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Seismic Slope Stability

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ABSTRACT

The performance of soil slope during an earthquake is generally analyzed by three different approaches which are pseudo-static methods, Newmark's Sliding Block method and numerical techniques. In pseudo-static approach, the effects of an earthquake are represented by constant vertical (k_v) and horizontal (k_h) seismic acceleration coefficients and the factor of safety is evaluated by using limit equilibrium or limit analysis or finite element method of analysis. Newmark's sliding block method evaluates the expected displacement of slope subjected to any ground motion obtained from the integration of the equation of motion for a rigid block sliding in an inclined plane. Numerical methods determine the expected displacements obtained from the stress – strain relationship of a soil mass. In this paper the stability of a model soil slope, comprising of an embankment with two canal bunds at the top, at different stages of construction, i.e. only embankment, embankment with empty canal bunds and embankment with canal bunds filled with water, with different foundation soils in different seismic zones have been analyzed and results have been plotted in the form of variation of factor of safety with horizontal seismic acceleration coefficient (k_h). The critical case has been further analyzed under dynamic conditions. Dynamic analyses have been carried out by plotting the response spectrum curve and selecting 2001 Bhuj earthquake motion as the typical ground motion.

Keywords: *Soil stability , Slope , Pseudo static , Newmark block sliding , Seismic acceleration , Static moment, Pseudo static moment.*

I. Introduction

Slope stability is an extremely important consideration in the design and construction of embankments, earth dams, trenches and various other geotechnical structures. The failure of slopes or manmade embankments, excavations and dams is an old-age phenomenon which has exposed heavy loss on life and property. When an earthquake occurs, the effect of earthquake induced ground shaking is often sufficient to cause failure of slopes that were marginally stable before earthquake. According to Ranjan and Rao (2004), the tendency of the slope to move is construed as instability. However slope failure occurs if there is actual movement of soil mass. The resulting damage may vary from insignificant to catastrophic, depending upon geometry and typical characteristic materials of the slope.

The primary purpose of slope stability analysis in most engineering applications is to contribute to the safe and economic design of excavations, embankments, earth dams and soil heaps. The stability of slopes under both short term and long term conditions are assessed, which enables an economic usage of materials and labors. Slips and landslides which have already occurred are analyzed to understand the failure mechanism under the influence of various environmental factors. This helps in redesign of failed slopes with the adoption of suitable preventive measures. These subsequent analyses enable an understanding of the nature, magnitude and frequency of slope problems that are required to be solved. The present study aims at analyzing the stability of a model soil slope,

comprising of an embankment and two canal bunds, at various construction stages when subjected to earthquake forces. Dynamic analysis of the same have been carried out by subjecting the soil slope to 2001 Bhuj earthquake motion.

II. Pseudo-Static Slope Stability Analysis

Terzaghi (1950) first applied a pseudo-static approach to analyze seismic slope stability. This approach uses a single, monotonically-applied horizontal and/or vertical acceleration to represent earthquake loading. (Although the vertical acceleration can be included in a pseudo-static analysis, it is rarely used in practice, as explained below.) The horizontal and vertical pseudostatic forces, F_h and F_v , respectively, act through the sliding mass centroid and are defined as:

$$F_h = \frac{a_h W}{g} = K_h W$$

$$F_v = \frac{a_v W}{g} = K_v W$$

where a_h and a_y = horizontal and vertical accelerations, respectively; k_h and k_v = dimensionless horizontal and vertical pseudo-static coefficients, respectively; and W = weight of the failure mass.

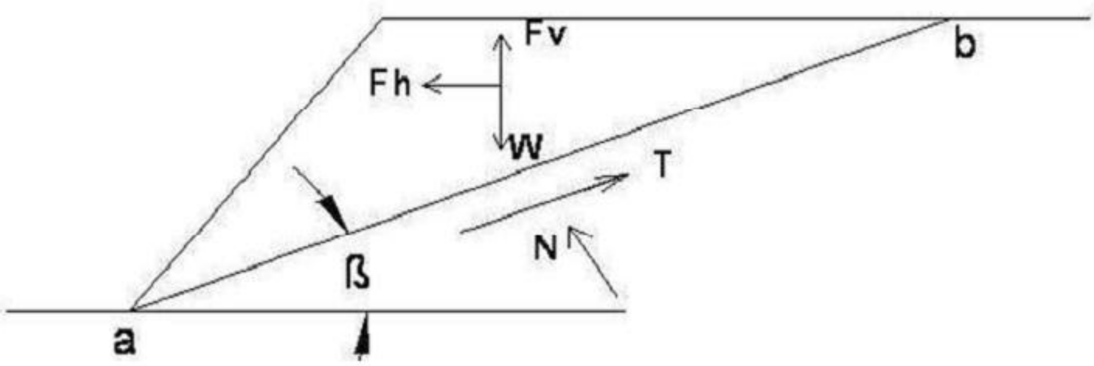


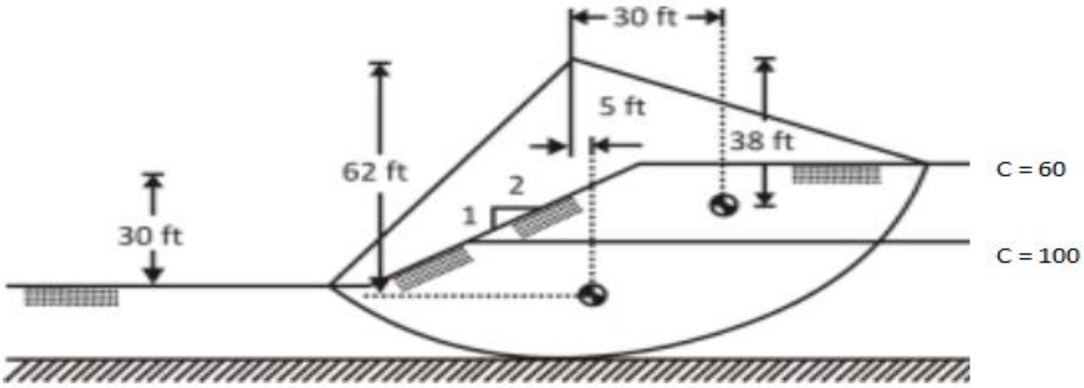
Fig1. Force acting on triangular wedge of soil above failure plane.

$$\text{FOS} = \frac{resisting\ \ force}{driving\ \ force} = \frac{Cl_{ab} + [(W - F_v)\cos\beta - F_h \sin\beta]\tan\emptyset}{(W - F_v)\sin\beta + F_h\cos\beta}$$

Where c & Ø are the Mohr-Coulomb strength parameters that describe the shear strength on the failure plane and lab is the length of the failure plane. The horizontal pseudo static force clearly decreases the factor of safety-it reduces the resisting force (for Ø > 0) and increases the driving force. The vertical pseudo static force typically has less influence on the factor of safety since it reduces (or increases, depending on its direction) both the driving force and the resisting forces a result, the effects of vertical accelerations are frequently neglected in pseudo static analyses. The pseudo static approach can be used to evaluate pseudo static factors of safety for planar, circular, and noncircular failure surfaces.

Example :

Assuming $K_h = 0.1$ and $K_v = 0.0$, compute the static and pseudostatic factors of safety for the 30-ft high 2:1 (H:V) slope, shown in fig.
When C = 60 lb/ft^2, $\emptyset = 0, \gamma = 110\ lb/ft^3$, C = 100 lb/ft^2 , $\emptyset = 0, \gamma = 125\ lb/ft^3$



III. Solution

Using a simple moment equilibrium analysis the factor of safety can be defined as the ratio of the moment that resist rotation of a potential failure mass about the center of a circular potential failure surface to the moment that is driving the rotations. The critical failure surface, defined as that which has the lowest factor of safety, is identified by analyzing a number of potential failure surfaces. Shown below are the factor-of-safety calculations for one potential failure surface which may not be the critical failure surface.

Computations of the factor of safety require evaluation of the overturning the resisting moments for both static and pseudostatic conditions. The overturning moment for static conditions results from the weight of the soil above the potential failure surface.The overturning moment for psuedostatic conditions is equal to the sum of the overturning moment for static conditions and he overturning moment produced by the pseudostatic forces. The horizontal pseudostatic forces are assumed to act ion directions that produce positive (clockwise, in this case) driving moments. In the calculations shown in tabular form below, the soil above the potential failure mass is
divided into two sections.

IV. Overturning moments

Section	Area (ft^2)	γ (lb/ft^3)	W (kips/ft)	Moment Arm (ft)	Static Moment (kip-ft/ft)	K_hW (kips/ft)	Moment Arm (ft)	Pseudostatic Moment (kip-ft/ft)	Total Moment (kip-ft/ft)
A	177.988	110	19.578	30	587.34	2.0	38	76	663.34
B	228.906	125	28.613	5	143.065 Total (A + B) = 730.405	2.86	62	177.32	320.385 Total (A + B) = 983.725

Resisting moment:

Section	Length (ft)	C (lb/ft^2)	Force (kips)	Moment Arm (ft)	Moment (kips-ft/ft)
A	31.4	60	1.884	82	154.488
B	169.56	100	16.956	82	1390.392 Total (A + B) = 1544.88

Factor of safety:

Static FOS = $\frac{Resisting\ \ Moment}{Static\ \ Overturning\ \ Moment} = \frac{1544.88}{730.405} = 2.11$

Pseudostatic FOS = $\frac{Resisting\ \ Moment}{Static\ +Pseudostatic\ \ Overturning\ \ Moment} = \frac{1544.88}{983.725} = 1.57.$

V. Newmark Sliding Block Analysis

The pseudo static method of analysis, like all limit equilibrium methods, provides an index of stability (the factor of safety) but not information on deformations associated with slope failure. Since the serviceability of a slope after an earthquake is controlled by deformations, analyses that predict slope displacement provide a more useful indication of seismic slope stability. Since earthquake induced accelerations vary with time, the pseudo static factor of safety will very throughout an earthquake. If the inertial forces acting on a potential failure mass become large enough that the total (static plus dynamic) driving forces exceed the available resisting forces, the factor of safety will drop below 1.0. Newmark (1965) considered the behavior of a slope under such conditions. When the factor of safety is less than 1.0, the potential failure mass is no longer in equilibrium consequently, it will be accelerated by the unbalanced force. The situation is analogous to that of a block resting on an inclined plane fig. Newmark used this analogy to develop a method for prediction of the permanent displacement of a slope subjected to any ground motion.

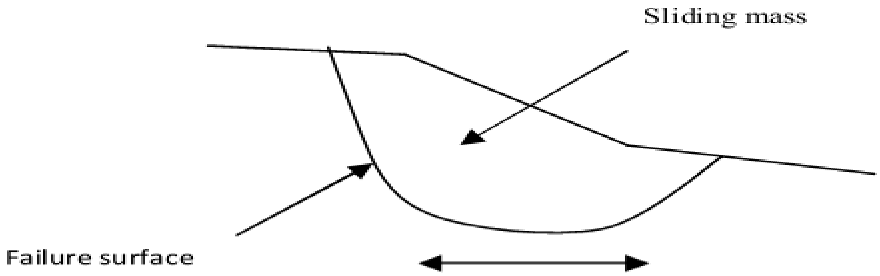


Fig. 1: A potential landslide

Assuming that the block resistance to sliding is purely frictional (C=0), then static factor of safety is:

$$\mathrm{FS} = \frac{Available\ \ Resisting\ \ Force}{Pseudostatic\ \ Driving\ \ Force} = \frac{\tan \emptyset}{\tan \beta}$$

where $\emptyset$ is the angle of friction between the block and plane.

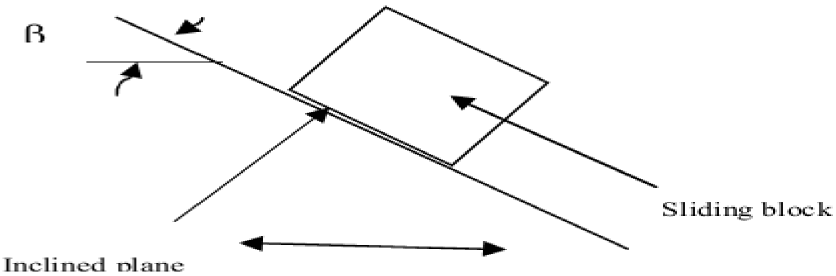


Fig. 2: A block resting on an inclined plane

Considering the effect of inertial forces transmitted to the block by horizontal vibration of the inclined plane with acceleration $a_h = k_h g$. When the inertial force acts in the down slope direction, resolving forces perpendicular to the inclined plane gives (Kramer, 2012) the following expressions for the dynamic factor of safety FSd:

$$\mathrm{FS_d} = \frac{[\cos \beta - k_h \sin \beta] \tan \emptyset}{\sin \beta + k_h \cos \beta}$$

Table For Calculating FOS by using various value of K_h :

CASE 1: For, $\emptyset = 20, \beta = 20$

k_h	FOS
0.1	0.7537
0.2	0.5985
0.3	0.4881
0.4	0.4074
0.5	0.3445
0.6	0.2950

CASE 2 : For, $\emptyset = 30, \beta = 20.$

K_h	FOS
0.1	1.1989
0.2	0.9495
0.3	0.7744
0.4	0.6463
0.5	0.5465
0.6	0.4680

CASE 3 : For, $\emptyset = 40, \beta = 20$

k_h	FOS
0.1	1.7420
0.2	1.380
0.3	1.1255
0.4	0.9393
0.5	0.7943
0.6	0.680

There are graphical representation between seismic horizontal coefficient (k_h) and factor of safety.

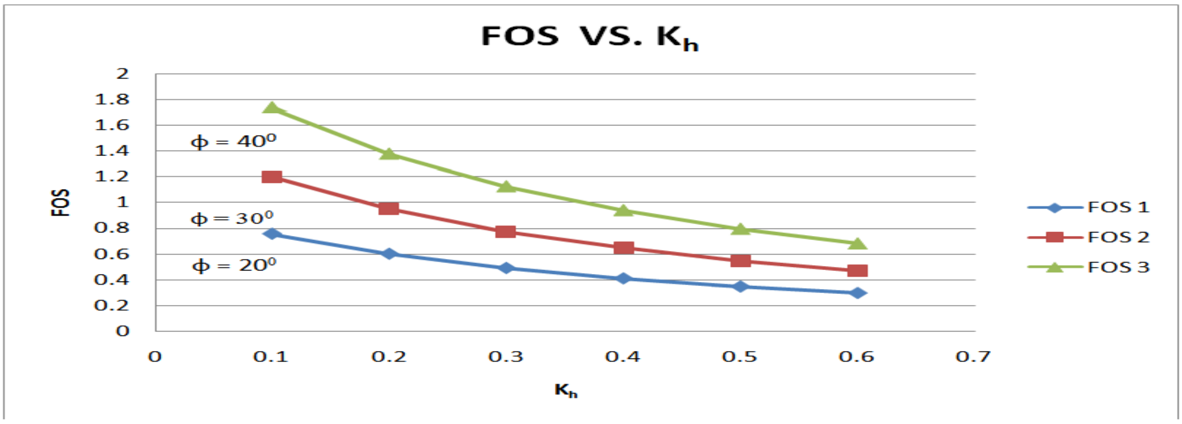


Fig 3 : Variation of pseudostatic factor of safety with horizontal pseudostatic coefficient for block on plane inclined at 20^0. For $\emptyset = 20^0$, block is at the point of failure under static conditions, so the yield coefficient is zero. For $\emptyset = 30^0$ and $\emptyset = 40^0$, yield coefficient are 0.19 and 0.28 respectively.

VI. Conclusion

The three families of analyses for assessing seismic slope stability each have their appropriate application. Pseudo static analysis, because of its crude characterization of the physical process, should be used only for preliminary or screening analyses. It is simple to apply and provides far more information than does pseudo static analysis. Rigid block analysis is suitable for thinner, stiffer landslides, which typically comprise the large majority of earthquake-triggered landslides.Newmark rigid block analogy is not relevant for this purpose. This study proposes a similarly simple layer idealization for the assessment of run-out distance.

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