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Finite Difference Method of the Seismic Analysis of Earth Dam

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Abstract**—**Many embankment dams have suffered failures during earthquakes due to the increase of pore water pressure under seismic loading. 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, Embankment Dam, pore water pressure.

I. 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 Algeria are faced with this problem and they 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; [1] 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 [2]. Zeghal et al. [3] worked on the elastic-plastic dynamic behavior of earth dams by the finite element method. Cascone et al. [4] studied the dynamic response of the earth dam of Marana Capacciotti (Italy) by comparing two numerical methods.

A large number of earth dams in earthquake-prone areas have suffered partial or total damage. Recent 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 1925 Santa Barbara earthquake (M 6.3) earthquake 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 [5]. This was followed by major improvements by [6]-[14].

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.

II. 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 I 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.

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 (Δl) should be such that the wave transmission is accurate.

The cut off frequency (f_C) of the earthquake motion can be obtained using (1):

$$f_C = \frac{C_S}{10\Delta l} \tag{1}$$

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 [15]. 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.

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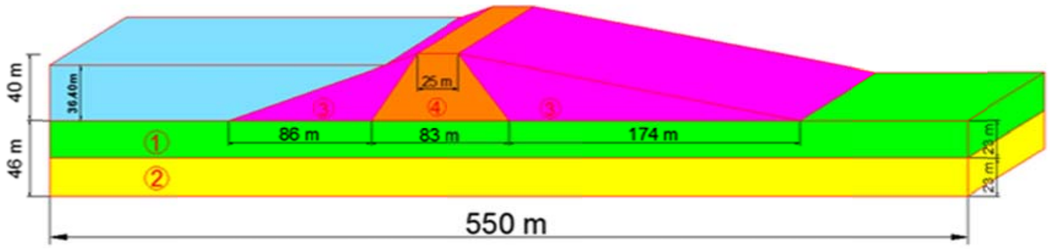


Fig. 1 Geometry of earth dam

TABLE I
PROPERTIES OF FOUNDATION AND EARTH DAM SOILS

		Soil 1	Soil 2	Soil 3	Soil 4
γ	dry density (Kg/m^3)	2000	2000	1800	1900
E	young's Modulus (MPa)	610	610	328	328
υ	poisson's ratio	0.3	0.3	0.3	0.3
C	cohesion (KPa)	4.0	8.0	6.0	6.0
Φ	friction angle (°)	40	40	35	35
ψ	dilation angle (°)	0.0	0.0	0.0	0.0
	porosity	0.3	0.3	0.3	0.3
	permeability (m/s)	10^{-6}	10^{-7}	10^{-6}	10^{-7}

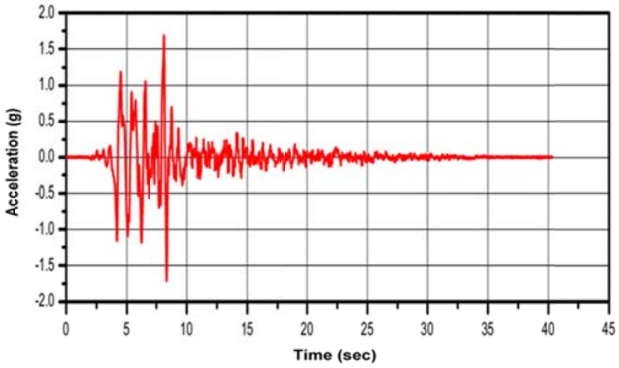


Fig. 2 Acceleration time histories (Loma Prieta earthquake)

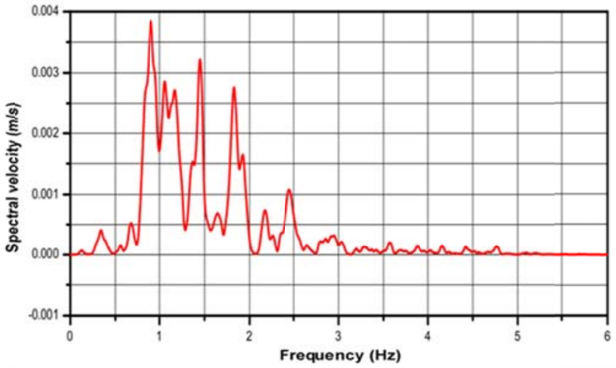


Fig. 3 Fourier spectra of velocity component

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 [16].

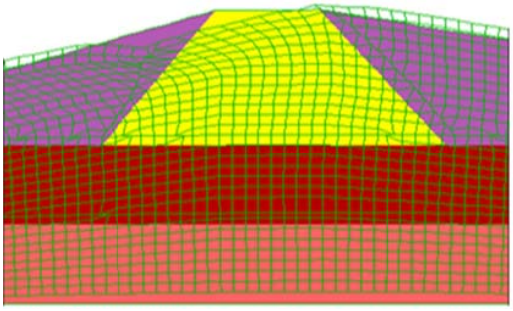


Fig. 4 Close-up view of the deformation of earth dam

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 Fig. 2. A Fast Fourier Transform analysis of the acceleration results in a power spectrum as shown in Fig. 3. This figure indicates that the highest frequency is less than5 Hz.

III. RESULTS AND DISCUSSION

The response of earth dam at the maximum excitation is presented in Fig. 4. It shows an increase in the horizontal amplification at the upper part of the dam. Fig. 5 shows the failure mechanism. It shows that in this part there is a risk instability of soil.

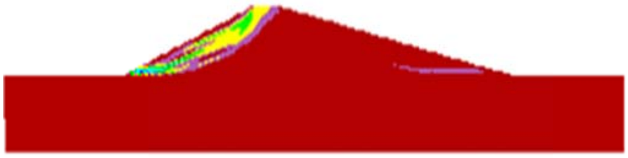
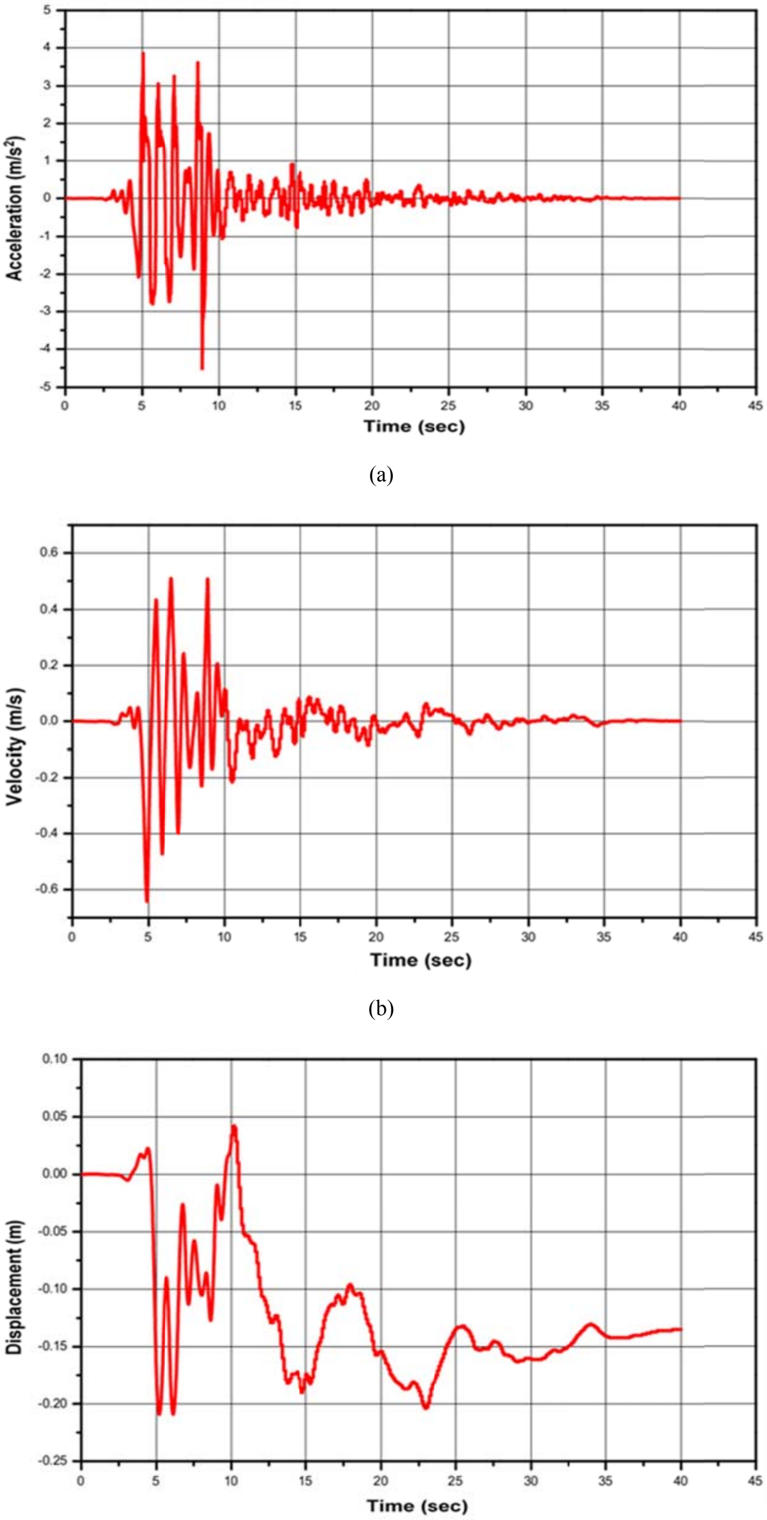


Fig. 5 Failure mechanism (shear deformations)

Fig. 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_{max} = 4.50 m/s^2 and velocity even for v_{max} = 0642 m/s. For horizontal displacements, we notice at the end of seismic loading a residual (permanent) displacement of 0.135 m.



(a)

(b)

(c)

Fig. 6. Variation of the amplification (acceleration, velocity and displacement)

Fig. 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.

Fig. 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.

Fig. 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.

IV. 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.

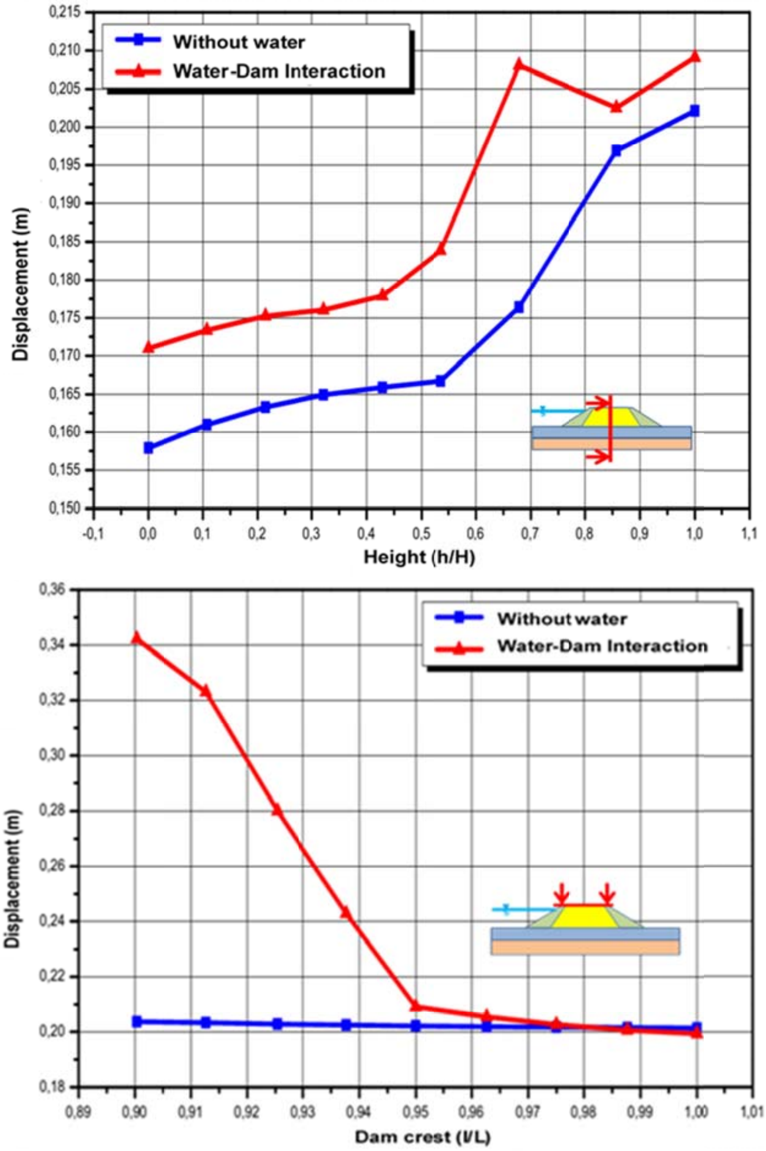


Fig. 7 Variation of the maximum horizontal displacement

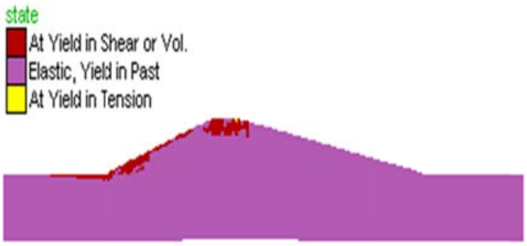


Fig. 8 Distribution of plasticity in the earth dam

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 its 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.

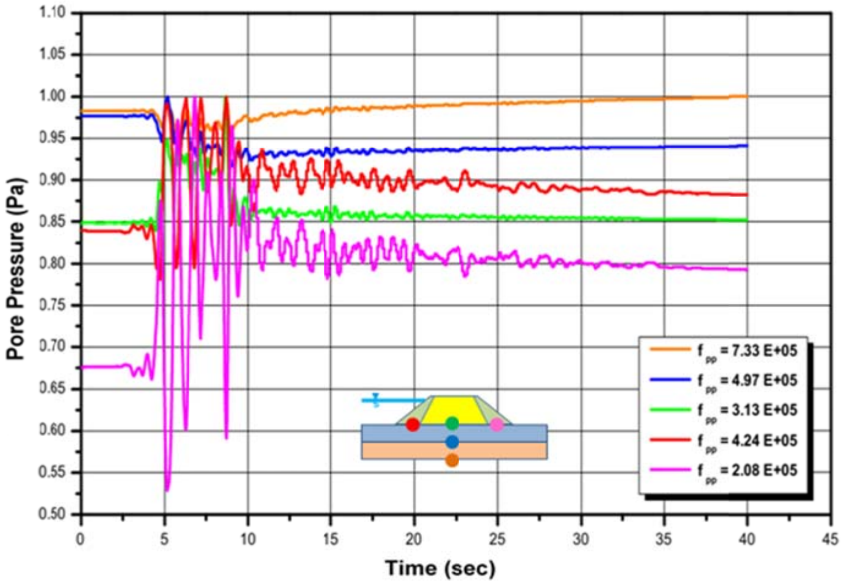


Fig. 9 Time history pore pressure at different points of earth dam

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