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New development of artificial record generation by wavelet theory

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Abstract. Nowadays it is very necessary to generate artificial accelerograms because of lack of adequate earthquake records and vast usage of time-history dynamic analysis to calculate responses of structures. According to the lack of natural records, the best choice is to use proper artificial earthquake records for the specified design zone. These records should be generated in a way that would contain seismic properties of a vast area and therefore could be applied as design records. The main objective of this paper is to present a new method based on wavelet theory to generate more artificial earthquake records, which are compatible with target spectrum. Wavelets are able to decompose time series to several levels that each level covers a specific range of frequencies. If an accelerogram is transformed by Fourier transform to frequency domain, then wavelets are considered as a transform in time-scale domain which frequency has been changed to scale in the recent domain. Since wavelet theory separates each signal, it is able to generate so many artificial records having the same target spectrum.

Key words: wavelet theory; artificial accelerogram; target spectrum; frequency content.

1. Introduction

Earthquake records highly depend on fault mechanism, rock properties, local soil condition, and other effects. It is important for us to record an earthquake record to apply in a dynamic analysis instead of a static analysis. The best accelerogram is one which has compatible characteristics with desired area. Therefore, it is difficult or may be impossible in some cases to choose a proper record for a design area; because the recorded and processed accelerograms of the design location are few. Besides, other location records do not satisfy the geo-seismic characteristics on desired location. In this case, artificial earthquakes that are statistically generated based on desired properties are very useful for analysis or design operation.

Since earthquake is a random base phenomenon, it is impossible to detect clearly a possible future earthquake in specified location. Most studies have been conducted to identify some parameters such as magnitude, PGA, strong motion duration and so on. Yet, it seems difficult to predict properties of an earthquake which may happen with a certain probability of occurrence. In dynamic analysis, several proper records should be selected to be applied, preferably natural accelerogram records with

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similar geo-seismically properties that usually are not adequate. Actually, there wouldn't be any possibility of the reoccurrence of any past earthquake event, thus the generation of any artificial records is necessarily highlighted. The most important point is that the used records should be similar to the previous record of the specified location in shape and some other important parameters. These parameters such as PGA, duration, and frequency content are used to generate an artificial earthquake. In the next section, the control criteria of generated accelerograms are discussed.

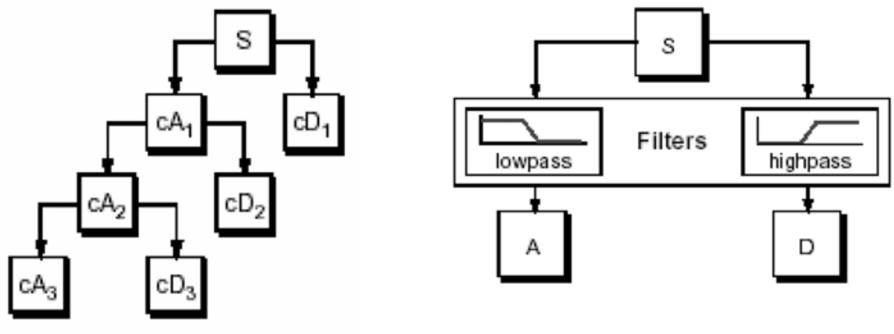
Random and geophysics models are two famous methods to generate artificial records (MacCann and Shah 1979). Since the theory of geophysics has not been sufficiently developed, random models are more applied. New models have been obtained on the basis of statistical studies of various accelerograms recorded at different areas. The most famous patterns are White Noise, Stationary, Non Stationary pattern in amplitude and frequency, and Modified Stationary. Besides, there are random models such as combination of Sinusoidal waves. A random algorithm for earthquake simulation has been previously presented (Suzuki *et al.* 1998). In order to generate artificial records, different patterns are applied such as Random Pulse Train Model, Shot Noise, Modified Stationary Pattern (with filter of type I, II, and continuous) and Autoregressive ARMA (which is used for analysis of discrete time series) that each one has its own special properties (Box and Jenkins 1970).

2. Wavelet theory

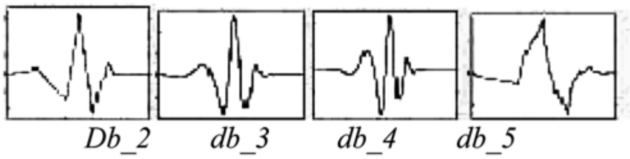
Wavelet theory is a mathematically based method as well as Fourier method and has been used for solving partial differential equations. Soon, it was developed in engineering Science especially signal processing in electrical engineering. Now, it is one of the powerful tools of time-frequency analysis (Newland 1994). This theory enables us to identify frequency details in each individual time step. The most applicable usage of wavelet transform is decomposition of time series by low and high pass filters.

One of the disadvantages of Fourier transform is that it presents the frequency content of whole earthquake duration, but the frequency of a specific time is not identified. The reason is that Fourier transform integration is in the range of $(-\infty, \infty)$, so it is not capable of giving frequency content of a definite time. In this way, if a local oscillation appears at a certain time, it will affect the Fourier transform, but its occurrence time will be lost.

The purpose of classic wavelet is to provide an alternate way of breaking a signal down into its constituent parts. Low and high frequencies have narrow and wide bands, respectively. Therefore a signal as illustrated in Fig. 1(a) could be separated into two sub-signals of approximation (A) and detail (D) by using low and high pass filters. If decomposition of approximation component (A) goes on, a line is obtained that is the simplest shape of an analysis. Also, decomposition operation could be accomplished for high pass branch. The structure of operation is similar to a tree with two branches in any step. Assume that input record is a series of 2^n points. So after n level of decomposition, signal is separated into $n + 1$ sub signals. The simplest way for above procedure is Mallat algorithm (Williams and Amaratunga 1994). In this algorithm, first of all, some coefficients (C) are calculated, called wavelet coefficients, then the record decomposition is attained by multiplying coefficients to an arbitrary base function as it is shown in Fig. 1(b). Here, there are some base functions which are presented by famous peoples such as Haar (db_1) and Daubechies (db_n) with different degrees (n).



(a) Detail and Approximation



(b) Daubechie base functions

Fig. 1 Signal decomposition using low and high pass filters

3. Proposed method

The studies of Fourier, energy, power, and response spectra show that though the pattern of different earthquake records are not similar even in an specified area, but a certain pattern of response spectra could often be attained for the specified area because of their similarities (Ghaboussi and Lin 1998, Lin and Ghaboussi 2000). In fact, a design spectrum is derived by smoothing according to geophysical and geotechnical parameters. The problem is that design spectrum may derive from different records which are related to different accelerograms of that location. Therefore, it is easy to calculate the spectra, but the inversion operation to attain an artificial record is almost impossible. So it should be calculated with a non-classic method and then compared with target spectrum at the end. In this case, the artificial record has to satisfy static analysis conditions, therefore the related spectrum should be approximately equal to design spectrum.

Obviously, lots of artificial records should be generated to achieve a reliable response of structure at dynamic analysis. The purpose of this paper is to generate so many records compatible with the same spectrum. A distinct feature of the proposed method is that it is easy to impose the shape of the envelope function which is derived from various records. For a definite earthquake record named (a) with its related spectrum, an artificial record is simulated like the accelerogram of the earthquake (b), having a spectrum similar to earthquake (a). This study has been accomplished for 40 selected records of Iran (Ramezi 1997). The key features of the selected accelerograms are presented in Table 1.

Generally, the main idea of the proposed method is to use wavelet theory. The record decomposition results in coefficient sets of approximation (cA), which includes frequency contents,

Table 1 Data of selected base accelerograms

Number	Occurance date	Name of station	Magnitude	Modified PGA (cm/s^2)	Ground type (Table 2)	Duration (sec)
1	1976.11.07	Ghaen	6.4	115		19.54
2	1977.03.21	Bandar Abbas	6.9	90	IV	45.22
3	1977.40.06	Naghan	6.1	700	I	20.96
4	1978.09.16	Dayhouk	6.7	272	I	58.38
5	1978.09.16	Tabas	7.3	832	II	49
6	1978.09.16	Bajestan	7.3	78	III	39.58
7	1978.11.04	Moshtabar	6.2	171		18.96
8	1979.01.16	Khaf	6.8	69	III	32.42
9	1978.09.16	Ferdos	7.3	76	IV	53
10	1979.11.27	Kashmar	7.1	70	III	67.92
11	1979.11.27	Bajestan	7.1	104	III	33.20
12	1979.11.27	Ghaein	7.1	186		30.16
13	1979.11.27	Taeibad	7.1	75	III	60
14	1979.11.27	Ghonabad	7.1	69	IV	50.52
15	1979.11.27	Khaf	7.1	127	III	58.04
16	1981.07.28	Gholbaf	7	217	III	59.32
17	1984.06.01	Shalamzar	5	299	III	18.66
18	1985.02.02	Gheer	5.3	290	I	15.34
19	1988.12.06	NourAbad	5.6	85	III	17.28
20	1990.06.20	Abhar	7.7	127		29.48
21	1990.06.20	Roudsar	7.7	91	IV	53.10
22	1990.06.20	Lahijan	7.7	111	IV	60.54
23	1990.06.20	Tonekabon	7.7	130	IV	35.94
24	1990.06.20	Ghachsar	7.7	63		49.48
25	1990.06.20	Zanjan	7.7	125	III	59.78
26	1990.06.20	Robat Kareem	7.7	64	III	12.58
27	1990.06.20	Eshtehard	7.7	71		45.78
28	1991.11.28	Roudbar	5.7	268	I	19.94
29	1994.06.20	Meymand	6.1	394		27.14
30	1994.03.20	Zarrat	5.5	196	I	33.24
31	1994.06.20	zarrat	5.9	289	I	43.50
32	1994.06.20	Firouz Abad	5.9	235	II	38.36
33	1994.06.20	Zanjeeran	5.9	841	II	63.98
34	1994.01.24	Feen	4.9	433		31.96
35	1976.11.24	Mako	7.3	86	I	28.06
36	1977.03.21	Band arAbas	6.9	98	IV	41.06
37	1979.11.14	Khaf	6.8	74	III	39.20
38	1980.01.12	Tabas	5.8	150	II	29.74
39	1979.11.27	Khezri	7.1	94	IV	35.98
40	1981.07.28	Kerman	7	98		38.04

Table 2 Ground classification according to “Iranian Earthquake Code of practice, Standard No. 2800”

Ground Type	Explanation of materials	Shear wave velocity (m/s)
I	Un-weathered igneous rocks, hard sedimentary rocks and metamorphic rocks (as gneisses and crystalline silicate rocks) Very hard conglomerates very compact and very hard sediment	Vs>750
II	Soft igneous rocks e.g. tuffs, clay stones, shale and semi-weathered or altered rocks Crushed (but not hardly) hard rocks, foliated metamorphic rocks, conglomerate and compact sand and gravel	375<Vs<750
III	Weathered rocks, semi-compact sands and gravels, other compact sediments Compact sandy clay soils, with low ground water level	175<Vs<375
IV	Soft sediments, clay soils, weak cemented and un-cemented sands, incompact soils with high ground water level Any kind of soft soils	Vs<175

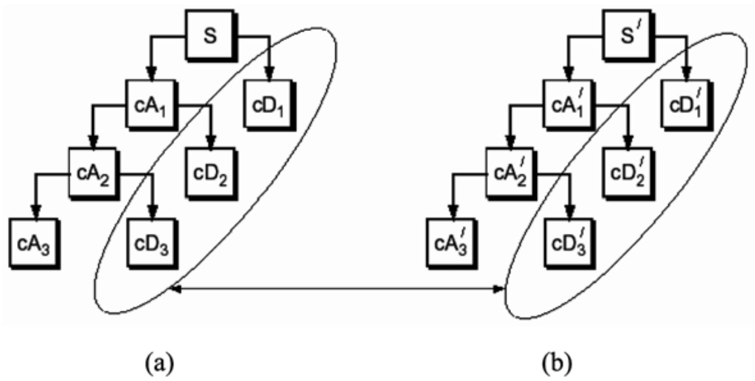


Fig. 2 Substitution of signal components

and detail (cD). So it is possible to decompose a signal to many levels, say 3 steps, as shown in Fig. 2. As shown in this figure, most of frequency contents are imbedded in the cA3 component. Also, coefficients of wavelet are divided by two in each level. For example, in this study all records have Δt = 0.02 sec, and 2^{11} = 2048 points consequently. Therefore, a series of zeros is added to the records which are shorter than desired length (2048 × 0.02 = 40.96 sec) to gain proper length, and for the longer ones, the strong duration of records of longer length is considered according to MacCann and Shah algorithm. So the length of cA1 & cD1 are 1024, cA2 & cD2 are 512, and for cA3 & cD3 are 256 points. Obviously, the initial record is attained from cA3, cD3, cD2, and cD1. It is noted that records have been scaled with the maximum acceleration equal to *g*. Besides, response spectra is calculated applying Naeim method (ζ = 0.05) (Naeim 1999).

Since cA3 contains most frequency contents, if cD is chosen randomly then a special record is achieved by inversion method with similar frequency contents to the primer record. Here, records of Iran are used instead of random records (Table 1). As shown in Fig. 2, in inversion method, the artificial record is similar to record (b), but its spectrum is similar to (a). Therefore, Inverse Discrete Wavelet Transform (IDWT), after scaling, generates artificial records. Obviously, it is possible to generate an artificial record like (a) with spectrum similar to (b). In this study, coefficients of wavelet and inversion are calculated with Mallat Discrete Wavelet Transform (DWT) and IDWT, respectively. More information about wavelet artificial records is indicated in reference (Iyama and Kuwamura 1999).

In some cases, an artificial earthquake can be considered “critical” when the shape of its record is similar to the shape of a real earthquake, and its spectrum is similar to the spectrum of another real earthquake record.

4. Analytical samples

Generally, there are three types of classical horizontal earthquake accelerograms, each representing different accelerogram shapes and frequency contents in this paper. The first type contains a wide range of frequencies and several episodes of strong motion. The second type of accelerogram represents a single pulse loading with dominant lower frequencies. The third type accelerogram has high frequency content and shaking with long duration.

In this chapter, the previous method has been applied with MATLAB software (MATLAB 1999) for all types of earthquake records.

As shown in Fig. 3, beneath the Tabas record, a record has been simulated for Tabas having similar shape to Taybad record, but its PSV spectrum (dash line) is similar to that of Tabas (solid line). In the same way, another artificial record is made for Taybad record. Here, it is not necessary to use envelope functions and simulated record is made in a realistic way.

Fig. 4 indicates another example of Khaf and Bajestan. The horizontal and vertical axes of the simulated record are time and acceleration, respectively. Also, the horizontal and vertical axes of response spectra are frequency and pseudo-velocity, respectively.

In Figs. 3, 4, 5, 6, and 7, Haar or db_1 is selected as the base function. The other base functions could also be applied.

Fig. 8 depicts five simulated records obtained for Tabas which the shapes are similar to that of Bajestan, Deyhouk, Khaf, Ferdos, and Feen records, respectively. The indicated simulated records are derived from the wavelet base function db_10.

Figs. 9 and 10 show five simulations of base function db_1 to db_5 for Ghaen and Gachsar records, respectively. In Figs. 8, 9, and 10, the spectrum of real records are represented by thick lines.

The artificial earthquake records generated by the use of the proposed method which are obtained by the combinatorial application of previous earthquakes are more probable earthquake events.

In Figs. 3 to 7, it can be observed that the PSV spectrum of the earthquake event is very similar to that of obtained simulated record.

Also, in Figs. 8 to 10, it can be observed that the PSV spectrum of the real earthquake record is approximately coincides with spectrum of all the five simulated records.

As it can be observed, by the combination of two real accelerogram records, two probable simulated records can be generated according to each base function.

Two initial records are needed in this method, which are to be attained from a certain area or simulated by the old method. Eventually, this method produces records with any arbitrary shape.

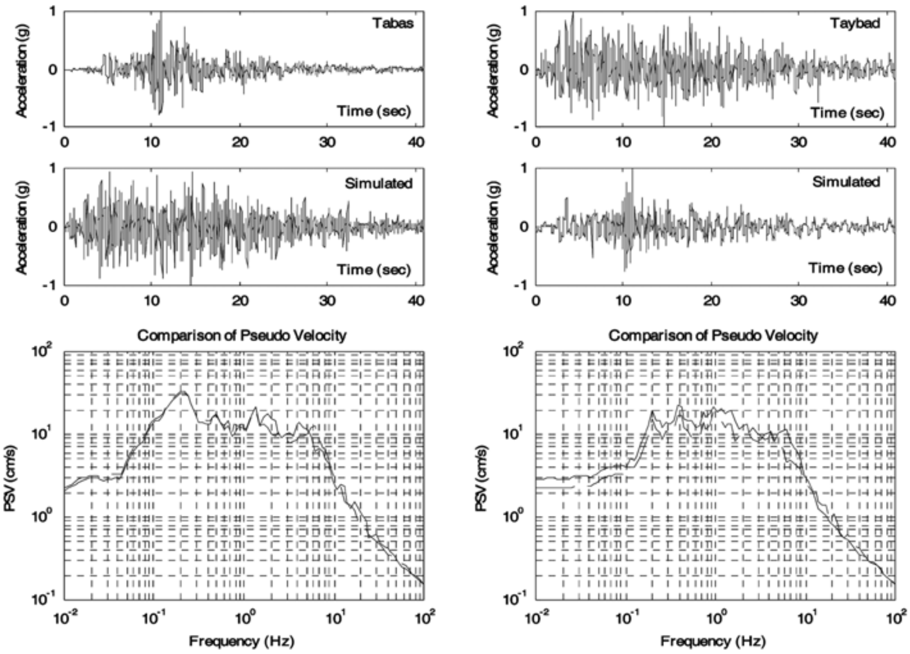


Fig. 3 Artificial records of Tabas and Taybad and comparison of their response spectra (dash line for simulated record)

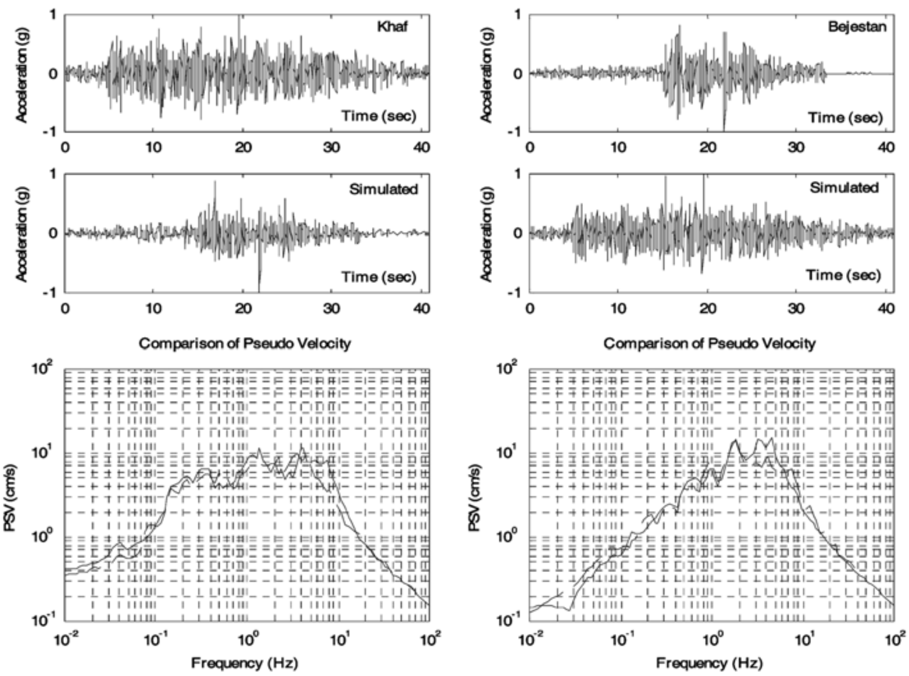


Fig. 4 Artificial records of Khaf and Bajestan and comparison of their response spectra (dash line for simulated record)

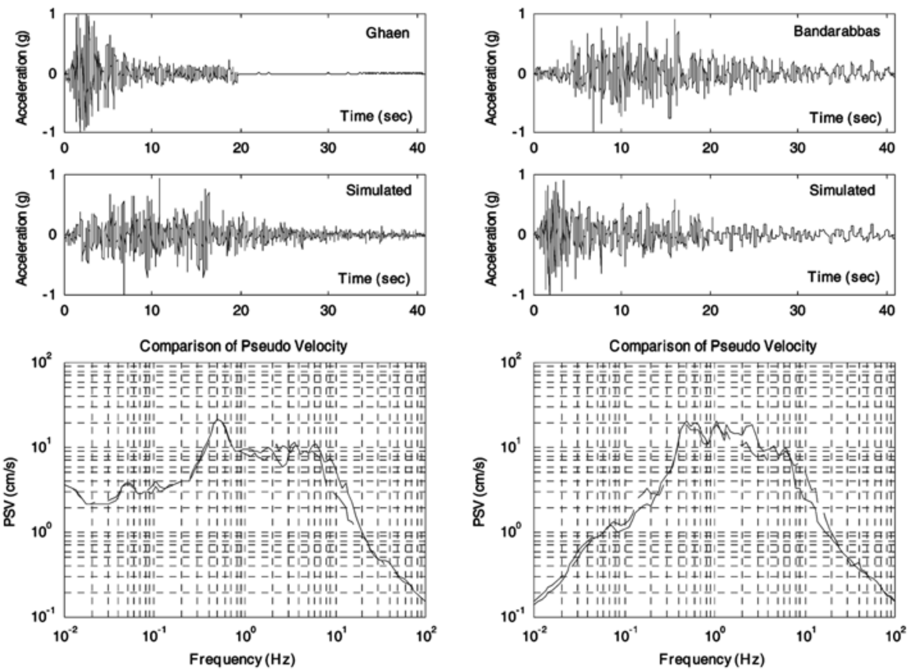


Fig. 5 Artificial records of Ghaen and Bandar-Abas and comparison of their response spectra (dash line for simulated record)

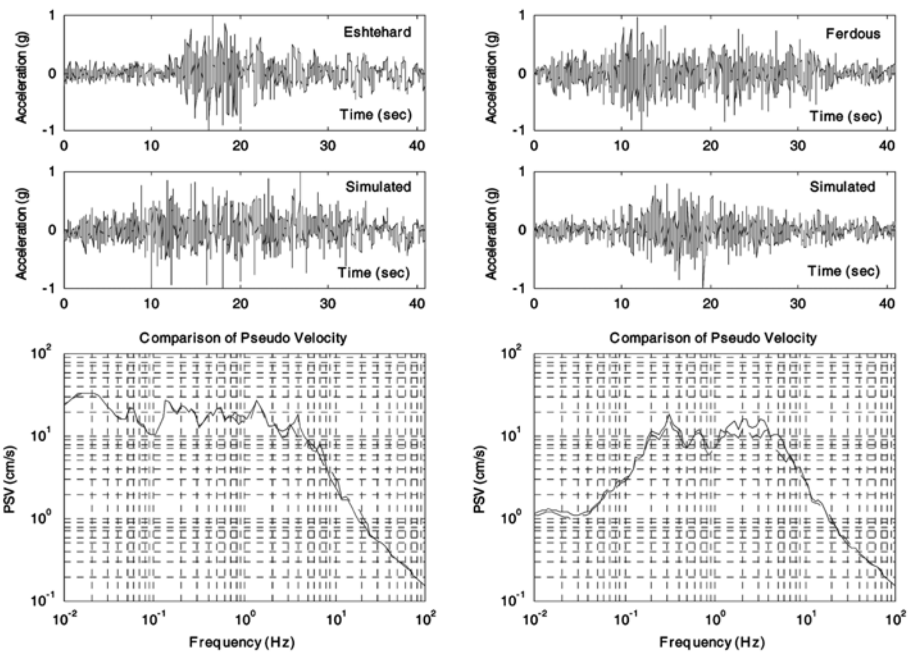


Fig. 6 Artificial records of Eshtehard and Ferdos and comparison of their response spectra (dash line for simulated record)

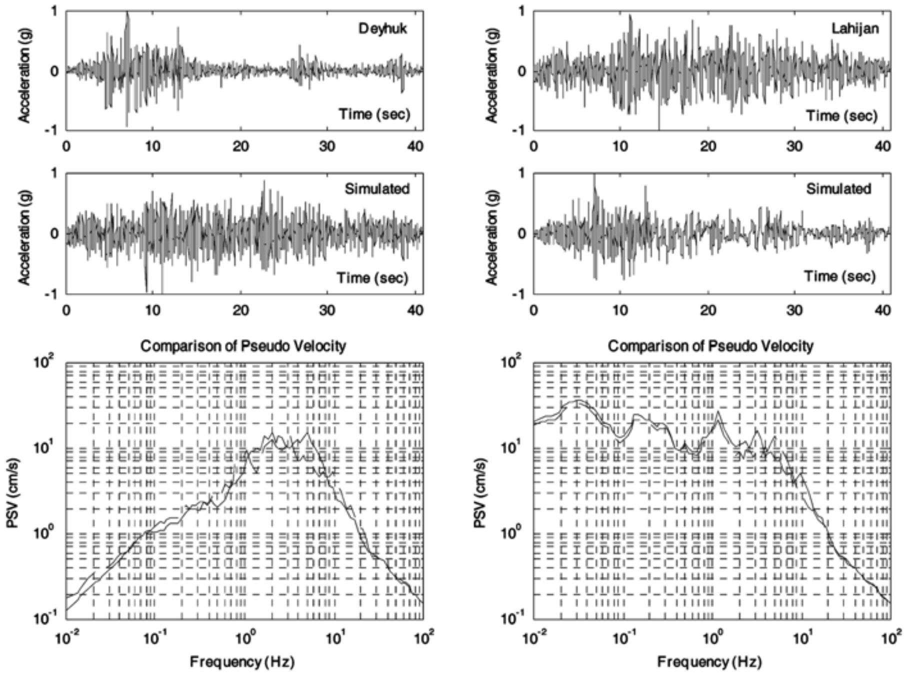


Fig. 7 Artificial records of Dayhouk and Lahijan and comparison of their response spectra (dash line for simulated record)

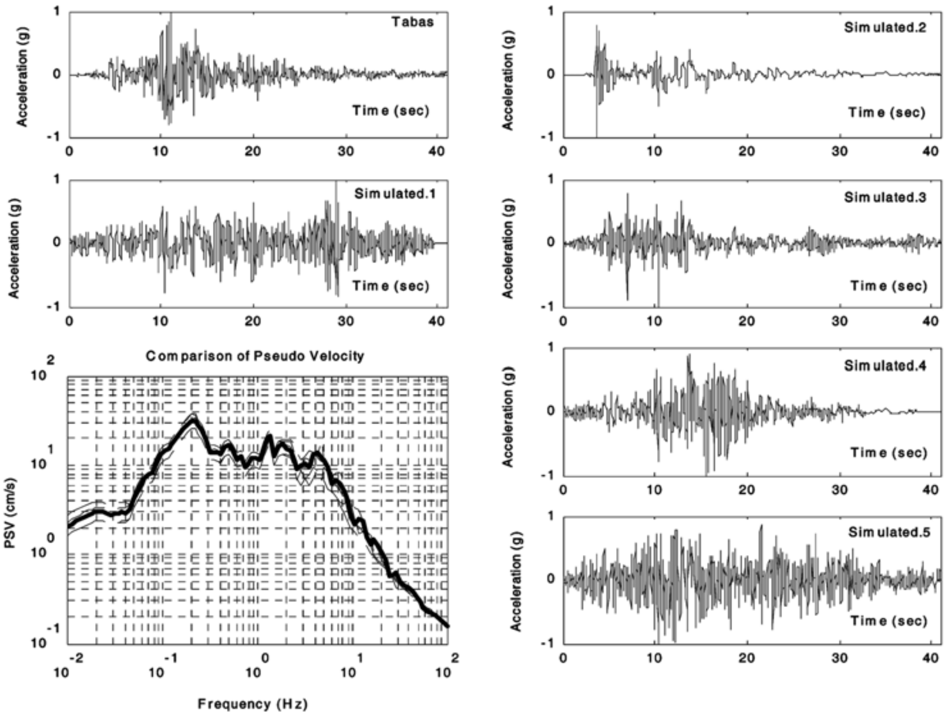


Fig. 8 Artificial records of Tabas and comparison of its response spectra (thick line for real record)

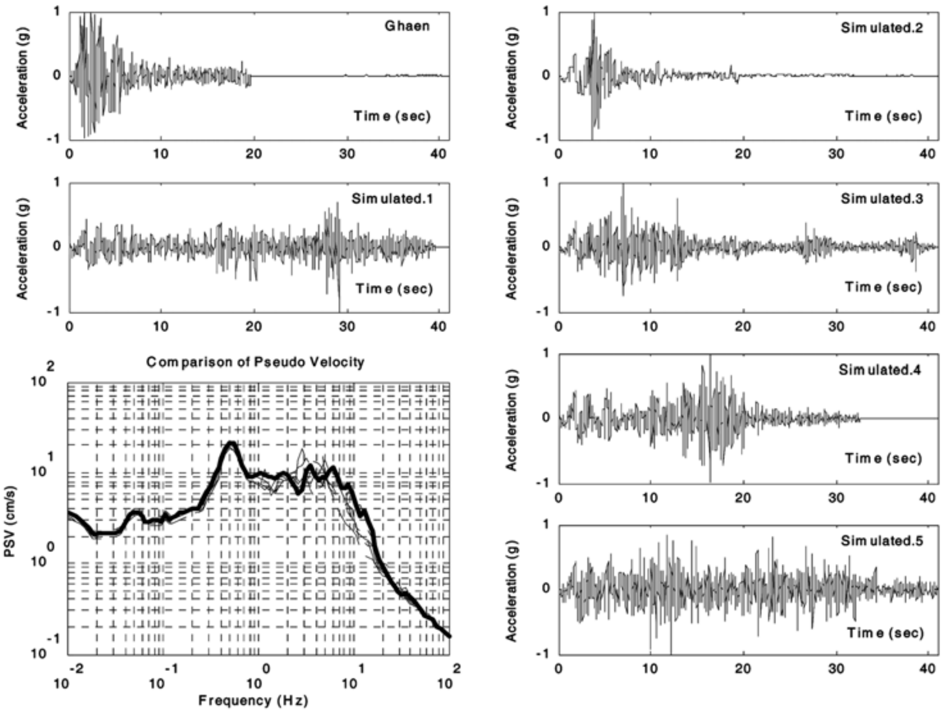


Fig. 9 Artificial records of Ghaen and comparison of its response spectra (thick line for real record)

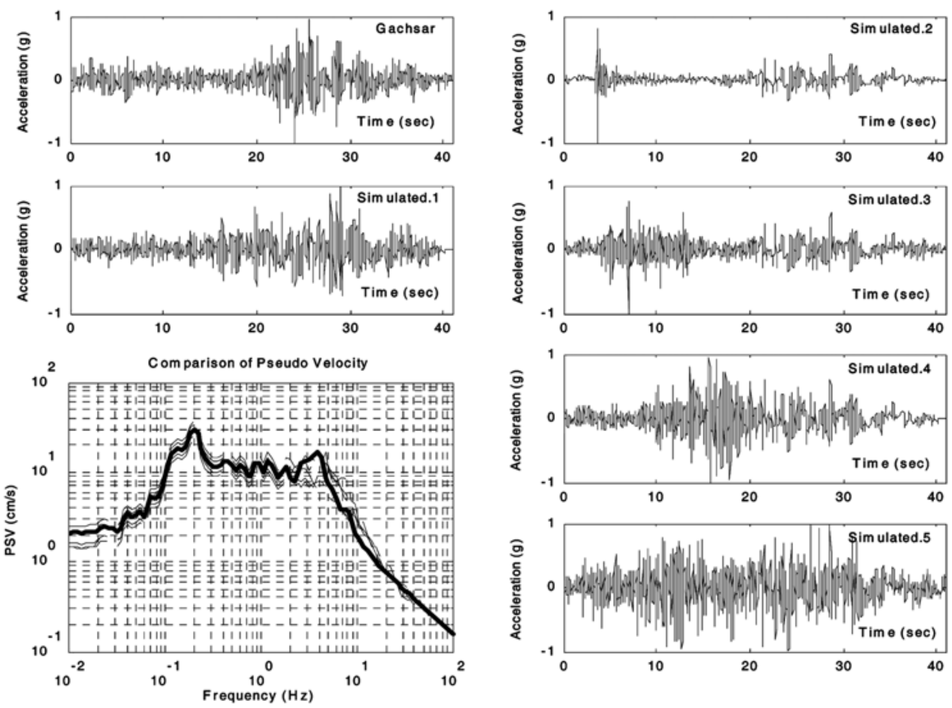


Fig. 10 Artificial records of Gachsar and comparison of its response spectra (thick line for real record)

5. Conclusions

Wavelets are capable to decompose the frequency components of accelerograms into low and high frequencies by filters. The simplest way is to apply Discrete Wavelet Transform (DWT) by Mallat algorithm. This method determines wavelet coefficients (cA, cD) by using matrix analysis and the inversion operation simulates initial records. Frequency components are replaced after a simple substitution of wavelet coefficients of two accelerogram records. Finally, inversion of coefficients produces a different record related to initial accelerogram which has different shape but the same response spectrum.

This paper presents a simple and applicable method to generate many realistic artificial records having the given spectrum. Besides, the method applies real records which are more reliable than other random methods.

The feasibility and reliability of the proposed method have been verified with different examples of Iran.

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