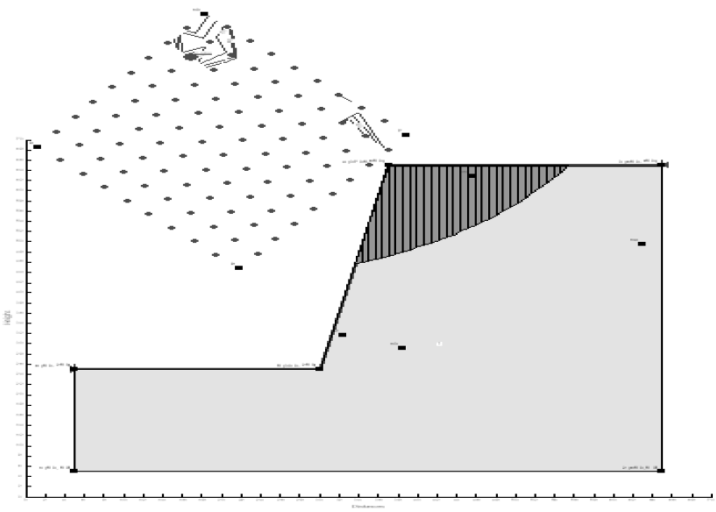

Fig. 4. *Critical failure surface due to analysis using limit equilibrium method*

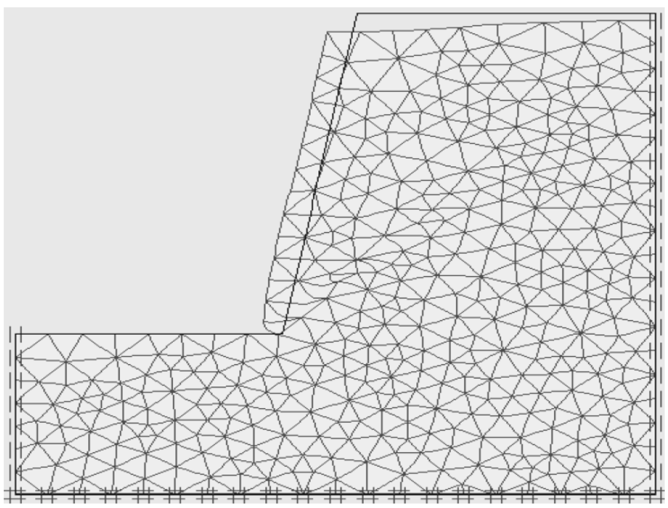

Fig. 5. *Meshed deformed slope using finite elements method*

6. DATA ANALYSIS AND DISCUSSION ABOUT THE RESULTS

Taking the assumed geomechanical characteristics into account we do analysis in the two dry and saturated states for the two limit equilibrium and finite elements methods. To create a good comparison, Bishop and Janbu methods are used for limit equilibrium. After, analysis, results can be shown on a table as follows:

Table 2. Safety factors resulted from analysis

Row	Slope Degrees	A	B	C	D	E	F	G	H
1	45	1.8	1.853	2.032	1.980	0.91	0.861	1.344	1.278
2	50	1.71	1.743	1.839	1.817	0.71	0.654	1.180	1.141
3	55	1.61	1.609	1.702	1.711	0.49	0.477	1.071	1.069
4	60	1.54	1.466	1.579	1.636	0.25	0.248	0.958	0.989
5	65	1.46	1.352	1.465	1.558	-	-	0.858	0.911
6	70	1.4	1.243	1.386	1.544	-	-	0.782	0.875
7	75	1.35	1.129	1.254	1.405	-	-	0.655	0.743
8	80	1.32	1.011	1.157	1.339	-	-	0.547	0.668
9	85	1.28	0.914	1.153	1.272	-	-	0.553	0.653
10	90	0.95	0.708	1.097	1.226	-	-	0.507	0.554

A: safety factor for dry state with the help of FLAC software
B: safety factor for dry state with the help of PLAXIS software
C: safety factor for dry state using Bishop Method
D: safety factor for dry state using Junbu method
E: safety factor for dry state with the help of FLAC software
F: safety factor for dry stated with the help of PLAXIS software
G: safety factor for saturated state using Bishop Method
H: safety factor for saturated state using Junbu Method
Considering the above table into account the following diagrams may be drawn

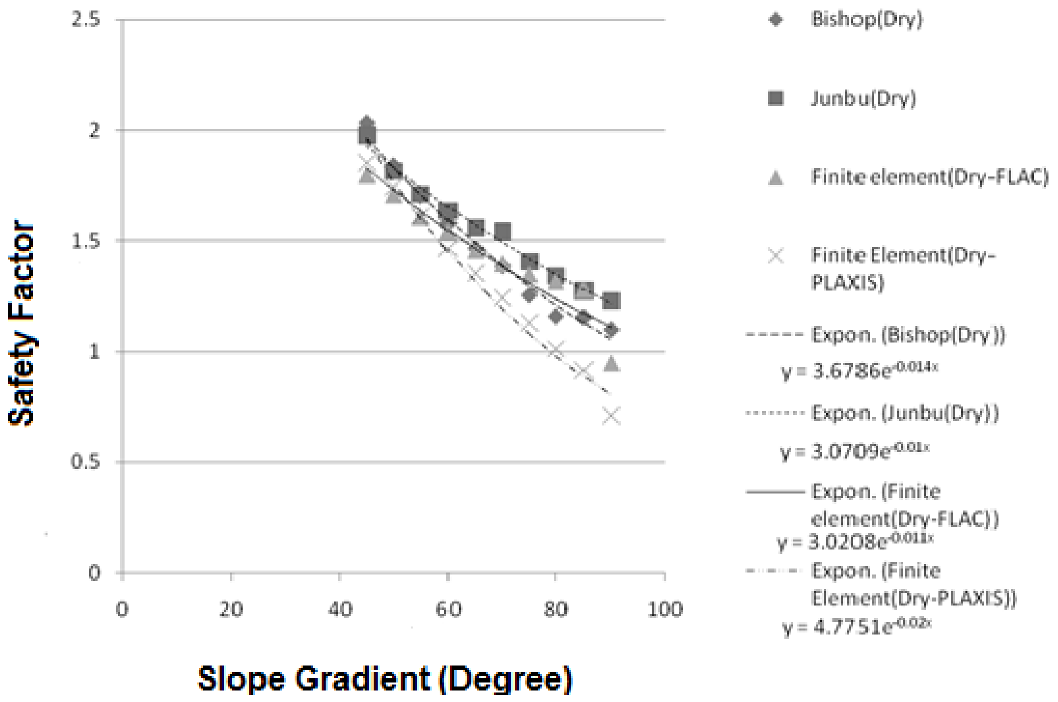

Fig. 6. *Safety factor diagrams for dry state*

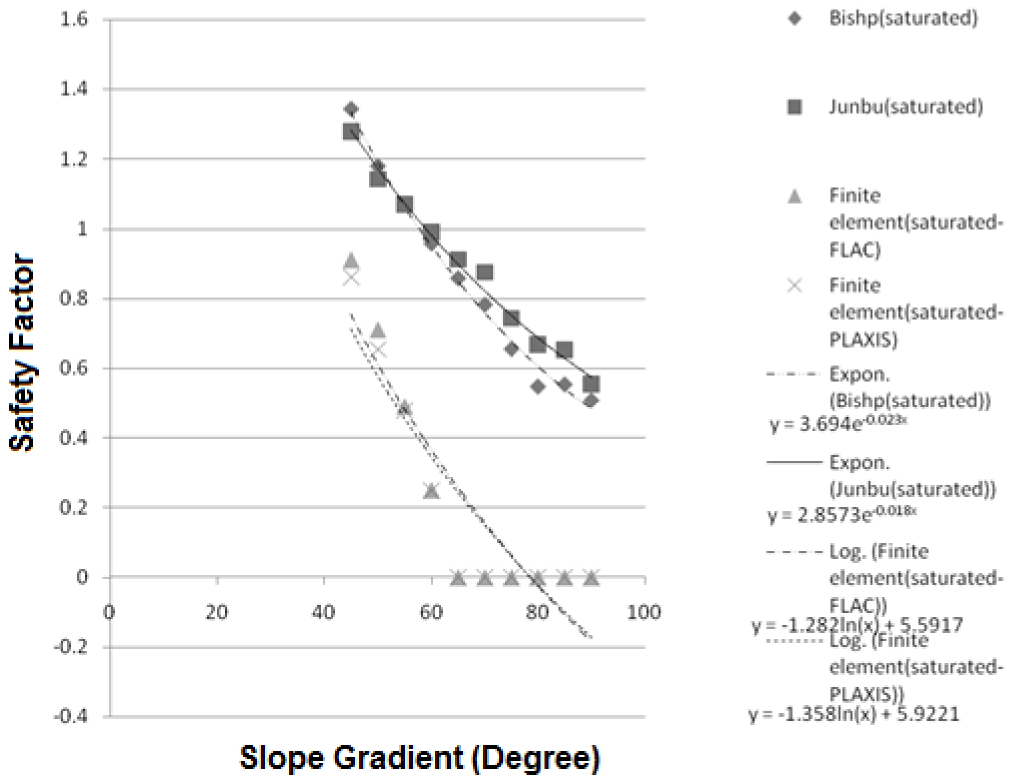

Fig. 7. *Safety factor diagrams for saturated state*

Taking the above table and obtained figures we analyze the results. Clearly, gradient angle is reversely proportional to safety factor in both cases of dry and saturated states. This is also true in both finite elements and limit equilibrium methods. It is seen that slopes in dry state are more stable than in saturated state. Even in saturated state, because of shear resistance parameters reduction, safety factor reduces to less than half of that of dry state, too.

In dry and saturated states, limit equilibrium method, gives more amounts of safety factor than that of finite elements method. Increase in gradient angle from 65 to 90 degrees, also causes this difference to be increased. Also, difference is saturated state is increased and somehow shows the weakness of PLAXIS software in saturated state. Of course this difficulty has been resolved in the latest version of this software and even, modeling for unsaturated soils [23] is also possible in it. In dry and saturated states and in gradients up to 50 degrees, Bishop Gives more safety factors than Janbu and in gradients 50-90 degrees, Janbu gives more safety factors than Bishop. This difference is due to difference in assumptions of these methods.

7. CONCLUSION

This study investigates the failure probability of both saturated an dry Earth slopes. Considering the above discussions, following results can be concluded:

1. In both dry and saturated states gradient angle is reversely proportional to safety factor versus the slide.
2. In saturated state, because of reduction in shear resistance parameters reduction, safety factor reduces to less than half of that of dry state.
3. In both dry and saturated states limit equilibrium method gives more amounts of safety factor than finite elements method. This difference is more in saturated state than in dry state.
4. In gradients up to degrees and in gradients 50 -90 degrees, Bishop and Janbu give more safety factor, respectively, than other methods mentioned in the present study. And, this conclusion is true for dry and saturated states. These differences are due to differences in assumptions of these methods.

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