# Study on the Failure Pattern of Layered Soil using Finite Element Method

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**ABSTRACT:** In geotechnical engineering, it has always been a tough yet herculean task and also a subject of concern to carry out the stability analysis of slopes, since numerous failures of slopes and large settlements have been taking place causing a huge destruction of property and life. In this paper, various non-homogenous soil slopes with different layers of soil have been considered. A rigorous limit equilibrium method of slices i.e. Morgenstern-Price method is used to analyse the stability of the slope. Finite element shear strength reduction technique is also used for displacement calculations and comparison with limit equilibrium method. The soil parameters (c and φ) were kept as constants in each soil model. Thus, considering different slope angles of the soil mass, the Factor of Safety for each slope, pattern of formation of the slip surfaces along with the vertical, horizontal and total displacement has been studied.

**KEYWORDS:** Non-homogenous slope, Mohr-Coulomb failure, Finite element method, Factor of safety, Critical failure surface.

## 1. INTRODUCTION

In geotechnical engineering, stability analysis of slopes has always been a tough yet herculean task and also a subject of concern, since numerous numbers of slope failures and large settlements have been taking place causing destruction of property and life very severely. Slopes may be artificial (man-made), such as cuttings and embankments, earth dams, landscaping operations, etc. There may also exist natural slopes such as hillside and valleys, river cliffs, etc. There is a diverse amount of engineering structures which require the foundations to be placed near an existing slope; hence the slopes must be protected and prevented from any kind of failure. For the assessment of the stability of slopes, Limit Equilibrium Method (LEM) has been one of the most consecutively used techniques. However, through LEM, proper and accurate results cannot be guaranteed and a number of arbitrary assumptions are needed to be made before the analyses are done and thus the results obtained are not very accurate. To overcome such limitations, Finite Element Method (FEM) has been used in this paper, which is another well-known approach for the analyses of slopes. In FEM, the necessities of advanced assumptions have been eliminated.

Many researchers have carried out different type of studies and analyses of homogenous as well as non-homogenous soils using different methods. The most commonly adopted methods by most of the researchers to model non-homogeneity with a soil mass are Spencer (1967) method and Morgenstern and Price (1965) method. Fredlund and Krahn (1977) adopted various methods to perform slope stability analysis for non-homogenous soil using LEM. Griffith and Lane (1999) adopted finite element technique to various homogenous and non-homogenous soil slope. Kumar and Samui (2006) computed the stability number of layered soil slopes using Upper Bound (UB) limit analysis where they included the pore water pressure effects and earthquake forces. Sazzad and Moni (2015) carried out stability analysis of slopes for homogenous and layered soil using FEM and LEM and compared their results with each other. Mohr-coulomb model and Drucker-Prager model were considered by them to compute the Factor of Safety (FOS) for each slope. They found that FOS of layered soil slope in a decreasing trend with increase in h/t ratio up to a definite value and then, the FOS increased again. When the weak or fragile soil layer was situated near to the base of the slope, the FOS was observed to be minimum. Qian et. al. (2015) proposed some stability charts for a two-layered soil slope using purely cohesive soil by FEM. Sazzad et. al. (2015) carried out seismic slope stability analysis of homogenous and layered soil using LEM. For both the slopes of homogenous and layered soil, they found that after escalating the horizontal seismic co-efficient, the FOS decreased. They also discovered that the joint effect of vertical and horizontal seismic co-efficient was less severe than the solo effect of horizontal seismic co-efficient. They also reported that the failure surface extends beyond the top layer of soil to the fragile layer when a strong layer of soil is located above a fragile or weak layer of soil. Chatterjee and Krishna (2018) carried out stability analysis of a two-layered non-homogenous slope under different conditions of load applications. A model was prepared using silty clay at the top layer of the slope and silty sand at the bottom layer. Water table and pseudo static earthquake force has also been taken into account. They observed that the silty clay soil made the two-layered slope more firm and stable by imparting strength to it. Moreover, they also observed that the failure of shallow slope parallel to slope surface occurred for slopes with sandy soil, whereas, deeper slope failure occurred for clay soil. Zhou et. al. (2019) carried out stability analysis of a layered soil slope and computed the FOS based on random field theory and compared it with horizontal integration. Chatterjee and Krishna (2019) carried out stability analysis of a two-layered non-homogenous slope using FEM and LEM. They considered three different soils and prepared a soil model incorporating two layers with coarse-grained and fine-grained soil to understand the behaviour of non-homogenous soil. They made different arrangements of all the soil types and prepared different soil models. They found that the soil 3 model which was a fine-grained soil and was obtained from literature was unstable and susceptible to failure. Translational failure type was observed in slopes of coarse-grained soil, whereas, for slopes with fine-grained soil, rotational type of failure was observed. Different researchers considered non-homogeneity in soil slope in different ways. Some of the researchers studied the effect of variation of cohesion with depth (Koppula, 1984); some showed the effects of drawdown, tension cracks in layered soil (Hammouri et al., 2008). The application of genetic algorithm on non-homogenous slopes have found to be very advantageous in searching the critical slip surface with varying parameters like population size, number of generations and crossover probability (Sabhahit and Rao, 2013).

The key purpose of this paper is to study the performance of the soil slopes using a series of FEM and LEM models and analysing them to know about the failure surfaces and displacement. Here, non-homogenous or layered soil has been considered and variation of the weak or fragile layer along the height of the slope has been studied. This will help in understanding the behaviour of the failure surface and the type of failure that will occur in the slope.

## 2. METHODOLOGY

A number of methods are available for stability analysis of soil slopes and each of the methods are having some advantages and disadvantages of their own. LEM gives the factor of safety of slope and the position of critical slip surface but failed to give the information on deformations occurring within the soil slope. To overcome this, FEM is also selected for this study. A model (Figure 1) has been developed to represent the non-homogenous soil slope using GeoStudio and Plaxis software. Soil 1 is having high plasticity while soil 2 is non-plastic in nature. The slope angle, β is taken as 30° and the slope height is 20 m. The Mohr-Coulomb failure criterion and plane strain condition is used for developing the soil model. Undrained parameters are selected for shear strength parameters for soil 1 while drained parameters are selected for soil 2. Young's modulus value for the two soils are taken as 5000 kN/m$^2$ while the Poisson's ratio is taken as 0.35 for soil 1 and 0.3 for soil 2. Unit weight of soil 1 is taken as 16 kN/m$^2$ while for soil 2 it is taken as 17 kN/m$^2$. Cohesion values for soil 1 and 2 is 45 kN/m$^2$ and 5 kN/m$^2$, respectively. Friction angle values are 20° and 31° respectively. A small layer of soil has been considered from the top of the slope up to a certain depth which is considered as the strong or well-built layer and is represented by d. β represents the slope angle. Another small layer which is sandwiched between the two strong layers and is considered as the weak or fragile layer is represented by t and is shown in the Figure 1. The strong and weak layer is differentiated based on the cohesion of soil slope.

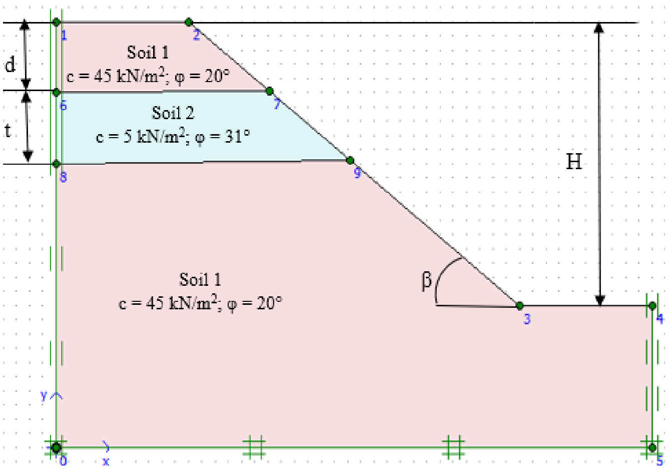


Figure 1 Geometry for a slope of non-homogenous soil

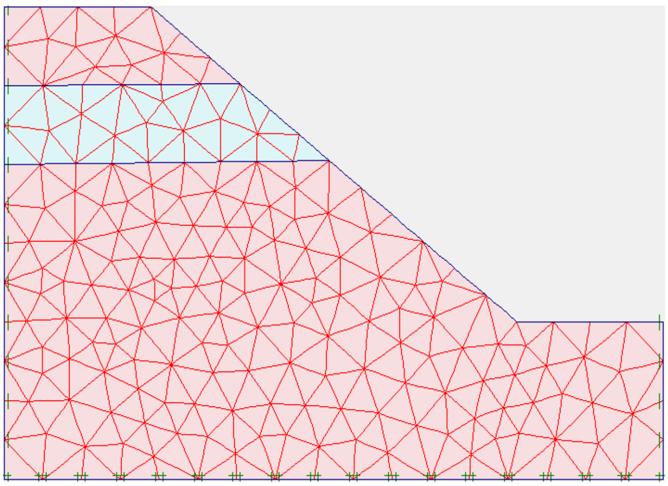

Figure 2 Geometry and mesh for a slope of non-homogenous soil

The height of the weak layer is kept constant and its position is varied along the depth of the soil slope. The mesh is then generated considering fine global coarseness with 15 nodal elements as shown in Figure 2. The water table is considered to be at the base of the soil slope. The safety factor or strength reduction factor (SRF) is calculated using FEM by varying the d/t ratio as shown in Table 1. To know the position of the critical slip surface, the slopes are analysed again for different cases shown in Table 1 using a rigorous LEM of slices i.e. Morgenstern-price method. The slip surface is developed by considering entry and exit method in the direction of left to right.

Table 1 Variation of d/t ratio

| d/t ratios | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| d (m) | 0 | 5 | 10 | 15 | 20 |

## 3. RESULTS AND DISCUSSION

The slope has been analysed using two different approaches, their results and comparisons are shown in Table 2.

Table 2 FOS values by using LEM and FEM

| d/t ratios | | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| FOS | LEM | 1.525 | 1.180 | 1.125 | 1.110 | 1.105 |
| | FEM | 1.478 | 1.140 | 1.086 | 1.075 | 1.066 |

Upon increasing the values of d/t ratios i.e., as the weak layer goes down the slope, the FOS and the strength reduction factor (SRF) decreases. The model outputs obtained by FEM and LEM are superimposed to study the variation of critical slip surface with the total displacement contours occurring within the soil slope. One such example is shown in Figure 3.

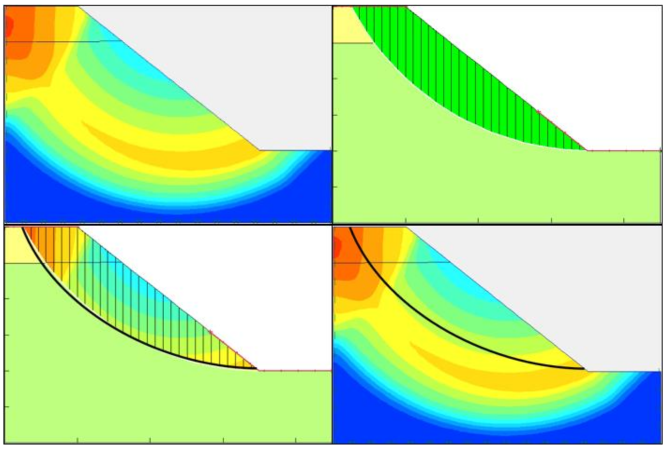

Figure 3 Superposition of FEM and LEM models for d/t = 0

The total displacement contours and the critical slip surface from LEM for the different values of d/t ratio are developed in a similar pattern and shown in Figures 4 (a), (b), (c) and (d).

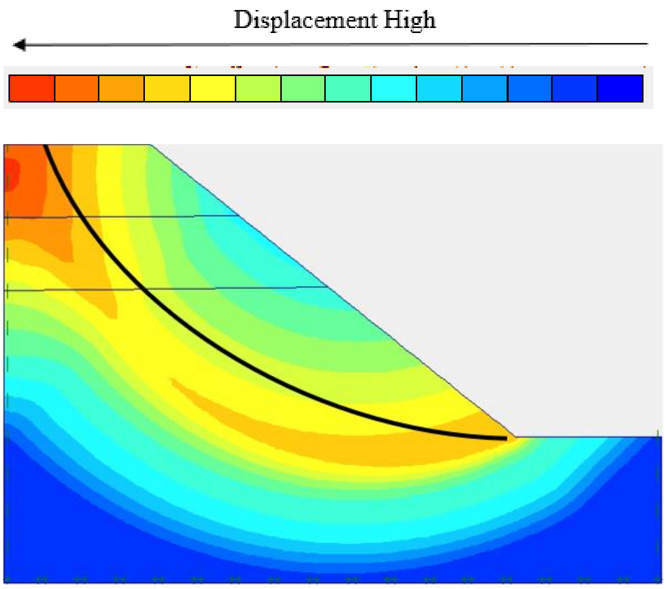


Figure 4 (a) Slip surface developed for d/t = 1.0

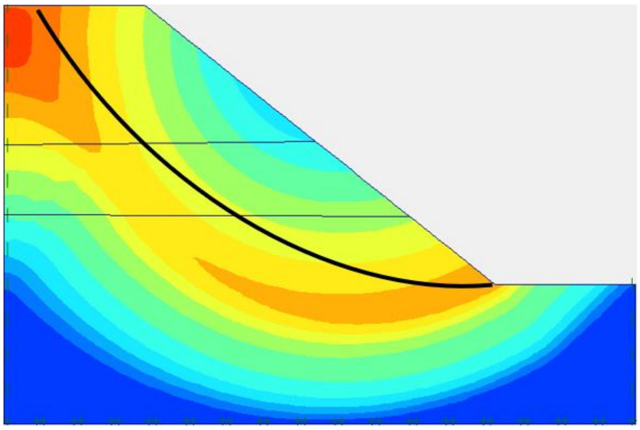

Figure 4 (b) Slip surface developed for d/t = 2.0

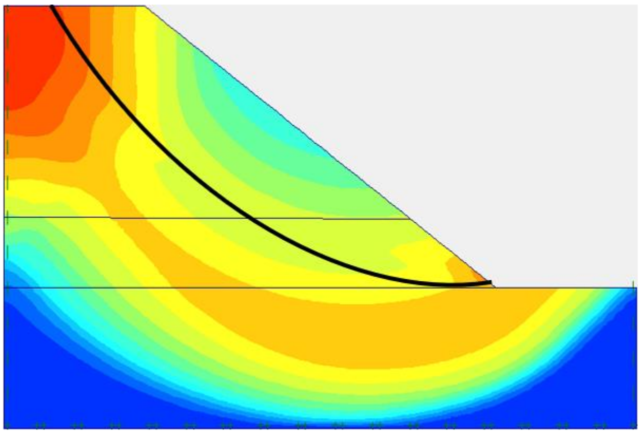

Figure 4 (c) Slip surface developed for d/t = 3.0

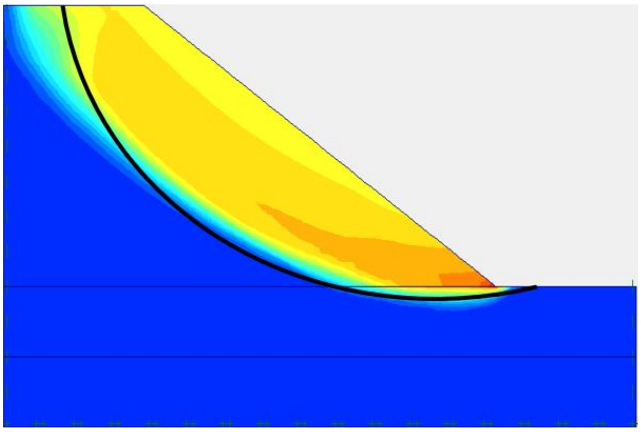

Figure 4 (d) Slip surface developed for d/t = 4.0

It is seen from the above figures that the total displacement increases upto d/t = 3.0 and thereafter, it decreases. The maximum displacement is 569.25 mm. It is seen that, the zone of failure increases and is seen spreading outwards upto d/t = 3.0 and becomes parallel to the slope while the slip surface obtained from LEM is small and is mainly confined to the toe region. It is also seen that for d/t = 4.0, the total displacement contour nearly coincides with the critical slip surface obtained from LEM. For this height, the maximum displacement is 110.25 mm.

The position of weak layer can be used to study the failure pattern of the soil slope. It is seen that as the weak layer goes down the slope, there is likely to change in the failure pattern from toe failure to base failure. Moreover, the horizontal, vertical and total displacement for each slope is studied and their values are compared with different slope angles for different d/t ratios. It is also seen that as the slope angle increases, the total displacement increases. Similar trend is observed in both the cases of horizontal and vertical displacement.

Case I: For d/t= 0

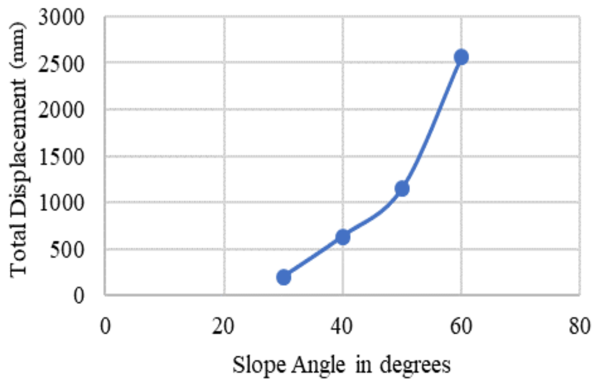


Figure 5 (a) Variation of total displacement with the slope angles for d/t = 0

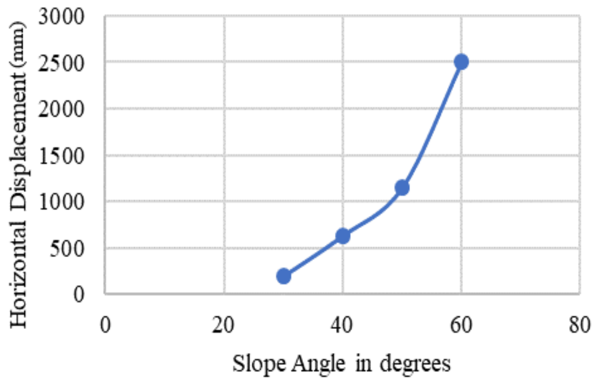


Figure 5 (b) Variation of horizontal displacement with the slope angles for d/t = 0

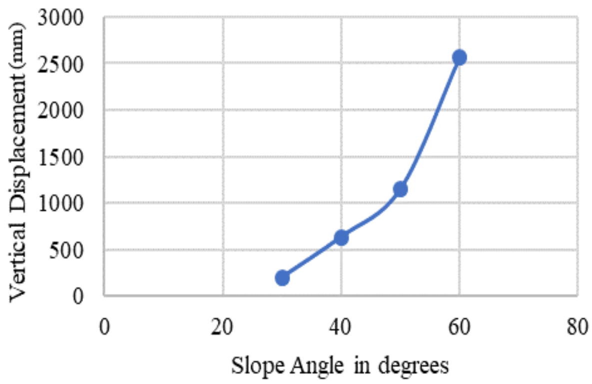


Figure 5 (c) Variation of total displacement with the slope angles for d/t = 0

In case I, d/t = 0 (Figures 5 (a), (b) and (c)) implies that the weak layer of soil is at the top of the slope. The total displacement along the slope ranges from 198.35 mm to 2570 mm, horizontal displacement ranges from 195.23 mm to 2500 mm and vertical displacement ranges from 198.22 mm to 2570 mm. It was also observed that maximum displacement occurred when the slope angle was 30° and for 60° slope angle, minimum displacement occurred. Therefore, the percentage increase for total displacement was found to be 92% when the slope angle increases from 30° to 60°. Similarly, for horizontal and vertical displacement the percentage increase was found to be above 90%.

Case II: For d/t= 1.0

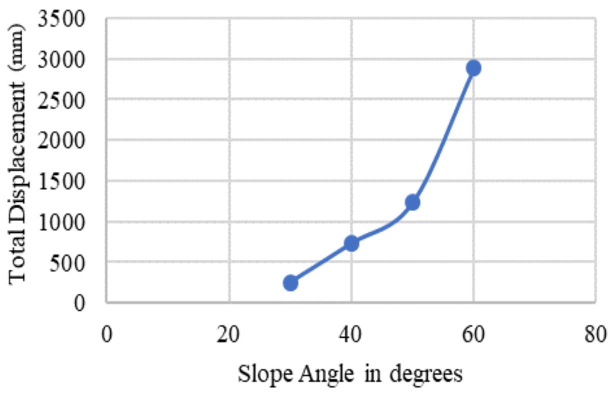


Figure 6 (a) Variation of total displacement with the slope angles for d/t = 1.0

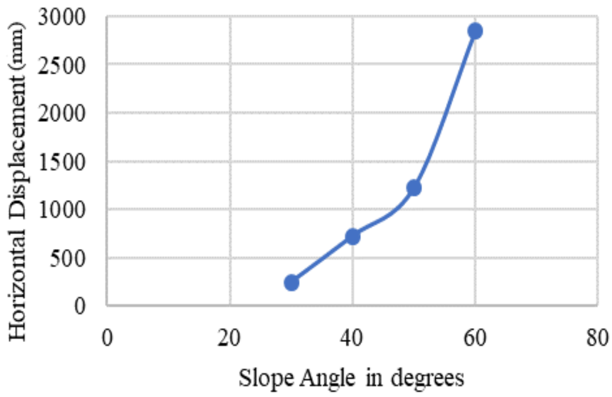


Figure 6 (b) Variation of horizontal displacement with the slope angles for d/t = 1.0

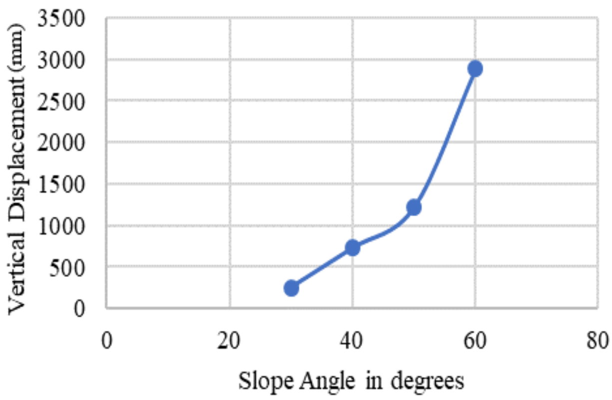


Figure 6 (c) Variation of total displacement with the slope angles for d/t = 1.0

In case II, d/t = 1.0 (Figure 6 (a), (b) and (c)) implies that the weak layer of soil moved somewhat downwards the slope. The total displacement along the slope ranges from 254.23 mm to 2890 mm, horizontal displacement ranges from 245.32 mm to 2850 mm and vertical displacement ranges from 253.25 mm to 2890 mm. It was again found that when the slope inclination increases from 30° to 60°, the percentage increase for total displacement was found to be 91%. Similarly, the percentage increase was found to be above 90% for both horizontal and vertical displacement.

Case III: For d/t= 2.0

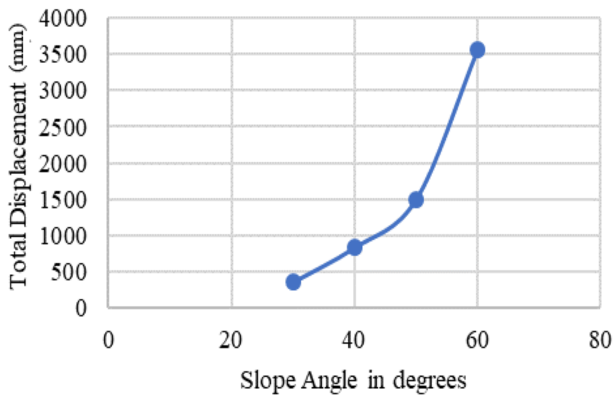


Figure 7 (a) Variation of total displacement with the slope angles for d/t = 2.0

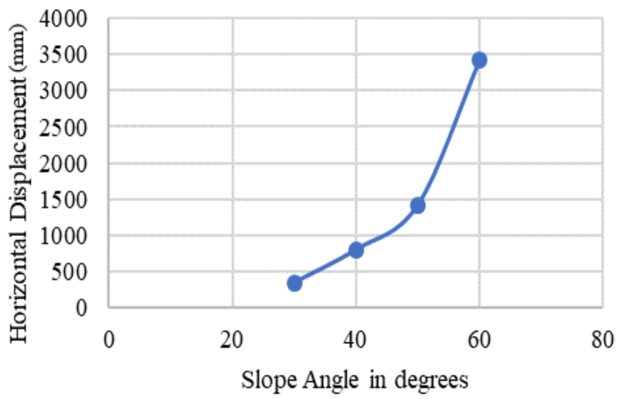


Figure 7 (b) Variation of horizontal displacement with the slope angles for d/t = 2.0

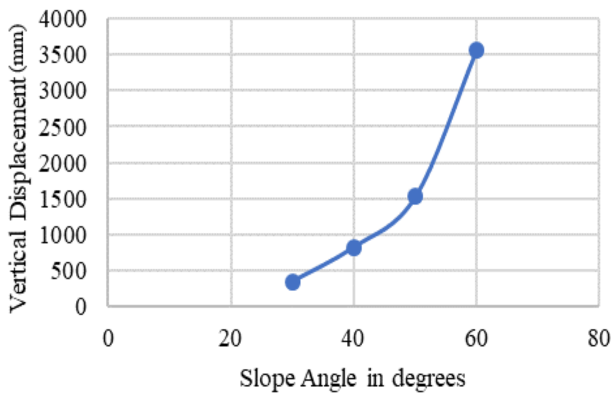


Figure 7 (c) Variation of vertical displacement with the slope angles for d/t = 2.0

In case III, d/t = 2.0 (Figure 7 (a), (b) and (c)) implies that the weak layer of soil is at the middle of the slope. The total displacement along the slope ranges from 354.25 mm to 3570 mm, horizontal displacement ranges from 350.35 mm to 3425 mm and vertical displacement ranges from 350.78 mm to 3570 mm. Thus, the percentage increase for total displacement was found to be 90% when there is an increase in the slope angle from 30° to 60°. Similarly, for horizontal and vertical displacement the percentage increase was found to be above 85%.

Case IV: For d/t = 3.0

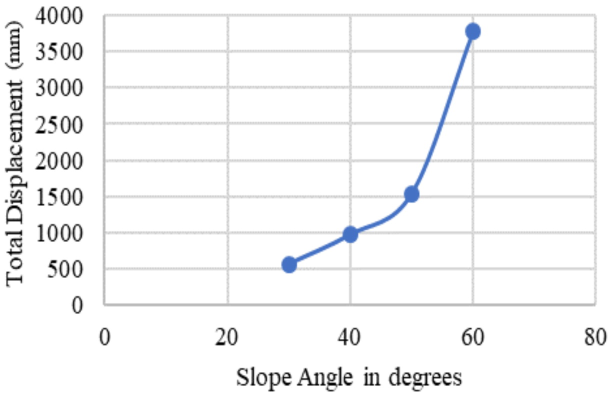


Figure 8 (a) Variation of total displacement with the slope angles for d/t = 3.0

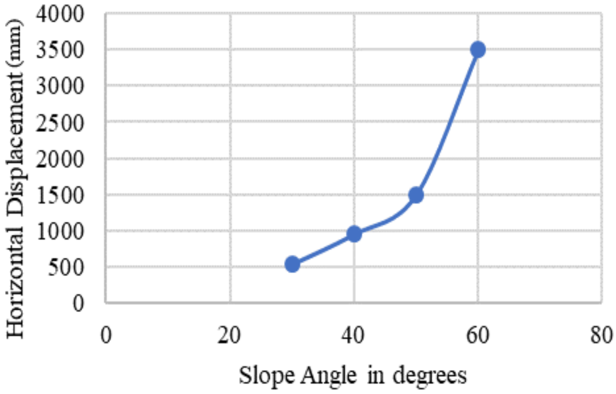


Figure 8 (b) Variation of horizontal displacement with the slope angles for d/t = 3.0

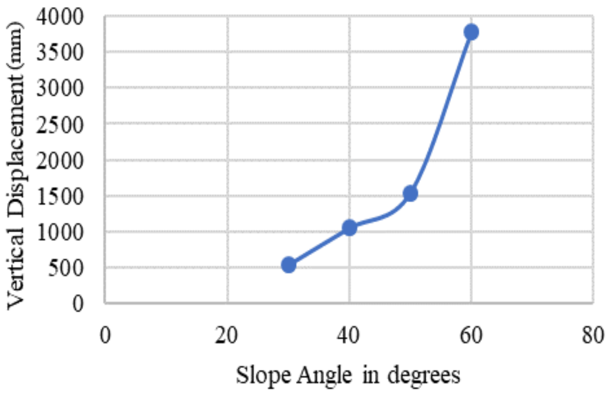


Figure 8 (c) Variation of vertical displacement with the slope angles for d/t = 3.0

In case IV, d/t = 3.0 (Figures 8 (a), (b) and (c)) implies that the weak layer of soil is somewhat at the bottom of the slope. The total displacement along the slope ranges from 569.25 mm to 3780 mm, horizontal displacement ranges from 537.24 mm to 3500 mm and vertical displacement ranges from 534.25 mm to 3780 mm. Therefore, the percentage increase for total displacement was found to be 85% when the slope angle increases from 30° to 60°. Similarly, for horizontal and vertical displacement the percentage increase was found to be above 80%.

Case V: For d/t= 4.0

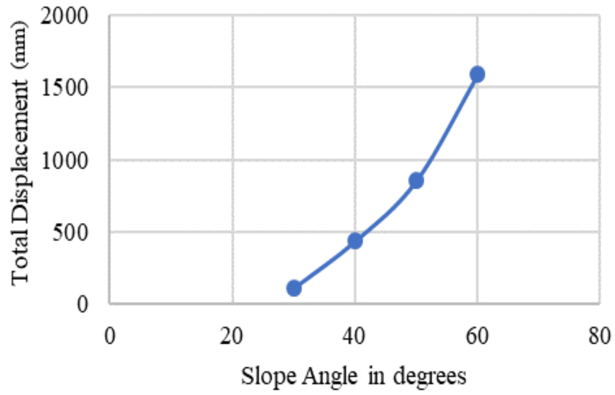


Figure 9 (a) Variation of total displacement with the slope angles for d/t = 4.0

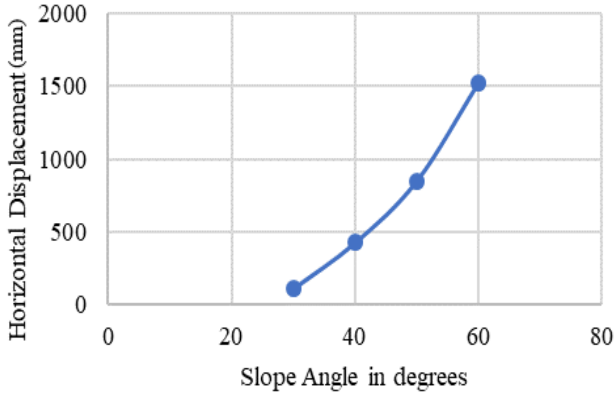


Figure 9 (b) Variation of horizontal displacement with the slope angles for d/t = 4.0

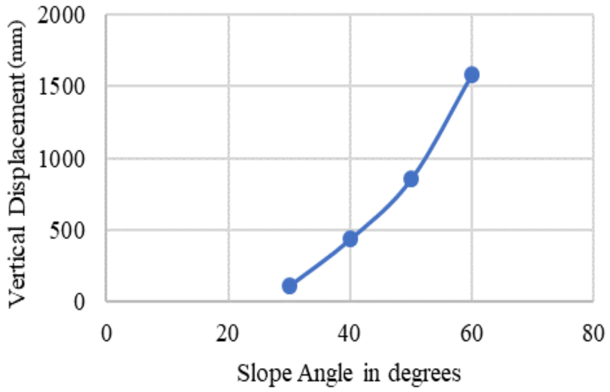


Figure 9 (c) Variation of vertical displacement with the slope angles for d/t = 4.0

In case V, d/t = 4.0 (Figures 9 (a), (b) and (c)) implies that the weak layer of soil is at the bottom of the slope. The total displacement along the slope ranges from 110.25 mm to 1587 mm, horizontal displacement ranges from 109.25 mm to 1525 mm and vertical displacement ranges from 110 mm to 1582.75 mm. Further, it was found that when the slope inclination increases from 30° to 60°, the percentage increase for total displacement was found to be 93%. Similarly, the percentage increase was found to be above 90% for both horizontal and vertical displacement.

## 4. CONCLUSIONS

Using FEM and LEM, a proper numerical analysis of a layered or non-homogenous soil slope for different slope angles is carried out and the FOS for each slope angle is calculated. The variation of the fragile layer with depth including the displacements along the slope is studied to know the behaviour of the slip surface. Upon increasing the values of d/t ratios i.e., as the weak layer goes down the slope, the FOS and the strength reduction factor (SRF) decreases. The model outputs obtained by FEM and LEM are super-imposed to study the variation of critical slip surface with the total displacement contours occurring within the soil slope. The total displacement increases upto d/t = 3.0 and thereafter, it decreases. The maximum displacement is obtained for d/t = 3. With the increase in d/t ratio, the zone of failure increases and is seen spreading outwards. However, the total displacement contour nearly coincides with the critical slip surface for d/t = 4.0. The total displacement, horizontal displacement and vertical displacement show an increasing trend with the increase in the slope angle. 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.

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