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The Effects of Strength Parameters on Slope Safety Factor in 2D & 3D Analyses using Numerical Methods

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ABSTRACT

Slope stability is one of the important issues in geotechnical engineering. In this regard, due to the growth in the number of numerical approaches, the two and Three-dimensional Finite Element Method (FEM) and the Finite Difference Method (FDM) are more important. In this paper, the effects of friction angle and cohesion on the safety factor of slopes were investigated, and the results of 2D & 3D FD were compared with those of FE analyses. The results of 600 analyses indicated that in cohesive soils (friction angle equal to zero) it was not necessary to analyze the slope in the 3D analysis, because the results of 2D & 3D were the same, with a difference of less than 0.3%. In granular slopes (cohesion equal to zero) the safety factor obtained in the 2D analyses (both FEM and FDM) were similar. However, the values in the 3D state were higher, and this indicated that in such a condition, unlike cohesive soils, the results of the 2D analysis were more conservative. It should be noted that in the 2D FDM for pure granular soils, the safety factor values for fine and medium mesh types were close. For the coarse mesh, however, the results were higher, and in pure cohesive slopes, in all three states (fine, medium, and coarse mesh tyes), the results were the same.

Keywords : *Friction Angle, Factor of Safety, FEM, FDM, Slope*

1. Introduction

Slope stability analysis is one of the most significant issues in soil mechanics, which have specific importance in geotechnical engineering. Slope stability analysis is a procedure in which the safety of natural or artificial slopes is controlled. This control includes the computation of shear stresses along the most critical slip surface and its comparison with shear strength. The definition and calculation of the factor of safety (FOS) is an important and disputable issue in slope stability analysis. In general, the final aim of stability analysis is the calculation of FOS against sliding and failure. Based on the applied method, 2D and 3D analyses have different outcomes for calculating FOS. These various relationships of FOS follow one specific object, which is illustrating the proportion between shear stresses and shear strength. In slope stability problems, when FOS=1, it means that the slope is on the verge of failure and generally, the acceptable value is about 1.5 [1] depending on the application of slope in different conditions.

In limit equilibrium methods, assumptions must be made to achieve a balance of equations and unknowns. Therefore, the different values of FOS are obtained. This discrepancy is due to the omnifarious assumption and dissension of the slip surface in each method. The 2D FOS value in critical sections (minimum FOS) is less than that of 3D analysis (although it is not necessarily true) [2]. Certain papers, such as seed et al. [3], indicated that the critical section does not necessarily present the minimum FOS and conversely, the minimum FOS does not necessarily present the critical section.

Currently, slope stability analyses are usually based on plane strain and are performed in 2D states. The reason for the popularity of the 2D state over the 3D analysis is the difficulty of using 3D software and the conservative calculation of FOS. 3D slope stability analysis can be obtained by extending 2D slope stability analysis and the value of FOS for 3D is usually greater than that of 2D. For example, Hovland's [4] method extended the ordinary slice method, which is a two-dimensional approach, and the gained results were blunder because the obtained FOS values were less than those of the 2D state. Also, the development of the Spencer method proposed by Chen and Chameau [5] resulted in the same mistake [6].

Generally, it can be indicated that slope stability analysis, which obtains higher FOS values in the 3D state compared to the 2D state, is more accurate. Some methods have a constant ratio between FOS in two and three-dimensional states. Azzouz et al. [7] determined the ratio of F_{3D}/F_{2D} for undrained cohesive slopes to be 1.07/1.3. In this regard, various research studies have been performed for earth slope stability [8-18]. The workability of FEM was also proved in Ref. [19].

In this research, 600 models were analyzed, and the results of FOS were compared in two and three-dimensional conditions. These analyses were performed to investigate the effects of soil cohesion and friction angle on the value of FOS.

2. Characteristics of modeling

In this paper, three software packages were used, including 2DFEM, 2DFDM, and 3DFDM slope geometry, as shown in Fig. 1. In the three-dimensional state slope, the width was 6 m. The characteristics of the soil are presented in Table 1. Lateral boundaries were fixed along x and y axes, and the bottom boundary was fixed along x, y (and z) axes. Results of sensitivity analyses for FEM and FDM are illustrated in Tables 2 and 3, respectively. The optimal mesh for 2D FEM was obtained 399 (run in 14 minutes), and for 3DFDM, it was 17792 (run in 47 minutes). In total, 600 models were analyzed in both dry and saturated conditions.

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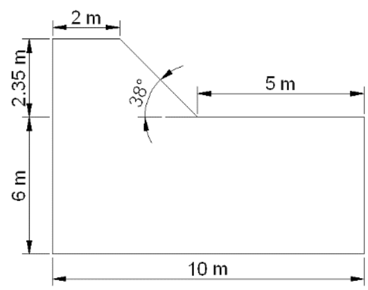

Fig. 1. The geometry of modeled slopes.

Table 1. Slope properties.

Parameter	Value
Constitutive Model	Mohr-Coulomb
Elastic Modulus (MPa)	15
Unit Weight (KN/m3)	16
Friction Angle (°)	0 to 50
Cohesion (kPa)	0 to 50
Poisson Ratio (-)	0.3

Table 2. Sensitivity Analysis for 2D FEM (C=0.0 & φ=40°).

Mesh Number	279	399	11171	1279	4845
FOS	1.017	1.014	1.016	1.012	1.012

Table 3. Sensitivity Analysis for 3D FDM (C=0.0 & φ=35°).

Mesh Number	12650	16382	17250	17792	19750	21000	24750
FOS	1.02	1.00	1.00	0.99	0.99	0.99	0.99

3. Exclusively cohesive soil

The results of cohesive soil analysis (friction angle equal to zero) indicated that all three software computed the same value and the rate of increase in FOS was linear due to an increase in cohesion (Fig. 2). This issue demonstrated that instead of using difficult 3D analysis for cohesive slopes, one could use 2D analysis because their value was the same and the differences were less than 0.3%. This behavior is analogous to that of saturated conditions.

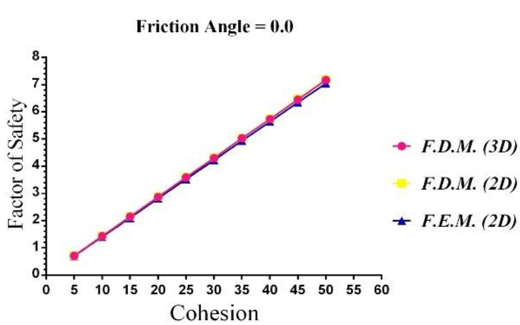

Fig. 2. Slopes stability analysis for φ=0.0 using 2D&3D FDM and 2D FEM software.

4. Purely granular soil

In this condition, a slope with zero cohesion was modeled and analyzed, which indicated that unlike the previous section, not only the results were not identical, but also the increase rate was not linear either (Fig. 3). As illustrated, in 2D analysis, the values of FOS were less than that of the 3D analysis, meaning that 2D models obtained more conservative results. It was noticed that both 2D analyses (F.E.M & FDM) coincided. The results of this special case (cohesion=0.0 & friction angle=30°) are shown in figures 4-6. As indicated, the maximum x displacement for both 2D and 3D analyses were close enough to verify the obtained results. In conditions that cohesion was the least (cohesion=5kPa & friction angle=0), 3D software correctly showed an instability error, while both 2D software, regardless of this issue, calculated FOS. Similar results were obtained in the saturated state.

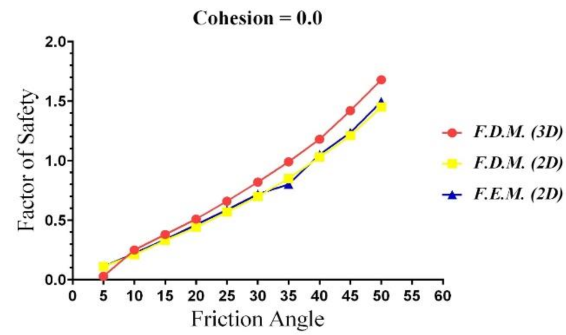

Fig. 3. Slopes stability analysis for C=0.0 using 2D&3D FDM and 2D FEM software.

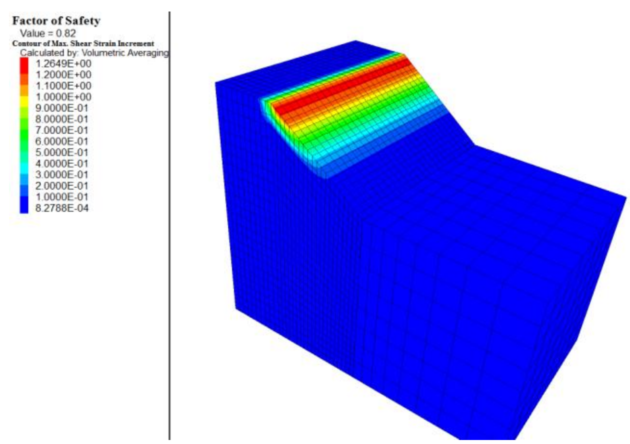

Fig. 4. Slopes FOS=0.82 for soil with C=0.0 & φ=30° using 3D FDM software.

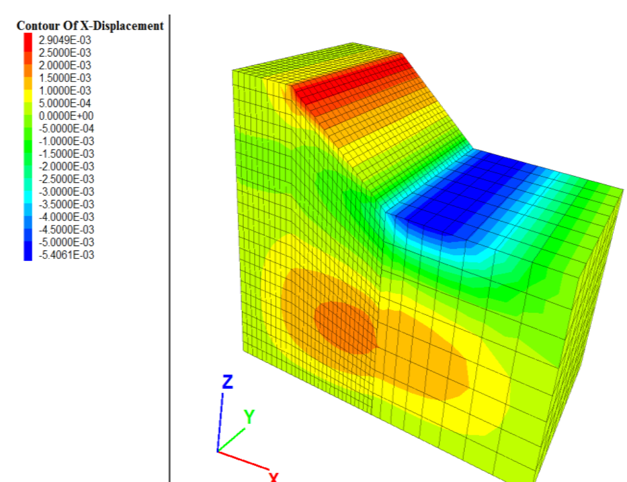

Fig. 5. The contour of X-Displacement for soil with C=0.0 & φ=30° using 3D FDM software (Maximum displacement=2.9 ×10^{-3} m).

5. Mixed soil

In this part, the mixture of different cohesion and friction angle was examined. Results indicated that the effect of cohesion on the increase of FOS was far more than the effect of friction angle, as evident in figures 7-12, in both dry and saturated slopes. For example, based on Fig. 7, if cohesion was 5 kPa and friction angle was 50°, the value of FOS would be 3.09 while if cohesion was 50 kPa and friction angle was 5° the FOS value would be obtained 7.60 (about 2.5 times difference). The procedure of FOS increase by each step of increasing cohesion or friction angle had a specified pattern. e.g., in all three software, for the cohesion of 5 kPa and by each 5° increase in friction angle, the rate of FOS enhanced 1.11 times of the pervious step, and this rate would eventually decrease (Table 4). The most important achievement of this research is that by the use of Table 4 and figures 7-12, we can predict the behavior of slopes with similar conditions. As indicated in Fig. 9, in dry condition, by increasing friction angle, the gap between 2D and 3D analyses became smoother.

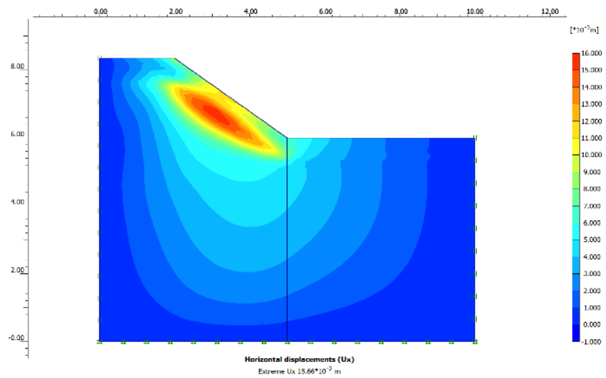

Fig. 6. The contour of X-Displacement for soil with C=0.0 & φ=30° using 2D FEM software (Maximum displacement=15.6 ×10^{-3} m).

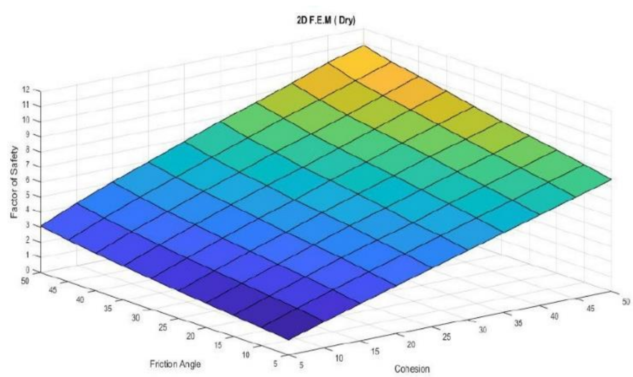

Fig. 7. Three-dimensional diagram for 2D FEM analysis in the dry condition.

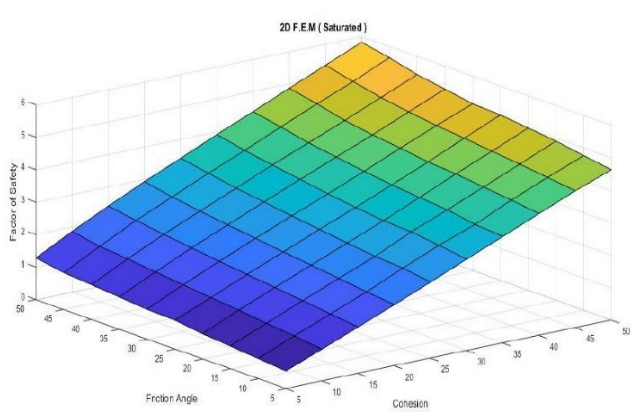

Fig. 8. Three-dimensional diagram for 2D FEM analysis in the saturated condition.

Also, the 2D analysis resulted in more conservative results. While for pure cohesive slopes, the pattern for both 2D and 3D analyses were the same. For the saturated slope, the pattern was vice versa. As friction angle increased, the results of both 2D and 3D analyses became closer and finally merged. While increasing cohesion, the gap between the two graphs became sharper. From these two figures, one can understand that the 2D finite difference method in the condition of dry slope provided more conservative results compared to 3D finite difference analysis. However, in the case of the saturated slope, their pattern was not identical to the previous state.

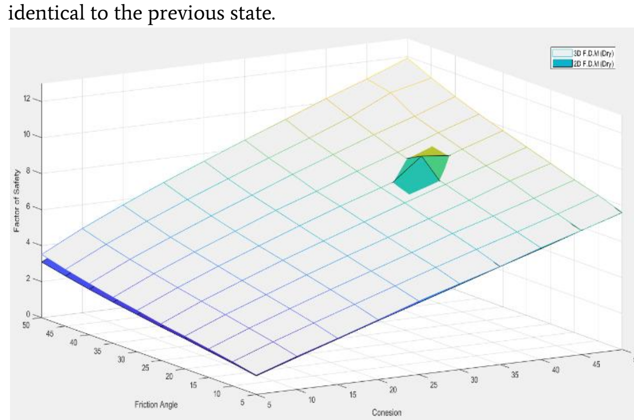

Fig. 9. Three-dimensional diagram for both 2D & 3D FDM analysis in the dry condition.

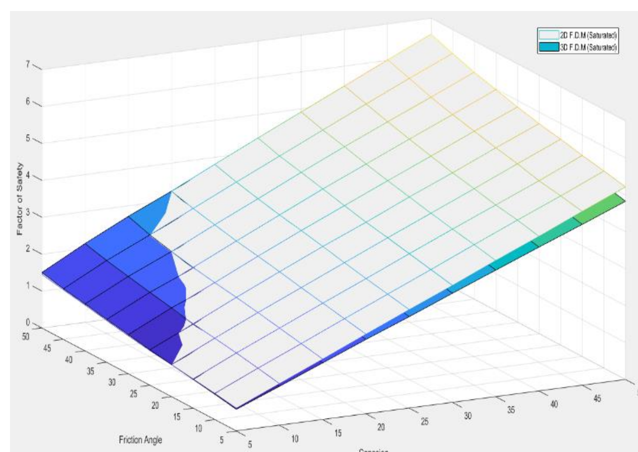

Fig. 10. Three-dimensional diagram for both 2D & 3D FDM analysis in the saturated condition.

Table 4. Increase steps of Factor of Safety in all three software for each 5° increase in Friction Angle.

	C=5 kPa	C=10 kPa	C=15 kPa	C=20 kPa	C=25 kPa
FOS Increasing steps	1.11	1.09	1.08	1.07	1.07
	C=30 kPa	C=35 kPa	C=40 kPa	C=45 kPa	C=50 kPa
FOS Increasing steps	1.06	1.06	1.05	1.05	1.05

6. Effects of mesh

In this section, the effects of three types of used mesh types in the 2D analysis is investigated. These mesh types are: coarse, medium, and fine. For friction angle equal to zero, the results of both software were the same, and no difference was observed in various mesh types (figures 11-12). This indicates that for a cohesive slope, the 2D analysis with a coarse mesh would provide the same result to the 3D analysis with a fine mesh. This is a significant result, showing why under such circumstances, instead of using 3D analysis for 47 minutes, one can perform the 2D analysis with coarse mesh under 4 minutes and will achieve the same result. However, the result is different for a cohesionless state. In FDM (Fig. 13), coarse mesh resulted in a higher amount of FOS (although the results of medium and fine mesh were so close). FEM outcomes were totally different, and the result for the coarse mesh was an irrelevant amount (Fig. 14), but medium and fine mesh types had similar values. For different mesh analysis in pure cohesive slopes, regardless of the mesh type, the values were practically the same. However, for the granular slope, using a different mesh would lead to different FOS results.

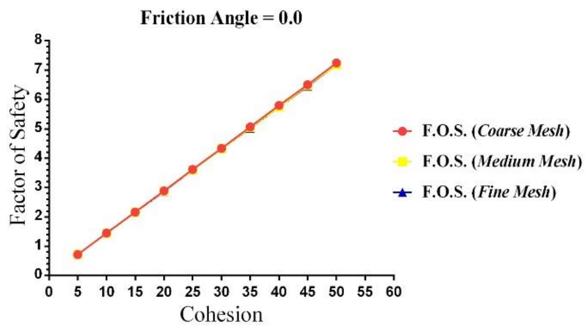

Fig. 11. 2D F.D.M analysis for φ=0.0 in different mesh states.

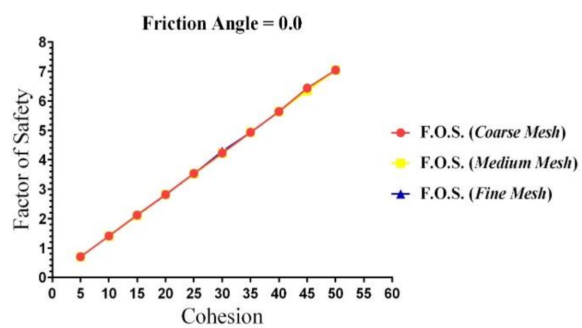

Fig. 12. 2D F.E.M analysis for (φ=0.0), in different mesh states.

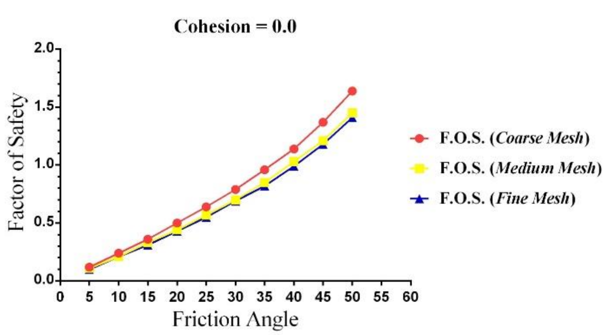

Fig. 13. 2D F.D.M analysis for C=0.0 in different mesh states.

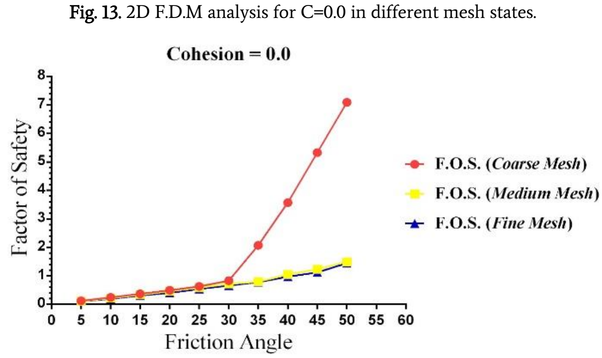

Fig. 14. 2D F.E.M analysis for C=0.0 in different mesh states.

7. Results and discussion

In this paper, by performing 600 analyses in different conditions, the effects of cohesion and friction angle in calculating FOS were investigated, which provided impressive results. The most important achievement of this research is that in the condition of a pure cohesive slope, not only there is no need to use time-consuming 3D analysis, but also the application of a 2D analysis with a coarse mesh type provides the same results. However, for granular or mixed slopes, the FOS obtained in the 3D states are more realistic and the 2D analysis is more conservative. The type of mesh has a great impact on the results (cohesive slopes are excluded), in a way that 2D FEM will result in irrelevant values for the coarse mesh, which is an important issue and should be taken into account carefully. By gradually increasing the slope friction angle (as shown in Table 4), the process of FOS enhancement follows a specific pattern and the application of this algorithm will help to predict different cases. Also, the use of the graphs presented in this paper would lead to better and easier understanding of other cases.

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