Analysis of the behavior of embankment dams under seismic loading

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ABSTRACT

Researchers and Engineers are currently attempting to remediate earth dams to prevent damaging effects of potential seismic loading. The actual state of knowledge needs to be improved at least in the two following fields: soil properties and seismic response calculation techniques. Moreover, the effect of earthquake acceleration on the response of the dam needs to be further understood especially as far as amplification effects are concerned. In this paper, the assessment of the failure is given both from geotechnical as well seismic points of view. A comprehensive parametric study covering the effects of soil cohesion and soil friction angle on the values of yield accelerations is carried out. A dynamic factor of safety has been established as a function of earthquake acceleration. Furthermore, the outcomes on crest response spectra of input earthquake acceleration, soil shear wave velocity, and reduction of soil small strain shear modulus G_{max} with induced deformations is deeply analyzed. Results are promising and will be a contribution to the geotechnical earthquake dam engineering domain.

Keywords: earth dam, earthquake, acceleration amplification, shear modulus.

1 INTRODUCTION

Many researchers and geotechnical engineers have paid particular attention to the study of the dynamic behavior of soil structures in general and particularly earth or embankment dams (Newmark, 1965; Sarma, 1973; Makdisi and Seed, 1978; Seed et al. 1973, Marcusson, 1981; Choudhury et al., 2004; Wieland, 2003 and 2006; Lopez-Querol and Moreto, 2008). Significant progress, involving both a better assessment of seismic risk, and an experimental determination of the dynamic properties of the materials of the earth structure and its foundation was achieved in the field of earth dams (Seed, 1979; Sica et al. 2002; Sharp and Adalier, 2004). More sophisticated methods for assessment of dynamic behavior embankment dams are proposed.

Originally, the development of dam safety evaluation under earthquake loading has been strongly influenced by the seismic or dynamic analysis methods. The San Fernando earthquake in 1971 (California, USA), which severely damaged the lower dam of San Fernando, gave an important trigger in the implementation of the seismic analysis of dams (Triffunac, 1974; Seed et al. 1978; Seed et al. 1989; Blazquez and Lopez-Querol, 2007). Until recently, dams were built to withstand earthquakes through the use of a pseudo-static approach. For embankment dams, conventional slope stability calculations were carried out, taking into account the static inertia forces

equivalent to the sliding mass. However, this method has often proved inadequate because it cannot quantify the effects induced by earthquakes on dams.

Later, when a large number of dams were seriously affected by the action of earthquakes, major developments relating to the definition of the cyclic behavior of soils and dams response to seismic loading have been made. Among the methods for modeling the response of materials to cyclic loading that are currently widely used, one may refer to the method based on equivalent linear characteristic values of the soil.

In general, for earth dams, a two-dimensional finite elements model is sufficient. Solicitations may be considered parallel to the main axes of the earth structure. The finite elements calculations are based on dividing the earth structure studied in several elements interconnected by nodes. The movements are calculated using the equilibrium conditions and material behavior laws in each node. Stresses and deformations of the elements result from displacements in the nodes.

In this study, important topics related to the analysis of seismic stability of earth dams are dealt with. Seismic stability analysis procedures will be presented. Next, the effects induced by earthquakes on dams will be discussed based on a sensitivity study. It is proved that the seismic resistance of earth dams depends on several characteristics related to the mechanical properties of the soil as well as seismic loads.

2 METHODOLOGY AND CASE STUDY

In order to highlight the important effect of geotechnical properties on the behavior of an embankment dam under earthquake loading, the lower San Fernando dam will be considered in the present paper. Our aim is to give our analysis a broad application and to share our conclusions with the exhaustive reassessments of the stability of the lower San Fernando dam that already exist in the literature. It is essential to recall that the San Fernando earthquake that hit southern California on February 9, 1971, had a very significant effect on the two dams of San Fernando, and the lower San Fernando Dam has suffered severe damage particularly on its upstream side. During the earthquake, an important shift has occurred on the upstream face of the lower dam, carrying its peak and 9.2 meters of material from its downstream slope. The epicenter stood at nearly 13 km north-east of the site. Recordings indicated that the ground movements in the vicinity of the dam had a peak acceleration of about 0.55g to 0.6g.

For achieving the current study, the lower San Fernando dam is initially analyzed under static conditions. The treated soil is modeled as a linear-elastic material whose characteristics are the following: the unit weight (γ kN/m³), Young's modulus (E kPa), Poisson's ratio (ν), cohesion (c kPa) and friction angle (ϕ degree). These settings will be suitably chosen. Two soil types will be considered: the embankment fill ($c = 97.7$ kPa; $\phi = 10$ deg; $E = 176,800$ kPa; $\nu = 0.3$) and alluvium ($c = 150$ kPa; $\phi = 30$ deg; $E = 638,400$ kPa; $\nu = 0.3$). The dam will be just under its own weight. The criterion of Mohr-Coulomb is used. These materials properties are identical to those considered by Karray et al. (2001), and they have been selected to validate the results obtained in this study with those already published. This model will be used to establish initial conditions for deformations and stresses. In the stability analysis, the method of Morgenstern-Price will be considered. Geotechnical parameters are then modified to check the variation of the static safety factor.

In the second part of this research, a horizontal seismic coefficient k_h is applied to the sliding slope to study different aspects. To understand the pseudo-static safety factor, an analysis of the effect of geotechnical parameters based on the seismic coefficient will be realized. The horizontal acceleration will cause the instability of the slope of the dam. Soil cohesion will be modified to examine its effect on the value of this critical yield acceleration.

And afterwards, in the third part the dynamic analysis is conducted using the finite elements method. Equivalent linear model will be considered for the dynamic calculations of the dam. This is the most common model used by geotechnical earthquake engineers to reproduce the transmission of the waves in

the different soil layers. The actual non-linear behavior of the shear modulus and the damping factor in dynamic loading conditions can be simulated approximately by the equivalent linear analysis. In an equivalent linear analysis, the shear modulus G and the damping factor D are used for a dynamic analysis step. The new shear modulus G and damping ratio D are calculated from the measured cyclic deformation.

The earthquake accelerogram used is defined as a movement imposed on the bedrock. This is the El Centro earthquake that took place on May 18, 1940 at the Imperial Valley in the US. It has a magnitude 7.1 and the duration of the earthquake is 10s.

In the dynamic analysis, a variation of different parameters is carried out to determine their influence on the seismic behavior of the dam. The covered themes are presented as follows: variation of the safety factor based on the maximum acceleration the rock; variation of the safety factor with time of the quake; variation of the safety factor according to the maximum deformation of the dam; variation of the displacement at the base and the top of the slope (crest) based on the maximum acceleration of the rock; evolution of the amplification factor based on the maximum acceleration the rock; variation of the spectral acceleration as a function of the shear wave velocity; variation of the spectral acceleration with maximum acceleration on rock; ratio of response spectra as a function of shear wave velocity, maximum acceleration on rock and plasticity of soils.

The seismic analysis of the dam remains far required for the design and sizing of future earth dams. The lower dam of San Fernando became a famous case in the history of seismic geotechnical engineering. Indeed, the dam became the subject of several research projects and publications. Based on the data of the dam of San Fernando, this work aims on contributing to the understanding of the role of geotechnical parameters in the stability of the dam under seismic loading.

3 ANALYSIS AND DISCUSSION

The lower San Fernando dam has a height of 44m. The upstream slope is 1H: 2.5V and the downstream slope is 1H: 4.5V. A finite elements mesh comprising 510 elements as well as 551 nodes was used. Fig. 1 gives a presentation of shape of the analyzed dam.

3.1 Static analysis

The static limit equilibrium analysis based on Morgenstern and Price approach gave a factor of safety of 2.389. Fig 2 shows the most critical failure surface under static loading. Keeping all data constant and changing the cohesion from 30 kPa to 120 kPa increases the safety factor from 1.45 to 2.55, while increasing the friction angle from 10 deg to 40 deg (with cohesion = 0), the safety factor increases from 2.0 to 3.5.

3.2 Pseudo Static analysis

The critical failure surface gives a lower factor of safety with increasing acceleration factor k . However, these factors of safety remain greater than 1 till reaching an acceleration factor k of 0.412 (corresponding to $a_{\max} = 0.412g$) with a factor of safety equal to 1. This acceleration is called the yield acceleration. Fig. 3 shows the variation of yield acceleration with cohesion. The yield acceleration becomes higher with increasing values of soil cohesion; hence, the value of yield acceleration is very sensitive to soil cohesion. Soil cohesion is difficult to measure unless we have undisturbed samples. This explains the significance of measuring correctly soil properties.

Fig. 1. Cross section of the analyzed dam.

Fig. 2. Most critical surface under static loading conditions.

Fig. 3. Yield acceleration of the slope as function of cohesion.

3.3 Dynamic analysis

A detailed dynamic finite element analysis is carried out with the aim of understanding the effect of an earthquake on embankment dam. For the analysis, the El Centro accelerogram shown in Fig. 4 is used.

One of the objectives of the present study is to examine the soil behavior on the crest. Fig. 5 shows the crest maximal acceleration as a function of maximum acceleration on rock. Again, soil properties play a major role in determining soil response to earthquake loading. It is obvious that the highest amplification (ratio of crest acceleration to base rock acceleration) is measured in the case of small rock accelerations (Rahhal and Lefebvre, 2006b). Fig. 6 gives the maximum crest displacement as a function of maximum rock acceleration. It is observed that beyond an acceleration of 0.1g, higher displacements are obtained.

Fig. 4. El Centro earthquake acceleration as a function of time.

Fig. 5. Maximum acceleration at the crest as a function of maximum acceleration on the rock.

Fig. 6. Maximum displacement at the crest as a function of maximum acceleration on the rock.

Another aspect that was studied in this paper is the dynamic factor of safety. In fact, this dynamic factor of security is measured during the earthquake loading and is not constant. This is the importance of using a dynamic approach because the dynamic factor of safety may be monitored and one may detect at what time during the loading, the safety is at the lowest level. This is an advantage when comparing with the pseudo-static method where the factor of safety is approximate and applied safely in the case of low accelerations. Fig.7 shows that for accelerations greater than 0.2g, the dynamic approach should be considered because it is more conservative, and smaller factors of safety are measured. Fig. 8 shows the variation of the dynamic factor of safety with the crest displacement. Rahhal (2014) investigated the relevance of the dynamic factor in a slope stability analysis.

Fig. 7. Dynamic and pseudo-static factor of safety as a function of acceleration.

Fig. 8. Dynamic factor of safety as a function of displacement.

As far as the acceleration response spectra is concerned, different rock accelerations were tested to see how the crest acceleration response spectra changed depending on the level of earthquake loading. As it may be seen from Fig. 9, the highest amplifications are obtained in the presence of higher rock accelerations. The two different peaks identified in the response spectra correspond to the first and second mode of resonance of the analyzed embankment.

In the same framework, different shear wave velocities were used to measure the soil response to earthquake loading. Shear wave velocities were chosen considering a homogeneous embankment and values between 200 m/s and 500 m/s. The value of V_s indicates the state of rigidity of the soil. Fig. 10 shows that higher amplifications in the crest acceleration response spectra are obtained in the presence of higher shear wave velocities. The peaks appear to be positioned for the same periods as the ones in Fig. 9.

Fig. 9. Crest Response Spectra for different rock accelerations.

Fig. 10. Crest Response Spectra for different shear wave velocities V_s .

Finally, an attempt was made by the authors to explain the relevance of using correct $G/G_{\max}$ curves as a function of the induced cyclic shear strain. It is known that small strain shear modulus is of upmost importance in characterizing soil behavior under earthquake loading. The value of $G_{\max}$ is related to soil rigidity, the same way the value of shear wave velocity V_s does. Relations between $G_{\max}$ and V_s have been presented by Lefebvre et al. (1994). But in the presence of severe earthquakes, the value of $G_{\max}$ diminishes as a function of the induced cyclic shear strain. The curves giving the relations between $G/G_{\max}$ and cyclic shear strain have been proposed by Rahhal and Lefebvre (2004, 2006a). A special attention is given to the threshold cyclic shear strain (TCSS), a value below which the $G/G_{\max}$ is equal to unity or 100%. When the cyclic shear strain becomes greater than the TCSS, the shear modulus decreases rapidly. The decrease in $G_{\max}$ takes place at smaller TCSS in the case of sands than in the case of clays (Rahhal and Lefebvre, 2004 and 2006a). And in the case of clays, the plasticity index controls the decrease of $G/G_{\max}$: the more plastic the clay is, the higher the TCSS and the smaller the decrease $G/G_{\max}$. Fig. 11 and 12 show the relation between crest acceleration and displacement with $G/G_{\max}$.

When the ratio $G/G_{\max}$ remains equal to unity for higher cyclic shear strain, the soil starts losing its rigidity at higher deformations and this may be explained with the higher displacements measured. As far as crest acceleration is concerned, lower accelerations are measured when $G/G_{\max}$ has already diminished, implying that acceleration amplification may be very important in the case where the shear modulus does not lose its value until reaching high cyclic shear strains

levels. At this point, we may emphasize that crest acceleration and displacement will be much higher in the soils where the threshold cyclic shear strain has a more significant value. This is the case of highly plastic clays. Actually, these clays are prone to acceleration amplifications during earthquakes. This fact has been evidenced during many earthquakes especially the very famous Mexico earthquake in 1985.

Fig. 11. Maximum crest acceleration as a function of $G/G_{\max}$.

Fig. 12. Maximum crest displacement as a function of $G/G_{\max}$.

What is interesting to observe in the above mentioned results is that a 10% decrease in shear modulus ($G/G_{\max}$ dropping from 100% to 90%) yields crest acceleration decreasing from 0.85g to 0.35g, and crest displacement decreasing from 0.075 m to 0.050 m.

These observations are to be related with earlier observed results in this paper where higher spectral accelerations were measured in the presence of higher shear wave velocities in the embankment. The analysis brings to light the importance of having laboratory and in situ data including shear modulus $G_{\max}$ values as well as $G/G_{\max}$ ratio behavior with induced cyclic shear strain in the soil.

4 CONCLUSIONS

The present study uses the example of the lower San Fernando dam to put forward the importance of the geotechnical earthquake engineering field. The analysis carried out highlights the significance of considering a dynamic analysis, as far as factors of safety are concerned. The factor of safety obtained in the dynamic analysis is more representative for what is happening during earthquake loading. Another issue was to emphasize on the amplification of acceleration through the embankment, and trying to relate it to the rigidity of the soil. Finally the decrease in shear modulus $G_{\max}$ as a function of the induced cyclic shear strain was discussed. The crest acceleration as well as the crest displacement are both function of the decrease in shear modulus model that is selected to represent the soil. Results obtained in the present paper should contribute to the actual understanding of the effects of soil properties on the earth dam seismic response. More results are forthcoming.

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