Comparing Recorded Earthquake Signals of MS Embankment Dam with Numerical Modeling Results

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ABSTRACT :

Some earth dams in seismic areas have experienced damage or partial failure during earthquakes. It is recommended to use the results of recorded earthquake signals on embankment dams to verify the mathematical models used in design stage for a better prediction of dam behavior in the future. It should be mentioned that, obtained results from earthquake records are more useful than other in situ tests such as forced, ambient and explosion tests, since these in situ tests are concerned with vibrations of much smaller amplitude than those normally encountered in earthquakes. In this paper, the measured response of the Masjed Soleiman (MS) dam body (the highest embankment dam in Iran) during some small earthquakes was used. Based on the results of these records, the modal frequencies of the dam body were evaluated by using classical (such as FFT, power spectra density, cross spectra and coherency) and modern signal processing methods (time-frequency and wavelet methods). Using recorded earthquake signals in the basement of the dam as input excitation, dynamic analysis of the dam body was also performed and the results of the numerical modeling was compared with recorded earthquake signals on the dam body. The rigidity and flexibility effects of the foundation and abutments, their depths and inertial properties on the dynamic characteristics of the dam body were investigated. This comparison leads to more appropriate modeling of the dam body in earthquake loading condition.

KEYWORDS: earthquake, embankment dam, signal processing, wavelet, numerical

1. Introduction

Prediction of the seismic behavior of an embankment dam during earthquakes is one of the most complicated problems to geotechnical subjects. A careful study of the behavior of dams during earthquake occurrences provides a valuable insight into earthquake – resistant design of dams. Nevertheless some existent lack of information the following failure mechanisms can be selected: sliding or shear distortion of embankment or foundation or both, transverse cracks, longitudinal cracks, loss of freeboard due to compaction of embankment or foundation, rupture of underground conduits, overtopping due to seiches in reservoir, overtopping due to slides or rockfalls into reservoir, disruption of dam by major fault movement in foundation, differential tectonic ground movements, failure of spillway or outlet works, piping failure through cracks induced by ground motions and liquefaction of embankment or foundation. These failure mechanisms show the importance of studying dynamic behavior of embankment dams.
Relevant available dynamic analysis methods contain some simplifying assumptions both in modeling the soil behavior and modeling the earthquake excitation [Abdel Ghaffar, A. and Elgamal, A., 1987, Dacoulas, P.,1990, Elgamal A. et al., 1987, Gazetas, G., 1985 and Prevost, J. et al., 1985]. The seismic stability evaluation of the dam includes a dynamic response analysis of the embankment using two dimensional (2-D) and three dimensional (3-D) finite element procedures.
Analysis of strong motion accelerograms recorded at Leroy Anderson Dam near Morgan Hill, California during two earthquakes provided the basis for earthquakes. These data were used to identify the modes of vibration of the dam. Observed natural frequencies were compared with frequencies predicted by 1-and 2-dimensional theories for earth dam vibrations [Fedock, 1988].
Elgamal used computational models to investigate the nonlinear earthquake induced response of earth dams. Based on the shear sclice vibration concept, a series of models are proposed to study upstream-downstream (UD), longitudinal (L) and vertical (V) earth dam dynamic response. These models range from simple 1-dimensional (1D) to elaborate 3D which account for gravitational effects and actual canyon configuration [Elgamal, 1988].
Using recorded earthquake signals on dam body is a very powerful tool to study the seismic behavior of embankment dam during an earthquake event. Mejia and his co-workers used the accelerogram recorded by the instrument station at the abutment to calculate the dynamic response of the Ririe dam. This rock-fill dam is located in southeastern Idaho, about 25 Km northeast of the city of Idaho. the October 28, 1983 Mt. Borah earthquake triggered five strong-motion instruments installed at the crest, left abutment, downstream toe and outlet tower of Ririe dam [Mejia et al. 1991].
Recently, for the first time in Iran, the recorded earthquake, explosion, ambient and forced vibration tests are used to evaluate dynamic characteristics of an embankment dam. Dynamic characteristics of Masjed Soleiman embankment dam, the highest embankment dam in Iran, are extracted based on classical and modern signal processing methods [Jafari 2006, Davoodi et al. 2007, Davoodi and Amel Sakhi, 2008, Davoodi et al. 2008].
As the available softwares can not evaluate the exact solution of dam-foundation interaction problem, they use mass-less foundation theory. In this theory, the mass of foundation is neglected in dynamic analysis. But this approach is not necessarily the exact solution. Consequently the mass of foundation should be studied in seismic analysis of embankment dams.
Using earthquake recorded signals on different installed accelerometers stations, MS embankment dam dynamic response is computed in January 6, 2004 earthquake. The accelerogram recorded by the instrument station at the gallery is used to calculate the dynamic response of the dam during the earthquake. In this paper the related results based on dam-foundation interaction problem and dynamic behavior of MS dam during earthquake are presented and discussed in time-frequency domain.

2. Description of the Masjed Soleiman (MS) Embankment Dam

The Masjed Soleyman dam is a rock-fill type with clay core and a maximum height of 177m located on the Karun River in southwest Iran. This dam is located in Khuzestan province and 25.5 km to Masjed-E-Soleyman town. The view of MS embankment dam is presented in figure 1. Length of the crest is 480 meter and the dam body volume is nearly 13.4 million m^3. The objective capacity of the power plant is to generate 2000 MW of hydroelectric energy. The width of the dam at foundation and the width of the crest are 480 and 15 meter respectively.

Figure 1 Masjed Soleyman embankment dam view

3. Description of the Earthquake Records and Dynamic Analysis

To study the dynamic behavior of MS embankment dam, the recorded acceleration time histories are used. In this research, GeoSIG sa 99 accelerometers were used and the sample per second (SPS) for each record were 200. The accelerometers locations on Masjed Soleiman dam body are presented in figure 2 that can be seen, they were located in gallery, in the middle height of the dam and the crest of dam body. One sample of installed accelerometers on dam body is presented in figure 3. The earthquake signals used in the analysis were recorded in three components in January 6, 2004 earthquake.

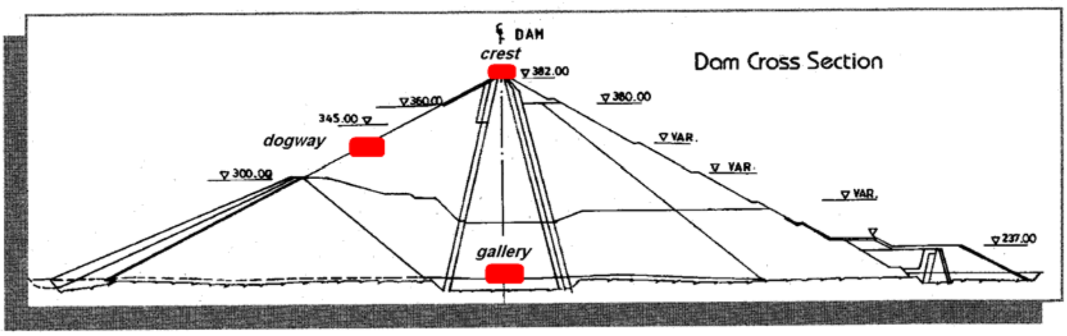

Figure 2 The location of the accelerometers on dam body

Before analyzing the earthquake records, in all the records, the base line has been corrected and the band pass filter has been used. For example one of the recorded events is summarized in table 1.

Figure 3 The located accelerometer on the crest

Table 1 General characteristics of recorded earthquakes on Masjed Soleiman dam dated 2004.1.6

File name	Position	Direction	PGA (mg)
Taj1610-003-x	crest	U-D	38.32
Taj1610-003-y		L	21.6
Taj1610-003-z		V	31.68
Dog-way16-10-82-03-x	dog - way	U-D	17.76
Dog-way16-10-82-03-y		L	20.16
Dog-way16-10-82-03-z		V	11.2
Gtb16-10-82-x	gallery	U-D	10.88
Gtb16-10-82-y		L	8.48
Gtb16-10-82-z		V	5.56

Note: U-D: Upstream-Downstream direction
L: Longitudinal
V: Vertical

4. Earthquake Response of MS Embankment Dam

In order to analysis the MS embankment dam to earthquake excitation, the following method is used:

- First of all, based on finite element method theories, different element numbers are examined and the optimum element number is selected. After modeling the MS dam and using optimum element numbers, the initial stresses in the embankment dam are determined.
- An appropriate acceleration time history is selected. This time history is expected to develop in the foundation of the dam. It should be mentioned that for using the recorded earthquake signals in the analysis, the base line are corrected and the band pass filter are applied. In this research, the recorded earthquake signal in the gallery station is selected as the excitation signal.
- Finally the dynamic response of dam body due to the earthquake under consideration is obtained. In this step, dam body is tested to the combination of pre-earthquake stress conditions, and super-imposed dynamic stress applications in order to determine the seismic strength and deformation characteristics.

In the next step to dynamic analysis of dam body against the earthquake record, the input motion is applied to the numerical model. This input motion is recorded in the gallery station. The acceleration time history and energy spectral density and also the time – frequency plot of the input acceleration is presented in figure 4. Because of non – stationary characteristics of earthquake excitation, time – frequency distribution method is selected to process the recorded earthquake signals. This time history is related to upstream – down stream component of the recorded event. This 2D plot shows that 1.4-1.5, 1.7-1.8, 3.2-3.4, 3.8-4.0, 4.7-4.8 and 6-6.1 Hz are dominant frequencies of dam body in upstream – down stream direction. These dominant frequencies are obtained based on processing all recorded earthquake accelerograms by modern signal processing methods such as Time – Frequency Distributions (TFD) and the Wavelet transform.

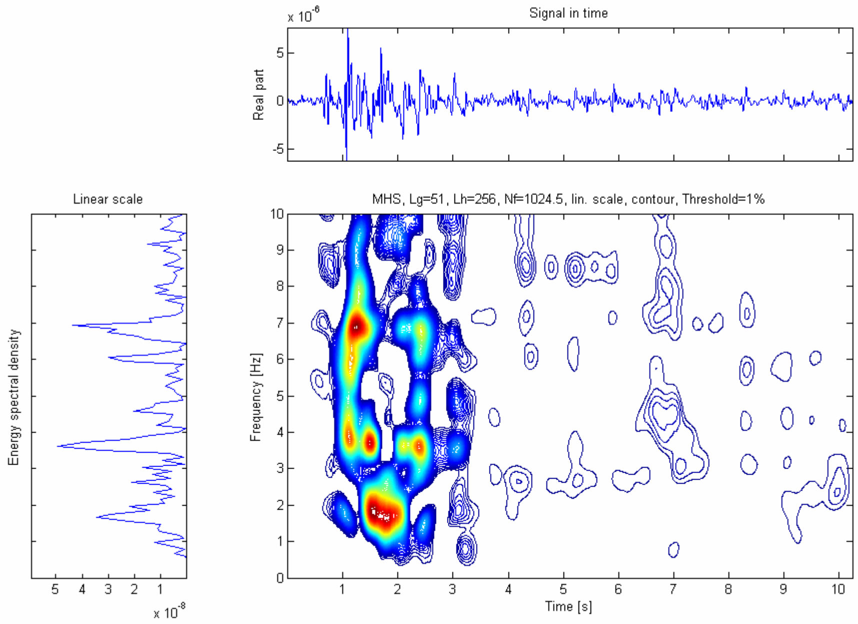

Figure 4 Recorded acceleration time history of Masjed Soleiman dam gallery in upstream – down stream direction (top), and its corresponding power spectral density (left) and its TFD contour plot (right)

As the recorded event is a weak motion, the linear elastic model is used in the analysis. To study dynamic behavior of MS dam, two different cases are analyzed, mass-less foundation and foundation with full mass. TFD presentations of the calculated results based on these two cases are plotted in figures 5 and 6. The recorded earthquake signal in the crest is also shown in TFD presentation in figure 7.

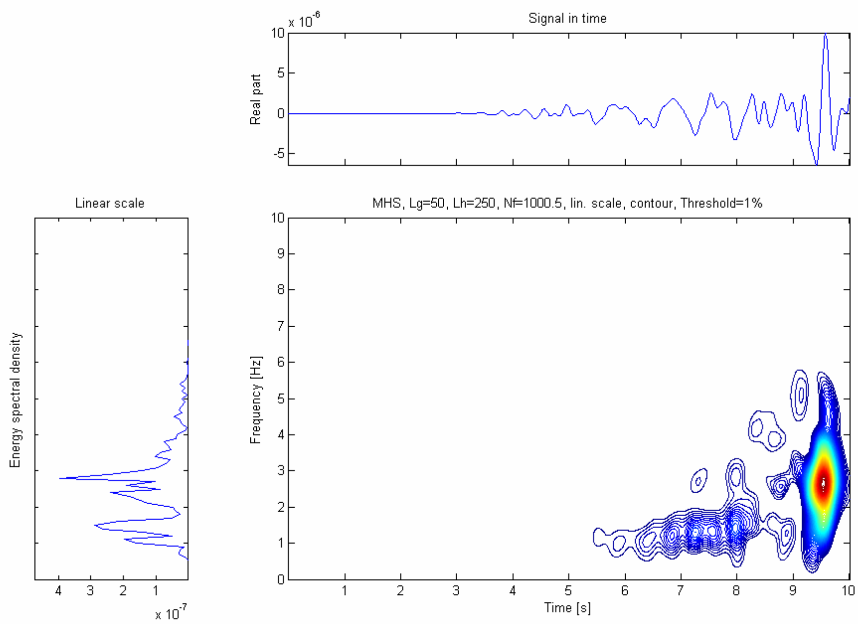

Figure 5 Calculated acceleration time history of Masjed Soleiman dam crest in upstream – down stream direction in total mass foundation(top), and its corresponding power spectral density (left) and its TFD contour plot (right)

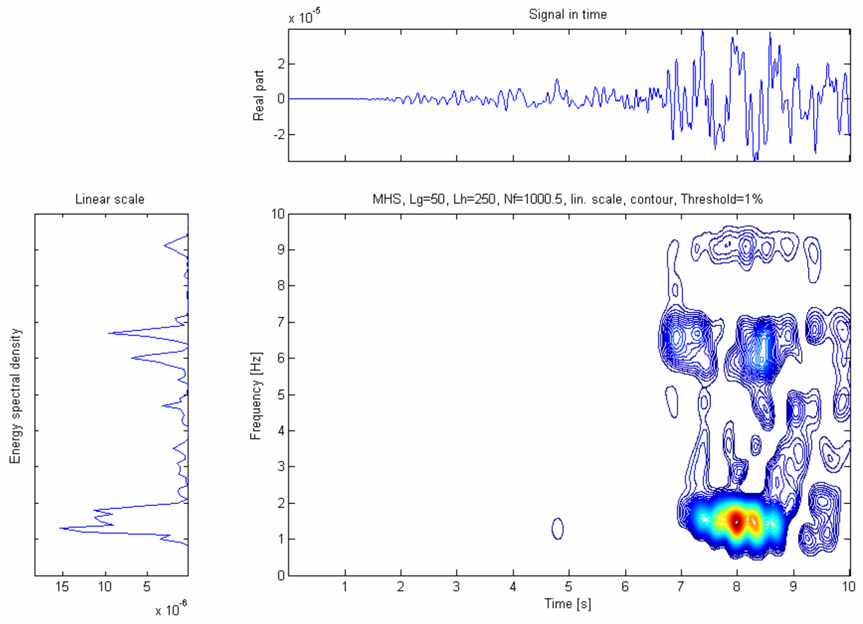

Figure 6 Calculated acceleration time history of Masjed Soleiman dam crest in upstream – down stream direction in mass-less foundation(top), and its corresponding power spectral density (left) and its TFD contour plot (right)

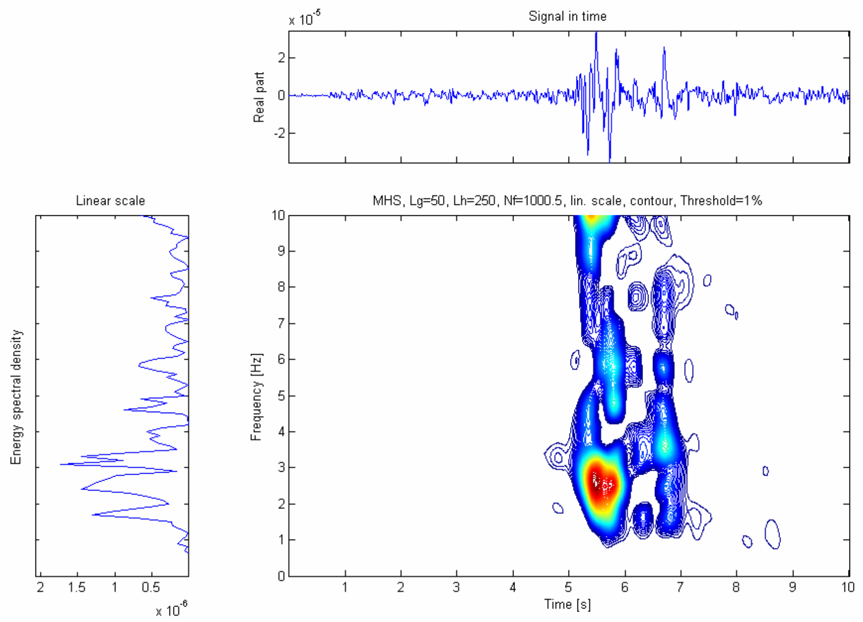

Figure 7 Recorded acceleration time history of Masjed Soleiman dam crest in upstream – down stream direction (top), and its corresponding power spectral density (left) and its TFD contour plot (right)

The obtained results show that considering total mass foundation is not a correct solution to solve the dam-foundation interaction problem. As can be seen from figures 5 and 7, accelerogram time histories and also frequency contents of these two responses are different. Comparing mass-less foundation result and recorded signal (figures 6 and 7) are more similar to each other in their frequency contents in comparison with before mentioned cases (figures 5 and 7). As can be extracted from both of figures 6 and 7, 1.4-1.5, 3.2-3.4 and also 6-6.1 Hz are proposed dominant frequency of dam body. Consequently, in dynamic analysis of embankment dams, studying different cases to model foundation's mass is necessary.

The amplification phenomena against dam height, is presented in figure 8. This figure is obtained based on dynamic numerical analysis. The selected points are the gallery, mid-height and also crest of the dam. It can clearly be seen from the amplification diagram that as the dam's height increases, the maximum acceleration of dam body increases. This phenomenon can be seen in both mass-less and total mass foundation.

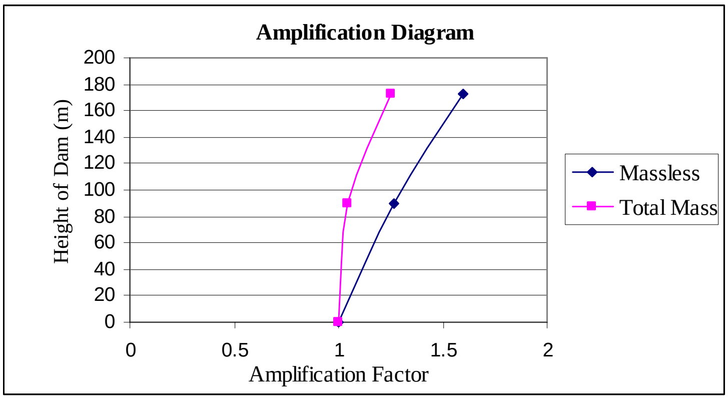

Figure 8 Amplification diagram in dynamic analysis of dam body

The results show that the dynamic response of dam body is clearly weak in the comparison with the static analysis. In the other words, by applying the acceleration time history in the numerical model, horizontal, vertical and shear stresses are increased a little. This behavior is based on weak recorded earthquake signal on dam body. As it is known, the factor of safety is related to the accumulated vertical and shear stresses in dam body during a seismic event. Consequently, it can be said that in this case, because of weak earthquake event, the safety factor of dam body against failure doesn't change any more in the static and dynamic analysis.

5. Conclusion

In this paper, in the first step dominant frequencies in up stream – down stream direction obtained by classical and modern signal processing methods are presented. Classical signal processing methods powerful, easy and straight forward tools to process stationary signals. Modern signal processing methods that process the non – stationary signals (such as earthquake signals) in both time and frequency domains, are powerful tools in comparison with classical methods.

In the next step, using recorded earthquake signal in the gallery station, dynamic analysis of Masjed Soleiman embankment dam is performed and a comparison between the calculated and the measured dynamic response of MS dam during January 6, 2004 earthquake is presented. The obtained results show that the changes in vertical, horizontal and shear stresses between static and dynamic cases are very small. This is related to a little increasing in vertical and shear stresses in dynamic analysis in comparison with static analysis. This important result, clearly shows that based on the used recorded earthquake signal (recorded in the gallery), the safety factor in static and dynamic analysis doesn't change. So dynamic stability of this dam under the mentioned excitation is guaranteed. Thus it may be concluded that the 2-D finite element model of the maximum height section of MS dam and the selected dynamic material properties provide a reasonable analytical representation of the measured dynamic response of the dam during the January 6, 2004 earthquake.

Considering two different mass for modeling the foundation indicate that using total mass to model foundation didn't reach to a proper solution in dam-foundation interaction problem. The result of mass-less foundation model and the recorded earthquake signal on dam body are more similar to each other in frequency content. But it should be mentioned that carefully studies should be employed on selecting proper mass of foundation in the dynamic analysis of embankment dams.

Also the amplification behavior can be distinguished based on obtained numerical results in the height of the dam. The obtained time history response of dam's crest is processed by classical and modern signal processing methods and dynamic characteristics of dam body are extracted.

The obtained results indicate that in-situ measurements can provide properties that are in good agreement with numerical calculated responses of the embankment dams. Also, in-situ measurements are powerful tools to study the dam's dynamic responses.

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