SEISMIC STABILITY ANALYSES OF SOIL SLOPES USING ANALYTICAL AND NUMERICAL APPROACHES

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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: seismic slope stability, pseudo-static, sliding block method, FLAC.

1. 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.

2. LITERATURE REVIEW

The behavior of slopes during an earthquake depends on the static gravitational pressure that exist before an earthquake and the horizontal and vertical stresses induced by the earthquake. Terzaghi (1950) gave the first explicit application of the pseudo-static approach for analyzing seismic slope stability problems. The effects of earthquake shaking were represented by constant horizontal or vertical accelerations that produced horizontal inertial forces, $F_h$, and vertical inertial forces $F_v$, acting through the centroid of the failure mass. A technique for estimating displacements generated during an earthquake, characterized by a given acceleration time history $a(t)$, was given by Newmark (1965) called the Sliding Block Procedure. The approach consisted of double integration of $a(t)$ above the threshold value $k_c g$, where $k_c$ was the critical acceleration coefficient and $g$ denoted acceleration due to gravity.

Cala and Flisiak (2001) computed the factor of safety of slopes having different geometry with FLAC, using the shear strength reduction technique, and compared the results with the conventional limit equilibrium analysis. Shahgoli et al. (2001) proposed the horizontal slice method for seismic analysis of reinforced soil slopes. The failure surface was assumed and the failure wedge was divided into a number of horizontal slices. A generalized framework, to incorporate twelve widely used existing limit equilibrium method of slices for slope stability analysis with a general slip surface, was formulated by Zhu et al. (2003). Kim and Sitar (2004) developed direct expressions of yield accelerations for some commonly used method of slope stability analysis. Baker et al. (2006) presented design charts for pseudo-static analysis of homogenous slopes applicable over a wide range of input parameters. Choudhury et al. (2007) used a simplified method of vertical slices to obtain the dynamic factor of safety of a sliding soil mass of a generalized earth slope. Interfacial forces between two consecutive slices were considered and limit equilibrium analysis for these slices were implemented under the influence of static forces and pseudo-static seismic forces. Choudhury (2008) proposed a two degree of freedom mass spring dashpot dynamic model to estimate the displacement time history response on soil slope under free and forced vibration modes of typical earthquake loading conditions.

3. PRESENT STUDY

In the present study, the analysis of soil slope under static and seismic loading using FLAC$^{2D}$ have been carried out. The model of the slope is composed of three regions: foundation, embankment and two canal-bunds. The side slope of the embankment and the canal-bunds have been kept constant at 2H: 1V. The foundation width, the depth of the embankment and canal-bunds has been kept constant at 10m, 6m and 6.5m respectively as shown in Fig. 1. The position of the ground water table (G.W.T.) has been kept at N.G.L., giving rise to the most critical case since it simulates undrained condition because of rapid loading within very short duration. The embankment and canal-bunds are composed of the same soil which has been kept constant for different stages of analysis. The foundation soil has been changed
varying from stiff clay, soft clay, dense sand and finally loose sand, each soil having different properties. The various soil properties considered for the present analysis have been tabulated in Table 1.

3.1 Static and Pseudo-static analysis

According to IS 1893: Part 1 (2002), 4 different zones have been selected for the present work with $k_v/k_h = 0.5$ for each zone. Stability analyses have been implemented at different stages of construction of the model, i.e., only embankment, empty canal bund and canal bund filled with water. In all the cases the dimensions of the model and position of the ground water table have been kept constant. Static and pseudo-static analyses have been carried out by varying the soil type and hence soil properties of the foundation soil. The results of the analysis have been obtained in terms of factor of safety and displacements along the face of the slope.

![Figure 1: Model comprising of foundation, embankment and canal-bund considered in the present study.](image)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Foundation Soil</th>
<th>Embankment Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stiff Clay</td>
<td>Soft Clay</td>
</tr>
<tr>
<td>Young’s Modulus $[E]$ (MPa)</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>Poisson’s Ratio $[\mu]$</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>Bulk Modulus $[K]$ (MPa)</td>
<td>83.3</td>
<td>50</td>
</tr>
<tr>
<td>Shear Modulus $[G]$ (MPa)</td>
<td>27.78</td>
<td>5.17</td>
</tr>
<tr>
<td>Unit weight $[\gamma]$ (kN/m$^3$)</td>
<td>17.3</td>
<td>14.2</td>
</tr>
<tr>
<td>Cohesion $[c]$ (kPa)</td>
<td>75</td>
<td>30</td>
</tr>
<tr>
<td>Friction angle $[\phi]$</td>
<td>5°</td>
<td>5°</td>
</tr>
<tr>
<td>Shear wave velocity $[V_s]$ (m/s)</td>
<td>126.7</td>
<td>67.90</td>
</tr>
</tbody>
</table>

3.2 Dynamic Analyses

After carrying out both static and pseudo-static analysis, dynamic analysis has been carried out by subjecting the developed model to an input motion. The input motion has been chosen by plotting the response spectrum curve for 2001 Bhuj earthquake motion.
3.2.1 Selection of Ground Motion

The input earthquake motion for the present study has been selected by plotting the response spectrum curve between spectral acceleration along the abscissa and time period (sec) along the ordinate as shown in Fig. 2.

The current model is considered as a linear single degree of freedom system and its vibration period ‘T’ is calculated according to the relation proposed by Bathurst and Hatami (1998),

\[
f = \frac{1}{4H} \sqrt{\frac{G}{\rho}} \left(1 + \frac{2}{1 - \mu} \frac{H}{B}\right)
\]

Eq. (1)

where, \( f \) is the fundamental frequency of the system, \( B \) and \( H \) are the width and height of the proposed model, \( G, \mu \) and \( \rho \) are the shear modulus, Poisson’s ratio and density of the soil respectively. Using the above relation, the value of \( T \) for the present study comes out to be 0.33 sec.

According to IS 1893 (Part 1): 2002 for medium soil sites and soft soil sites the value of spectral acceleration coefficient \( (S_a/g) \) for a vibration period of 0.33 sec is 2.50. Based on this result the response spectrum curve is prepared. The spectral acceleration data for 2001 Bhuj earthquake motion have been superimposed on the plotted curve. It is observed that the response spectrum curve for 2001 Bhuj earthquake motion falls within the IS codal provisions of soft and medium soil sites. Hence 2001 Bhuj earthquake motion, having a PGA of 0.106g, is selected as the input ground motion for the present study.

![Response Spectrum Curve](image)

**Figure 2:** Response Spectrum curve obtained in the present study

4. RESULTS AND DISCUSSIONS

The results of the analysis have been obtained in terms of factor of safety and permanent displacements along the face of the slope for static and pseudo-static cases and acceleration response in case of dynamic loading.
4.1 Results of Static and Pseudo-static Analyses

The results of static and pseudo-static analyses have been represented by graphs to illustrate the effects of types of soil, stages of construction and deformation mechanism on the factor of safety and displacement and hence on the stability of the proposed model, as shown in Figs. 3, 4, 5 and 6.

4.1.1 Effect of Stages of Construction

- The factor of safety for static case decreases from only embankment stage to full canal bund stage for a particular soil. The decrease is more for loose sand than for stiff clay due to high values of cohesion and other elastic properties of the former.
- In pseudo-static case with increase in \( k_h \) value the factor of safety also decreases with change in construction stage from only embankment to full canal bund. For example, in the canal full case, for dense sand as the foundation soil with \( k_h = 0.24 \) and \( k_v/k_h = 0.5 \), the factor of safety is 1.28 and rises to 1.58 for only embankment stage. However for soft clay under the same conditions, the rise is from 0.72 to 0.88. Thus different behavior of the soils is noticed.
- Displacement is decreasing as the cohesion value of the soil increases from loose sand to stiff clay. This is because with increase in cohesion the soil particles offer a greater resisting force which resists the displacement due to seismic force.

Figure 3: Variation of factor of safety with \( k_h \) for (a) only embankment stage (b) empty canal bund stage and (c) full canal bund stage of construction of model with \( k_v/k_h = 0.5 \).
• For the same value of cohesion the displacement for loose sand is more compared to dense sand which implies the elastic properties of soil plays an important role in slope stability analysis.
• The intersection of the line FOS=1 with each of the curves gives the yield acceleration coefficient for a particular soil for that particular construction stage.

4.1.2 Effect of Soil Type

![Diagrams showing variation of factor of safety with kₜ for different types of soil](image)

**Figure 4:** Variation of factor of safety with kₜ for (a) stiff clay (b) soft clay (c) dense sand and (d) loose sand as foundation soil.

• The factor of safety for static case is more for stiff clay and decreases in this order: stiff clay > dense sand > loose sand > soft clay
• For all types of soil with an increase in kₜ value, the factor of safety decreases. The trend of the curves obtained is very much identical.
• For a particular soil at a fixed kₜ value, factor of safety decreases for different stages of construction in the following order:
  - only embankment > empty canal bund > full canal bund
• The nature of curves obtained for full canal bund and empty canal bund stages are identical for both soft clay and stiff clay. It indicates that the addition of water does not cause any significant decrease in factor of safety. However for dense sand and loose sand there is a variation of factor of safety for these two stages.
4.1.3 Deformation Mechanism

Depending upon the intensity of seismic loading and the type of foundation soil, various deformation mechanisms of the present model, in the form of distorted mesh, are generated in FLAC, as shown in Fig. 5. Fig. 6 shows the displacement contours of the slope which explains the direction of particle motion under different intensities of seismic loading.

**Figure 5:** Distorted mesh of the model slope for *full canal bund* condition with soft clay as the foundation soil for $k_v/k_h = 0.5$

**Figure 6:** Displacement contours of the model slope for *full canal bund* condition with soft clay as the foundation soil for $k_v/k_h = 0.5$

4.2 Results of Dynamic Analyses

Dynamic analysis has been carried out using 2001 Bhuj motion having P.G.A. of 0.106g. The top left most and right most points of the left and right canal bund (marked as A and B respectively as shown in Fig. 1) has been chosen and the peak ground acceleration at these points due to the input motions have been noted. Results of dynamic analysis have been illustrated in the form of graphs as shown in Figs. 7, 8 and 9.

**Figure 7:** Typical displacement contours of the model slope subjected to a ground motion.
The vertical displacement of the model soil slope is less for Bhuj motion due to a low PGA of 0.106g.

The PGA graphs for position A and B subjected to Bhuj motion are identical, even though the canal bunds are of different width. This is due to low PGA of Bhuj motion and its dynamic effect is almost uniform over the entire structure.

For Bhuj motion the maximum ground acceleration at points A and B are obtained for foundation composed of dense sand and it decreases in the following order: dense sand > stiff clay > soft clay > loose sand

The amount of vertical displacement of the structure for a particular foundation soil subjected to a definite ground motion is independent of the hysteretic model used for the present analysis.

The ground accelerations at A and B are maximum when analysis is carried out with Hardin model of hysteretic damping.

The vertical displacement of the model slope is minimum for stiff clay foundation and maximum when foundation soil is loose sand.

5. SUMMARY AND CONCLUSIONS

From the various factor of safety contours it can be inferred that there is maximum displacement at the top of the slope which goes on decreasing towards the toe. There is almost negligible displacement at the bottom of the slope.

For any type of soil, factor of safety is maximum for only embankment during stage of construction and it decreases gradually and is lowest when the canal bunds are filled with water.
As cohesion of soil increases, displacement of slope under seismic excitation decreases. Hence to stabilize slope, increasing cohesive property of soil upto a limited amount can be good practice for mitigating slope instability under seismic load.

The displacement along the face of the slope increases with an increase in seismic horizontal acceleration and stages of construction. Therefore the stability of the slope is significantly challenged.

The present results also indicate that soft clay is a very poor foundation soil and it is not recommended as a foundation material for any construction purpose subjected to dynamic loads.

In the dynamic analysis, factor of safety is not obtained from FLAC analysis since direction of seismic force is not constant and changes with time.

For the dynamic analysis along with soil properties, seismic parameters like input ground motion and type of damping also govern the displacement of the slope.

Most of the results of dynamic analyses obtained from FLAC are found to be within permissible limits as per NEHRP (2000), which is 2 – 5 inches, i.e. 50 – 125 mm.

REFERENCES