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Simplified Pseudostatic Analysis of Earthquake Induced Landslides

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ABSTRACT

Landslides are major problems in hilly areas. There have been many damaging landslides in recent times that have taken huge toll of life. Cloud burst, heavy rains and earthquake are among many triggering mechanisms causing landslides. Recent earthquakes in Sikkim (2013), Nepal (2015), and Kumamoto (2016) have all caused seismic induced landslides leading to heavy damage. Hence, it is extremely important to assess the performance of slopes during earthquakes. Earthquakes are unpredictable and uncertain. The behavior of soil slopes are complex and it is hard to collect relevant input data. These result in difficulty in assessing the seismic performance of slopes. It may, therefore, be necessary to simplify the analysis of slopes subjected to earthquake. One simplified approach is to idealize the dynamic earthquake force by equivalent static inertial force. This idealization is acceptable considering the massive volume and weight of geotechnical structures. The majority of failures happen in first mode of vibration and failures are mainly due to weakening of the strength and stiffness characteristics of soil. This paper focuses on the use of GEOSTUDIO, a finite element software for problems associated with geotechnical engineering, to solve seismic slope stability problems from pseudostatic approach. The effects of horizontal and vertical components of acceleration on the factor of safety against slope failure are assessed and represented in graphical form. The influence of slope geometry on seismic slope instability is presented.

Key words: *Pseudostatic analysis, Stability of slopes, Earthquake, GEOSTUDIO, Landslides.*

1. INTRODUCTION

A slope is an unsupported, inclined surface of soil mass. Slopes can be natural or manmade. These may be above ground level as embankments or below ground level as cuttings. Earth slopes are formed for railway embankments, earth dams, canal banks, levees, and at many other locations. Instability related issues in engineered, as well as natural slopes, are common challenges to both researchers and professionals. Instability may result due to rainfall, increase in groundwater table and change in stress conditions. Similarly, natural slopes that have been stable for many years may suddenly fail due to changes in geometry, external forces, and loss of shear strength [2]. In addition, the long-term stability is also associated with the weathering and chemical influences that may decrease the shear strength. Earthquakes are the most common external forces that result in building up of stresses in sloping soil mass leading to landslides. Sliding may occur along any of a number of possible surfaces and shear strength generally varies with time. It is, therefore, normal in practice to use appropriate safety factors when analyzing slope stability.

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Some of the recent earthquakes that stuck India which resulted in major landslides are listed below:

- The 2005 Kashmir earthquake occurred on 8 October in the Pakistani territory of Kashmir. It was centered near the city of Muzaffarabad. It registered a moment magnitude of 7.6 and had a maximum Mercalli intensity of VIII (Severe). The severity of the damage caused by the earthquake is attributed to severe up thrust.
- The 2011 Sikkim earthquake occurred with a moment magnitude of 6.9 and was centered within the Kanchenjunga Conservation Area, near the border of Nepal and the Indian state of Sikkim, at 18:10 IST on Sunday, 18 September. At least 111 people were killed during the earthquake.
- The April 2015 Nepal earthquake killed over 9000 people and injured more than 23,000. It occurred on 25 April with a magnitude of 7.8 Mw and a maximum Mercalli Intensity of IX (Violent).

All the above earthquakes resulted in many landslides that not only took away many lives but caused huge economic loss. Some of them even buried habitation.

2. PSEUDOSTATIC ANALYSIS

Pseudostatic approach is one of the simplest methods of idealizing the slope subjected to earthquake force. Although earthquake force is dynamic, it is possible to consider the inertial force as the major element responsible for instability. Considering the massive volume and weight of geotechnical structures, majority of failures happen in first mode of vibration and failures are mainly due to weakening of the strength and stiffness characteristics of soil. Hence, the assumption that inertial force is static is acceptable for moderate level earthquakes. In the pseudostatic approach, the acceleration generated by earthquake shaking is considered to create inertial forces. These forces act in the horizontal and vertical directions at the centroid of each slice. The forces are defined as [6]:

$$F_h = \frac{(a_h * w)}{g} = K_h * W \tag{1}$$

$$F_v = \frac{(a_v * W)}{g} = K_v * W \tag{2}$$

Here, a_h and a_v are, respectively, horizontal and vertical pseudostatic accelerations, g is the gravitational acceleration constant, and W is the slice weight. The acceleration ratio a/g is a dimensionless coefficient K. The inertial effect is specified as K_h and K_v, the coefficients of acceleration in horizontal and vertical directions, respectively. These coefficients can be considered as a percentage of g. A K_h coefficient of 0.2, for example, means the horizontal pseudostatic acceleration is 0.2 g. The horizontal inertial forces are applied as a horizontal force on each slice. Vertical inertial forces are added to the slice weight.

Vertical coefficients can be positive or negative. A positive coefficient means earthquake force is acting downward in the direction of gravity; a negative coefficient means earthquake force is acting upward against gravity. The application of vertical seismic coefficients often has little impact on the safety factor. The reason for this is that the vertical inertial forces alter the slice weight. This alters the slice base normal, which in turn alters the base shear resistance. If, for example, the inertial force has the effect of increasing the slice weight, the base normal increases and then the base shear resistance increases. The added mobilized shear arising from the added weight tends to be offset by the increase in shear strength. This is true for frictional strength components only and not for cohesive strength components. Horizontal inertial seismic forces can have a dramatic effect on the stability of a slope. Even relatively small seismic coefficients can lower the factor of safety greatly, and if the coefficients are too large, it becomes impossible to obtain a converged solution. It is consequently always good practice to apply the seismic forces incrementally to gain an understanding of the sensitivity of the factor of safety to this parameter. It is often useful to create a graph. As the seismic coefficient increases; there should be smooth gradual decrease in the safety factor. The difficulty with the pseudostatic approach is that the seismic acceleration only acts for a very short moment in time during the earthquake shaking [5]. As we will see in the next section, the factor of safety in reality varies dramatically both above and below static factor of safety. The factor of safety may even momentarily fall below 1.0, but this does not mean the slope will necessarily totally collapse. Looking at this issue more realistically requires knowledge of the shear stress variation during the earthquake shaking. This can be handled more precisely with a dynamic finite element analysis [3].

In this work, SLOPE/W module of GEOSTUDIO, a finite element package for solution to geotechnical problems is used [4].

3. RESULTS AND DISCUSSIONS

A typical soil slope of height (H) with an inclination (i), cohesion (c), angle of internal friction (φ), unit weight (ϒ), weight due to gravity (W), and acceleration (a) is considered in the analysis as in Figure 1. The analysis is performed for H=10 m, c=15 kN/m^2, Ø=20° and γ=20 kN/m^3.

A typical accelerogram consisting of three components (namely, East-West, North-South and up-down or vertical) is shown in Figure 2. Normally, up-down component will be a fraction of horizontal component and is neglected in most of the approximate analyses. However, it should be noted that the effect of vertical component is more pronounced closed to the epicenter and it decreases with increase in epicentral distance. As landslides mostly happen near the epicenter, it is appropriate to consider the effect of vertical acceleration.

Figure 3 presents the variation of factor of safety with changes in horizontal coefficient of acceleration for varying soil slopes from i=10° to i=60°. It can be seen that the effect of increase in the horizontal coefficient of acceleration is to reduce the factor of safety against

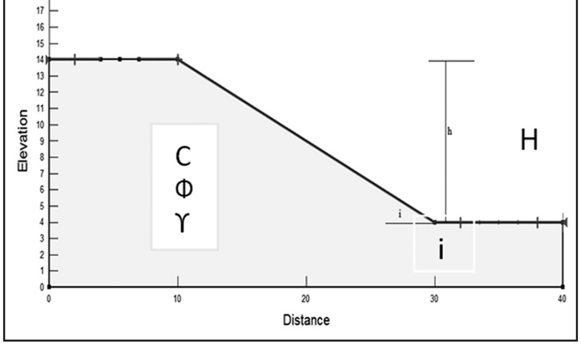

Figure 1: A typical soil slope with its parameters.

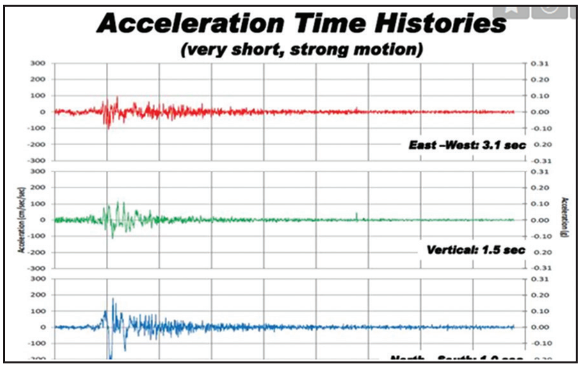

Figure 2: A typical accelerogram with North-South, East-West and Up-Down components.

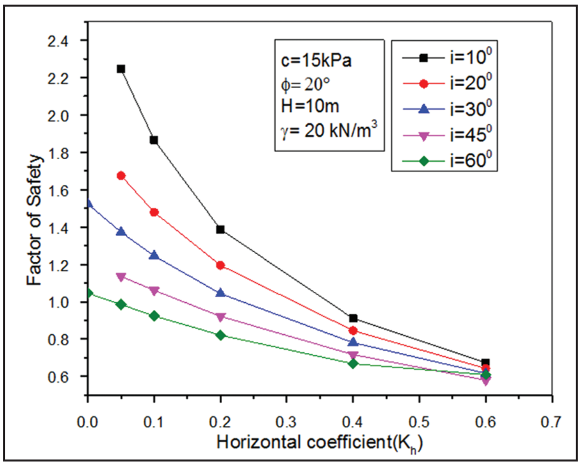

Figure 3: Variation of factor of safety of a soil slope with horizontal coefficient (K_h).

slope stability and the variation is nonlinear. Further, the factor of safety decreases with increase in slope angle of soil slope. Besides, at all slopes, the factor of safety converges within a narrow range with increase in K_h.

The ratio of vertical coefficient to horizontal coefficient of acceleration K_v/K_h generally ranges from 0.1 to 0.4, being smaller for large epicentral distances and bigger for short epicentral distances. Figure 4 presents a graph between the factor of safety along vertical axis and acceleration along the horizontal axis for slopes of varying slope angles at K_h=0.3. It can be observed that the effect of vertical component of acceleration is to reduce the factor of safety. Hence, increase in acceleration ratio reduces the factor of safety against slope stability.

Figure 5a and b shows the variation of factor of safety of a soil slope with the ratio of vertical coefficient (K_v) to horizontal coefficient (K_h) of accelerations for different K_h values.

It can be observed that the effects of acceleration ratio are less pronounced when the soil slope is steeper

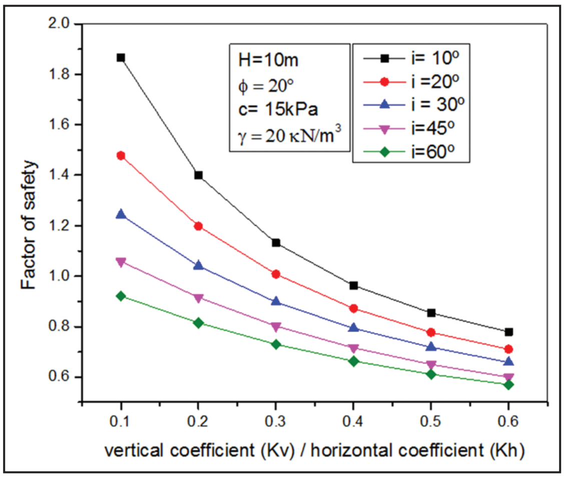

Figure 4: Variation of factor of safety of a soil slope with the ratio of vertical coefficient to horizontal coefficient of acceleration for K_h=0.3.

and when the magnitude of horizontal acceleration is smaller.

It is more convenient to relate the factor of safety against slope stability with magnitude of earthquake. For this purpose, the attenuation relationship suggested by Campbell [1] for near field earthquakes is used. The data required in the equation are peak ground acceleration and epicentral distance in km. The equation is applicable for epicentral distance up to 50 km. It is assumed that horizontal acceleration coefficient is equal to peak ground acceleration. In this analysis, the vertical coefficient of acceleration is ignored. Figures 6 and 7 show the relationships between factor of safety against slope stability and magnitude of earthquake for typical slopes at epicentral distances of 25 and 50 km, respectively, for different earth slopes. It can be observed that the factor of safety decreases with increase in magnitude of earthquake. At very large magnitude of earthquake, factors of safety of all slopes converge to a narrow range. The influence of increase in epicentral distance is to reduce the damaging effect. It can also be observed that the slopes will be unsafe only when the magnitude of earthquake is higher than 6 and the epicenter is within 50 km radius. These graphs can be generated for earth slopes of varying geometry, heights, and soil properties which will provide as good ready reckoners for designers.

4. CONCLUDING REMARKS

The following are a few important inferences from this work.

1. The increase in ground acceleration results in the reduction in factor of safety against slope stability and the variation is nonlinear. The effects are more pronounced in steeper slopes
2. The effect of increase in K_v is to reduce the factor of safety against slope stability. However, the

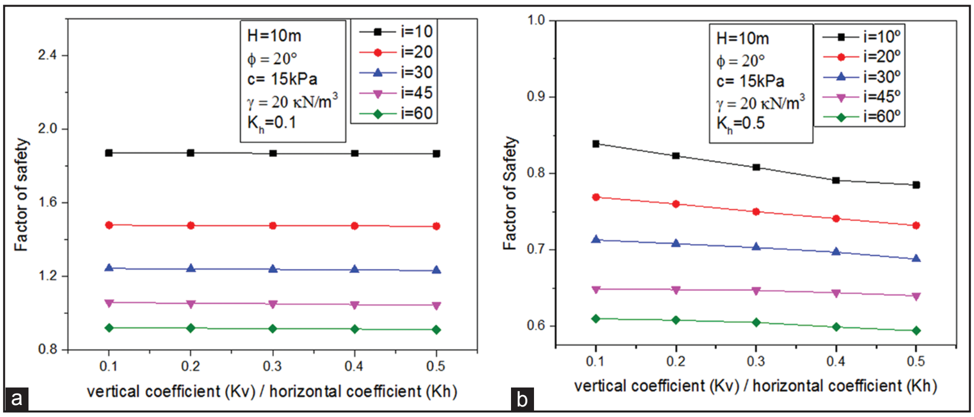

Figure 5: (a) Variation of factor of safety of a soil slope with the ratio of vertical coefficient (K_v) to horizontal coefficient (Kh) of acceleration when Kh=0.1, (b) variation of factor of safety of a soil slope with the ratio of vertical coefficient (K_v) to horizontal coefficient (K_h) of acceleration when Kh=0.5.

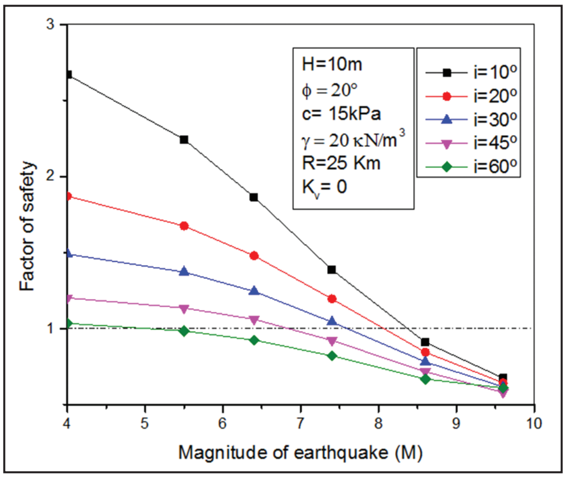

Figure 6: Variation of factor of safety of a soil slope with the magnitude of earthquake when epicenter is 25 km.

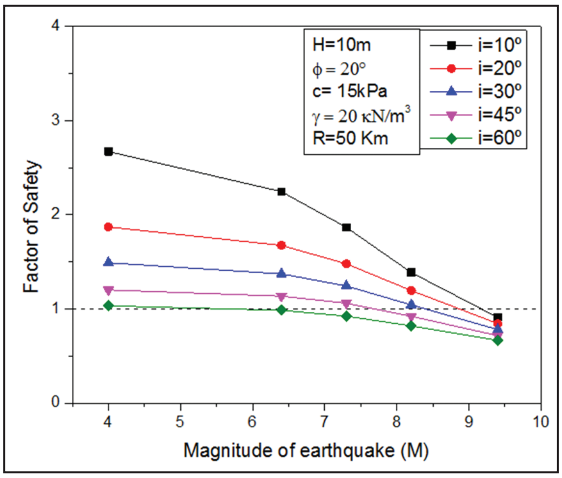

Figure 7: Variation of factor of safety of a soil slope with the magnitude of earthquake when epicenter is 50 km.

effects are less significant. Further, for flatter slopes and lower levels of shaking, the effects are negligible.

3. Higher the magnitude of earthquake and lesser the epicentral distance, lower is the factor of safety against slope stability. Vulnerability to landslides is significant at magnitudes >6.

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***Bibliographical Sketch**

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