

## Comparing the classical and modern signal processing techniques in evaluating the modal frequencies of the Karkheh embankment dam during earthquakes

Masoud Amelsakhi<sup>1\*</sup>

<sup>1</sup> Assistant Professor, Department of Civil Engineering, Faculty of Engineering, Qom University of Technology, Qom, Iran

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### Abstract

System identification, such as extracting modal frequencies of structures, is an important tool to identify a system and also to study a system before and after the earthquake to evaluate the demolition effects on the system. Using classical signal processing methods, FFT and other well-known methods, has some limitations. For example, these signal processing methods extract frequencies in only the time or only frequency domain. In this research, modern signal processing methods are performed to obtain modal frequencies of Karkheh embankment dam, and the obtained frequencies are compared with extracted frequencies with classic signal processing methods. Since the amplitude and also the frequency contents of earthquake signals vary efficiently with time, as is called non-stationary signals, the classical signal processing techniques have some limitations in extracting the exact characteristics of non-stationary signals. To overcome this limitation, TFD (Time Frequency Distribution) and Wavelet analyses are performed. In this paper, recorded earthquake signals of Karkheh dam, one of the highest rock fill dams in Iran, are used to extract dominant frequencies of the dam body. Also, the ambient signals are recorded at three different levels of this dam. Using classical and modern signal processing methods, the proposed modal frequencies of the dam body are evaluated, and the obtained results are compared. Differences between the two methods are described, and the benefits of the modern signal processing method are discussed. The obtained results show that some frequencies are extracted by modern time-frequency methods, whereas they can't be obtained based on classical methods. These results prove the benefits and advantages of time-frequency signal processing methods as a powerful method for extracting modal frequencies of different structures. This advantage is mainly obvious in processing non-stationary signals such as earthquake and blasting signals.

**Keywords:** Time frequency distribution, embankment dam, modal frequencies

## 1 Introduction

In order to evaluate a dam's safety during earthquakes, special studies are necessary. Seismic behavior study of embankment dams can be performed by different methods: observations made from dam response during earthquakes, experiments such as blasting and ambient tests on prototype dams to determine dynamic properties, experiments on reduced-scale models such as shaking tables or centrifuge testing, and finally, analytical studies. It is recommended to use the results of recorded earthquake signals on embankment dams to verify the mathematical models used in the design stage for a better prediction of dam behavior in the future. Several previous studies have used ground motion data to estimate modal responses of embankment dams during seismic events with different approaches (Abdel-Ghaffar and Scot, 1981, Abdel-Ghaffar and Koh, 1981, Gazetas, 1981a, Gazetas, 1981b, Fedock, 1986). Kassa embankment dam, located in Japan, 90m high and 478 m length, was triggered by an earthquake, and the system identification was performed. The 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 (Allen, 1977). Leroy Anderson Dam, an earth and rockfill structure was strongly excited by the Morgan Hill earthquake of April 24, 1984. The Mt. Lewis earthquake of March 31, 1986, also triggered strong motion recorders at the dam site. The records obtained from these earthquakes were used to analyze the response of the dam body (Fedock, 1988). The earthquake of May 5, 1986, in Turkey caused extensive longitudinal cracks at the crest of the Surgu dam and possible loss of slope stability. The researchers used numerical analysis in strong and

weak motions to compare the damage that occurred on the dam body (Ozkan and Erdik, 1990). The seismic stability assessment of the Ririe dam near Idaho was studied by the U.S. Army Corps of Engineers. The seismic analysis included a dynamic response analysis of the dam using the three-dimensional finite element method (Mejia and Sykora, 1991). The responses of the Masjed Soleiman (MS) dam body to forced vibrations, ambient vibrations, and large explosives were measured (Jafari and Davoodi, 2006). There are a few studies in the literature using the Wavelet transform and TFD method to study the dynamic behavior of embankment dams under seismic loadings. Using the Wavelet transform method in processing the recorded explosion signals on embankment dams is proposed (Davoodi and Jafari, 2007). Also, the application of the wavelet method is performed in signal processing and system identification of a building in Iran (Davoodi et al., 2007). The time-frequency distribution has been used in analyzing the response of the Longyangxia dam to blasting excitation. Longyangxia dam is a 178-m-high concrete gravity arch dam located in China (Ghanaat and Chen, 1999). Wang et al. by combining the Covariance-driven stochastic subspace identification (SSI-COV) method and the multiple population genetic algorithms (MPGA), an optimization and updating method for the dynamic parameters of earth-rock dams based on modal parameter identification is presented. The collected weak earthquake records of the dam allowed the modal parameters (the natural frequencies and mode shapes) to be identified based on the SSI-COV method (Wang et al., 2023). Yousif et al., the impacts of the strong earthquake (M 7.3) on November 12, 2017, on the Darbandikhan Dam and its appurtenant structures were evaluated using a signal

processing method. From the results, it was observed that although the dam was strongly shaken, in general, its performance was satisfactory. This finding was fairly promising; however, this observation was influenced by the fact that the reservoir was low at the time of the earthquake (Yousefi et al., 2019).

As it is clear, there is no research on time-frequency distribution and wavelet methods to process the recorded earthquake signals on embankment dams. So in this research, using modern signal processing methods, wavelet and TFD, the dam body's natural frequencies are extracted and compared with the classical signal processing methods, such as FFT, are the benefits are described. It is important that using these modern signal processing methods is more difficult in comparison with classical signal processing methods. This is the main reason that we see very limited designs in civil engineering consulting companies and also related research in this field. It should also be mentioned that these signal processing methods are discussed in the electronics field, and civil engineering researchers are not very familiar with them. So this specific research is the civil engineering–electronic engineering interaction field.

## 2 Theory

The 4 spectra method is a powerful, easy, and straightforward method to process the stationary signals (Jafari and Davoodi, 2006, Davoodi et al., 2009). Since the 4-spectra method processes the signals in just the frequency domain, consequently, non-stationary signals should be analyzed in both the time and frequency domains. The time-frequency distribution (TFD) method maps a one-dimensional signal into a two-dimensional function of time and frequency and describes how the spectral content of the signal changes with time (Wang et al., 2023). Time-frequency

analysis dates its origin to the first half of the 20<sup>th</sup> century, but the major developments in its understanding, practical applications, and analysis have been recently accomplished. Different types of time-frequency distributions have been developed for this purpose. Many forms of TFD are developed based on Short-Time Fourier Transform (STFT), used to generate the spectrogram (SP) technique (Allen, 1997). Studies of the well-known linear STFT have been published by Nawab and Quatieri (Nawab and Quatieri, 1988). STFT originates 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 transform is applied.

The other form of TFD is the Wigner-Ville distribution (WVD). 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 WVD of a signal  $x(t)$  is defined as the distribution obtained from the following integral transform:

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

Where

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

is the product of the signal's autocorrelation.

The WVD satisfies a large number of desirable properties, but it suffers from cross-terms interference when applied to multi-component signals such as earthquake data. The cross-term interference causes the time-frequency distribution to occasionally be negative.

Furthermore, for multi-component seismic signals, the presence of cross-terms makes it almost impossible to carry out detailed signal identification, and only general characteristics are possible to identify. The Choi-Williams distribution overcomes the WVD limitation, supporting in great amount the cross-term interference, but some time-frequency resolution is lost. The reduced interference distribution (RID) overcomes this problem to a significant extent (Boashash, 1992). Right now, there are many TFD methods in processing the non-stationary signals that

should be examined to extract the best method in a case study to give the best resolution in both time and frequency domains.

### 3 Results

The Karkheh rock fill Dam is located in the north of Khuzestan province in the southwest of Iran. This dam has a maximum height of 127 m and 3030 m (Figure 2) and a dam body volume of nearly 27 million m<sup>3</sup>. The summary of the dam specification is presented in table1.

**Table1.** Karkheh embankment dam specifications.

Dam Type	Rock-fill type with clay core
Height from the foundation	127 m
Length of the crest	3030 m
Width of the dam at the foundation	1100 m
Width of the crest	12 m
Total volume of the reservoir	7300 million m <sup>3</sup>
Useful volume of the reservoir	4870 million m <sup>3</sup>
Total volume of the dam body	27 million m <sup>3</sup>

Material	E(kPa)	$\nu$	$\varphi(^{\circ})$	C (kPa)	$\psi (^{\circ})$	$\gamma(\text{kN/m}^3)$
Core (0-30m)	50000	0.35	22	20	0	20.1
Core (30m-60m)	42000	0.35	22	20	0	20.1
Core (60m-90m)	30000	0.35	22	20	0	20.1
Core (90m-120m)	25000	0.35	22	20	0	20.1
Shell	90000	0.25	38	0	10	20.5

\*key:

E: Young Modulus

$\nu$ : Poisson Ratio

$\varphi$ : Effective internal friction angle

C': Effective cohesion

$\psi$ : Dilation angle

$\gamma$ : Unit weight



**Figure 1.** Karkheh embankment dam's length view (crest).



**Figure 2.** Karkheh embankment dam (Google Earth).

### 3.1 Classical method

The ambient signals were recorded in three directions; upstream-downstream, longitudinal, and vertical. A MATLAB subroutine was coded with the following steps:

- a) In the preprocessing step, the file formats were converted to volt/sec, and instrument corrections were applied.
- b) The baseline correction and band pass filtering in the 0.6-30Hz frequency range were applied.
- c) The corrected signals were processed by three methods: the classical (4-spectra method), TFD method, and Wavelet method.

In the first step, using classical signal processing methods, proposed dominant frequencies of the dam body are extracted. Since the input signal in the earthquake records is not exactly known, the power spectral density (PSD) function, cross power spectra (CPS), and also coherence spectra between two points of response measurement, are used to obtain dynamic properties of embankment dams. A PSD peak at any response point either represents a resonance frequency associated with the mode of vibration of the dam system 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  $180^\circ$  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).

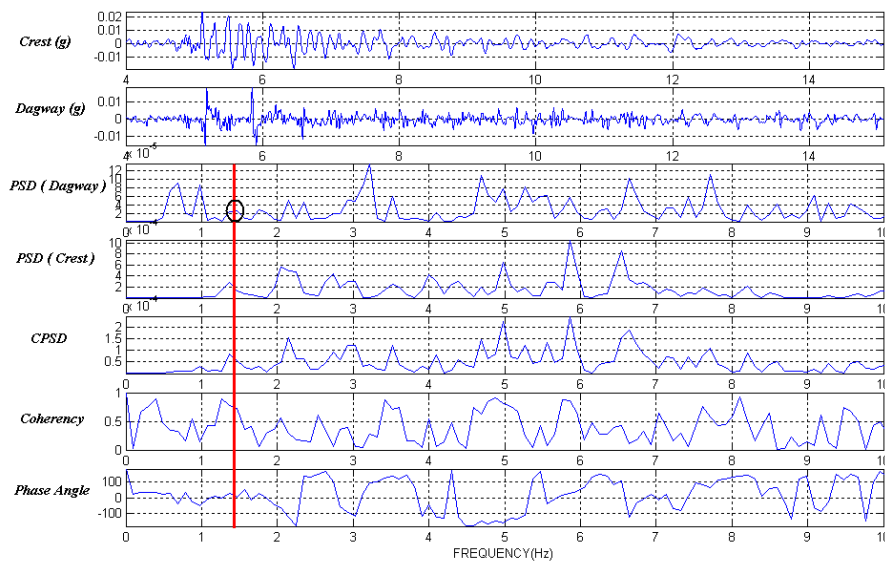
It should be mentioned that the high capability of the "4-spectra method" (using the PSD, CPS, CCPS, and CS, simultaneously) in the identification of different structural systems has been shown before. Based on these researches, the natural frequencies, mode shapes and modal damping values of two embankment dams (in forced vibration, ambient vibration and explosion tests) (Jafari and Davoodi, 2006, Davoodi, 2003), one 7-floor structure (during ambient vibration test) (Davoodi et al., 2008) and scaled model of a 4-floor structure (during ambient vibration and impulse testing) (Davoodi et al., 2007b,

Davoodi et al., 2007c) has been evaluated. Totally, it seems that the 4-spectra method is a powerful, easy, rapid, and straightforward tool to analyze the stationary signals. As an example, the processing results of the recorded earthquake signal in the longitudinal direction are presented in Figure 3. It is obvious that by comparing the PSD, CPS, CS, and CCPS of two points on the dam body (here, on the dam crest and the mid elevation height), the dominant frequency of 1.45-1.65, can be extracted clearly. Based on the complementary results of all the plots, the modal frequencies of the dam body are extracted in all three directions. Consequently, in the upstream-downstream direction, the 1.3-1.5, 1.7-1.8, 2.6-2.8, 5.1-5.3, and 5.8-5.9 Hz frequencies are extracted. In the longitudinal direction, the 1.45-1.65, 2.1-2.2, and 3.3-3.4 Hz frequencies are evaluated. Finally, in the vertical direction, the 1.9-2.1, 2.9-3.1, 3.8-3.9, and 5.7-5.9 Hz frequencies are extracted. The summary of all the obtained results is presented in table 3.

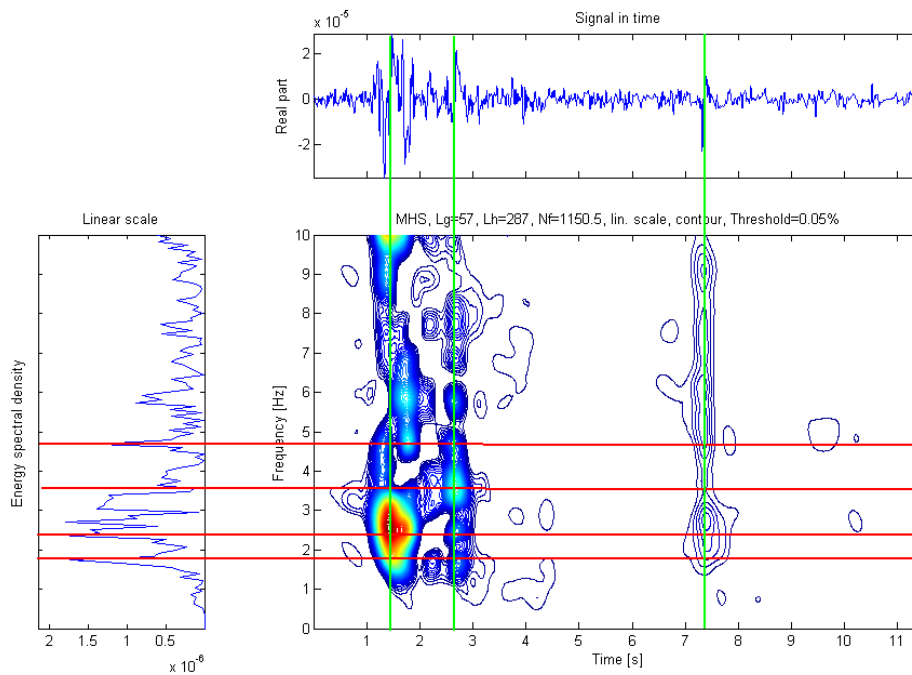
### 3.2 TFD method

In this research, many TFDs are examined, and finally Margenau-Hill-Spectrogram time-frequency distribution is selected. This distribution is selected because of its high resolution in both time and frequency domains. In the next step, earthquake records are analyzed based on the Margenau-Hill TFD method. An example of a processed earthquake signal in the longitudinal direction for the dam's crest is presented in Figure 4.

Figure 7 shows that the peak points in the 2D view are related to the proposed 1.7-1.8, 2.1-2.2, 3.3-3.4, and 4.6-4.8 Hz dominant frequencies. It should be mentioned that these dominant frequencies are extracted based on all the recorded signals on the dam body. Based on this figure and the complementary results, it is clear that low frequencies are dominant in the weak motion part of the signal, whereas in the strong motion part, both low and high frequencies appear. In other words, as the strong motion part of the signal passes, the dominant frequencies of the dam body decrease. Comparing the 2D plot



**Figure 3.** Typical processing results of the earthquake record on Karkheh dam in longitudinal direction by the 4-spectra method. From top to bottom: filtered time histories in dog-way and gallery locations, PSD amplitude of gallery and dog-way locations, their CPS, CS, and CCPS.



**Figure 4.** Recorded acceleration time history of Karkheh dam crest in longitudinal direction (top), its corresponding power spectral density (left), and related TFD contour plot (right).

And energy spectral density, as is shown in the left part of this figure, indicates that the dominant frequencies in the two plots are close to each other (which are shown by horizontal red lines). The vertical green lines show that the main shocks in the earthquake time history record can be distinguished in a 2D plot, too. These shocks can be seen as peak points in the frequency domain at each specific time. Also, these peaks clearly show the dominant excited frequencies in each shock. Consequently, it can be said that in each strong motion signal, special dominant frequencies are excited that may be different from each other. In other words, in an earthquake signal, the dominant frequencies in the weak motion part and the strong motion part are different. It is obvious that these results can be distinguished based on the 2D plot of the time–frequency distribution of non–stationary earthquake signals. The summary of the obtained results in all three directions is presented in table 3.

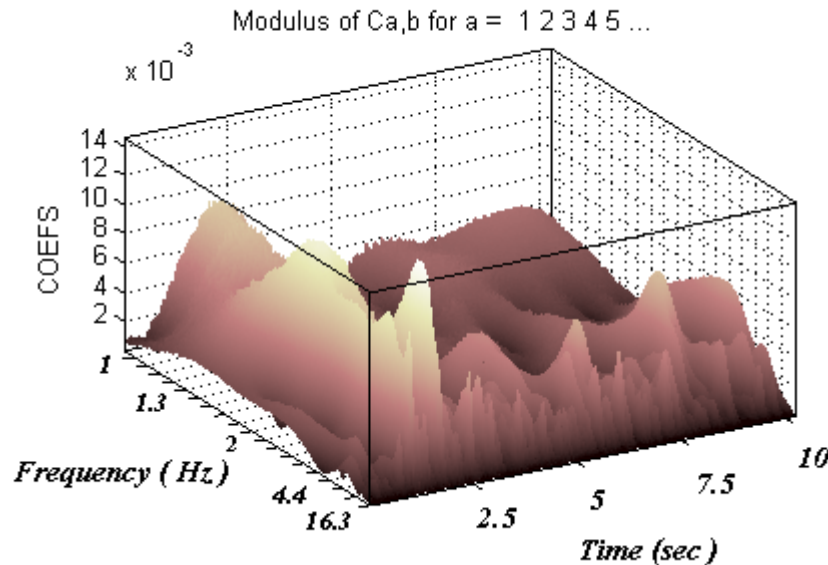
### 3.3 Wavelet method

In the TFD method, the resolution is constant for both low and high frequencies. But the wavelet method has this ability that the resolutions in the time domain and frequency domain aren't constant in low and high frequencies, and they can be changed based on different conditions. Consequently, the wavelet transform is a powerful tool to process non-stationary earthquake signals. In the next step, the earthquake records are analyzed using the continuous Morlet wavelet transform to describe the signal energy in the time domain. It should be mentioned that after examining many wavelet transforms, the Morlet transform is selected as a proper wavelet transform for analyzing the earthquake records. The results of the wavelet transform of a time series of data are presented on a three-dimensional scalogram as a function of two variables, time and scale.

For example, a three dimensional diagram of the recorded signal on the dam crest in longitudinal direction is shown in figure 5. The variation of

frequency content in a non-stationary signal, such as an earthquake signal, is distinguished in the time domain. This figure also demonstrates that at a specific time in the signal, what dominant frequencies exist. The higher resolution

and also peak points in the 3D dimensional figure indicate higher absolute values of the wavelet coefficients that are used to extract dominant frequencies of the system.



**Figure 5.** Three – dimensional surface plot of the wavelet coefficients for the earthquake signals recorded on the dam's crest in longitudinal direction.

It is necessary to mention that there is an inverse relationship between the wavelet scaling parameter "a" and the frequency of the signal:

$$f_a = \frac{f_s f_c}{a} \quad (7)$$

In this equation,  $f_a$  is pseudofrequency corresponds to scale "a" in Hz, as a function of the center frequency of wavelet,  $f_c$ . The center frequency of the wavelet is one of the characteristics of any given wavelet function. The center frequency for the Morlet wavelet is 0.8125. The  $f_s$  parameter in equation (7) is the sampling frequency of the original signal which is 200 samples per second as mentioned before. The inverse of the pseudofrequency is the pseudoperiod for any given scale, "a".

Based on the complementary studies, all the earthquake records on the dam body

were analyzed by above mentioned wavelet method. Dominant frequencies of dam body are related to the peaks in time – frequency domain which are clear in the figure 7. The 1.5, 1.7-1.8, 2.5-2.6 and 2.9-3.0 Hz frequencies in upstream – downstream direction, 1.7-1.8, 2.1-2.2, 3.0-3.2 and 3.6-3.7 Hz frequencies in longitudinal direction and 2.0-2.2, 2.7-3.0, 3.9-4.1 and 6.0-6.2 Hz frequencies in vertical direction are obtained as dominant frequencies of dam body. The summarized results are presented in table 3.

#### 4 Discussion

The obtained results clearly show that some frequencies are extracted from TFD and wavelet signal processing methods, that it is impossible to extract them from classical signal processing methods.

The extracted dominant frequencies based on different methods (4 spectra, wavelet, and TFD methods) are summarized in table 3. To compare these results with the results of the previous study (Davoodi, 2003); the modal frequencies of the previous results are also mentioned in this table. The previous results were based on ambient and forced vibration tests, and also numerical analysis. It should be noticed that ambient signals are stationary signals, so using classical signal processing methods such as the FFT may be sufficient. The recorded signals were analyzed by the 4 spectra method, as mentioned in the text. It is clear in the table that some hidden dominant frequencies, which are extracted in classical methods, are also extracted in TFD and wavelet methods, such as 3.6-3.7 and 4.6-4.8 Hz frequencies in longitudinal direction. Such a similar result can be distinguished in the upstream-down stream and vertical directions. The 2.5-2.6, 3.2-3.4, 3.8-4.0 and 4.7-4.8 Hz frequencies are extracted in upstream- downstream direction and the 4-4.3, 4.7-4.8, 5.2-5.3 and 6.8-7.1 Hz frequencies are extracted based on TFD and wavelet methods in vertical direction

of dam body. By comparing the obtained results in this research that are presented in table 2, it is clearly obvious that the modern signal processing methods which process a non-stationary signal in both time and frequency domains, are more powerful tools to analyze the non-stationary signals.

Detailed comparison between earthquake and ambient and forced vibration signal tests results, reveals that extracted frequencies obtained by earthquake signals are (0-10)% smaller than extracted frequencies based on forced, ambient and explosion tests (for example 4-4.3 Hz frequency obtained by TFD method in vertical direction in comparison with 4.4-4.5 Hz frequency obtained based on previous in situ tests). This difference may be related to stiffness decreasing of the soil because of earthquake excitation. It should be mentioned that the analyzed earthquake signals in this research are really weak motions, so the maximum differences between the results of this research and previous in situ test results are about 0-10 per cent in weak and strong motions respectively.

**Table 2.** Modal frequencies of Karkheh dam based on different signal processing methods.

**P. results:** indicate the results of previous study on the Karkheh dam body based on ambient, explosion, forced vibration tests and numerical modeling [18].

V Direction				L Direction				U-D Direction				N
P. results*	TFD	Wavelet	4 Spectra	P. results*	TFD	Wavelet	4 Spectra	P. results*	TFD	Wavelet	4 Spectra	1
2.0-2.2	2.0-2.2	2.0-2.2	1.9-2.1	1.7-1.8	1.7-1.8	1.7-1.8	1.45-1.65	1.45-1.5	1.4-1.5	1.5	1.3-1.5	2
2.9-3.0	3.0-3.2	2.7-3.0	2.9-3.1	2.1-2.25	2.1-2.2	2.1-2.2	2.1-2.2	1.75-1.8	1.7-1.8	1.7-1.8	1.7-1.8	3
3.65-3.9	3.6-3.9	3.9-4.1	3.8-3.9	3.3-3.4	3.3-3.4	3.0-3.2	3.3-3.4	2.5		2.5-2.6		4
4.4-4.5	4-4.3			3.6-3.7		3.6-3.7		2.9-3.0		2.9-3.0	2.6-2.8	5
4.7-4.9	4.7-4.8			4.6-4.8	4.6-4.8			3.2-3.4	3.2-3.4			6
5.3-5.5	5.2-5.3							3.8-4.0	3.8-4.0			7
5.9-6.2	5.9-6.1	6.0-6.2	5.7-5.9					4.7-4.8	4.7-4.8			8
6.8-7.1	6.8-7.1							5.2			5.1-5.3	9
								6-6.2	6.0-6.1		5.8-5.9	10

## 6 Conclusion

In this article, three methods for analyzing the earthquake records on Karkheh embankment dam have been performed. In the first step, by using 4-

spectra method, as a classical method; indicating a) power spectral density, b) cross power spectra, c) coherency spectra and d) the cross correlation phase spectra, the natural frequencies of dam body are

obtained. In the next step, for the first time, time – frequency signal analysis of earthquake records using TFD method and wavelet decomposition are used to identify the dominant frequencies of the Karkheh dam. The results clearly show that some hidden dominant frequencies in classical methods are extracted in TFD and wavelet methods in upstream-downstream, longitudinal, and vertical directions. This is due to this important matter that the TFD method analyzes signals in both time and frequency domains, and the wavelet method has the flexibility of separately varying resolutions in time and frequency domains. The time–frequency character of wavelet transforms and time-frequency distributions allows the adoption of both traditional time and frequency domain system identification approaches. It should be mentioned that classical signal processing methods such as FFT, power spectra density, and cross power spectra density are powerful, easy, and straightforward tools to process stationary signals. But these methods have some limitations in processing non-stationary earthquake and explosion signals. This paper demonstrates that using TFD and wavelet tools is more benefit in signal processing for non-stationary signals and it is the key parameter that specifies this research against previous researches based on classical signal processing.

It should be mentioned that this research can be modified with stronger earthquake signals recorded on different dams to ensure the benefit of the modern signal processing methods to extract modal frequencies of dams as a tool for system identification.

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