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A Review of Seismic Stability of Soil Slope

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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 (kv) and horizontal (kh) 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

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 pseudo-static 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 av = 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. Using an infinite slope analysis with this approach has the benefits of

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being simple and able to reasonably approximate shallow slope failures, including earthquake-induced shallow, disrupted landslides which constitute most of the landslides in the study areas. Due to the small thickness of landslide mass, it was assumed that the water table was below the sliding plane. For an infinite slope where horizontal and vertical pseudo-static seismic loads act through the sliding mass centroid, FS is calculated as:

$$\text{FS} = \frac{[(1-K_v)\cos i - K_h \sin i]tan\text{Ø}' + \frac{c'}{\gamma D_t}}{(1-K_v)\sin i \; + \; K_h \cos i}$$

where *c'* and □' are Mohr-Coulomb strength parameters that describe the shear strength on the failure plane; □□= unit weight of failure mass; *i* = slope and failure plane angles; and *D* = failure mass thickness. Resolving the forces on the potential failure mass in a given direction parallel to the failure surface,

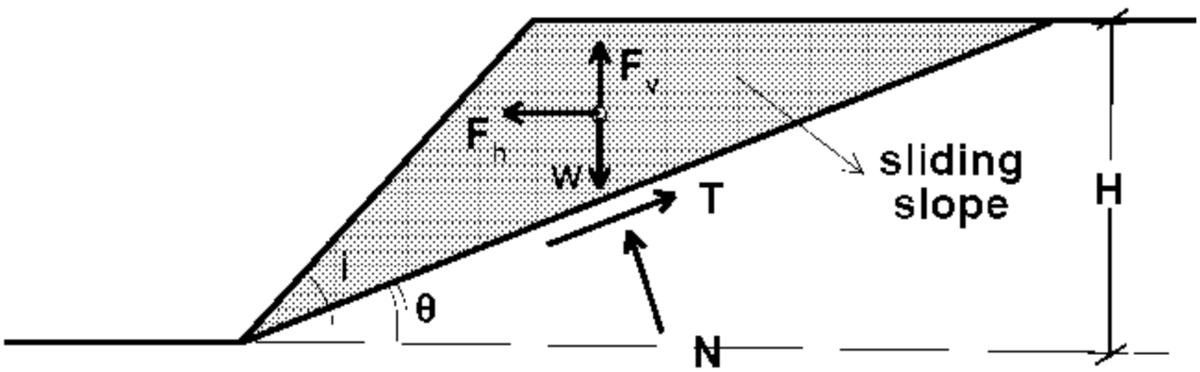

Figure 1: Forces acting on triangular wedge of soil above planar failure surface in pseudo static slope stability analysis.

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

Where c & Ø are the Mohr-Coulomb strength parameters that describe the shear strength on the failure plane and l_{ab} 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.
Many commercially available computed programs for limit equilibrium slope stability analysis have the option of performing pseudo static analyses.

III.SELECTION OF PSEUDO STATIC COEFFICIENT

The results of pseudo static analyses are critically dependent on the value of seismic coefficient,k_h . Selection of an appropriate pseudo static coefficient is the most important, and most difficult, aspect of a pseudo static stability analysis. The seismic coefficient controls the pseudo static force on the failure mass, so its value should be related to some measure of the amplitude of the inertial force induced in the potentially unstable material. If the slope material was rigid, the inertial force induced on a potential slide would be equal to the product of the actual horizontal acceleration and the mass of the unstable material. This inertial force would reach its maximum value when the horizontal acceleration reached its maximum value. In recognition of the factor that actual slopes are not rigid and that the peak acceleration exists for only a very short time, the pseudo static coefficients used in practice generally correspond to acceleration values well below a_{max} . Terzaghi (1950) originally suggested the use of k_h = 0.1 for “severe” earthquake (Rossi-Forel IX), k_h = 0.2 for “violent, destructive” earthquakes (Rossi-Forel X), and k_h = 0.5 for “catastrophic” earthquakes, Seed (1979) listed pseudo static design criteria for 14 dams in 10 seismically active countries; 12 required minimum factors of safety of 1.0 to 1.5 with pseudo static coefficients of 0.10 to 0.12. Marcuson (1981) suggested that appropriate pseudo static coefficients for dams should correspond to one-third to one-half of the maximum acceleration, including amplification or de-amplification effects to which the dam is subjected. Using shear beam models, Seed and Martin (1966) and Dakoulas and Gazetas (1986) showed that the inertial force on a potentially unstable slope in an earth dam depends on the response of the dam and that the average seismic

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coefficient for a deep failure surface is substantially smaller than that of a failure surface that does not extend for below the crest. Seed (1979) also indicated that deformations of earth dams constructed of ductile soils (defined as those that do not generate high pore pressure or show more than 15% strength loss upon cyclic loading) with crest acceleration less than 0.75g would be acceptably small for pseudo static factors of safety of at least 1.15 with k_h = 0.10 (M = 6.5) to k_h =0.15 (M = 8.25). This criteria would allow the use of pseudo static accelerations as small as 13 to 20% of the peak crest acceleration. Hynes-Grifin and Franklin (1984) applied the Newmark sliding block analysis described in the following section to over 350 accelerograms and concluded that earth dams with pseudo static factors of safety greater than 1.0 using $k_h = 0.5a_{max}/g$ would not develop “dangerously large” deformations. As the preceding discussion indicates, there are no hard and fast rules for selection of a pseudo static coefficient for design. It seems clear, however, that the pseudo static coefficient should be based on the actual anticipated level of acceleration in the failure mass (including any amplification or deamplification effects) and that is should correspond to some fraction of the anticipated peak acceleration. Although engineering judgments’ is required for all cases, the criteria of Hynes-Griffin and Franklin (1984) should be appropriate for most slopes.

IV. LIMITATIONS OF THE PSEUDO STATIC APPROACH

Representation of the complex, transient, dynamic effects of earthquake shaking by a single constant unidirectional pseudo static acceleration is obviously quite crude. Even in its infancy, the limitations of the pseudo static approach were clearly recognized. Terzaghi (1950) stated that “the concept it convey is earthquake effects on slope sis very inaccurate to say the least” and that a slope could be unstable even if the computed pseudo static factor of safety was greater than 1. Detailed analysis of historical and recent earthquake induced landslides (e.g., Seed et al., 1969, 1975; Marcuson et al., 1979) has illustrated significant shortcomings of the pseudo static approach. Experience has clearly shown, for example, that pseudo static analyses can be unreliable for soils that build up large pore pressures or show more than about 15% degradation of strength due to earthquake shaking. As illustrated in table 4, pseudo static analyses produced factors of safety well above 1 for a number of dams that later failed during earthquakes. These cases illustrate the inability of the pseudo static method to reliably evaluate the stability of slope susceptible to weakening instability. Nevertheless the pseudo static approach can provide at least a crude index of relative, if not absolute stability.

V. DISCUSSION

The pseudo static approach has a number of attractive features. The analysis is relatively simple and straightforward; indeed, its similarly to the static limit equilibrium analyses routinely conducted by geotechnical engineers makes its computations easy to understand and perform. It produces a scalar index of stability (the factor of safety) that is analogous to that produce by static stability. It must always be recognized, however, that ht eh accuracy of the pseudo static approach is governed by the accuracy with which the simple pseudo static inertial forces represent the complex dynamic inertial forces that actually exist in an earthquake. Difficulty in the assignment of appropriate pseudo static coefficients and in interpretation of pseudo static factors o safety, compiled with the development of more realistic methods of analysis, have reduced the use of the pseudo static approach for seismic slope stability analyses. Methods based on evaluation of permanent slope deformation, such as those described in the following sections, are being used increasingly for seismic slope stability analysis.

Dam	k_h	FS	Effect of Earthquakes
Sheffield Dam	0.10	1.2	Complete failure
Lower San Fernando Dam	0.15	1.3	Upstream slope failure
Upper San Fernando Dam	0-15	-2-2.5	Downstream shell, including crest slipped about 6 ft downstream
Tailings Dam (Japan)	0.20	-1.3	Failure of dam with release of tailings

TABLE 1 : Results of Pseudo static Analyses of Earth Dam That Failed during Earthquakes

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VI. 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.

$$FS = \frac{Available\ Resisting\ Force}{Static\ Driving\ Force}$$

VII. 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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