Stability Analysis of Residual Soil Slope Model by Numerical Modeling Using FEM Against LEM

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Abstract. Due to the advances of numerical simulation with computer modeling software, engineers and designers are gaining more interest in simulation methods for the prediction of soil behavior. Slope failure could be considered the most challenging aspect in geotechnical engineering. Accordingly, nowadays, many computer modeling software is employed for the evaluation of natural slope stability analyses. In this paper, the soil slope model analyses were implemented using the finite element analysis method (FEM) and simulated using PLAXIS-2D software. The parameters of soil layers used to feed these slope models were obtained from laboratory results by drained triaxial compression tests conducted on remoulded residual soil samples prepared under 200 kPa remodeling pressure. This paper aims to present numerical simulations of natural slope stability by determining the failure surface and the corresponding safety factor with consideration to the influence of various slope geometries. Then, the obtained (FOS) values were then compared with previous results of similar slope models that were calculated by limit equilibrium analysis method (LEM) using SLOPE/W software. The evaluated results indicated that the change in the slope geometries could considerably influence the calculated FOS. Furthermore, the FE method calculated the safety factor close to but slightly higher than the results calculated by the LE method. Nevertheless, both methods are satisfying in obtaining the ideal mechanism of slope failure behavior. However, the application of (FEM) offers an attractive alternative to traditional approaches to the problem, especially for (LEM).

Keywords: Stability; residual soil; finite element; limit equilibrium; numerical analysis.

1. Introduction
Essentially, in geotechnical projects, slope stability is considered an unpredictable problem that faces various construction sites of the natural slope and can be returned to ambiguity in several factors such as condition and location of the failure, geotechnical parameters of soil, and history of loading on the slope [1]. Furthermore, this issue gets even more serious when the slope is on residual soil, which means that, unlike sedimentary soils, the strength parameters of soil cannot be obtained trustfully based on stress-strain relationships, as discussed in [1]. Fundamentally, Salih and Ismael [2] indicated in their study; that soil strength characteristics play an important role in the trend of slope stability with consideration to the importance of the soil moisture content. In addition, the slope geometry conditions that control the failure mechanism's pattern that is considered a significant predictor of slope failure. Over the years, a wide variety of analytical procedures have been developed to implement slope stability analyses which have received a great deal of studies by various researchers; engineers, and designers due to the demand for more understanding about slope stability and the mechanism of failure in geotechnical projects [3]. Accordingly, many computer modeling software is employed to evaluate slope
stabilities analyses through simulation methods for the purpose of predicting soil behavior, such as the limit equilibrium analysis method (LEM) and finite element analysis method (FEM) [4]. Consequently, the slope stability analysis consists of determining the soil mechanical properties, the shape, and the position of the possible failure surface. Several studies have been carried out to illustrate the benefits of modeling different soil slope failure behavior by finite element methods. These methods have several advantages to model slopes with a degree of very high realism (complex geometry, sequences of loading, presence of material for reinforcement, the action of water, laws for complexes soil behavior…) and better visualize the deformations in soils in place [5]. Although the LEM does not consider the stress-strain relation of soil, it can provide an estimate for the safety factor of a slope without knowing the initial conditions, with the result that the LEM is favored by many engineers [6]. Khabbaz et al. [7] mentioned that the slope geometry, the soil unit weight, the strength parameters (c and φ), and forces affecting the slope are the most important factors in both limit equilibrium and finite elements slope stability analyses.

In this regard, the instability and failure characteristics of residual soil hillslope had been investigated and presented through this study by involving analysis and comparison of the stability through an estimate of the SF, and the critical failure surfaces obtained by SLOP/W and Plaxis-2D programs; whereas the adoption of (LEM) and (FEM) respectively.

2. Methods of slope stability analysis and modeling tools

Basically, this research involved a series of analyses and evaluations that were conducted by applying finite element analysis method (FEM) based software, Plaxis-2D, which is numerical simulation software. These analyses were conducted to obtain the expected failure surface and the corresponding safety factor, considering the influence of different conditions of slope geometry. Then, the obtained FOS results were compared with previous results of the identical slope models that calculated by limit equilibrium analysis method (LEM) using SLOPE/W software as presented in previous research [2]; that concerned about the stability concept of residual soil of natural hillslope as summarized in Table 2. Three different slope height cases were studied for the stability analysis: 6, 9, and 12 m in tall. In each case, variation in inclination of hillslope; was the scenario to make the comparative analysis.

Analyses performed using Plaxis-2D were applied by following Mohr’s-Coulomb material as the model, which corresponds to the basic assumptions of the analytical methods. The cohesion-friction angle reduction method was chosen as it is satisfy applying to almost all soil profiles and various slope geometries. The soil properties were obtained from drained triaxial tests conducted on residual soil samples which were prepared under 200 kPa remodeling pressure as mentioned previously in [2] and presented in Table 1. The soil was classified as low plasticity silt, cohesion, and angle of friction were 9.04 kPa and 29.79° respectively for the upper soil layer (layer 1, which was 3 m in thickness), and 1.42 kPa and 32.57° for the lower soil layer (layer 2). These soil properties were given as input parameters, and Poisson’s ratio of 0.3 was considered.15–triangular node elements were selected to model the soil layers and volume clusters. Furthermore, medium coarseness was selected for mesh generation. Initial stresses were generated in the first analysis phase considering the gravity loading and then followed by safety analysis for the next phase.

3. Material sets for soil interfaces

Fundamentally, the slope stability requirement is that the soil shear strength must be greater than the shear stress required for equilibrium. Specifically, a decrease in shear strength of the soil may result from different factors such as increased pore water pressure, slope cracking, swelling, development of slickensides, decomposition of clayey rock fills, creep under sustained loads, leaching, strain softening, weathering, and cyclic loading [8]. Additionally, the most critical slope failure conditions occur in the long term condition (Drained Condition). Consequently, it is necessary to adopt effective shear strength parameters for the Drained Analysis of the slopes in residual soils instead of undrained shear strength parameters.
3.1. Soil properties
The soil density, elastic modulus, and Poisson’s ratio are illustrated in Table 1, including other shear strength parameters for the simulated soil layers obtained in previous studies [2] from the drained triaxial test. Soil profile consists of two types of layers with different properties.

| Soil layer | 1      | 2     |
|------------|--------|-------|
| Soil type  | residual soil | residual soil |
| Elastic modulus E (kPa) | 15000 | 15000 |
| Poisson’s ratio ν | 0.3 | 0.3 |
| γ<sub>unsat</sub> (kN/m<sup>3</sup>) | 18 | 19 |
| γ<sub>sat</sub> (kN/m<sup>3</sup>) | 20 | 21 |
| Soil cohesion c’ (kPa) | 9.04 | 1.42 |
| Friction angle φ° | 29.79 | 32.57 |

3.2. Soil geometry
The geometric configuration of the simulated slope model analyzed by Plaxis-2D is clarified in Figure 1 by providing geometric parameters of the given slope model.

![Figure 1. The geometric configuration of the slope model that analyzed by Plaxis-2D and the material data settings window.](image)

4. Results of analyses and discussion
4.1. Sample graphs
Various geometries of the slope were analyzed as a plane strain model. Slope stability was studied in the case of homogeneity within each layer constituting the slope. The mechanical parameters are those derived from laboratory tests. The hillslope is considered in its natural state before any excavation. As proceed in Phi-c reduction method calculation, the concept of the incremental displacements worked as an indicator for the failure mechanism. The failure surfaces seem circular for the chosen slope profiles...
shown in Figures 2, 3, and 4. The safety factor obtained was equal to 1.525, 1.177, and 0.792 for profiles 1, 2, and 3, respectively.

**Figure 2.** Failure surface of profile 1, where $H = 6$ m and the land inclination $\beta = 30^\circ$, $FS = 1.525$.

**Figure 3.** Failure surface of profile 2, where $H = 9$ m and the land inclination $\beta = 35^\circ$, $FS = 1.177$. 
Figure 4. Failure surface of profile 3, where H = 12 m and the land inclination β = 45°, FS = 0.792

The results analyses reveal that the instability of soil layers occurs due to instability of soil mass according to the slope geometry apparently in preliminary aspects.

4.2. Comparative of output data
As mentioned above, the slope stability analyses were conducted using two software SLOPE/W [2] under the Morgenstern-Price’s method (MP), Spencer’s method (SM), Bishop’s method (BM), and Janbu’s method (JM) based on half sin function; and PLAXIS-2D using the Phi-c reduction approach. Table 2 outlines the calculated FOS values from the above-proposed methods.

| Slope geometry | H 6 m | 9 m | 12 m |
|----------------|-------|-----|------|
| LEM            | β 25° 30° 35° 40° 45° 25° 30° 35° 40° 45° 25° 30° 35° 40° 45° |       |      |
| MP             | 1.67 1.49 1.36 1.24 1.12 1.43 1.29 1.18 1.08 1.00 1.31 1.18 1.06 0.97 0.90 |
| SM             | 1.67 1.49 1.37 1.24 1.15 1.43 1.29 1.18 1.08 1.00 1.31 1.18 1.06 0.97 0.91 |
| BM             | 1.67 1.48 1.36 1.24 1.13 1.43 1.28 1.17 1.08 0.99 1.30 1.17 1.05 0.97 0.90 |
| JM             | 1.52 1.36 1.27 1.19 1.13 1.30 1.17 1.08 1.00 0.94 1.19 1.05 0.96 0.89 0.83 |
| FEM            | 1.75 1.52 1.31 1.13 1.01 1.63 1.37 1.17 0.96 0.79 1.55 1.29 1.06 0.89 0.79 |

4.3. Results discussion
Based on the implemented analyses, the findings of this study can be summarized as follows:
1) A stability check for the existing land slope heights was conducted and found stable for the angle of the land inclination as followed, besides slight deformations under gravity loading:
   • 25° – 45° for the slope height 6 m (for both LEM and FEM).
   • 25° – 40° for the slope height 9 m (for LEM).
25° – 35° for the slope height 9 m (for FEM).
25° – 35° for the slope height 12 m (for LEM except for JM).
25° – 35° for the slope height 12m (for FEM).

In general, a safety factor of slope decreases with taller heights in addition to steeper slope gradients.

2) By comparing FOS values computed by (FEM) with values of FOS that computed by (LEM) as predicted by a previous study [2]; it is clear to notice that results from (FEM) tend to give almost slightly higher values for the land inclination 25°, 30° and 35° respectively. Unlike for the land inclination 40° and 45° that gave lower FOS values. Essentially, these varieties of FOS values significantly produce because of the assumptions included and the limitations for every adopted method, then, for the corresponding conditions of slope geometry. However, the differences between the results of the two programs are small.

3) The results reveal clearly that the FOS values computed using (FEM) are more approximate to the results values obtained from Morgenstern-Price’s method (MP), Spencer’s method (SM), and Bishop’s method (BM), which are employed by SLOPE/W (LEM).

4) It is vital to notice that both methods (LEM) and (FEM) are satisfying in obtaining the ideal mechanism of slope failure behavior regardless of slight differences between the results obtained.

5) In the case of failed slopes, presented slope heights with different slope inclinations could be a potential reason for the failure, whereas the soil properties are identical for all simulated models.

6) The water table was assumed to be in the bottom of the soil layers so that any change of water table level would cause a reduction of the safety factor.

7) LE method can predict an estimation of the safety factor of a slope without prior knowledge of the initial conditions used with (FEM), so that many engineers prefer to use LEM over FEM.

8) Accordingly, the predicted results demonstrate an intelligible perception of the failure mechanism for slopes with similar configurations and geometries of the studied soil. Moreover, the application of (FEM) offers an attractive alternative to traditional approaches to the problem, especially for (LEM).

5. Conclusion

In general, the determination of the safety factor for slopes is considered an insufficient indicator to identify natural slope stability problems. This is because of the fact that it does not provide a perfectly comprehensive ideal conception of the slope stability behavior. Ideally, the stability of the slope results from the combination of several influences, including condition and location of the slope, geotechnical parameters of soil, and history of loading on the slope. However, these studies' importance is based on predicting the slope failure mechanism under different conditions, also defining several factors affecting slope stability. In this paper, residual soil slopes were modeled and analyzed to investigate the impact of different slope geometries on the corresponding safety factors. The findings of this study show that the safety factor of slope decreases with taller heights in addition to steeper slope gradients. Essentially, it is apparent that both adopting methods (FEM) and (LEM) determined almost identical critical slip surface shapes and locations. On the other hand, the FE method calculated the safety factor close to but slightly higher than the results calculated by the LE method. Meanwhile, the results of field tests must be used to enhance the approximation of the real behavior of the soil during failure. In summary, the application of these various analytical methods on slope stability analysis allows more than their comparison to highlight all previously mentioned factors and conditions that affect slope stability.

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