Numerical Analysis of Slopes Stability During Earthquakes: Case of Earth Dam

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Abstract

Many earth dams have been important failures during earthquakes due to the increase of pore water pressure during seismic loading. Recent publications of the International Commission on Large Dams (ICOLD) show that the most significant accidents concerns embankment dams. After analyzing of the behavior of embankment dams under severe earthquakes, major advances have been attained in the understanding of the seismic action on dams. The present study concerns numerical analysis of the seismic response of earth dams. The procedure uses a nonlinear stress-strain relation incorporated into the code FLAC2D based on the finite difference method. This analysis provides the variation of the pore water pressure and horizontal displacement.

Keywords: Earthquake, Numerical Analysis, FLAC2D, Displacement, Earth Dam - Pore Water Pressure.

1. Introduction

Earthquakes, because of their nature, are complex and dangerous phenomena. During the last century, their numbers are amplified, and their effects have proved disastrous. Thus several countries including ours, namely Algeria, are faced with this problem and seek to improve the design to deal with these earthquakes. Predicting the response of an earth dam during an earthquake is a major challenge. Factors such as dam characteristics, site conditions, and seismic loading characteristics strongly affect the dynamic responses of dams.

The stability of earth dams subjected to seismic action can be assessed by different approaches, Gazetas (1987) discussed the historical developments of theoretical methods for estimating the dynamic response of earth dams to earthquake ground excitation and outlined their major features, their benefits and restrictions. After the earthquake of 1971 San Fernando, California, major advances were achieved in the comprehension of earthquake action on dams (USCOLD 1992). Zeghal et al. (1992) worked on the elastic-plastic dynamic behavior of earth dams by the finite element method. Cascone et al. (2003) studied the dynamic response of the earth dam of Marana Capacciotti (Italy) by comparing two numerical methods.

The publications of the International Commission on Large Dams (ICOLD) show that the most significant accidents concerns embankment dams, it retains much studied failure the embankment dam of San Fernando (9 February 1971). The Santa Barbara earthquake (1925, M 6.3) caused catastrophic slope sliding failure of the Sheffield Dam, CA. This was the first recognition that shaking of embankments with low relative density materials may cause liquefaction failures. A wide region around the San Francisco Bay was affected during the 1989 Loma Prieta earthquake (M 7.1). About 100 embankment dams of various sizes were within 100 km of the epicenter.

The methods commonly used to study the seismic response of earth dams are derived in three parts: simplified methods, empirical methods and numerical methods. Numerical modelling techniques were first applied to the dynamic analysis of embankment dams by Clough and Chopra (1966). This was followed by major improvements by Ghaboussi (1967), Schnabel et al. (1972), Idriss et al. (1973), Martin et al. (1975), White et al. (1979), Zienkiewicz and Shiomi (1984), Finn et al. (1986), Medina et al. (1990) and Li et al. (1992).

The paper presents a numerical study of the seismic behavior of earth dams subjected to real earthquake records using fully nonlinear dynamic analysis and consider the water-dam interaction. The analysis uses a stress-strain relation integrated into the finite difference computer program FLAC2D.

2. Earth dam under consideration and numerical model

The selected problem is a simplified representation of typical earth dam geometry. The dam section assumed in the present study is a zone section with clay core and heterogeneous foundation as shown in Fig. 1. Geotechnical properties used in the analyses are presented in Table 1 for foundation soil and earth dam materials (Mohr Coulomb).
The first step for the dynamic numerical analysis of the dam sections involves the establishment of initial stresses and pore pressure distribution in the embankment dam body and foundation soil under static condition. The second step involves dynamic numerical analysis using acceleration time history record of the earthquake data.

**Figure 1. Geometry of earth dam**

**Table 1. Properties of foundation and earth dam soils**

<table>
<thead>
<tr>
<th></th>
<th>Soil 1</th>
<th>Soil 2</th>
<th>Soil 3</th>
<th>Soil 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (Dry density, Kg/m$^3$)</td>
<td>2000</td>
<td>2000</td>
<td>1800</td>
<td>1900</td>
</tr>
<tr>
<td>$E$ (Young’s Modulus, MPa)</td>
<td>610</td>
<td>610</td>
<td>328</td>
<td>328</td>
</tr>
<tr>
<td>$\nu$ (Poisson’s ratio)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$C$ (Cohesion, KPa)</td>
<td>4.0</td>
<td>8.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$\phi$ (Friction angle, °)</td>
<td>40</td>
<td>40</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>$\psi$ (Dilation angle, °)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Permeability (m/s)</td>
<td>$10^{-6}$</td>
<td>$10^{-7}$</td>
<td>$10^{-6}$</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
</table>

The size of each grid depends on the wave propagation velocity, i.e., shear wave velocity ($C_s$) in the material and the frequency content of the input motion and the size of the grid ($\Delta l$) should be such that the wave transmission is accurate. The cut off frequency ($f_c$) of the earthquake motion can be obtained using equation (1).

$$f_c = \frac{C_s}{10\Delta l}$$

The dynamic input motion is given as a stress boundary in order to apply “quiet boundary” condition along the same boundary as the dynamic input (Lysmer and Kuhlemeyer, 1969). The quiet boundary scheme involves dashpots attached independently to the boundary in the normal and shear directions in order to absorb most of the energy in the waves approaching to the boundary.

The dynamic damping in the model is provided by the Rayleigh damping option available in FLAC. Rayleigh damping is originally used in the analysis of structures and elastic continua, to damp the natural oscillation modes of the system. Rayleigh damping of $R_d = 6.5\%$ is adopted in the analyses to compensate for the energy dissipation through the medium (ITASCA Consulting Group, Inc. 2005).

The earth dam is subjected to seismic loading representative of the 1987 Loma Prieta earthquake in California. The earthquake input motion for this model is taken from that recorded at the left abutment of the Lexington Dam. The estimated peak acceleration is approximately 0.17 g, and the duration is approximately 40 sec. The record is shown in Figure 2. A Fast Fourier Transform analysis of the acceleration results in a power spectrum as shown in Figure 3. This figure indicates that the highest frequency is less than 5 Hz.
3. Results and discussion

The response of the interaction dam-reservoir at the maximum excitation is presented in Figure 4, there is a significant lateral deformation in the dam away from the foundation and at the upper part of the dam, such that the maximum displacement is measured at the crest of the dam and reaches a maximum value of 0.342 m. Figure 5 shows the failure mechanism (shear-strain deformations), there is a concentration of deformation in the upstream of the dam which indicates that in this region there is a risk of soil instability.
Figure 6 shows the seismic response of the dam on the variation of the acceleration, velocity and the displacement (amplification in the horizontal direction) for the node located at the crest of the dam, we observe an amplification of acceleration $a_{\text{max}} = 4.50 \text{ m/s}^2$ and velocity even for $v_{\text{max}} = 0.642 \text{ m/s}$. For horizontal displacements we notice at the end of seismic loading a residual (permanent) displacement of 0.135 m.

Figure 7 shows a comparison between the water-dam interaction and without water analyses at the maximum of horizontal displacement at the height of the dam and the crest. It can be observed that the horizontal displacement of the water-dam interaction is bigger and reach a maximum value of 0.342 m at the crest of the dam. As seen from this figure, it displays significant increase in the upper of the earth dam.
Figure 7. Variation of the maximum horizontal displacement

Figure 8 shows the location of the zones concerned by plastic deformation at the peak of the seismic excitation. It can be observed that the distribution of plasticity induced in the crest and the upstream of the dam. That in their regions there is a risk of soil instability. The majority part of the dam remains in the elastic domain.

Figure 8. Distribution of plasticity in the earth dam
Figure 9 shows the pore pressure ratio at five positions of the dam: the base, the middle height and the top of foundation. This variation follows that of the input motion: an important increase/decrease in a range of 5 to 10 seconds followed by stabilization. The numerical analysis procedure well captures the most important feature, i.e., pore pressure generation capability during seismic loading.

![Figure 9](image)

**Figure 9.** Time history pore pressure at different points of earth dam

4. Conclusion

This paper presents numerical analysis of earthquake effects on earth dams based on finite difference method using FLAC2D code. A simple elastic perfectly plastic constitutive model with Mohr Coulomb failure criterion is used to describe the stress strain response of the soil. Analyses were conducted for real earthquake records (Loma Prieta earthquake). The example is a simplified representation of typical earth dam geometry.

The influence of the water-dam interaction shows that the seismic loading induces significant lateral deformation in the dam away from the foundation. The distribution of plasticity induced in the crest and the upstream of the dam. The numerical analysis of water-dam interaction is recommended for the seismic analysis of the earth dam, because it takes into consideration the water flow in the dam.

The analysis should also be conducted with more realistic geometries and soil properties. In conclusion we recommend making a specific study using FLAC3D code with comparisons between the analytical and empirical methods to understand the seismic behavior of earth dams.

References


