Evaluating Masjed Soleyman Rockfill Dam Dynamic Characteristics by Earthquake Records

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Abstract

In this paper, Recorded earthquake signals on different stations by available accelerometers which have been installed on Masjed Soleyman embankment dam are used. As the earthquake signals are non-stationary, the classical signal processing techniques can't present the appropriate dynamic behavior of the dam under earthquake loadings and consequently, time–frequency distribution (TFD) analysis method is proposed. The recorded earthquake signals on dam are processed by classical and recently developed signal processing methods and the obtained results based on two methods are compared. The results show that hidden frequencies in classical methods can be extracted by TFD method.

Keywords: Earthquake Records, Embankment Dam, TFD Method

Introduction

In many practical cases, it is useful to combine numerical models and experimental results. Dynamic tests such as experiments on prototype dams, are conducted on structures such as concrete and embankment dams to determine their dynamic properties and also dynamic response characteristics for validating numerical models. 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.

There are some studies in the world that researchers used in-situ tests to identify characteristics of dam bodies. In 1978 the available accelerometers on Santa Felicia embankment dam (located in USA) recorded the components of an earthquake with M_L=4.7. The dam Height was 83m with a length of 389m. The signals of forced vibration tests on this dam were recorded by 8 seismometers. By comparing the forced vibration tests and earthquake records on the dam, shape modes and modal frequencies of the dam was extracted by classical signal processing methods [1]. El Infiernillo embankment dam was built in 1962-1964 in Mexican with 145m height and 350m length. This dam has experienced 8 strong earthquakes between 1985-1966. In 1970 by forced vibration tests on this dam, 8 mode shapes and modal frequencies of the dam were extracted based on classical processing methods. The results were compared with the results obtained by processed November 15, 1975 earthquake records [2]. Kassa embankment dam with 90m height and 478m length was built in Japan. This dam was investigated by classical signal processing techniques under forced, ambient and blasting tests and the obtained system identification results were compared with the results of earthquake records [3]. Also we can see some similar results based on researches on Kisenyama embankment dam, constructed in Japan [4], but all of these studies are based on classical signal processing methods (such as FFT) in order to obtain modal frequencies of dam bodies.

Ghanaat et. al. [5] excited the Longyangxia dam by blasting tests. Longyangxia dam is a 178-m high concrete gravity arch dam located near the headwaters of the Yellow River in China. The main purpose of the experiment was to excite the dynamic response of a large dam-water-foundation system and to further study the dynamic behavior of arch dams, including the dam-water-foundation interaction effects. In this research, the blasting records are analyzed by time-frequency distribution method.

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As an example of applying in-situ tests on embankment dams in Iran, for the first time, the Masjed Soleyman embankment dam can be mentioned. The responses to forced vibrations, ambient vibrations and large explosives were measured for Masjed Soleyman Dam, the highest embankment dam in Iran. The recorded signals were analyzed by classical signal processing methods such as power spectra density, cross power spectra density, coherency spectra and also phase spectra. Based on mentioned methods, dynamic characteristics of dam body were extracted. In the next step, dynamic characteristics of dam body were obtained based on numerical analysis and the results compared with in-situ test results (Jafari, 2006).

Signal processing methods should be used to identify dynamic characteristics of dam body based on recorded signals such as ambient, forced, explosion and earthquake records. There are classical and modern signal processing methods.

In classical signal processing methods, the time representation is usually the first and the most natural description of a signal we consider, since almost all physical signals are obtained by receivers recording variation with time. The frequency representation, obtained by the Fourier transform, is also way to describe a signal, mainly because the relevance of the concept of frequency is shared by many domains (physics, biology …) in which periodic events occur. The Fourier transform decomposes a signal into its constituent frequency components. Looking at the Fourier spectrum we can identify these frequencies; however we can not identify their temporal localization. One convenient way for examining the dynamic response of the dam is to compute power spectral density or PSD of the measured signals. The PSD is estimated from the Fast Fourier Transform (FFT) of the signal and is especially suitable for the detection of small signals containing information on the lower modes of the dam, which are usually buried in large high – frequency signals characterizing the earthquake signals. The picks in the PSD of the recorded dam responses generally can be assumed to represent either picks in the excitation spectrum or normal modes of the dam. The variation mode picks can be distinguished from the input spectrum peaks by taking advantage of the fact that all the points on a dam responding in a lightly damped normal mode of vibration are either in phase or 180 out of phase. As the frequency content of earthquake records varies very large with time and the signals are non stationary, so the classical signal processing techniques have limits to show exact characteristics of dams.

As has been argued [6], methods based on stationary assumption are generally inappropriate for spectral analysis of non-stationary signals. To overcome the available difficulties and limitations in classical processing methods, the new time frequency distribution (TFD) method is defined. On the processing and representation of non stationary dynamic signals, great importance has been taken on in the literature by the transforms in the joint time – frequency domain. Time-frequency analysis provides a powerful tool for the analysis of non-stationary signals [7]. Time–frequency distributions (TFDs) map a one-dimensional signal into a two-dimensional function of time and frequency, and describe how the spectral content of the signal changes with time. The aim of time-frequency analysis is to come up with appropriate candidates for the signal at time "*t*" and frequency *"f"*. More details about time-frequency distribution are presented in next section.

As can be seen in literature, there is no research on using modern TFD method to evaluate dynamic characteristics based on earthquake signals recorded on embankment dam body. In this paper for the first time, this modern signal processing method is used to extract dynamic characteristic of an embankment dam (Masjed Soleyman case study) by using recorded earthquake signals on dam body.

Time – Frequency Distribution Signal Processing

In recent years several authors have proposed the use of joint time – frequency domain analysis to study dynamic properties of the structures. The time-frequency distribution ideally describes how the energy is distributed, and allows us to estimate the fraction of the total energy of the signal at time *t* and at frequency *f*. TFD is an appropriate tool for non-stationary signal analysis, synthesis, and processing. Time-frequency analysis dates its origin to the first half of the 20th century, but the major developments in its understanding, practical applications, and the analysis have been recently accomplished. Different types of time-frequency distribution have been developed for that purpose. Two early forms of time-frequency analyses are: the Short-Time Fourier Transform (STFT), used to generate the spectrogram (SP) [8], and the Wigner-Ville distribution (WVD) [9]. Studies of the well known linear Short-Time Fourier Transform (STFT) have been published by Nawab and Quatieri, [10]. In order to achieve fine simultaneous time-frequency resolution in a non-stationary time series, we must deal with the uncertainty principle [11].

STFT's originate from the Fourier transform evaluation of the signal with the prior application of a suitable time window identifying the signal's stationary segments. However, the frequency resolution provided by this technique is limited and inversely proportional to the duration of the segments to which the transformed is applied. The ability to detect and model nonlinear characteristics is particularly important for seismic analysis, where large amplitude response and structural damage can include frequency variations and the participation of higher modes in the response that would be obscured in traditional Fourier analysis. The frequency resolution provided by STFT is limited and inversely proportional to the duration of the segment of signal transformed by applying the Fourier integral. To overcome this resolution limitation, we can imagine letting the resolution in time and frequency vary in the time – frequency plane to obtain a multiresolution analysis.

The Cohen class of transform makes it possible to obtain time – frequency representations possessing the important property of being invariant to time and frequency shifts. The first distribution of this type was proposed by Wigner in 1932. A Wigner – Vile distribution of a signal *x(t)* is defined as the distribution obtained from the following integral transform:

$$WD_x(t, f) = \int_{-\infty}^{+\infty} R_x(t,\tau) e^{-j2\pi f\tau} d\tau \tag{1}$$

Where

$$R_x(t,\tau) = x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2}) \tag{2}$$

is the product of the signal's autocorrelation. The WVD satisfies a large number of desirable properties but it has some limitation. To overcome these limitations, Kernel method is developed. There are some distributions based on kernel method such as Margenau-Hill, Kirkwood-Rihaczek, sinc, Page, Choi-Williams and Zhao-Atlas-Marks. Jeong and Williams in 1992 [12] have developed an approach for constructing kernels that generate distributions which reduce the interference terms. In this paper, a lot of time – frequency distributions is examined and finally the TFD results are based on Margenau-Hill-Spectrogram time-frequency distribution.

Description of the Masjed Soleyman Rockfill Dam and Earthquake Records

The Masjed Soleyman rockfill dam has a clay core with a maximum height of 177m and the body volume is nearly 13.4 million m^3. This dam is located on the Karun River in Khuzestan province in southwest Iran, 25.5km to Masjed Soleyman town (Fig.1). The dam has 700m width at the foundation and 15m width at the crest with 480m crest length. The objective is to generate 2000MW of Hydroelectric energy.

Fig1. Masjed Soleyman embankment dam view

In this research, GeoSIG sa 99 accelerometers were used and the sample per second (SPS) for each record were 200 sample per second. The accelerometers locations on Masjed Soleyman dam body are presented in Fig.2 that can be seen, they were located in gallery, dog way (in the middle height of the dam) and the crest. The earthquake signals used in the analysis were recorded in three components in January 6, 2004. For preprocessing the recorded earthquake signals, in all the records, the base line has been corrected and the band pass filter has been applied. The recorded signals are summarized in table 1.

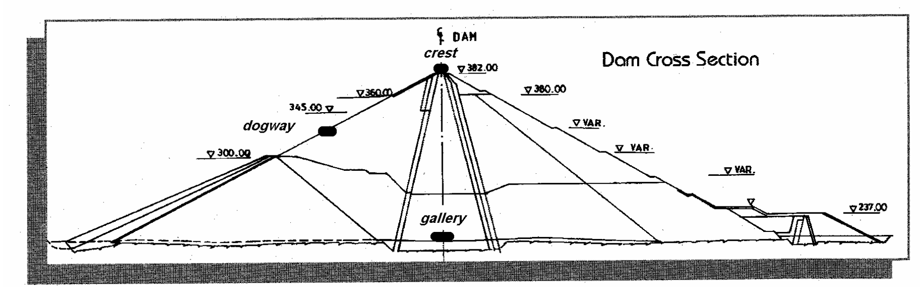


Fig2. The location of the accelerometers on dam body

Table 1-General characteristics of recorded earthquake signals on dam body

Record's 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

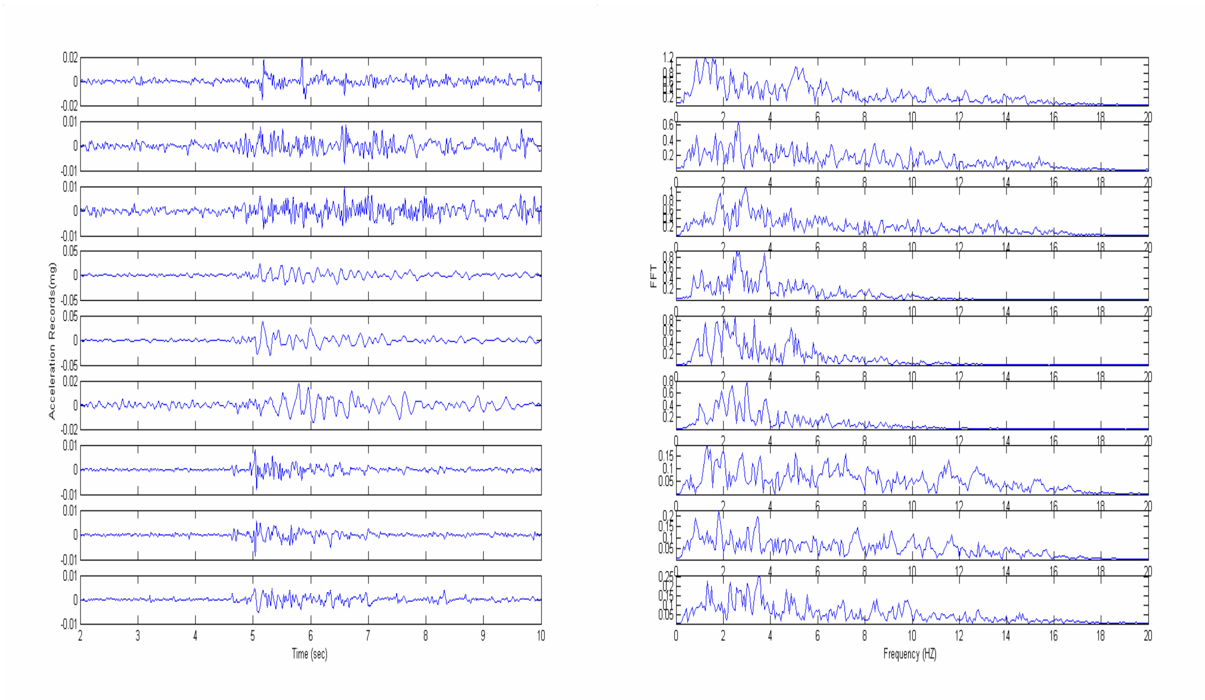
Note: U-D: Upstream-Downstream direction
L: Longitudinal
V: Vertical

Analysis of the Recorded Data

The time histories and the fast Fourier transforms (FFT) of the mentioned records are plotted in Fig.3. This research has two main steps: using classical signal processing and modern signal processing to identify dynamic characteristics of dam.

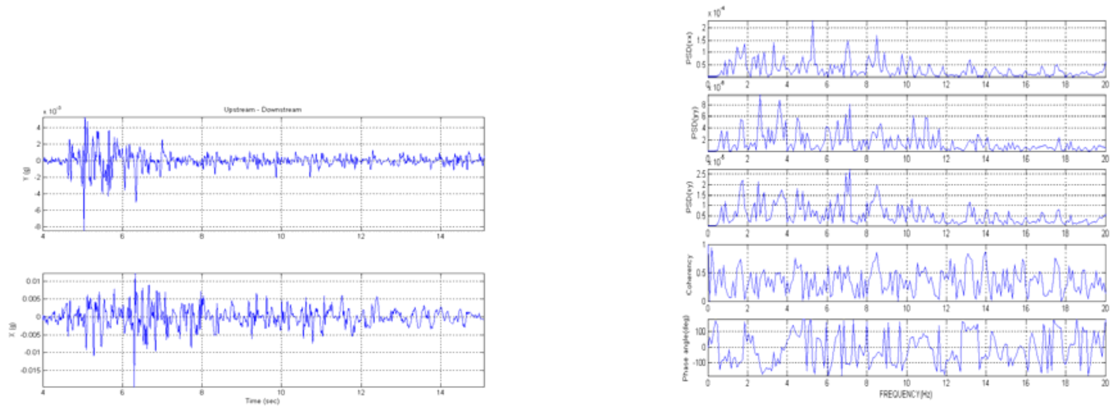
In the first step, the proposed natural frequencies of the dam are extracted based on classical signal processing methods. The power spectral density (PSD) function, cross power spectra (CPS) and also coherency spectra between two points of the dam were used to obtain dynamic properties of embankment dams. As mentioned before, a PSD peak at any response point either represents a resonance frequency associated with one of the mode shapes of the dam body or corresponds to a peak in the excitation spectrum.

To distinguish the spectral peaks representing the dam vibration modes from those corresponding to peaks in the input spectrum, the amplitude and phase of CPS may be used. That is, all points of the dam body in a lightly damped mode of vibration are in phase or 180° out-of-phase with each other, depending on the shape of the normal mode. The phase relationships between two response measurement points are obtained from the cross correlation phase spectrum (CCPS). Obtained power spectral density, cross power spectra, coherency spectra and the cross correlation phase spectra of the middle height station and the reference point (gallery station) is presented in Fig. 4.

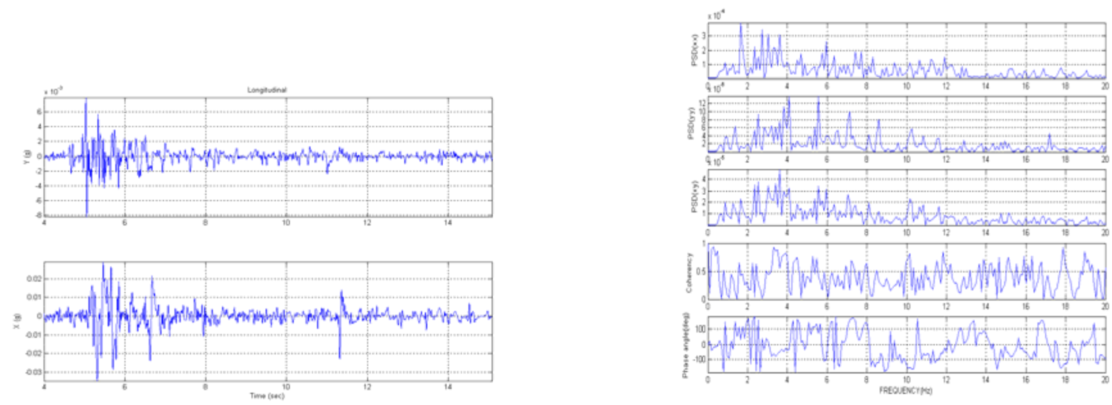


(a) (b)

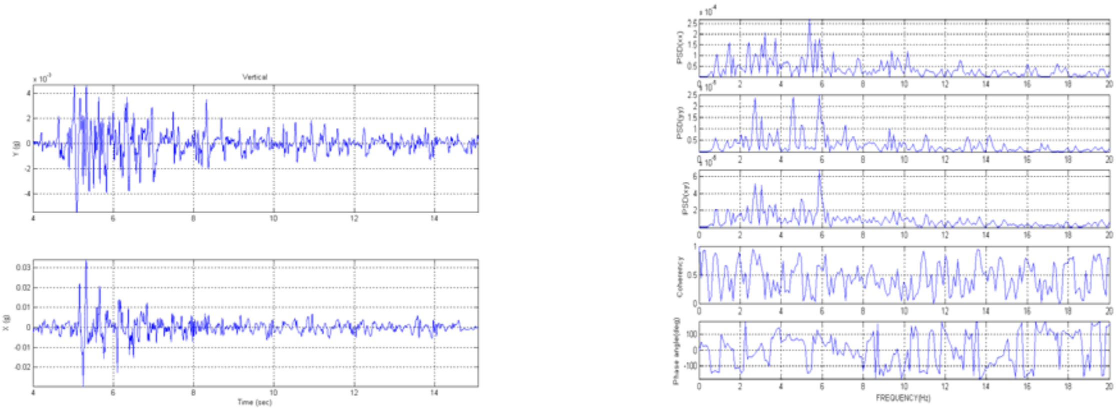
Fig3. a) Acceleration time histories and b) FFT values of the earthquake records of Masjed Soleyman embankment dam during the mentioned records of table 1, respectively.



(a)



(b)



(c)

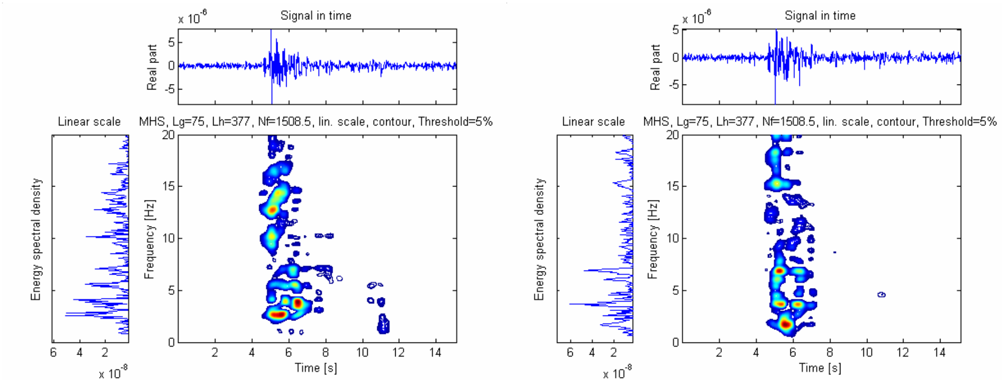
Fig4. Example of processed earthquake records (right) of Masjed Soleyman dam body in (form top to bottom: PSD of records of gallery and crest, CPS, CS, CCPS) and filtered records (left) - a) U-D direction, b) L direction and c) V direction during earthquake.

To obtain results, also the related plots for the crest station by considering the gallery station as the reference point are studied and the results are compared with each other. Based on the obtained results, proposed frequencies in three directions are presented in table 2.

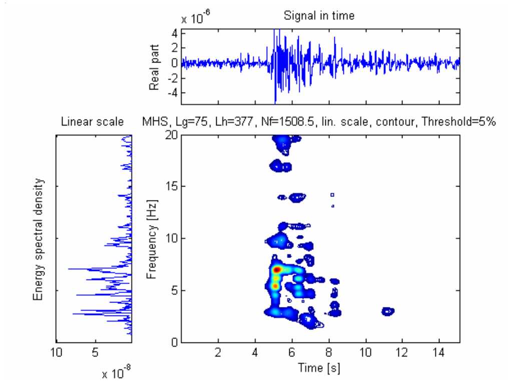
Table2- Proposed modal frequencies in all three directions by using: power spectral density, cross power spectra, cross coherency spectra and the cross correlation phase spectra

No.	Frequency, Up stream – Down Stream (Hz)	Frequency, Longitudinal (Hz)	Frequency, Vertical (Hz)
1	1.3-1.4	1.45-1.65	1.9-2.1
2	1.7-1.8	2.1-2.2	2.9-3.1
3	2.6-2.8	3.3-3.4	3.8-3.9
4	5.1-5.3		5.7-5.8
5	5.8-5.9		

In the next step, the recorded earthquake signals on dam body are analyzed using time – frequency distribution. For example the 2D view of recorded event in gallery station in time – frequency distribution is shown in fig. 5 in all three directions. In this figure the time history and energy spectral density of the signal are shown.



(b) **(a)**



(c)

Fig5. Time – frequency distribution of the gallery's record in: (a) longitudinal (b) upstream down stream (c) vertical directions

Based on the complementary studies, all the earthquake records on the dam body were analyzed by above mentioned TFD method. Based on the results of TFD method, the proposed natural frequencies of the dam is presented in table 4. It should be mentioned that because of limited stations, it is impossible to extract mode shapes of the dam body. As can be seen from TFD results in strong motion part in all three earthquake components, dominant frequencies of dam body are in the range of 1.5-10 Hz. In this case both low and high frequencies can be extracted. After passing the strong motion part, obtained results show that generally low frequencies are obviously extracted. In other words, decreasing a trend from high to low frequencies can be seen as the time passes in acceleration time history.

Table 3- Proposed frequencies in all three directions by time – frequency distribution method

No.	Frequency, Up stream – Down Stream (Hz)	Frequency, Longitudinal (Hz)	Frequency, Vertical (Hz)
1	1.4-1.5	1.7-1.8	2-2.2
2	1.7-1.8	2.1-2.2	3-3.2
3	3.2-3.4	3.3-3.4	
4	3.8-4.0	4.6-4.8	
5	4.7-4.8		
6	6.0-6.1		

The comparison of results of classical and TFD signal processing methods show that we can detect the proposed dominant frequencies of the embankment dam, but as we mentioned previously because of limited stations, it is impossible to define exactly the modal frequencies of the dam body. For the comparison the obtained results in this research, the results of the ambient and explosion tests on Masjed Soleyman embankment dam are summarized in table 4 based on the research of Davoodi [13].

Table 4- Modal frequencies (Hz) of the Masjed Soleyman dam body using classical signal processing technique on ambient and explosion records [13]

No.	Frequency, Up stream – Down Stream (Hz)	Frequency, Longitudinal (Hz)	Frequency, Vertical (Hz)
1	1.45-1.5 (1st – symmetry)	1.7-1.8 (1st – symmetry)	2.05-2.3(1st – symmetry)
2	1.75-1.8 (1st – unti symmetry)	2.1-2.25 (1st – unti symmetry)	2.85-3.0 (2nd – symmetry)
3	3.2-3.3 (2nd – symmetry)	3.3-3.4 (2nd – symmetry)	

The results show that it is impossible to extract the 1.5 Hz modal frequency in longitudinal direction and 3.2-3.3 Hz modal frequency in upstream-down stream direction by classical method whereas TFD method can extract them clearly. So TFD method obviously shows hidden modal frequency of the dam that it can't be extracted by classical signal processing methods. Comparison of obtained results in this research and the previous studies shows that because of reducing the stiffness of the dam and also the differences in the water level in two different researches, the modal frequencies are between (0-10)% smaller than obtained results by Davoodi [13]. It is necessary to mention that the reservoir's water level in earthquake records was about 370 and this level in ambient, forced and explosion test was 320 and also the used acceleration time histories of the earthquake is not in the range of high power earthquakes.

Comparison the current TFD results based on earthquake records (table 3) and classical signal processing methods based on explosion records (table 4), in all three directions, show that TFD method can be used to extract dominant frequencies of the dam body with a higher accuracy. As mentioned before, because of limited stations, it is impossible to extract the other modal frequencies of the dam body. By comparing the plots obtained by classical signal processing methods such as PSD, … with modern TFD signal processing methods, it can be seen that time – frequency distribution methods can present powerful information about a non-stationary signal in both time and frequency domain.

Conclusions

Earthquake records are known to be one of the non – stationary signals in both intensity and frequency content. By using classical signal processing method, it is impossible to analyze non – stationary signals correctly. To overcome this limitation it is necessary to use time – frequency distribution methods to process non – stationary signals. In this paper, two methods for analyzing the earthquake records on Masjed Soleyman embankment dam have been performed. In the first method, using power spectral density, cross power spectra, cross coherency spectra and the cross correlation phase spectra, the dominant frequencies of the dam body is obtained. In the next method, for the first time, time – frequency domain signal analysis of earthquake records using TFD decomposition was used to analyze the embankment dams. Proposed modal frequencies of dam body based on earthquake signals obtained by classical signal processing and time – frequency distribution methods are compared. The obtained results in this research and the results of in situ-tests that had been performed before, show that TFD results are closer to in-situ test results. As can be seen from the obtained results, hidden frequencies of the dam (such as 1.5 Hz modal frequency in longitudinal direction and 3.2-3.3 Hz modal frequency in upstream-down stream direction) can be extracted by this modern signal processing method. This study reveals that the TFD method is a powerful tool for evaluating dynamic characteristics of the embankment dam.

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