A DETAILED ANALYSIS OF SLOPE STABILITY USING FINITE ELEMENT METHOD (FEM)

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ABSTRACT
Instability related issues in engineered as well as natural slopes are common challenges to both researchers and professionals. This paper mainly focuses on the analysis of some simple soil slopes using finite element method (FEM). This is not a very new concept, but not so practiced in the field of geotechnical engineering. The finite element method overcomes the assumptions in other analysis methods and gives more accurate result. In this paper, we use PLAXIS which is a finite element based software developed for the evaluation of the slope stability under various scenario. The stability of slope has been analysed for four types of soil which are not homogeneous and then evaluated the safety factors for varying slope heights. Then the same analysis has been done for the same slopes comprising homogeneous soil and compares the results. The surcharge load is another important factor for the slope stability. A stable slope can sustain certain amount of surcharge load until the safety factor reaches its minimum value. Higher the safety factors, higher the load carrying capacity of the slope.

Keywords: Slope stability; Finite element method; factor of safety; PLAXIS

INTRODUCTION

In construction areas, instability may results due to rainfall, increase in groundwater table and change in stress conditions. Similarly, natural slopes that have been stable for many years may suddenly fail due to changes in geometry, external forces and loss of shear strength (Abramson et al., 2002).The instability of a slope is an on going concern in most construction and infrastructure projects. The engineering solutions to slope instability problems require good understanding of analytical methods, investigative tools and stabilization measures (Abramson et al., 2002). According to (Nash, 1987), a quantitative assessment of the safety factor is important when decisions are made. Likewise, the primary aim of slope stability analysis is to contribute to the safe and economic design of excavation, embankments and earth dams (Chowdhury, 1978). To deal with these slope stability issues various approaches have been adopted and developed over the years. Finite element method has been increasingly used in slope stability analysis. The advantage of a finite element approach in the analysis of slope stability problems over traditional limit equilibrium methods is that no assumption needs to be made in advance about the shape or location of the failure surface, slice side forces and their directions. The method can be applied with complex slope configurations and soil deposits in two or three dimensions to model virtually all types of mechanisms. The approaches now have been more of computational rather than the manual. There are a number of software packages that have been developed for geotechnical stability analysis which utilise the FEM. With the advancement in technology software packages utilising the FE methods have increased in popularity as they tend to possess a wider range of features (Hammouri et al., 2008).

Objectives of the study

The objectives of slope stability analyses are-
i) To determine the factor of safety for slopes of different heights.
ii) To assess the maximum surcharge load that can be carried by the stable slopes.
iii) To analyse the suitability of re-fill soil against the existing soils.

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PHI-C REDUCTION

Generally, there are two approaches to analyse slope stability using finite element method. One approach is to increase the gravity load and the second approach is to reduce the strength characteristics of the soil mass. The second approach is adopted in this study by using a powerful software finite element program called PLAXIS. In the *Phi-c reduction* approach the strength parameters tanΦ and c of the soil are successively reduced until failure of the structure occurs. The strength of structural objects like plates and anchors is not influenced by *Phi-c reduction*. When using *Phi-c reduction* in combination with advanced soil models, these models will actually behave as a standard Mohr-Coulomb model. The Phi-c reduction approach resembles the methods of calculating safety factors as conventionally adopted in slip-circle analyses. The mathematical expression of this model, as well known, is given by the following formula:

$$\tau = \sigma_n \tan\Phi + C \quad (1)$$

where: τ = shear strength of soil material on a certain failure plane, σ_n = normal stress on the failure plane, Φ = angle of internal friction of soil material, and C = cohesion intercept of soil material.
The shear strength of the sliding surface is denoted by τ_f and expressed as follows:

$$\tau_f = \sigma_n \tan\Phi_f + C_f \quad (2)$$

where, C_f and Φ_f are the factored shear strength parameters and they can be given as follows:

$$C_f = C / SRF \quad (3)$$

$$\Phi_f = \Phi_f / SRF \quad (4)$$

For Mohr-Coulomb material model, six material properties are required. These properties are the friction angle φ, cohesion C, dilation angle ψ, Young's modulus E, Poisson's ratio ν and unit weight of soil γ. Young's modulus and Poisson's ratio have a profound influence on the computed deformations prior to slope failure, but they have little influence on the predicted factor of safety in slope stability analysis.

Dilation angle, ψ affects directly the volume change during soil yielding. If $\psi = \varphi$, the plasticity flow rule is known as "associated", and if $\psi \neq \varphi$, the plasticity flow rule is considered as "no associated". The change in the volume during the failure is not considered in this study and therefore the dilation angle is taken as 0. Therefore, only three parameters (friction angle, cohesion and unit weight of material) of the model material are considered in the modelling of slope failure.

GEOMETRIC MODEL OF SLOPE

Fig. 1 shows the generalized profile of slope used in the study. The height of the slope varies as 3m, 4m, 5m and 6m. The model slopes contain both heterogeneous and homogeneous soil. The soil properties were obtained from soil tests. Table 1 gives the soil parameters for the geometric models. To calculate the global safety factor for the slopes first the geometric profile of slope is incorporated in PLAXIS. The soil properties are also incorporated according to the soil parameters in Table 1.Then in the *initial conditions* option phreatic level is drawn. In this study, the pore water pressure is not accounted. Then the mesh was generated. In this study 15-node triangular elements were used. The powerful 15-node element provides an accurate calculation of stresses and failure loads. The two vertical boundaries are free to move, whereas the horizontal boundary is considered to be fixed. A mesh generated slope is shown in Fig. 2.

Table 1 Soil parameters used in this study

Soil type	Depth in meter	γ_{unsat} (kN/m^3)	Saturated unit weight,γ_{sat} (kN/m^3)	Friction angle,φ (Degree)	Poisson's ratio,ν	Elastic modulus,E (kN/m^2)	Cohesion, c (kN/m^2)
Soil 1	0.0 to 1.0	13.73	17.76	16.5	0.31	170	2.0
	1.0 to 2.0			15.1	0.33	340	2.0
	2.0 to 3.0			14.8	0.30	1360	0.9
	3.0 to 4.0			18.9	0.31	2210	2.0
	4.0 to 5.0			20.6	0.33	2550	2.0
	5.0 to 6.0			22.3	0.32	2720	2.0
	6.0 to 9.0			16.5	0.31	3640	1.9
	9.0 to 12.0			15.7	0.30	3750	1.0
Soil 2	0.0 to 1.0	13.54	17.95	13.5	0.30	340	1.9
	1.0 to 2.0			14.1	0.33	170	2.0
	2.0 to 3.0			15.8	0.33	680	2.0
	3.0 to 4.0			18.7	0.34	1530	1.9
	4.0 to 5.0			17.6	0.35	1870	0.9
	5.0 to 6.0			19.2	0.32	2210	2.0
	6.0 to 9.0			18.0	0.33	5123	2.0
	9.0 to 12.0			16.5	0.34	2730	1.0
Soil 3	0.0 to 1.0	12.75	17.23	16.7	0.33	170	1.0
	1.0 to 2.0			17.8	0.33	340	2.0
	2.0 to 3.0			21.7	0.34	340	1.9
	3.0 to 4.0			22.8	0.34	850	2.0
	4.0 to 5.0			18.9	0.31	1190	2.0
	5.0 to 6.0			21.9	0.32	3740	2.0
	6.0 to 9.0			22.7	0.31	6200	1.9
	9.0 to 12.0			23.5	0.34	2550	2.0
Soil 4	0.0 to 1.0	13.44	18.15	13.8	0.31	680	1.9
	1.0 to 2.0			14.8	0.31	680	2.0
	2.0 to 3.0			18.6	0.32	170	1.0
	3.0 to 4.0			20.3	0.33	1360	1.9
	4.0 to 5.0			16.6	0.34	2040	1.9
	5.0 to 6.0			15.7	0.32	3060	2.0
	6.0 to 9.0			22.6	0.33	4260	2.0
	9.0 to 12.0			24.6	0.30	3850	2.0
Re-fill	0.0 to 12.0	17.0	21.0	33	0.30	1.2E5	1.0

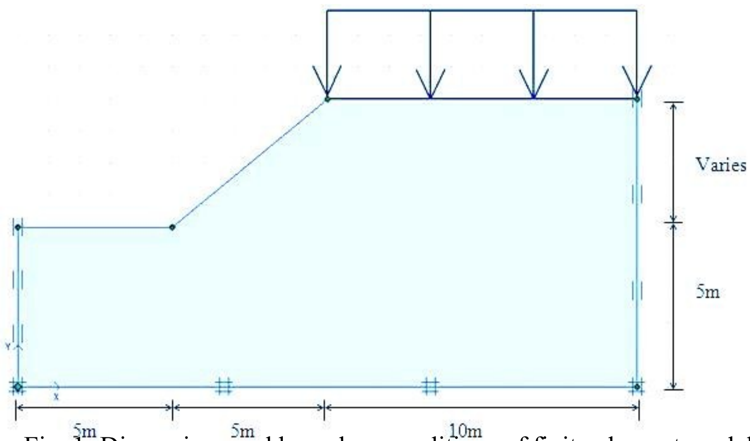

Fig. 1: Dimensions and boundary conditions of finite element model

Then the *calculation* window was opened to analysis. The *Phi-c reduction* calculation option is available in PLAXIS from the *calculation type* list box on the *General* tab sheet. If the *Phi-c reduction* option is selected the *Loading input* on the *parameters* tab sheet is automatically set to *Incremental multipliers*. A in the Parameters tab sheet the number of additional steps is automatically set to 100. Changing phenomena of stiffness matrix is followed after each iteration. The *Msf* value in the multiplier window is set to 0.1.

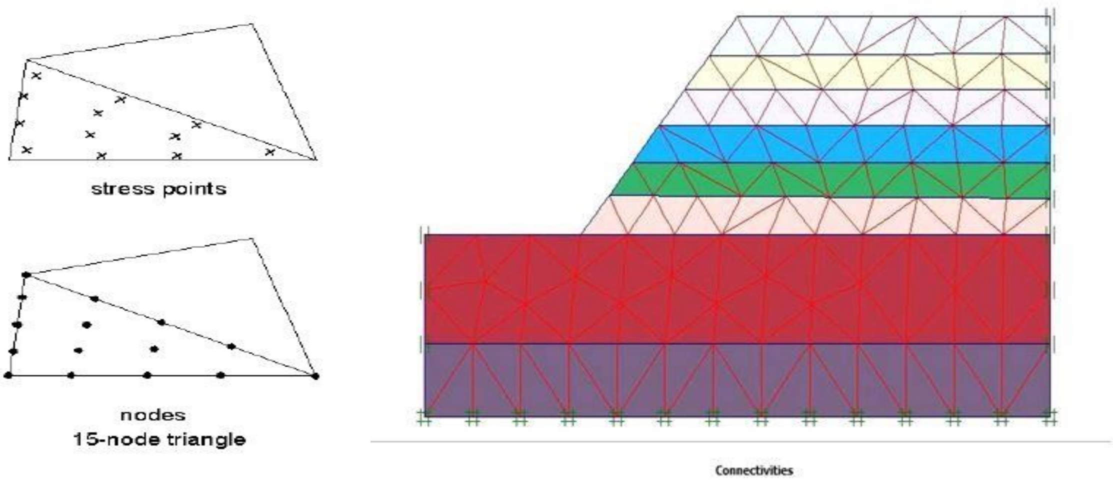

Fig. 2: 15-nodded triangular element and cross section of generated mesh

RESULTS AND DISCUSSIONS

Factor of safety

Fig. 3 shows the results of total displacement increments and factor of safety obtained from analysis for slope height of 4m consisting soil type 1 and re-fill soil.

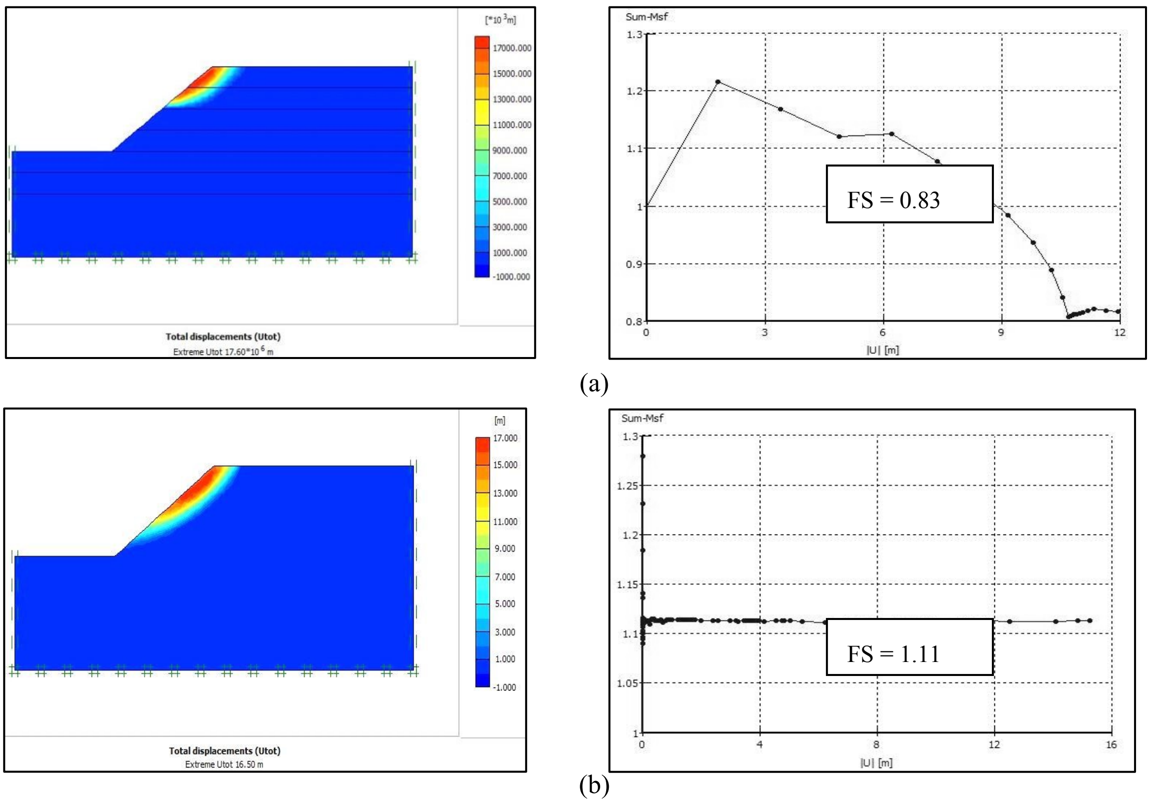

Fig. 3: Total displacement increments and factor of safety for (a) soil type 1 and (b) re-fill soil

Table 2 shows the factor of safety for slopes of different heights. It is obvious that, factor of safety gradually decrease as the slope height increases. From the table, we can depict that, only five times the value of factor of safety exceeds 1.0 which is the minimum value to call a particular slope stable.

Table 2: Factor of safety for varying heights of the slope

	3m	4m	5m	6m
Soil 1	0.95	0.83	0.72	0.64
Soil 2	1.33	0.98	0.80	0.62
Soil 3	1.41	1.08	0.89	0.76
Soil 4	0.98	0.83	0.73	0.63
Re-fill	1.50	1.11	0.90	0.76

Load carrying capacity

In this study the ultimate load carrying capacity of a stable slope is determined. The slope which has factor of safety greater than 1.0 can carry load. The uniform loads which can be carried by the stable slopes up to the verge of failure are tabulated in Table 3.

Table 3: Uniform load carrying capacity of the soil slopes

	Load carrying capacity (kN/m^2)			
Slope height	3m	4m	5m	6m
Soil 1	-----	-----	-----	-----
Soil 2	19.45	-----	-----	-----
Soil 3	14.00	8.00	-----	-----
Soil 4	-----	-----	-----	-----
Re-fill	46.20	22.00	-----	-----

CONCLUSIONS

In this study, detail analysis of slope stability is studied using FEM based software PLAXIS. The effect of slope height and the load carrying capacity is determined here. This evaluation is carried out for slopes comprising both existing in-situ soils and replaced re-fill soil. By comparing a number of data for both conditions some conclusions are drawn. As the height of the slopes increased the factor of safety decreased. In case of load carrying capacity, soil 1 cannot carry any load because the factor of safety is less than 1.0. Slope with height of 3m which is made of soil 2 can carry a surcharge of 19.45 kN/m^2 which is 28.02 % greater than that of the slope that made of soil 3 of same height. Re-fill soil has the most load carrying capacity. Thus, using PLAXIS, the stability and load carrying capacity of any proposed soil slope could be evaluated prior to the construction and thus safety is assured.

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