STABILITY ANALYSIS OF NON-HOMOGENEOUS SOIL SLOPES USING NUMERICAL TECHNIQUES

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ABSTRACT: This paper presents the stability analyses of non-homogeneous slopes under different loading conditions. A non-homogeneous soil slope with two different soil layers is considered. Special cases are created, varying the height of the layers, to account for the non-homogeneity of the earth slope. A water table is considered in this study to account for the seepage forces. Pseudo-static earthquake force is considered, taking into account both the forces in the horizontal and vertical directions. A rigorous limit equilibrium method of slices i.e. Morgenstern-Price method is used to analyze the stability of the slope. Finite element shear strength reduction technique is also used for displacement calculations and comparison with limit equilibrium method. Safety factor, critical slip surfaces and displacements with different loading conditions are studied and compared.

Keywords: Numerical model, non-homogeneous slope, displacements, critical surface

1 INTRODUCTION

Slope stability is a major area of concern for practicing engineers for filled slopes or cut slopes. Factor of safety is an important parameter in stability evaluation of slopes but the total displacements occurring can give a better idea about the zone of failure. Position of critical slip surface evaluation is another important issue in slope stability. Slopes can be man-made or natural and many external natural forces act on these earth structures making it vulnerable to failure. Out of these external forces, the effects of hydrology and seismicity are the most common. Rainfall affects the stability of slopes in numerous ways like the increase in height of water table in an area due to heavy downpour or the formation of phreatic line. In high seismic zones slopes suffer greater dynamic loadings which may eventually lead to instability. Varying soil properties make the slope non-homogeneous in nature. Many studies are available in literature like the effect of variation of cohesion with depth has been investigated by Koppula (1984). Kim et al. (2002) compared stability of complex soil slopes using upper bound and lower bound limit analysis. Hammouri et al. (2008) studied stability of layered slopes and showed effects of drawdown, tension crack and undrained clay soils. Qian et al. (2015) proposed stability charts for two-layered cohesive slopes. This paper deals with a two-layered non-homogeneous slope whose layer height is varied, water table is introduced, pseudo-static forces are applied and then the stability of the slope is evaluated.

2 METHODOLOGY

Various methods are available for stability determination of earth slopes, they have their own advantages and limitations. Limit equilibrium method gives the factor of safety of slope and position of critical slip surface. It doesn't give information on deformations occurring within the slope so to overcome this, finite element method is selected as well.

2.1 Limit Equilibrium Method

It is a statically indeterminate method, hence for the solution; some assumptions are required to make it determinate. Therefore, anon-circular failure surface is assumed and the soil mass is divided into a number of slices and each slice is checked for equilibrium of forces and moments. Figure 1 depicts the various forces acting on a typical slice.

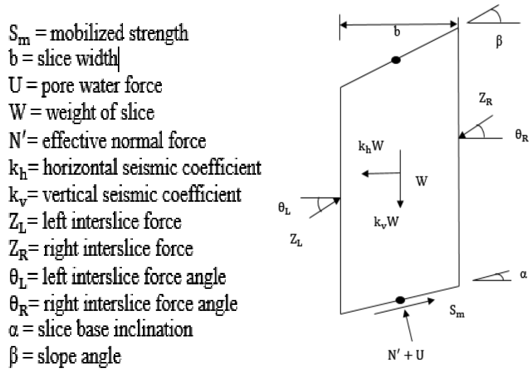

Fig.1 Slice representing various forces

Depending upon the type of equilibrium satisfied, various methods are formulated for the factor of safety of slope such as ordinary method of slices (Fellenius, 1936), Bishop's Simplified method (Bishop 1955) and Janbu's generalized method of slices (Janbu 1968). Complete equilibrium is followed by Spencer (1967) and Morgenstern and Price (1965) methods. Then a search procedure is used to find the critical slip surface giving the minimum factor of safety of the slope. Morgenstern and Price (1965) method with a half sine function has been used throughout this study. Circular slip surface is assumed for homogeneous profiles while non-circular is taken for non-homogeneous profiles. The number of slices is fixed at 20 while the tolerance is taken to be 0.005.

2.2 Finite Element Method

Zienkiewicz et al. (1975) studied c-ϕ slopes using the finite element method showing good comparison with slip circle results. With more use and confidence gained, researchers like Matsui and San (1992), Ugai and Leshchinsky (1995), Griffiths and Lane (1999) and Cheng et al. (2007) used it for stability analysis of slopes. The safety factor, *F* is defined as the factor by which the strength parameters need to be reduced to bring the slope to a failure point.

$$c_f' = \frac{c'}{F} \quad (1)$$

$$\tan\phi_f' = \frac{\tan\phi'}{F} \quad (2)$$

This method is known as the shear strength reduction technique. Here failure is taken as that point where the solutions fail to converge within a specified number of iterations. The stress distribution fails which implies that the Mohr-Coulomb failure criterion and the global equilibrium is not satisfied. Failure of slopes is accompanied by a sudden rise of displacements.

3 DEVELOPMENT OF NUMERICAL MODEL

A numerical model (Figure 2) has been developed in to represent the homogeneous and nonhomogeneous slope in Rocscience software suite using Phase and Slide modules (Rocscience, 2016). Soil-1 is silty clay while soil-2 is silty sand in nature. The slope angle is taken as 2:1 (H:V) and the slope height is 20m and depth factor *D* is 2. The Mohr-Coulomb failure criterion is used for modelling the soils. Drained values are selected for shear strength parameters of the two soils. Young's modulus value for the two soils are taken as 5MPa while the Poisson's ratio is 0.3. Total unit weight of 16 kN/m^3 is applied to the layered soil model. Cohesion values for soil-1 and 2 is 10kPa and 0kPa, respectively. Friction angle values are 30º and 36º, respectively. The permeability values of the two soils are 4×10^{-7}m/s and 8.2×10^{-6}m/s, respectively.

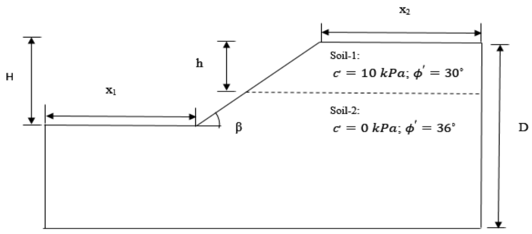

Fig.2 Non-homogeneous slope model

Stability of slopes being an unconfined problem, the selection of the dilation angle doesn't make much of a difference in the analysis (Griffiths and Lane, 1999). A non-associated flow rule has been used throughout this study. The soil model consists of 2700 uniform triangular 6-noded elements and 5500 nodes. The height of the top layer is varied from zero to total depth, *DH*. In essence the first and the last case becomes a homogeneous slope with either of the soil layers. Table 1 shows the variation of the layer height. The *h* values shown in table represent the depth of layer from the ground surface. When the ratio is increasing the soil in the upper region is actually forming the major portion of the slope. A pseudo-static seismic coefficient of 0.2 is taken representing violent earthquakes. Both horizontal and vertical pseudo-static acceleration are taken equal as suggested by Shukha and Baker (2007). A water table is introduced and classified as case-2 while the other case i.e., case-1 is free of pseudo-static force and water table.

Table 1 Variation of *h*/*D* ratio

h/D	0	0.2	0.4	0.6	0.8	1
h (m)	0	8	16	24	32	40

4 RESULTS

The slope has been analyzed using two different approaches, their results and comparison is shown in Tables2 and 3 for homogeneous and non-homogeneous cases, respectively. Difference in safety factor values between the two methods range from 0.19-12.45% for the non-homogeneous slopes.

Table 2 Homogeneous slope with two different soils

Slope Model	Factor of Safety					
	LEM		FEM		Difference (%)	
	Case-1	Case -2	Case -1	Case -2	Case -1	Case-2
Soil-1 h=D	1.687	1.114	1.68	1.05	0.41	5.74
Soil-2 h=0D	1.453	0.999	1.48	0.98	1.85	1.90

Table 3 Non-homogeneous slope with two soil layers

Layer Height	Factor of Safety					
	LEM		FEM		Difference(%)	
	Case-1	Case-2	Case-1	Case-2	Case-1	Case-2
h=0.2D	1.478	1.018	1.55	1.02	4.87	0.19
h=0.4D	1.578	1.088	1.64	1.05	3.92	3.49
h=0.6D	1.736	1.188	1.68	1.05	3.22	11.61
h=0.8D	1.736	1.188	1.68	1.05	3.22	11.61

The factor of safety increases with layer height and becomes constant after *h*=0.6*D*. The increase in content of the silty clay layer within the slope increases its safety factor value. In terms of the two cases considered, the factor of safety from case-2 show a huge decrease from case-1. Figure 3 depicts the critical slip surfaces for various layer heights corresponding to case-1. Critical surface for homogeneous slope with silty clay soil show a toe type of failure. Shallow slope failure is observed for layer heights *h*=0.2*D*, 0.4*D* and homogeneous slope with silty sand soil. Critical surface for layer heights *h*=0.6*D* and 0.8*D* coincide with each other having a deeper slope failure. The increase in the silty clay layer shifts the critical slip surface deeper into the slope simultaneously increasing the factor of safety as well.

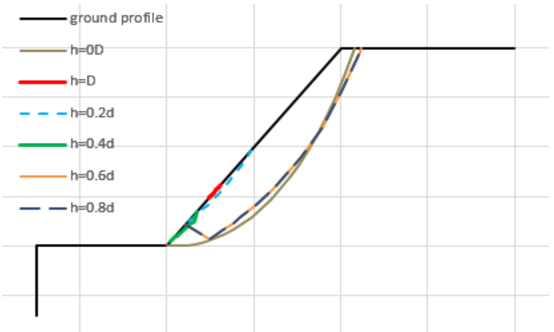

Fig.3 Critical surfaces for various layer heights for case-1using the limit equilibrium method

Critical slip surfaces for various layer heights corresponding to case 2 is shown in Figure 4. For *h*=0.2*D* and *h*=0.4*D* the slip surface is shallow and parallel to the slope while for the other two heights they coincide with each other having a deep slip surface. From the figure it is evident that the slope with more silty sand soil has a critical slip surface which is shallow and parallel to slope while with more silty clay soil the failure is a deep slope failure. The total displacement contours and the critical slip surface from the limit equilibrium method for case-2 and four layer heights are shown in Figure 5. The displacement increases with increase in layer height i.e., the zone of failure increases and parallel to the slope while the slip surface from limit equilibrium method is small and confined to the toe region.

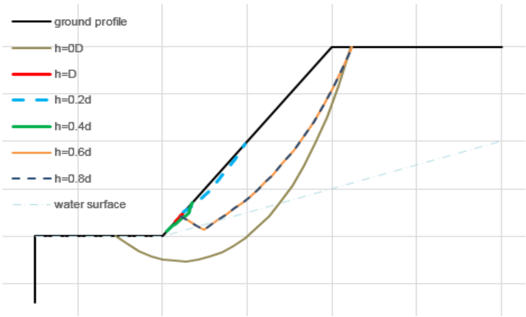

Fig.4 Critical surfaces for various layer heights for case-2 using the limit equilibrium method

The maximum displacement is 0.067m. The same is observed for *h*=0.4*D* but here the zone of failure increases but the slip surface from limit equilibrium method is much smaller. For this height the maximum displacement is 0.11 m. For h=0.6*D* and *h*=0.8*D* the zone of failure increases and it is seen spreading outwards.

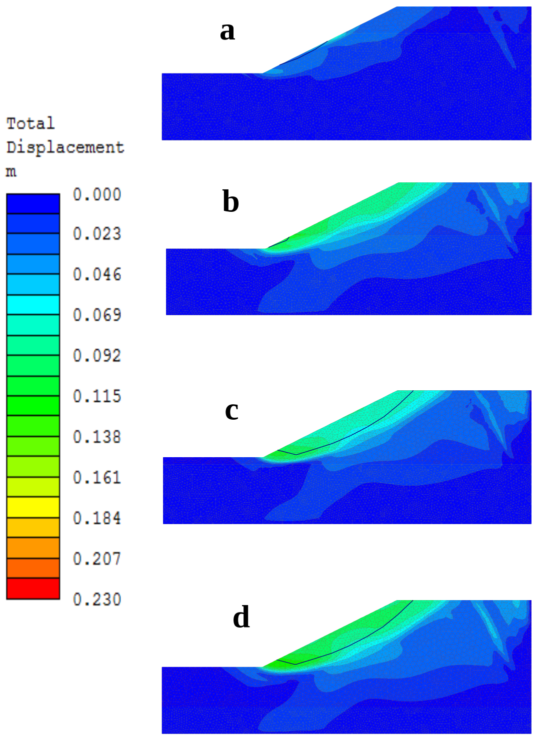

Fig.5Contours of total displacements from FEM and critical surface from LEM for case-2 and layer height (a) *h*=0.2*D* (b) *h*=0.4*D* (c) *h*=0.6*D* and (d) *h*=0.8*D*

For the last two layer heights the critical slip surface from limit equilibrium method is same and they coincide while finite element method depicts that their displacements are not the same, layer height *h*=0.8*D* has more displacement than height *h*=0.6*D*. The maximum displacement for the last two layer heights are 0.122m and 0.126m respectively. The variation of factor of safety with layer height to depth factor ratio for case-1 and case-2 is shown in Figure 6. Out of the two cases considered it is seen that for case-1the factor of safety values are higher than that of case-2. The factor of safety increases with layer height to depth factor ratio up to height 0.6*D* and stays constant after that.

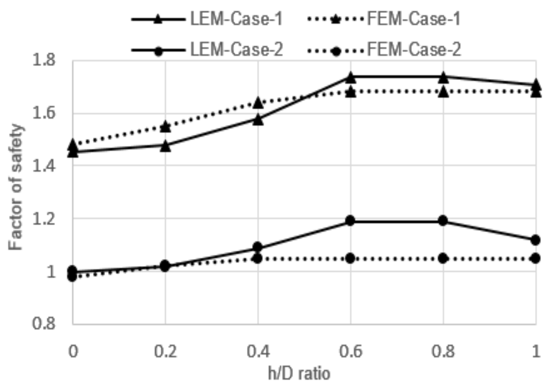

Fig.6 Variation of safety factor with height ratio for case-1 and 2

5 CONCLUSIONS

A two-layered non-homogeneous slope with a silty clay layer at the top and silty sand layer at the bottom is prepared. Two cases are considered here of which case-2 is more critical where a water table and pseudo-static force has been introduced. Considering only the non-homogeneous profiles, the factor of safety and strength reduction factor is getting increased with increase in layer height from 0.2*D* to 0.6*D* then it stays constant. The minimum safety factor is observed for layer height *h*=0.2*D*. It is clear that the silty clay soil imparts strength to the two-layered slope and makes it more stable. For layer height 0.2*D* and 0.4*D* the critical surfaces are shallow and parallel to slope while the surface coincides for heights 0.6*D* and 0.8*D* which has a deeper surface depicting a slope failure. Hence it is found that slopes with sandy soil have a shallow slope failure parallel to slope surface and slopes with clay soil have a deeper slope failure. Displacements show an increasing trend with increasing layer height i.e., with increase in layer height the silty clay soil in the slope increases and with it the differential displacement also increases indicating a deeper zone of failure.

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