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THE EFFECT OF EARTHQUAKE ACCELERATION RECORDS AND THEIR EQUIVALENT DYNAMIC LOADS ON EARTH-DAM RESPONSES

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This paper studies the dynamic behavior of a typical earth-dam using non-linear dynamic analysis under different earthquake records. One of the most important components in non-linear dynamic analysis of earth-dams is the evaluation of their stability considering the permanent displacement as a performance indicator. Varieties in acceleration time histories coupled with various geometry and heterogeneous material properties of the earth structures lead to diversity in non-linear responses under different real accelerograms. In this study, an equivalent harmonic load related to earthquake records with specific magnitude and frequency is defined and is applied to a 70m tall earth-dam during four real acceleration time histories. The induced-displacements were then measured under each real time record along with their defined harmonic loads at the dam crest. The resulting displacements and their harmonic equivalent loads are compared showing a good agreement in their deformations at the crest. Appropriate parameters including equivalent number of cycles and peak ground acceleration (PGA) for unique equivalent harmonic load were obtained based on the response analyses.

Keywords: Displacement analysis, Non-linear dynamic response, Time history.

1 INTRODUCTION

Evaluating the effect of an earthquake on the behavior of earth structures, such as earth-dams, is important since structural failure due to large displacements can result in significant damage and loss of life. There are different dynamic factors that can significantly influence the behavior of earth structures. In dynamic analysis, induced permanent displacement has been considered as one of the important indicators to measure the safety and stability of earth-dams during earthquakes (Siyahi and Arsalan 2008). To numerically predict dynamic deformations, the underlying soil properties and earthquake characteristics should be defined. Important dynamic parameters in numerical simulations of earth structures consist of acceleration, speed, frequency contents, and the duration of earthquakes. All these parameters could be affected by characteristics and source of earthquakes as well as the distance from the source (Refahi 2006). Seed *et al.* (1975) have shown that the spectrum response can be reduced in soft soils, compared with hard deep soils, leading to an extension in the maximum desired spectrum response. They have also concluded that for earthquakes with small to average maximum acceleration (less than 0.4) the maximum induced acceleration in soft soils is higher than those in rock and hard soil deposits. However, for the earthquakes with larger accelerations, the recoded accelerations in soft soils are typically less than those in rocks (Rao 2003). This is attributed usually to the non-linear behavior and low stiffness in softer soils.

The selection of earthquake records for non-linear dynamic analyses mostly depends on the importance of the site, the structure, and the type of analysis. Hence, in order to choose appropriate acceleration time history, the primary design and risk analyses should be considered. Krinitszky and Chang (1979) pointed out that the scaling factor used for earthquake records should be as much as close to 1, while it is between 0.15 and 4. Vanmarcke (1979) stated that the important differences, such as frequency content and earthquake duration, could not be captured accurately through scaling of only the acceleration time history. Krinitszky and Chang (1979) proposed a suitable range for linear elastic analyses, where the range was limited to about 0.5 to 2 for the liquefied soils. Studies on Sheffield and San-Fernando earthquakes have shown that static analyses could not predict the failure of dams sufficiently. It has been also reported that different dynamic responses in soils could be expected in the models due to the uncertainties of earthquake loads, heterogeneity of the materials, and the simplifying assumptions used in the dynamic analysis (Parish 2007).

In this study, first an equivalent harmonic load related to each earthquake record with specific magnitude and frequency is defined based on the method suggested by Seed *et al.* (1975). The geometry and geotechnical properties of material used in in the body of earth-dam are then introduced. The results obtained from non-linear analyses under earthquakes are subsequently investigated and equivalent harmonic loads are defined and presented. Finally, the results of both earthquake records and their harmonic loads are compared.

2 CONSTITUTIVE MODEL AND GEOMETRY

Numerical analyses are carried out using the finite difference program FLAC^{2D} 5.0 based on a continuum finite difference discretization. The nonlinear behavior of dam materials is described using a simple non-associated Mohr-Coulomb criterion. In dynamic analyses, damping must be appropriate in shape and magnitude to reproduce energy dissipation that can develop during loading and unloading cycles due to material nonlinear behavior. For this purpose, hysteretic damping is applied in the elastic range; while, the natural damping provided by the constitutive model is applied in the inelastic range. All the dynamic analyses have been carried out using a dam 70 meters in height. The slopes of the upstream and downstream shells are 1V: 2H and 1V: 1.9H; respectively. The ratio of crest length to height of dam meets the stability standards for two dimensional analyses.

The dam is discretized into plain strain finite difference grids. The geometry and finite difference element mesh is illustrated in Figure 1. Krinitzsky (2002) showed that maximum mesh dimension must be less than approximately one-tenth of the wave length associated with the highest frequency component of the input earthquake records in order to have an accurate representation of wave transmission through the model. The geometry is further discretized using various mesh sizes due to the stress concentration. So, the upper part at near the crest incorporates finer elements than other places. To reduce the reflection of wave propagation from left and right boundaries when it travels, free-field elements are applied. These elements are available in FLAC^{2D} 5.0 and used in the boundaries of the model for dynamic analysis.

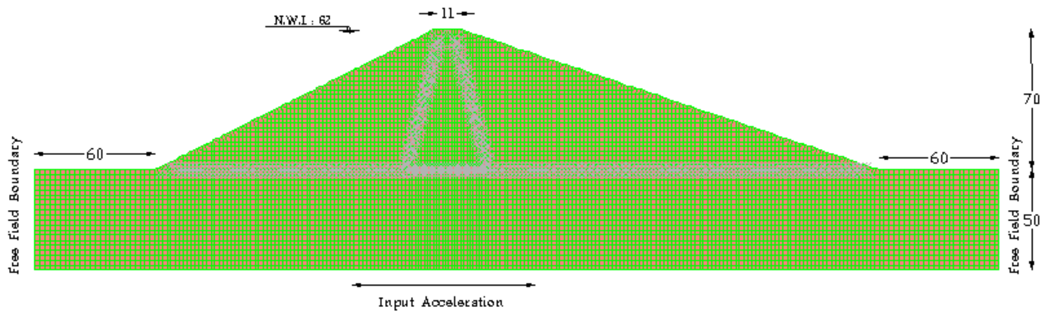

Figure 1. Dimensions of the model and finite difference mesh.

3 GEOTECHNICAL DESIGN PARAMETERS

Mechanical properties of materials in different areas of dam body are presented in Table 1.

Table 1. Materials properties in dam body and foundation of proposed model (Baris and Darendeli 2000).

Parameters	*Unit*	*Shell*	*Core*	*Foundation*
Dry density	*kN/m^3*	20	17	23
Friction Angle	*(Deg)*	40	25	40
Cohesion	*kN/m^2*	0	30	35
Porosity	-	0.25	0.3	0.15
Elastic module	m^2	50000	25000	100000

4 CHARACTERISTIC OF EQUIVALENT HARMONIC LOADS

Each acceleration time history often has three stages. First and third stage includes mild and weak earthquake motions whereas; movements in the second stage consist of moderate to severe vibration. Since cyclic loads may lead to numerical unsuitability due to sudden stimulation at the beginning of the analyses, an equivalent harmonic load is defined in this paper according to Eq. (1). This form of harmonic load represents a similar movement characteristic trend to the earthquake time histories. It is also more compatible with numerical analyses in terms of time and effect. Number of cycles as well as the shape of each equivalent load are developed using MATLAB code. For each earthquake record, accelerations are divided into the maximum acceleration amplitude at every 0.01 second. Then, the equivalent number of each ratio is found utilizing the graph represented in Seed's graph (1975). There are three main factors that are used in defining the equivalent harmonic load. These include the maximum acceleration amplitude, time duration, and the predominant period. Here, all selected earthquake records are recorded on the rock being compatible with graphs suggested by Seed *et al.* (1975).

$$Y = 2a_{hmax}(i)\sin(2\pi f i) \tag{1}$$

Here, i, a_{hmax} and f indicate time, peak acceleration amplitude and frequency; respectively. In this equation, i starts from zero and increase to the desired time leading to the obtained total number of cycles. Analyses are carried out using different amplitudes of acceleration as a function of maximum amplitude of real records. These analyses are continued until the permanent displacement is in reasonable agreement under both real and equivalent loading cases at the dam crest. The relation between two acceleration amplitudes is expressed in Eq. (2).

$$a_{hmax} = ka_{rmax} \tag{2}$$

The actual maximum acceleration is represented by a_{rmax}. Table 2 shows the characteristics of earthquake records with the magnitude of 7 to 8 on the Richter scale.

Table 2. Characteristic of earthquake records in magnitude of 7 to 8.

	Magnitude	**Number of equivalent cycles**	**Predominant Period (sec)**	**Station**
Chi-Chi	7.6	19	0.285	CHY028
Sabat	7.9	12	0.285	TABAS
Duzce	7.1	10	0.285	LAMONT 375

5 ACCELERATION TIME HISTORIES IN DYNAMIC ANALYSIS

All dynamic analyses are conducted using real acceleration time histories and their corresponding equivalent harmonic loads as illustrated from Figures 2 to 4. Figure 2 shows that maximum Fourier amplitude in Chi-Chi earthquake occurs in frequencies of 1.3 and 2.5 HZ. It can also be observed that the frequency content is almost open in a wide range of frequencies and that the acceleration time history contains high energy. Hence, the number of equivalent cycle increases. Figure 3 demonstrates that the frequency content, similar to Chi-Chi earthquake, has high energy in the vast range of frequencies. However, the time duration is less than those in Chi-Chi earthquake. Due to the extensive frequency content, energy is consequently assigned using different frequencies. Figure 4, representing the Tabas earthquake, shows that the energy of acceleration time history in the limited range of frequencies is high and lead to less number of equivalent cycles. Figure 4b shows that that maximum Fourier amplitude of spectrum is 2.5 HZ. The frequency content does not expand in the extensive range of frequencies like it was in the Duzce earthquake. Time duration of both earthquake are almost equal; but, the different energy distribution among the frequencies leads to the Tabas record showing high energy as well as large number of cycles in comparison with Duzce earthquake.

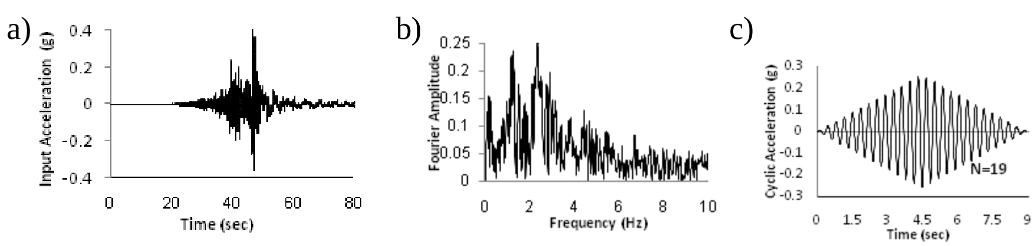

Figure 2. a) Chi-Chi acceleration time history; b) Fourier amplitude spectrum; c) Equivalent cyclic loading.

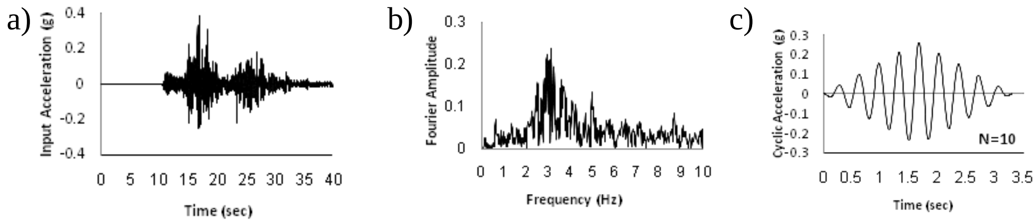

Figure 3. a) Duzce acceleration time history; b) Fourier amplitude spectrum; c) Equivalent cyclic loading.

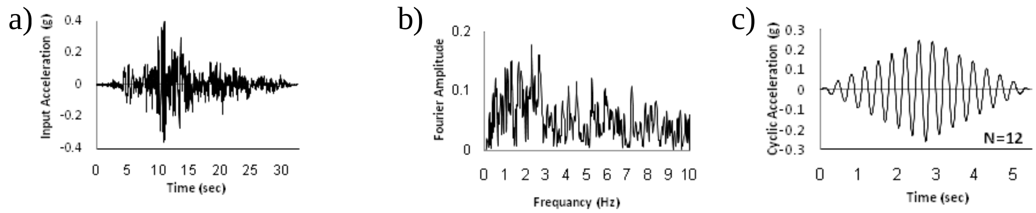

Figure 4. a) Tabas acceleration time history; b) Fourier amplitude spectrum; c) Equivalent cyclic loading.

6 DYNAMIC ANALYSES RESULTS

Dynamic analyses are carried out on the dam cross-section shown in Figure 1 using horizontal components of six records of earthquake and their equivalent cyclic loadings. Time histories of displacements at the crest are recorded in Figure 5. Comparing the deformation histories, the analysis shows that there is an acceptable agreement in permanent displacements at the crest of dam.

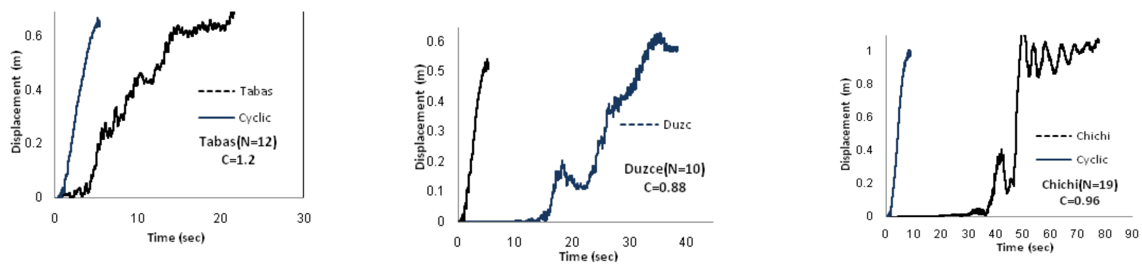

Figure 5. Displacement time history at crest (7.5-8 Richter).

7 CONCLUSION

The dynamic response of earth dams depends on the frequency and the acceleration amplitude in earthquake records. In this paper, an appropriate harmonic load is defined and applied to capture the effect of real seismic records. It is shown that earthquakes of high magnitudes can contain large frequency amplitudes in an extensive range of frequencies. This leads to large number of cycles and acceleration coefficients in equivalent harmonic loads. With respect to an increase in the number of cycles and the predominant frequency in each equivalent harmonic load, the deformations can transform from elastic strains to plastic deformations and this could lead to a decrease in shear modulus of the material and an increase in the hysteresis damping. Consequently, the large permanent displacements would occur at the crest. It is also found that the number of cycles in an equivalent harmonic load depends on the time duration and frequency contents of earthquake histories. To thoroughly understand the dynamic response of earth structures under different acceleration time histories, a variety number of earthquake records should be used. However, an equivalent harmonic load, presented in this paper, can help limit the resulting various responses and complexity of dynamic analyses while having the similar effect to real time histories on the final deformations.

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