Seismic Stability Analysis of Homogeneous and Layered Soil Slopes by LEM

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ABSTRACT
The stability of slopes is a major concern in the field of geotechnical engineering. Usually two-dimensional analyses based on limit equilibrium methods are implemented in this field due to their simplicity and effectiveness. In this paper, the stability of model soil slopes for homogeneous and layered soil with and without earthquake has been analyzed and the related results have been reported. It is noted that the factor of safety decreases with the increase of horizontal seismic coefficent for both the slopes of homogeneous and layered soil. Horizontal seismic coefficent alone affects the stability of slope severely than the combined effect of horizontal and vertical seismic coefficients. The effect of slope angle and cohesion of soil on the stability of slopes have also been reported in this study. The factor of safety of slope increases with the increase of the ratios of cohesion of two soil layers c_2/c_1 (c_2 is variable while c_1 is constant) up to a certain value and beyond that, the factor of safety remains constant.

General Terms
Slope stability analysis considering earthquake effect.

Keywords
Slope Stability, Seismic coefficients, Factor of Safety, Cohesion, LEM.

1. INTRODUCTION
Slope stability analysis is an enormously important deliberation in the design and construction of earth dams, embankments, bridge abutments, retaining walls and various other civil engineering structures. In construction areas, the slope may fail due to rainfall, increase in ground water table and change in stress condition. Likewise, the natural slopes that have been stable for many years may suddenly fail due to change in geometry, external forces and loss of shear strength (Abramson et al. 2002). Tayler and Burns (2005) reported that the earthquake is the greatest threat to the long term stability of slopes, particularly in earthquake active zones. Earthquake induced ground shaking causes failure to slopes that were marginally stable before earthquake. In such circumstances, the proper assessment of the stability of slope becomes the primary concern.

The stability analysis of slope considering the effect of earthquake can be analyzed by different methods such as the pseudo-static method, Newmark's sliding block method and numerical techniques. In the present study, the pseudo-static method is used in which the earthquake loading is represented by a horizontal static force. This horizontal static force is computed by multiplying the weight of structure by the seismic coefficients. The advantage of this method lies in its simplicity. There were several studies in the literature that considered the effect of earthquake in the stability of slopes.

For example, Melo and Sharma (2004) carried out a parametric study on the choice of the seismic coefficients in a more rational way to investigate the effect of earthquake for pseudostatic analysis. Similar study was carried out by Kandolkar et al. (2010). Miraboutalebi et al. (2011) studied the effect of bedrock inclination on the seismic slope stability. Chatterjee and Choudhury (2012) reported the seismic stability analysis of soil slopes using the analytical and numerical approaches. Recently, Gao and Lie (2013) studied the effect of seismic action direction on the stability of slope and reported that the stability of slope is lower than the stability of natural condition when the direction of horizontal earthquake inertia force outside toward slope. Even though several research works have already been conducted for the stability analysis of slope by limit equilibrium method (LEM). and finite element method (FEM) considering the effect of earthquake for homogeneous soil; however, a very limited study for layered soil on the stability analysis of slope considering the earthquake has been reported so far. Consequently, this paper presents a comprehensive study of the stability of model soil slopes of homogeneous and layered soil subjected to earthquake. The main objectives of this study are: (i) to study the effect of seismic coefficients on the stability of slopes of both homogeneous and layered soil; (ii) to examine the effect of cohesion and slope angle on the stability of slope for varying seismic coefficients. For this purpose, the slopes of homogeneous and layered soil are analyzed and the associated results are presented.

2. ANALYSIS TECHNIQUE
2.1 Load-based Seismic Slope Stability Analysis
Load-based procedure is one of the earliest procedures for seismic slope stability analysis. In this approach, the earthquake loading is represented by a horizontal static force, which is equal to the weight of soil multiplied by the seismic coefficient. The coefficient can be estimated empirically. The pseudo-static force is then incorporated in a conventional limit equilibrium analysis and the factor of safety is computed (Tan, 2006).

2.2 Limit Equilibrium Principle
Mohr-Coulomb model is the most widely used material model which is utilized to determine the shear strength (τ_f) along the sliding surface (Aryal, 2006). According to Janbu (1973), a state of limit equilibrium exists when the mobilized shear stress (τ) is expressed as a fraction of the shear strength. The shear strength is usually expressed by the Mohr-Coulomb linear relationship, where the τ_f and τ are defined by-

Shear strength (available):

$$\tau_f = c' + \sigma' \tan \phi' \qquad (1)$$

Shear stress (mobilized):

$$\tau = \frac{\tau_f}{F} = \frac{c' + \sigma' \tan \phi'}{F} \qquad (2)$$

where, c' and ϕ' are the effective cohesion and friction angle, respectively, and F is the factor of safety (FOS).

The shear strength that is available depends on the type of soil and the effective normal stress, whereas the shear stress that is mobilized depends on the external forces acting on the soil mass. The FOS can be defined in three ways: Limit equilibrium, force equilibrium and moment equilibrium (Abramson et al. 2002). The first definition is based on the shear strength whereas the second and third definitions are based on force equilibrium and moment equilibrium conditions for resisting and driving force and moment components, respectively (Aryal, 2006).

2.3 Limit Equilibrium Methods
Conventionally, the slope stability analysis is carried out by LEM. This method is statically indeterminate. Presumption is needed to determine the factor of safety using the LEM. Among the LEMs, the Bishop method (1955) is the widely used. The application of LEM is limited to the slope of simple geometry. The solution of LEM can become inadequate in case the slope fails by complex mechanism such internal deformation, brittle failure, etc.

2.4 Geometric Model of Slope
A number of problems for different slope angles are solved in this paper. Fig. 1 shows the geometric model of a slope of homogeneous soil while Fig. 2 presents the geometric model of a slope of layered soil. In Figs. 1 and 2, β indicates the angle of slope with the horizontal.

2.5 Material Properties
The properties of soil used in the present study are presented in Table 1. Two types of soils are considered. Either soil-1 or soil-2 is used for the analysis of a slope of homogeneous soil whereas both soil-1 and soi-2 are used for the stability analysis of slopes of layered soil.
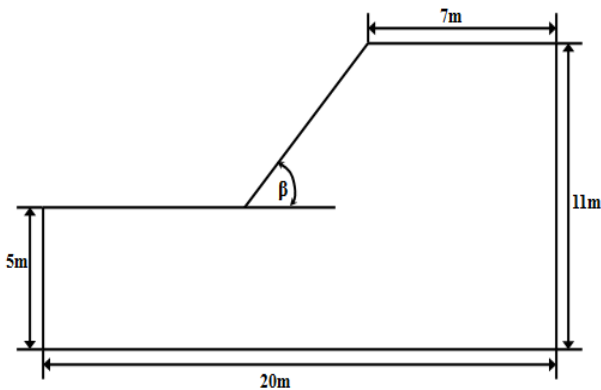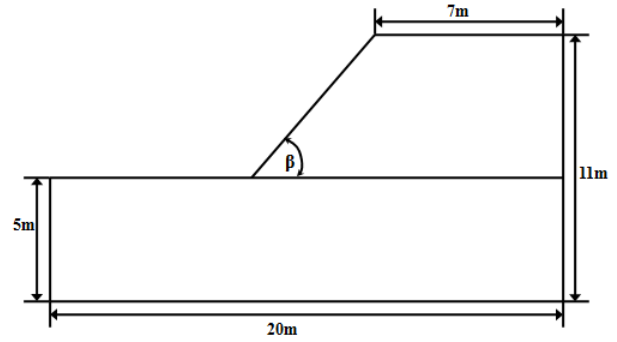
Fig 1: Geometric model of a slope of homogeneous soil

Fig 2: Geometric model of a slope of layered soil

Table 1 Properties of soil considered in the present study

Material	Unit weight (kN/m³)	Friction angle (degree)	Cohesion (kN/m²)
Soil-1	18.5	10	25
Soil-2	17	5	15

3. NUMERICAL ANALYSIS BY LEM
In the present study, a number of numerical analyses have been performed by the software GEO5 (2014). Bishop method (1955) is used for limit equilibrium analysis. For LEM, the geometric model is incorporated in the GEO5 software. After incorporating the model, the properties of soil are assigned for the specified interface. In the analysis stage, a slip surface is added. In this paper, circular slip surface is used. After assigning the properties of soil and adding a suitable slip circle, the analysis method is chosen. In this paper, optimization type is taken as analysis type. Finally, seismic coefficients are added to the slope and the stability analysis of slope is carried out.

4. RESULTS AND DISCUSSION
4.1 Slope of Homogeneous Soil
An idealized slope of 11 m height with β of 30, 45, 60 and 75 degrees has been selected for the present work. The analyses have been carried out by using two types of soil (soil-1 or soil-2, whichever applicable).

4.1.1 Effect of Earthquake
The stability of slope of homogeneous soil-1and slope of homogeneous soil-2 with $\beta = 45^\circ$ is first analyzed using GEO5 (2014) considering the effect of earthquake. Note that the effect of earthquake is incorporated here using the suitable seismic coefficients. Fig. 3 depicts the variation of the factor of safety with K_h for a constant $K_v / K_h = 0.5$, where K_v and K_h are the vertical and horizontal seismic coefficients, respectively. The factor of safety without considering any earthquake (i.e. without any K_v or K_h) shows a higher value of factor of safety compared to that with considering the earthquake for a particular soil, as expected. From Fig. 3, it is also observed that the factor of safety decreases with the increase of K_h. Note also that the trend of decreasing factor of safety is almost same for both the slope of homogeneous soil-1 and slope of homogeneous soil-2.
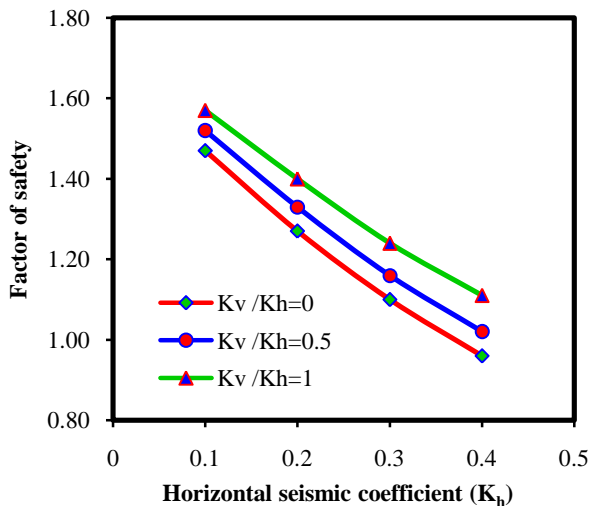
Fig. 4 depicts the variation of factor of safety with different K_v/K_h for slope of homogeneous soil-1 (β =45°) while Fig. 5 shows the variation of factor of safety with different K_v/K_h for slope of homogeneous soil-2 (β=45°). From Figs. 4 and 5 it is clear that the factor of safety is minimum when $K_v/K_h = 0$ i.e, when only K_h affects on slope. It reveals that the role of K_h is dominant in the analysis of slope while considering the effet of earthquake. Effect of K_h is more hazardous than the combined effect of K_v and K_h .
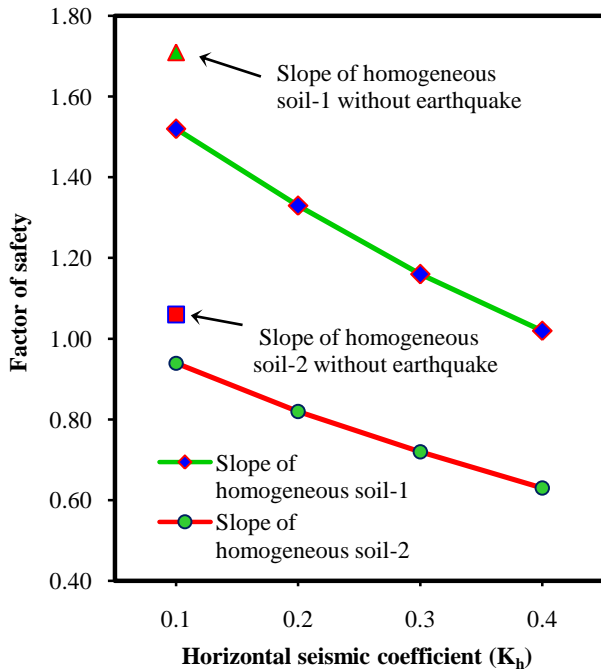
Fig. 3: Variation of the factor of safety with K_h for $K_v/K_h = 0.5$ with β=45°

Fig. 4: Variation of factor of safety with different K_v/K_h for slope of homogeneous soil-1 (β=45°)
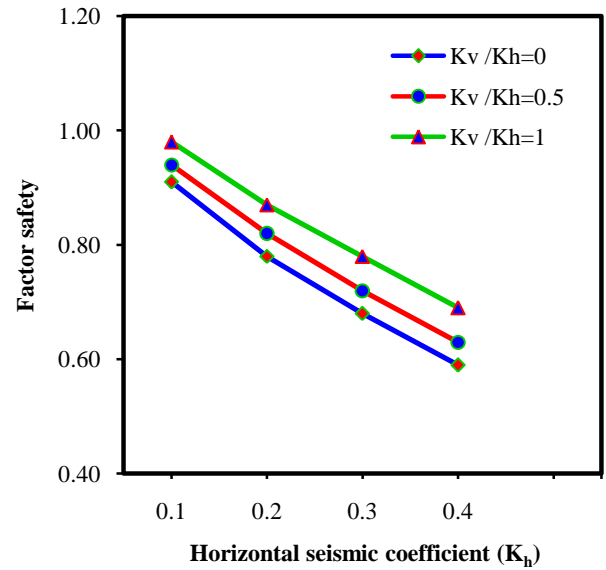

Fig. 5: Variation of factor of safety with different K_v/K_h for slope of homogeneous soil-2 (β=45°)

4.1.2 Effect of Slope Angle

Four different slope angles (30°, 45°, 60° and 75°) are considered in this study. A number of analyses have been performed considering earthquake and no earthquake conditions for both the slope of homogeneous soil-1 and homogeneous soil-2. Fig. 6 shows the effect of slope angle on the factor of safety of slope of homogeneous soil-1 while Fig. 7 shows the effect of slope angle on the factor of safety of slope of homogeneous soil-2. From Figs. 6 and 7, it is observed that the factor of safety decreases as the slope angle increases considering earthquake and no earthquake conditions.
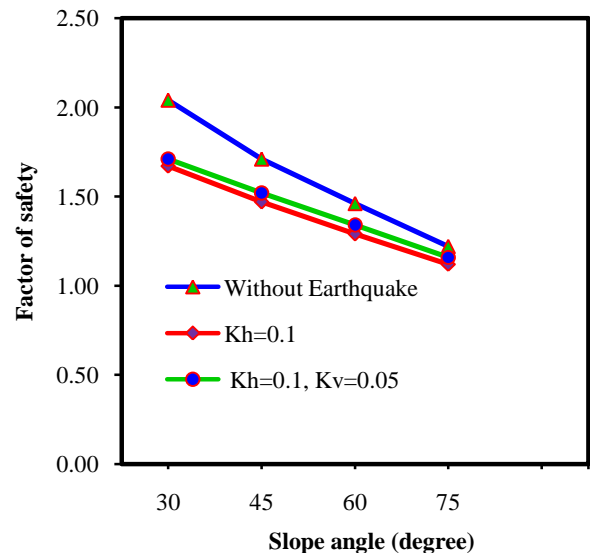

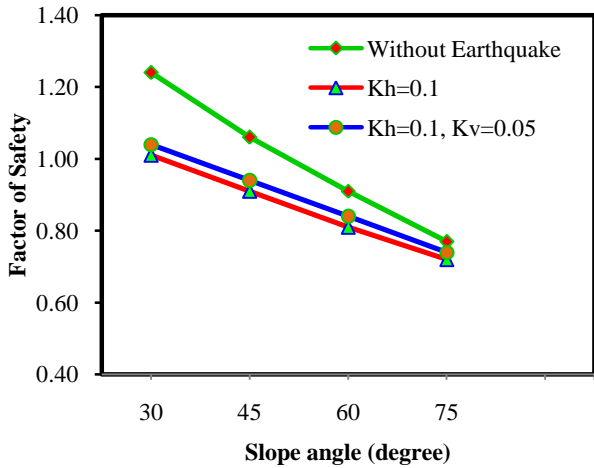**Fig. 6: Effect of slope angle on the factor of safety of slope of homogeneous soil-1**

Fig. 7: Effect of slope angle on the factor of safety of slope of homogeneous soil-2

4.2 Slope of Layered Soil

The stability of slope of layered soil has been analyzed considering two cases. In analysis case-1, soil-2 is used in upper portion of the slope and soil-1 is used in the foundation layer. In analysis case-2, soil-1 is used in the upper portion of the slope and soil-2 is used in the foundation layer. This is done with a view to assess the effect of the position of the relatively weak soil layer on the stability of slopes considering earthquake.

4.2.1 Effect of Earthquake

Fig. 8 depicts the variation of the factor of safety of slope of layered soil for different K_v/K_h ratios with β =45° considering the analysis case-1 while Fig. 9 presents the variation of the factor of safety of slopes of layered soil for different K_v/K_h ratios with β =45° considering the analysis case-2. From Figs. 8 and 9, it is observed that the factor of safety is minimum when K_v/K_h = 0, i.e. when only K_h affects the slope. The result is similar to that of homogeneous soil. Effect of K_h is more severe than the combined effect of K_v and K_h. Note that the popsition of the relative weak soil layer either above the foundation soil or as a foundation soil has no significant influnce in computing the factor of safety.

However, it has noticeable effect on the formation of the slip circle during earthquake. Fig. 10 shows the slip surface of the slope of layered soil (β =45°) for case-1 with earthquake (K_h = 0.1 and K_v = 0.05) while Fig. 11 shows the slip surface of the slope of layered soil (β =45°) for case-2 with earthquake (K_h = 0.1 and K_v = 0.05) using LEM. When soil-2 (a relatively weak soil) is placed in the upper portion of the slope of layered soil, the slip surface runs within the upper layer only. However, when soil-2 is placed in the foundation layer, the slip surface extends beyond the upper layer of the soil to the foundation layer.
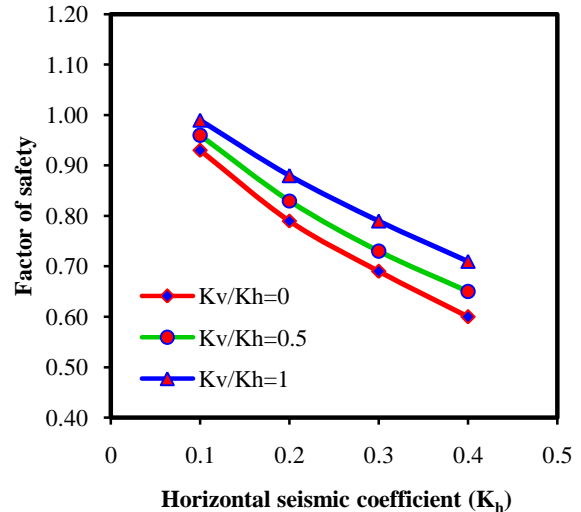

Fig. 8: Variation of factor of safety for various K_v/K_h ratio for a slope of layered soil (β=45°) for case-1
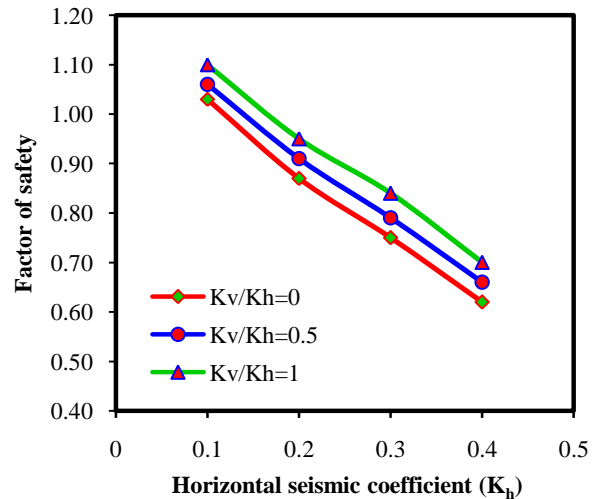

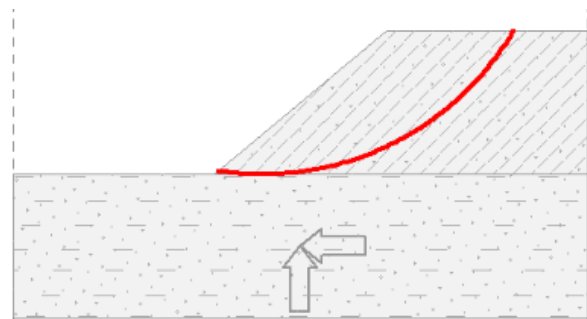**Fig. 9: Variation of factor of safety for various K_v/K_h ratio for a slope of layered soil (β=45°) for case-2**

Fig. 10: Slip surface in layered soil (β =45°) for case-1 with earthquake (K_h =0.1 and K_v =0.05) using LEM
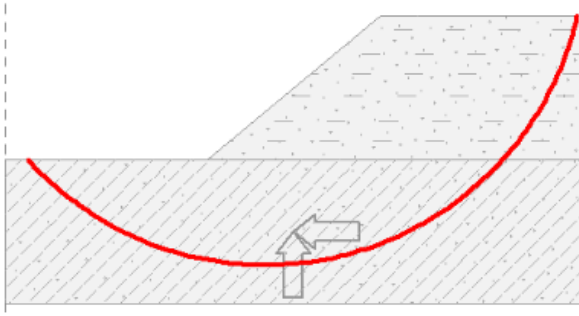
Fig. 11: Slip surface in layered soil (β =45°) for case-2 with earthquake (K_h =0.1 and K_v =0.05) using LEM

4.2.2 Effect of Cohesion

Several analyses are carried out using soil-1 for ϕ =0 condition to account for the effect of cohesion on the factor of safety during earthquake only. The analyses are carried out using a constant value of cohesion for upper layer of soil (c_1) and nine different values of cohesion (c_2) for foundation layer.
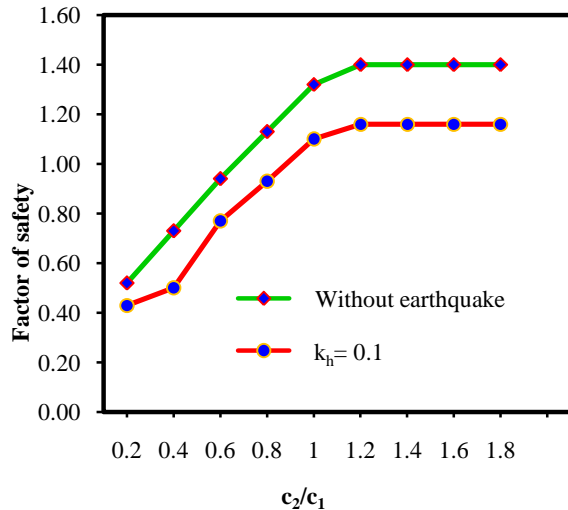

Fig 12: Effect of c_2/c_1 on a slope of layered soil (β=45°)

Fig. 12 depicts the effect of the variation of c_2/c_1 on the factor of safety of slope of layered soil (β =45°) with and without earthquake. It is worth noting that the factor of safety increases gradually with c_2/c_1 up to a value of 1.2 and beyond that value, the factor of safety remains constant for a slope of 45°. Similar result is observed in Fig. 13 for β =60°. Factor of safety varies up to a value of c_2/c_1 =1 and beyond that, factor of safety remains constant for a slope of 60°.
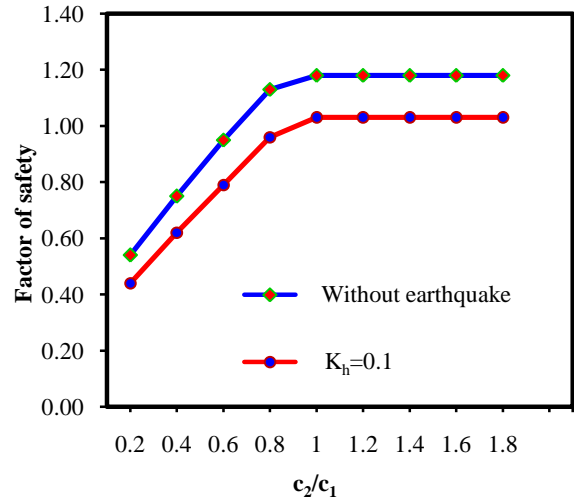

Fig. 13: Effect of cohesion (c_2/c_1) variation for a slope of layered soil (β=60°)

5. CONCLUSIONS

In the present study, numerical analysis is carried out to investigate the effect of earthquake on the stability of slopes of homogeneous and layered soil. The major findings of the study are as follows:

(1) The factor of safety decreases with the increase of the horizontal seismic coefficient (K_h) for both the slope of homogeneous and layered soil.

(2) Effect of the horizontal seismic coefficient K_h is more severe than the combined effect of vertical seismic coefficient (K_v) and horizontal seismic coefficient (K_h).

(3) If a relatively weak soil layer is located below the good soil layer, the slip surface extends beyond the top soil layer to the weak soil layer.

(4) The factor of safety of slopes of layered soil increaes with the increase of the ratios of cohesion of two soil layers c_2/c_1 up to a certain value and beyond that, the factor of safety remains constant.

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