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STABILITY ANALYSIS OF SLOPES FOR HOMOGENEOUS AND LAYERED SOIL BY FEM

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ABSTRACT

This paper illustrates a finite element approach to analyze the responses of slopes of homogeneous and layered soil with shear strength reduction (SSR) technique. Slope failure may occur owing to the reduction of shear strength with the increase of plastic strains induced by loading. The present approach allows this failure process and analysis is carried out using Mohr-Coulomb failure criterion and Drucker-Prager yield criterion in which the shear strength parameters are reduced. To assess the reliability of the numerical result for slope stability analysis by the finite element SSR technique, itscomparison with thewell-known conventional limit equilibrium methods namely Bishop Method (1955), Fellenius Method (1936) and Spencer Method (1967) isdepicted considering the slope of homogeneous and layered soil.A very good agreement is found between the conventional limit equilibrium methods (LEM) and finite element method (FEM).However, the factor of safety computed by FEM depicts the higher values than that of LEM and the factor of safety considering the Mohr-Coulomb model depicts the lower value than that of Drucker-Prager model irrespective of slope angle for both the slopes of homogeneous and layered soil.The effect of the variation of weak soil layer from top of slope to the foundation soil has been reported as well. The factor of safety of the slope of layered soil decreases in relation to the increasing of distance of a thin soil layer from the top of the slope to layer thickness ratio up to a certain value and beyond that, the factor of safety increases again. Finally, failure surfaces for both the LEM and FEM have been assessed. It can be noted that FEM depicts deeper localization of slip surface than LEM for a slope of homogeneous soil; however, for a slope of layered soil, LEM depicts deeper localization of slip surface than FEM.

Keywords*: Slope stability, Finite element method, Limit equilibrium method, Layered soil*

1. INTRODUCTION

Slope stability analysis is one of the most important areas of interest in geotechnical engineering. There are a lot of engineering structures which require foundation systems to be placed near an existing slope such as bridge abutment, tower footings, basement construction of high rise building, etc. In construction areas, slope may fail due to heavy rainfall, increase in ground water table and change in stress condition. Similarly, natural slopes that have been stable for many years may suddenly fail due to change in topography, external forces, loss of shear strength and weathering (Abramson *et al*. 2002). Therefore, it is a common challenge to both researchers and professionals to analyse the stability of slopes and evaluate the certainty of the factor of safety.Lin and Cao, 2010 conducted the effect of shear strength parameters cohesion and internal friction angle on the stability of slope through theoretical derivation and limit equilibrium method. In their study, changes in the factor of safety of slope and slip surface were investigated. Namdar,2010 presented the three-wedge method for stability analysis of slope. The influence of root trees on slope stability was studied and different factors like geometry and gradient, geologic materials, stratigraphy, hydrology and the local effects on the shore process were analyzed as well. Cala and Flisiak,2003 performed many simulations for isotropic and homogeneous slope using shear strength reduction (SSR) technique and limit equilibrium methods (LEM). The influence of elastic properties (Young's modulus = E , Poison's ratio = ν) on slope stability analysis were investigated and it was noted that elastic properties negligibly influenced the factor of safety of slope. In these studies, the effect of slope angle and slope height was carried out as well and the results obtained by SSR technique were compared with that of LEM.

Duncan,1996 proposed that the stability and deformation of slope can be analyzed by finite element method (FEM). Griffiths and Lane, 1999 discussed several examples of FEM based slope stability analysis by comparing with other solution methods. Zhang *et al*.,2010 evaluated the channel slope stability of the East Route of the South-North Water Diversion Project in China. Typical channel cross section in Sanding Province was evaluated using SSR-FEM. To describe the stress-strain relationship of the soils, Duncan-Chang nonlinear constitutive model was employed. The factor of safety calculated by strength reduction method was compared with LEM.He and Zhang, 2012 described the stability analysis of a homogeneous

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slope and showed that the equivalent area circle Drucker-Prager yield criterion was suitable for the stability analysis of slope.
For the stability analysis of slopes, the calculation of thefactor of safety can be evaluated through different numerous methods. Over the past four decades, numerical analysiswas conducted mainly through conventional LEM. This method is statically indeterminate and needs to make pre-assumption to determine the factor of safety. The application of LEM is limited to the simple slope and not available for complex geometries. On the contrary, the numerical methods such as FEMwere widely used over the last two decades. In FEM, any assumption in advance of the failure shapeand location of the failure surface is not necessary(Griffiths and Lane, 1999).
Even though many researches have been carried out for the stability analysis of slope by LEM and FEM for homogeneous soil but a few studies for layered soil on the stability analysis of slope have been reported in the literature. Recently, Moni and Sazzad, 2015 studied the effect of surcharge on the stability of slope for homogeneous soil but they did not consider layered soil. It should however be noted that thelayered soil is more common in nature than the homogeneous soil. As a result, the consideration of the layered soil in stability analysis of slope is significant and more practical. Consequently, the main objectives of this study are:to compare the FEM based analysis result with that of LEM, to evaluate the effect of soil layer on the stability of slope and to examine the mode of slope failure obtained from FEManalysis and compare with LEM.

2. METHODS OF EVALUATING FACTOR OF SAFETY OF SLOPE

2.1 Limit equilibrium methods

Conventionally for most of the cases, slope stability analysis is carried out by limit equilibrium method (LEM). This method is statically indeterminate. Pre-assumption is needed to determine the factor of safety using the LEM. Bishop method (Bishop, 1955), Fellenius method (Fellenius, 1936) and Spencer method (Spencer, 1967) are the examples of widely used LEM. The application of LEM is limited to the slope of simple geometry. The solution in LEM is simple and can become inadequate in case the slope fails by complex mechanism such internal deformation, brittle failure, etc.

2.2 Finite element method

Finite element method (FEM) is a powerful numerical tool for solving many engineering problems and mathematical physics. Due to the rapid development of computer technology, FEM has gained increasing popularity over the traditional methods in geotechnical engineering. Generally, there are two approaches to analyze the stability of slope using FEM. One approach is to increase the gravity load of soil element and the second approach is to reduce the strength characteristics of the soil mass usually called Shear Strength Reduction (SSR) technique. The SSR technique is adopted in the present study by using a powerful FEM basedsoftware GEO5 (2014).The SSR method is a new technique and it is used in FEM to calculate the failure limit state of slope and factor of safety. In SSR technique, it is assumed that slope materials have elasto-plastic behavior. The SSR is based on progressive reduction of soil strength parameters, $\phi$and$c$until the failure of slope occurs.In this technique, the Mohr-Coulomb material shear strength is reduced by a factor F . The definition is expressed as follows:

$$\frac{\tau}{F}=\frac{c'}{F}+\frac{tan\phi'}{F} \quad (1)$$

Equation(1) can be written as follows:

$$\frac{\tau}{F}=c^{*}+tan\phi^{*} \quad (2)$$

where, $c^{*}=\frac{\tau}{F}$ (3)

$$\phi^{*}=arctan\left(\frac{tan\,\phi'}{F}\right) \quad (4)$$

For details of SSR technique, readers are referred to Griffiths and Lane (1999).

2.3 Geometric model of slope

A number of problems for different slope angles are solved in this research. Figure 1 shows the geometric model of a slope of homogeneous soil whileFigure2 presents the geometric model of a slope of layered soil. In both the models,β represents the angle of slope and it is variable. In Figure2,h and t represents the distance of a thin soil layer from the top of the slope and thickness of thin layer, respectively. Here,h is variable and t is constant. The finite element models of slopes of homogeneous and layered soilare shown in Figures 3 and 4, respectively.

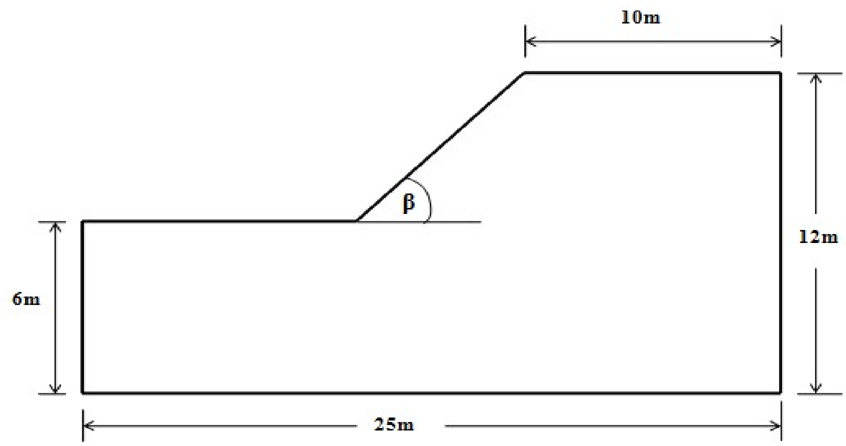

Figure1: Geometric model of aslope of homogeneous soil

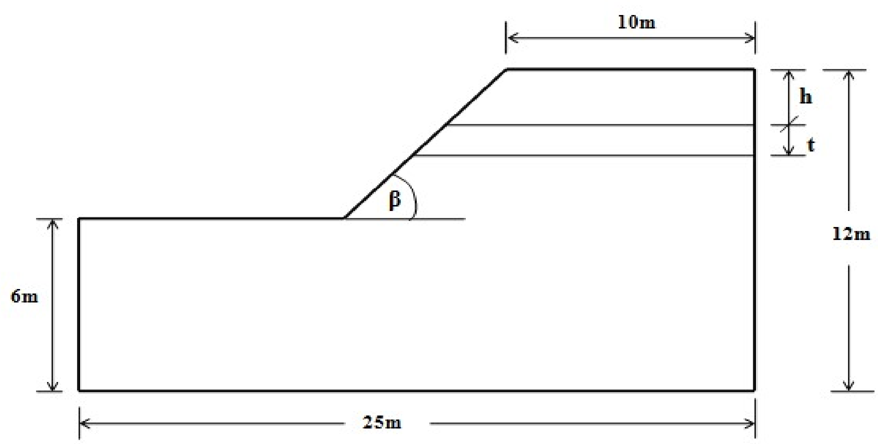

Figure 2: Geometric model of aslope of layered soil

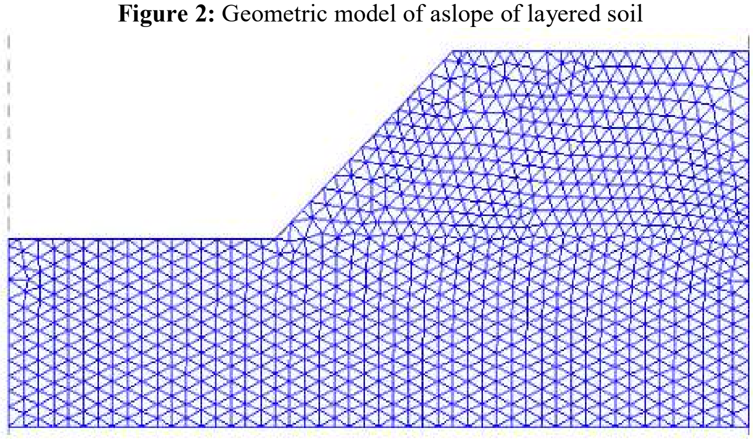

Figure 3: Geometry and mesh for a slope of homogeneous soil

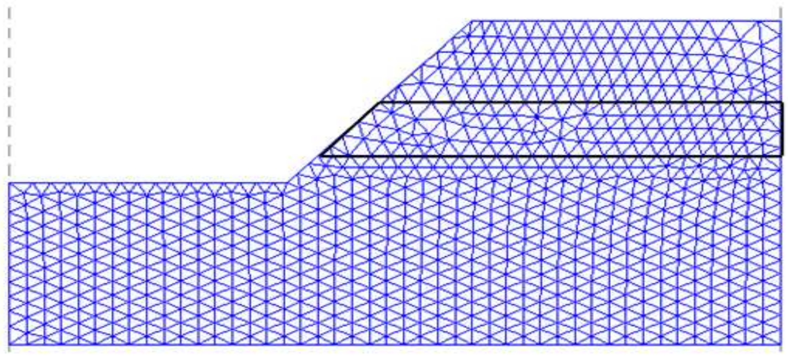

Figure 4: Geometry and mesh for a slope of layered soil

2.4 Material properties

The properties of soil used in this study are presented in Table 1. Two types of soils were considered. Soil-1 was used in the analysis of a slope of homogeneous soil whereas both Soil-1 and Soi-2 were used in the analysis of a slope of layered soil. Soil-2 was used for thin layer of slope of layered soil.

Table 1: Properties of two types of soil considered in this study

Material	Unit weight (kN/m^3)	Friction angle (degree)	Cohesion (kN/m^2)	Modulus of elasticity (MN/m^2)	Poisson's ratio	Dilation angle (degree)
Soil-1	20	18	10	8	0.3	0
Soil-2	20	10	6	8	0.3	0

2.5 Loading and Boundary conditions

In all cases, it is assumed that there is no external load other than the gravitational forces (i.e. body force). Two different geometric models were used in this study. In both the models, the geometric boundaries were horizontally constrained on the left and right sides and completely fixed at the bottom of the geometry.

3. NUMERICAL ANALYSIS BY LEM AND FEM

In this study, a number of numerical analyses were performed by the software GEO5 (2014). Bishop method (Bishop, 1995), Fellenius method (Fellenius,1936)and Spencer method (Spencer, 1967)were used for limit equilibrium analysis. Mohr-Coulomb failure criterion and Drucker-Prager yield criterion were used in finite element analysis.For LEM, the geometric model wasincorporated in the GEO5 software. After incorporating the model, the properties of soil were assigned for the specified interface. In the analysis stage, a slip surface was added. The slip surface may be circular or polygonal. In this study, circular slip surface was used. After assigning all properties and slip circle, the analysis method was chosen. Then, analysis type namely standard or optimization was chosen. In this study, optimization type was taken. Finally, a surcharge was added on the terrain of slope and analysis was carried out.For stability analysis using FEM, the first step was to set the project parameters. Plane strain project type was selected. Later, analysis type was set. The geometric model was incorporated in the GEO5 same as LEM. After incorporating the model, the properties of soil was assigned for the specified interface. The material model out of several models such as elastic, elastic modified, Mohr-Coulomb, modified Mohr-Coulomb, Drucker-Prager, etc. was to be set. In this paper, Mohr-Coulomb and Drucker-Prager modelswere used.For FEM analysis, meshes were generated.After generating the meshes, a strip surcharge was added on the terrain of slope. Finally, analysis was performed using the SSR method (Griffiths and Lane, 1999).

4. RESULTS AND DISCUSSION

4.1 Slope of homogeneous soil

Three different types of slope angles (30, 45 and 60 degrees) wereconsidered in this study. From the numerical analysis, it was noted that the computed factor of safety ranges from 1.37 to 1.56 for a slope of 30°, 1.06 to 1.17 for a slope of 45°and 0.81 to 0.93 for a slope of 60°.Factor of safety between FEM and LEM is compared and provided in Table 2. Factor of safety by Fellenius method (Fellenius, 1936)was found to be lower than that of Bishop (Bishop, 1955) and Spencer (Spencer, 1967). Drucker-Prager model showedthe higher factor of safety than that of Mohr-Coulomb model and LEM results werealso closed to FEM for a slope of homogeneous soil.The effect of slope angle$\beta$is depictedin Figure5. The factor of safety decreases in relation to the increasing of slope angle.Figure6 shows the contours of the equivalent plastic strain for homogeneous soil with a slope angle of 30° by FEM whileFigure7represents the failure of a homogeneous soil with a slope angle of 30° using the LEM. The results depicted in Figure6 have reasonable correspondence with that in Figure 7. Figure8 depictsthe contours of the equivalent plastic strain for a slope of homogeneous soil with a slope angle of 45° by FEM whereasFigure9 shows the failure of a slope of homogeneous soil with a slope angle of 45°using limit equilibrium method. Figure10 depicts the contours of the equivalent plastic strain for a slope of homogeneoussoil with a slope angle of 60° by FEM whileFigure11represents the failure of a slope of homogeneous soil with a slope angle of 60° using LEM. Similarity of the slip surfaces for FEM and LEM analysis is observed as well for 45° and 60°, respectively. It is also obvious inFigures6, 7, 8, 9, 10 and 11 that slip surfaces obtained from FEM are localized deeper than LEM irrespective of slope angles for a slope of homogeneous soil.

Table 2: Comparison of factor of safety between FEM and LEM ($\beta = 45°$)

Material model and methods	Factor of safety	% variation of FEM results with respect to minimum LEM result
Drucker-Prager	1.17	10.38%
Mohr-Coulomb	1.08	1.89%
Bishop	1.09	-
Fellenius	1.06	-
Spencer	1.10	-

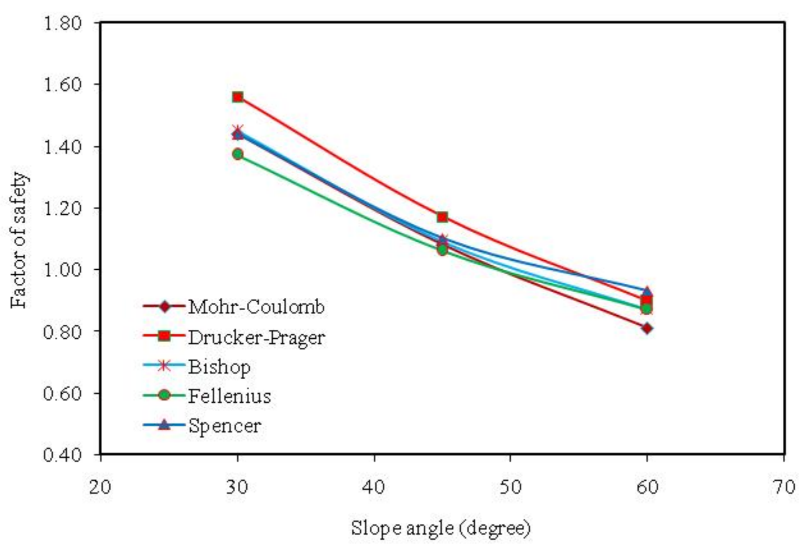

Figure5: Effect of slope angle on the factor of safety of slope with LEM and FEM

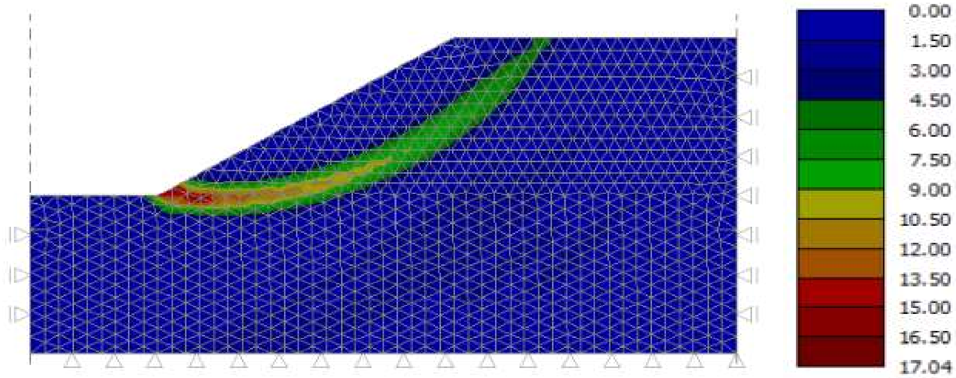

Figure6: Contours of the equivalent plastic strain for a slope of homogeneous soil (β =30°) by FEM

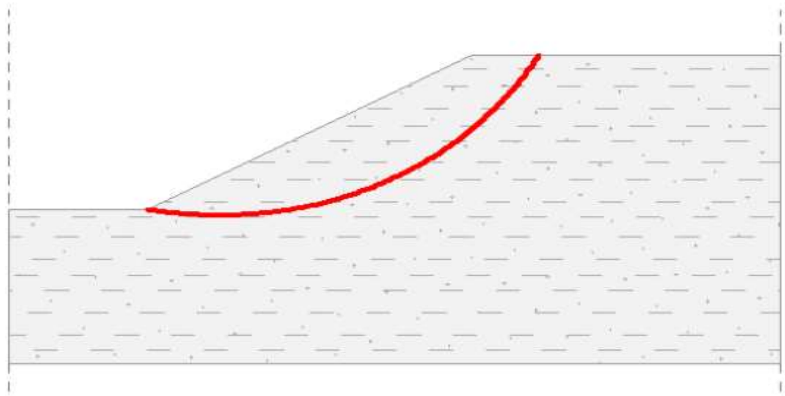

Figure7: Failure of a slope of homogeneous soil(β =30°) using LEM

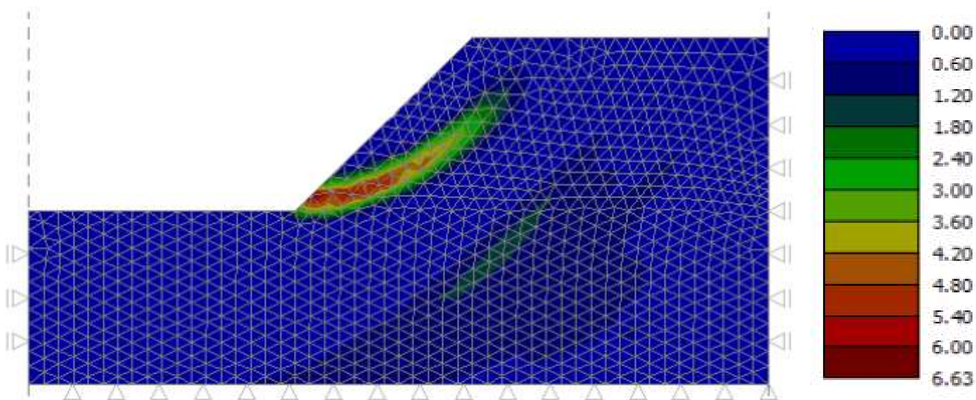

Figure8: Contours of the equivalent plastic strain for a slope of homogeneous soil (β =45°) by FEM

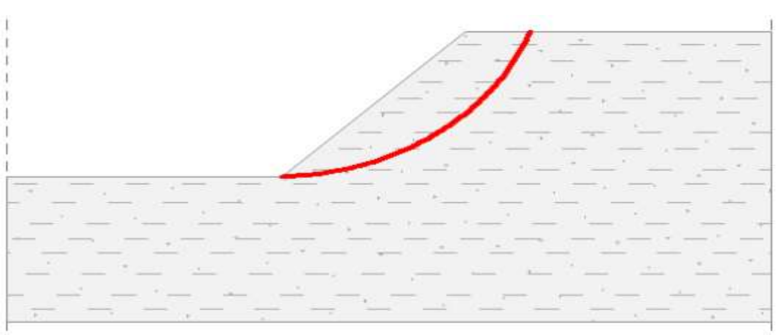

Figure9: Failure of a slope of homogeneous soil (β = 45°) using LEM

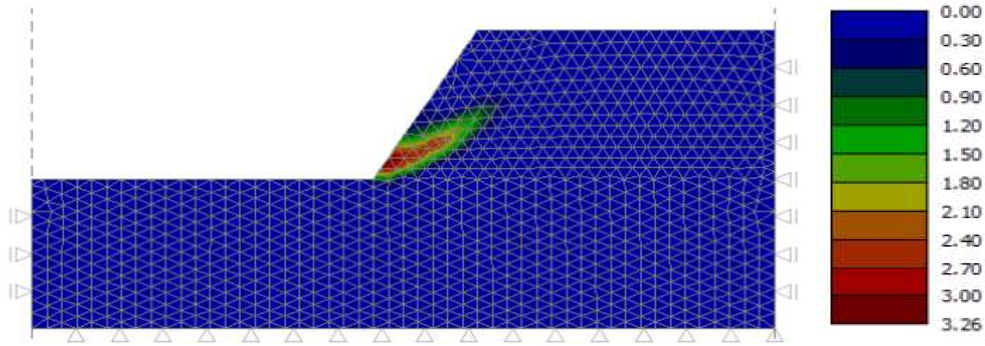

Figure10: Contours of the equivalent plastic strain for a slope of homogeneous soil (β =60°) by FEM

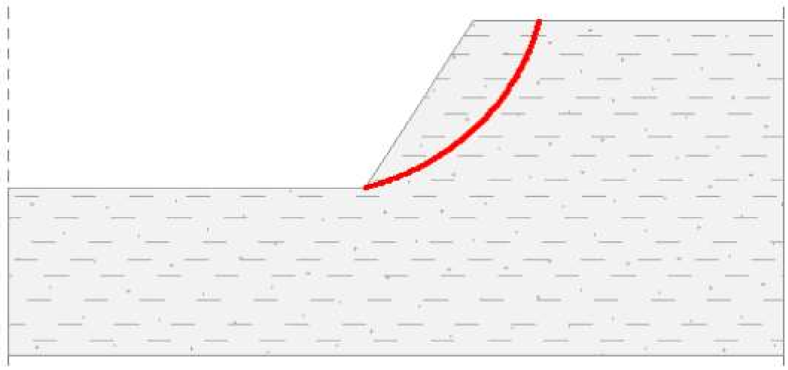

Figure11: Failure of a slope of homogeneous soil (β =60°) using LEM

4.2 Slope of layered soil

In this study, numerical analyses were performed for different cases of layered soil using both the FEM and LEM. A soil layerof 2 m height (t) wasvaried from the top of slope to the foundation layer of slope and the variation of factor of safety wascomputed in every cases. Here, three different types of slope angles of 30°, 45° and 60°were considered as well.Figure12 depicts the effect of the variation of 2 m soil layer on the factor of safety of slope for various slope angles.

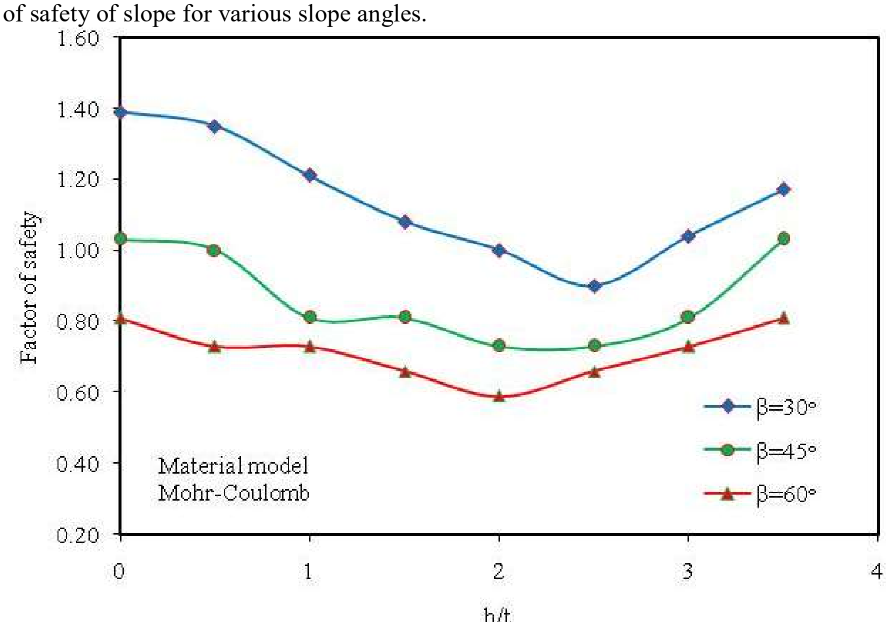

Figure12: Effect of variation of soil layer on the factor of safety of slope for Mohr-Coulomb model by FEM

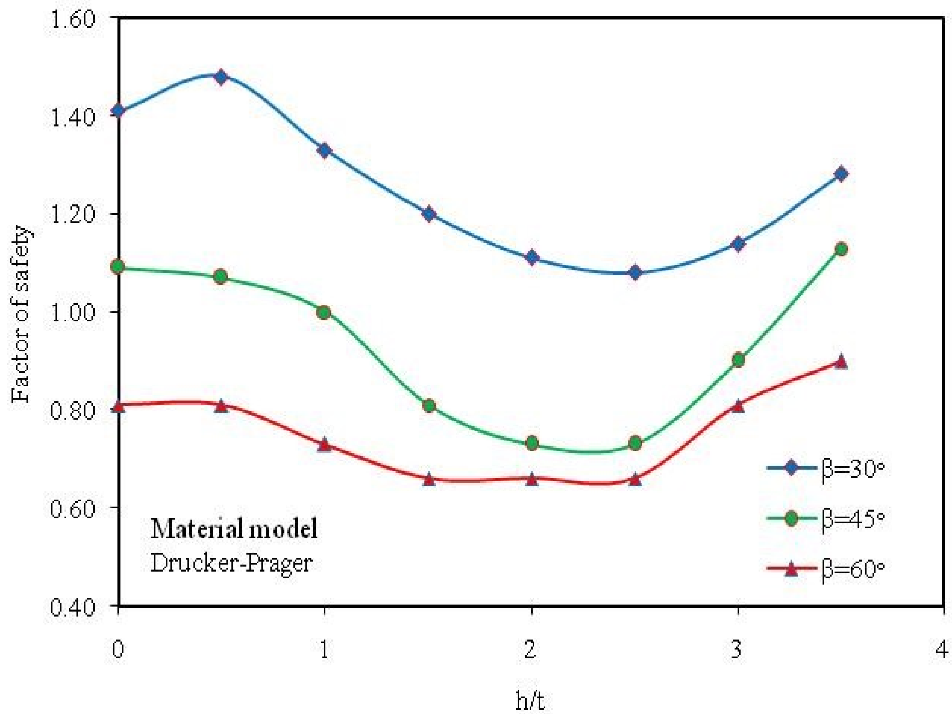

Figure13: Effect of variation of soil layer on the factor of safety of slope for Drucker-Prager model by FEM

Figure 13 indicates that factor of safety decreases with the increasing of h/tratio up to a certain level and beyond that level, the factor of safety starts increasing again. The tendency is similar regardless of the slope angles and materials models (Figures 12 and 13). So, it can be concluded that the minimum factor of safety is obtained when a relatively weak soil layer is situated near the base of the slope height ($h/t = 2 - 3$).

Figure 14 shows the comparison of the FEM results with LEM for a slope angle of 45°. As expected, LEM results are very close to FEM indicating the perfectness of the FEM results. Figure15 shows the contours of the equivalent plastic strain for layered soil with a slope angle of 30° by FEM when the ratio of $h/t = 0$ while Figure16 presents the failure of a layered soil with a slope angle of 30° by LEM when the ratio of$h/t = 0$. When the weak soil layer is located at the top of the slope, the slip surface passes through the toe of the slope. Again, Figure17 shows the contours of the equivalent plastic strain for layered soil with a slope angle of 30° by FEM when the ratio ofh/t =3 while Figure18 presents the failure of a layered soil with a slope angle of 30° by LEM when the ratio ofh/t =3. When the weak soil layer is located at the foundation layer of the slope, slip surfaces pass through the foundation layer and base failure of the slope is occurred for both FEM and LEM.

Figure19 shows the contours of the equivalent plastic strain for a slope of layered soil by FEM (β =45°, $h/t = 2$) while Figure20 presents the failure of a slope of layered soil using LEM (β =45°, $h/t = 2$). The figures shows that the contours of equivalent plastic strain (slip surface) are located at the weak soil layer for FEM but for LEM, slip surface starts from the top of the slope and passes through the toe of the slope. Also slip surfaces obtained from LEM are localized deeper than FEM for a layered soil of slope angle 45°.

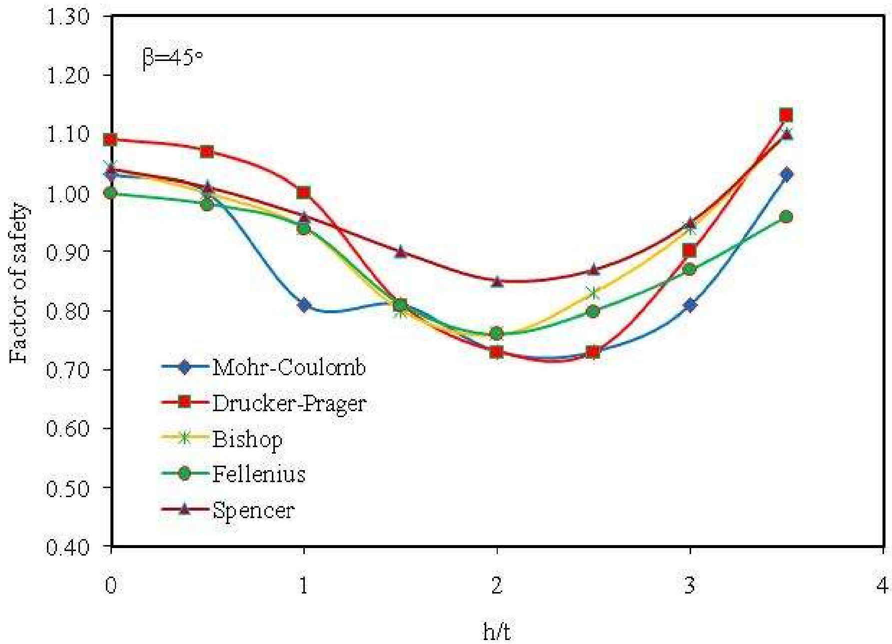

Figure14: Comparison of the factor of safety of slope for layered soil with a slope angle of 45° by LEM and FEM

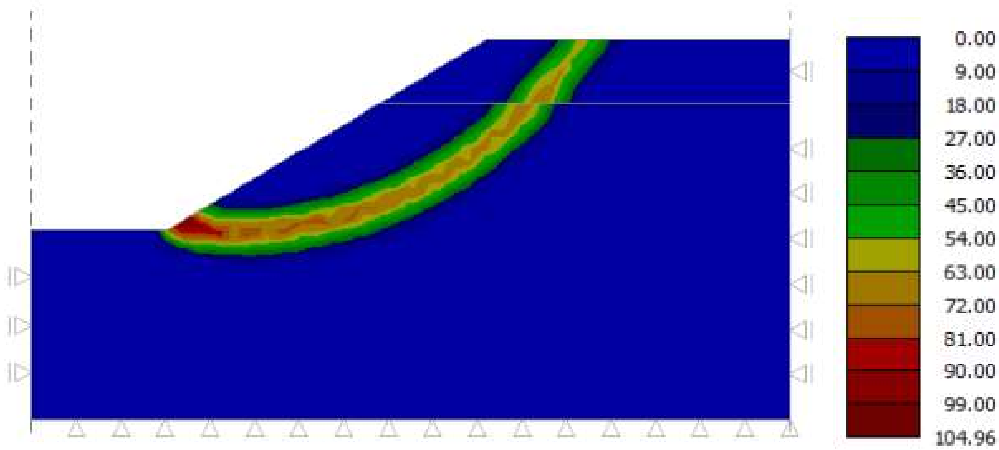

Figure15: Contours of the equivalent plastic strain for slope of layered soil by FEM (β =30°, $h/t = 0$)

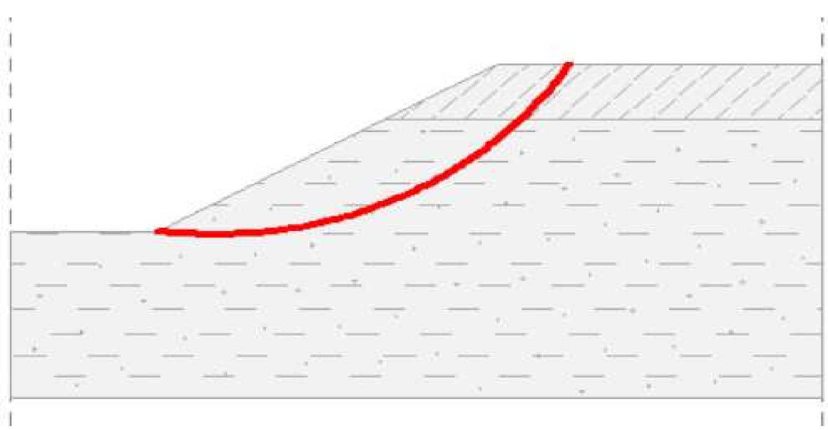

Figure16: Failure of a slope of layered soil by LEM (β =30°, $h/t = 0$)

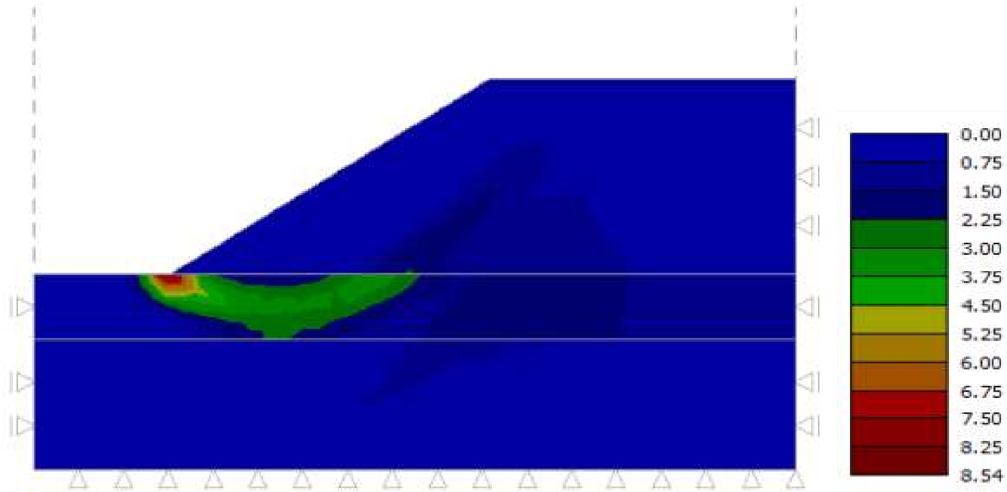

Figure17: Contours of the equivalent plastic strain for slope of layered soil by FEM (β =30°, $h/t = 3$)

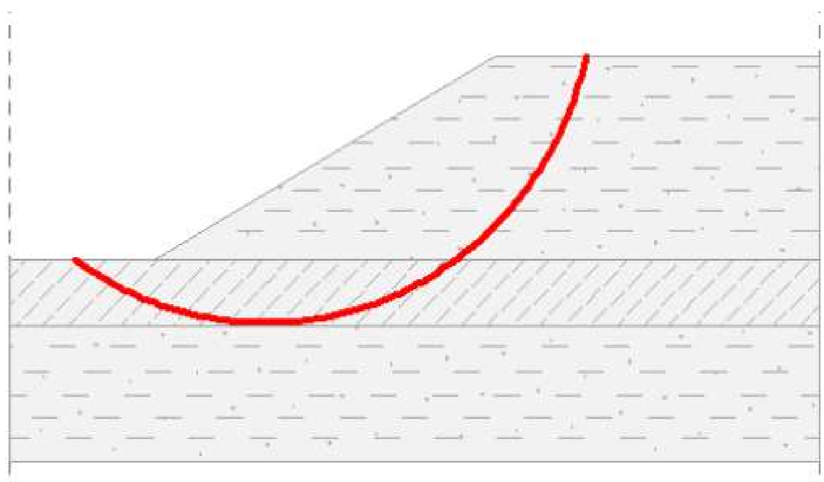

Figure18: Failure of a slope of layered soil by LEM (β =30°, $h/t = 3$)

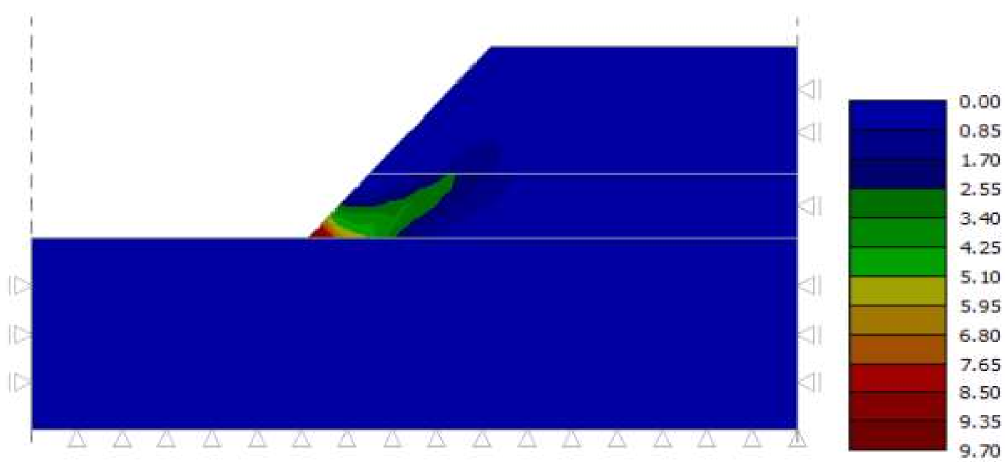

Figure19: Contours of the equivalent plastic strain for slope of layered soil by FEM (β =45°, $h/t = 2$)

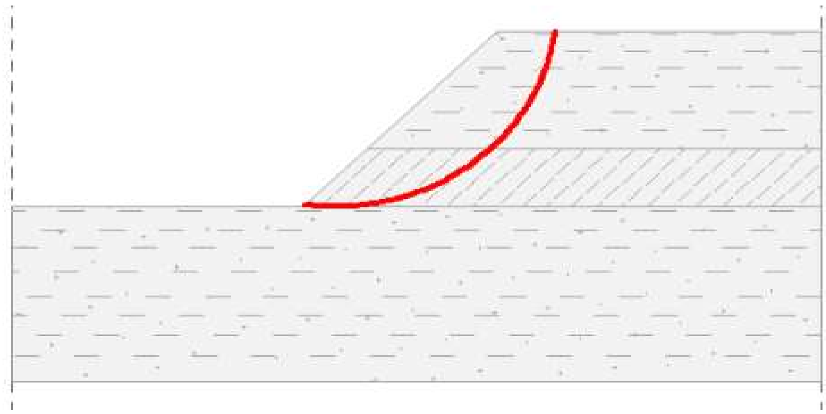

Figure20: Failure of a slope of layered soil by LEM (β =45°, $h/t = 2$)

5. CONCLUSION

A numerical investigation was carried out to compare the FEM results with LEM for slopes of homogeneous and layered soils and to study the effect of layered soil on the stability of slope both by the LEM and FEM. The major findings of the study are as follows:

i. The factor of safety computed by Fellenius method (Fellenius, 1936)gives a bit lower valuescompared to that of Bishop (Bishop 1955) and Spencer methods(Spencer 1967)irrespective of slope angles for both the slopes of homogeneous and layered soil.
ii. Factor of safety computed by FEM depicts the higher values than that of LEM and the factor of safety considering the Mohr-Coulomb model depicts lower value than that of Drucker-Prager model irrespective of slope angle for both the slopes of homogeneous and layered soil.
iii. The factor of safety of the slope of layered soil decreases in relation to the increasing of distance of a thin soil layer from the top of the slope to layer thickness ratio (h/t) up to a certain value and beyond that, the factor of safety increases again.
iv. The minimum factor of safety is obtained when a relatively weak soil layer is situated near the base of the slope height ($h/t = 2 - 3$).
v. FEM depicts deeper localization of slip surface than LEM for a slope of homogeneous soil; however,for a slope of layered soil, LEM depicts deeper localization of slip surface than FEM.
vi. When the weak soil layer is located at the top of the slope, the slip surface passes through the toe of the slope. On the other hand, when the weak soil layer is located at the foundation layer of the slope, slip surfaces pass through the foundation layer and base failure of the slope is occurred for both FEM and LEM

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