The application of wavelet theory with denoising to estimate the parameters of earthquake

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Abstract
In this paper, strong ground mot (SGM) parameters are calculated using discrete wavelet transform (DWT) in different kinds of soils with different magnitudes. The main earthquake record (MER) is divided into approximation and detailed signals using wavelet transform with denoising. The high and low frequencies of MER are separated from each other. Previous studies showed that the approximation signal has the greatest effect on dynamic response and it is very similar to the main signal. Then SGM parameters of the new signal are calculated by DWT decomposition. This process continues over five levels and, in each level, SGM parameters are calculated and compared with the MER and its error percentage is presented. In DWT with the denoising method, the curve becomes softer such that the calculation time reduces. Results show that the error percentage in the first two levels is less than 1% and for the third level, this index is less than 3%. In addition, the reduction percentage of calculation time is 1%, 4%, and 8%, respectively, in the first to third levels. The best result is relative to the third decomposition level in which error value as well as computational time reduction is nearly 3% and 8%.

Keywords: strong ground motion; filter bank; wavelet; discrete wavelet; denoising; dynamic

1. Introduction
The three main characteristics of strong ground motion (SGM) for earthquake engineering applications are the amplitude, frequency, and duration of motion. Some SGM parameters can describe one of the main characteristics of the main earthquake record (MER), while some of the parameters describe two or more of the mentioned characteristics. Much research has been conducted investigating seismic parameters of SGM and their features and effect on structures. For instance, in discussing the seismic performance of structures in relation to probable future earthquakes, the seismic evaluation of existing buildings and designing new structures based on determining earthquake intensity measures has received considerable attention [1-3]. Time history analysis is the most important tool for seismic designations based on performance [4-6].
The most important concern in seismic analysis is making a monolithic and effective relation between the intensity index and the real damage to structures. Thus, seismic performance can be conducted with higher accuracy [7]. Modeling ground movement can be effective for determining the SGM intensity on structures. Two kinds of models are available for SGM. The first is related to the ground motion parameter equation relevant to the earthquake source, intensity, amplitude, frequency content, and movement duration [8] and the other model is related to ground motion time series [9]. Time series models include source-based deterministic models, source-based stochastic models, site-based stochastic models, and hybrid models that combine deterministic and stochastic [10]. Source-based deterministic models can describe the physical processes of source, site response, and wave propagation [11]. Many physical and stochastic methods (SM) have been suggested for better representation of wave propagation and their high frequency content [12-14]. The models performing according to SM based on source are calibrated from regions with different kinds of soil and can show frequency content higher than 0.2 Hz [15]. Source-based SM in near-fault earthquakes have been suggested; their modeling has been done according to physical parameters and some of the ground motion features such as time and spectral features and rupture effects are properly determined [9]. This suggested model also contains some of the other models. For example, a white-noise filtered model [16, 17], applicable for describing the near-fault bandwidth, is used by the modified model function to better indicate the SGM amplitude.

In addition, other research has been conducted analyzing ground movement frequencies in near faults without additional pulse in which two parameters of $T_m$ and $T_0$ have been considered for separating high- and low-frequency components in near-fault regions [18]. A new predictive model for $T_m$ has been developed based on the horizontal components of ground motions selected from the expanded NGA-West2 database [19]. The interested reader is referred to further studies about the kind of selected soil and its effect on ground motion in [20, 21].

One of the best methods for separating earthquake frequencies is wavelet transform [22-24]. Wavelet transform is a new tool for analyzing signals and can give earthquake time and frequency information at the same time [25]. For the application of wavelets to processing earthquake records, separating the diffraction from the record and compressing information available in the record are important issues. Time history analysis has been performed for seismic analysis and fast wavelet transform (FWT) has been used for this purpose. For decomposing acceleration, two kinds of high- and low-pass filters have been used. For the most part, low-frequency waves have been used for analyzing earthquake records. Some of the earthquakes have been calculated using this method and its results have been compared with MER. Results showed that using the FWT method has provided excellent results transform [26]. In the research, the MER has been modified using wavelet transform at two levels and the earthquake record has been
Kaveh and Mahdavi presented a simple and accurate method for spectral adaption of ground motion [28]. Initially in this method, the main ground motions are decomposed into different levels using discrete wavelet transform (DWT) and then every level is multiplied by a coefficient. Finally, using an optimization method, variables are determined so that the error between the target and response spectrums is the lowest possible value. There are several optimization methods which can be used to find optimum solution of a problem [29-31]. Recently, Gholizadeh and Samavati [32] used the neural network and meta-heuristic optimization algorithms to obtain a reliable seismic design of steel structure.

Developing an appropriate wavelet network and replacing it by accurate analysis reduced the optimization time considerably, while the accuracy of operations did not decrease [22]. An application of DWT for damage detection of a framed structure subjected to strong earthquake excitation was described. Results showed the effectiveness of the DWT approach to damage detection in the framed structures [33]. Todorovska et al predicted wavelet approximation of earthquake SGM goodness of fit for a database in terms of predicting nonlinear structural response using earthquake wavelet approximation in which it was concluded that the development of strong motion records in a wavelet basis can be used to receive pulses from a strong motion record as well as represent strong motion records as the sum of pulses with relatively small number [34]. In addition, Haigh et al investigated the dynamic behavior of geotechnical structures using wavelet analysis. Wavelet transform and its application to the problems of soil dynamics and earthquake engineering have also been discussed [35].

In this paper, SGM parameters have been investigated using DWT in four kinds of soils with different magnitudes. For this purpose, these parameters are calculated initially using the earthquake record. Then, the MER is decomposed using DWT and its high and low frequencies are obtained, so that two signals including earthquake approximation and details are obtained. As previous studies indicated that the approximation signal has the greatest effect on dynamic response and it is very similar with MER, it is used as a new earthquake record (NER) and SGM parameters are calculated from this NER again. In the next level, the approximation wave is decomposed again and two new signals including approximation and detail are obtained. Again, the approximation signal is considered as a NER and SGM parameters are calculated. This work continues over five levels and SGM parameters of each NER are compared with MER. The Daubechies 4 mother wavelet [36] has been used for wavelet decomposition of the earthquake record. The earthquake record has been decomposed using a denoising method in discrete condition. This means that the number of record points has not been reduced and only high frequencies of the earthquake record have been omitted in each level and the earthquake record becomes softer. Although the number of MER points does not decrease in this method, in every decomposition level, the curve has become softer and the duration of calculations has been reduced. In every wavelet decomposition level, half of the noise in the previous level of wave has been omitted. Results showed that error percentage in the first two
levels is less than 1% and for third level is less than 3%. In addition, the percentage error of decomposition in the fourth and fifth levels is more than 10% and less than 40%, respectively. Calculation duration of SGM parameters has been reduced 8% in comparison with calculation duration of MER. The best result is related to the third level of decomposition in which the error value and time reduction are 3% and 8%, respectively. It should be noted that 28 earthquakes have been selected in this paper, so that they include different kinds of soils with different shear wave velocities, magnitudes and focal distances and also the accuracy of using wavelet transform is recognized well in all 28 earthquakes in all 5 levels. It should be noted that the wavelet transform used in this study can be applied to any other earthquake record.

2. Strong ground motion

Amplitude, frequency, and duration of motion are the three main characteristics of ground motion for earthquake engineering applications. Many parameters have been developed for determining the amplitude, frequency, and duration of SGM. Some of these parameters describe only one of the aforementioned characteristics. Three main ground characteristics including the amplitude, frequency content, and duration of movements have been described briefly in the following. Amplitude parameters, parameters such as acceleration, velocity, or displacement or all of them can be determined using time history. Amplitude parameters describe only the peak amplitude for the unique cycle from the time history of ground motion. Frequency content parameters describe the distribution of ground motion amplitude in different frequencies. The frequency content of earthquake motions is largely dependent on these movements. Motion duration parameters have a considerable effect on the earthquake destructions. The duration of SGM depends on the time required for releasing cumulated strain energy along a fault.

Peak ground acceleration (PGA) is the maximum recorded acceleration value in an earthquake. The maximum value of the recorded characteristic in the velocity–time graph of an earthquake is called the peak ground velocity (PGV) and the maximum displacement in the ground surface obtained from the displacement–time graph is the peak ground displacement (PGD). The ratio between PGV and PGA is shown with PVA. The acceleration spectral intensity (ASI) is known as the spectral acceleration integral of SGM that its value is usually between 0.1 and 0.5 seconds and it is used for expressing the SGM magnitude. In addition, the velocity spectral intensity (VSI) is the spectral velocity integral of the SGM and expresses the SGM magnitude. The third or fifth large value of acceleration or velocity time history are the sustained maximum acceleration (SMA) and sustained maximum velocity (SMV) of the earthquake record and indicate the frequency content of SGM. The A95 parameter shows the maximum
value of earthquake acceleration related to 95% of Arias intensity. The root-mean-square acceleration \(a_{RMS}\) expresses the average intensity of earthquake acceleration and can be determined as follows:

\[
a_{RMS} = \frac{1}{T_d} \int_{0}^{T_d} [s(t)]^2 \, dt
\]  

(1)

where \(s(t)\) represents the acceleration of ground motion and \(T_d\) represents the duration of the SGM.

The root-mean-square velocity \(V_{RMS}\) expresses the average intensity of the earthquake velocity and can be determined as follows:

\[
V_{RMS} = \frac{1}{T_d} \int_{0}^{T_d} [v(t)]^2 \, dt
\]

(2)

where \(v(t)\) represents the velocity–time ground motion.

The root-mean-square displacement \(D_{RMS}\) expresses the average intensity of earthquake displacement and can be determined as follows:

\[
D_{RMS} = \frac{1}{T_d} \int_{0}^{T_d} [d(t)]^2 \, dt
\]

(3)

where \(d(t)\) represents the displacement–time ground motion.

The Arias intensity \((I_a)\) for every earthquake indicates the energy value taken by the structure expressed as follows [37]:

\[
I_a = \frac{\pi}{2g} \int_{0}^{T_d} [s(t)]^2 \, dt
\]

(4)

The characteristic intensity \((I_C)\) has a linear relation with structural failure index due to the maximum deformations and attracted hysteretic energy and is determined as follows [38]:

\[
I_C = (a_{RMS})^\frac{3}{2} \cdot \sqrt{T_d}
\]

(5)

The specific energy density \((S_E)\) indicates the frequency content and amplitude parameter of the earthquake and is determined using

\[
S_E = \frac{\beta_s \rho_s}{4} \int v^2(t) \, dt
\]

(6)

where \(\beta_s\) and \(\rho_s\) represent the shear wave velocity and soil density of sampling site, respectively.

The cumulative absolute velocity (CAV) indicated is the area under the absolute acceleration graph. CAV can be used to show structural failure potentiality by Kramer [39].

\[
CAV = \int_{0}^{t_{max}} \left|s(t)\right| \, dt
\]

(7)
where $t_{\text{max}}$ is the total duration of the ground motion.

The Housner intensity ($I_H$) represents the input energy and is proportional with the square integral of ground acceleration. This index can be obtained as follows [40]:

$$ I_H = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} s(t) \, dt $$

where $I_H$ has been computed in the period range of $t_1=0.2$ to $t_2=2$ seconds.

In Table 1, ground motion characteristics described by mentioned parameters are presented. According to Table 1, SGM parameters have been divided into three groups.

1. Amplitude parameters, parameters determined by the time history directly. To obtain them we should have only one of the acceleration, velocity, or displacement graphs in terms of time and determine other parameters using derivation on integration. Amplitude parameters include PGA, PGV, PGD, and the ratio between PGV and PGA (PVA).

2. Parameters giving both frequency content and amplitude information of SGM. These parameters include root-mean-square acceleration, root-mean-square velocity, root-mean-square displacement, acceleration spectrum intensity, velocity spectrum intensity, SMA, SMV, Housner intensity, and specific energy density.

3. Parameters representing comprehensive information about amplitude, frequency content, and earthquake duration. This means that using one of the Arias intensity, CAV, characteristic intensity parameters, and A95 parameter, general movement of SGM in terms of amplitude, frequency, and its duration can be discussed.

### 3. Wavelet transform

The continuous wavelet transform (CWT) is expressed by the following equation

$$ CWT_s^{\psi} = \frac{1}{\sqrt{|a|}} \int s(t) \psi_{a,b}^* (t) \, dt $$

(9)

This equation is a function of two variables $a$ and $b$. Here $b$ indicates translation, $a$ represents scale and is corresponding to period. Index * shows complex conjugate, $s$ and $\psi$ are the main wave (earthquake record) and mother wavelet, respectively. The mother expression has been used because all of the functions used for CWT originate from a main (mother) function. In other words, the mother wavelet is the main wave for producing other functions. All the functions $\psi_{a,b}^*$ derived from the mother function are called wavelet functions or daughter wavelets and can be determined as follows:
\[ \psi_{a,b}(t) = \psi\left(\frac{t-b}{a}\right) \]  

(10)

DWT is a wavelet series sampled from CWT. The principals of DWT refer to a method namely sub-band coding (SBC) developed in 1976 [41]. The main idea of this method is similar to CWT in which a timescale description from the discrete signal is represented using digital filters. In fact, the wavelet transform indicates the similarity between the wave frequency (scale) content and wavelet function in different scales. To calculate CWT, the desired window is contracted (or expanded) and is transferred and then, by multiplying it by the signal, time integral is obtained. In DWT, filters with different frequencies are used for analyzing signals in different scales. By passing the signal through high- and low-pass filters, the different signals are analyzed. In discrete conditions, the signal resolution is controlled by filter operators and the scale varies using down-sampling or up-sampling. To calculate DWT coefficients, instead of the \(a\) and \(b\) values used in equation (8), they should be replaced by their discrete values (\(a=\frac{a_0}{j}\) and \(b=ka_0\)) as follows:

\[ \psi_{j,k}(t) = \frac{1}{\sqrt{a_0^j}} \psi\left(\frac{t-ka_0^j b_0}{a_0^j}\right) \]  

(11)

If we simplify the above equation, we have

\[ \psi_{j,k}(t) = a_0^{-j} \psi(a_0^{-j} t - kb_0) \]  

(12)

By replacing the above equation, the DWT is determined as follows:

\[ DWT_s^\psi = \int_{-\infty}^{\infty} s(t) \psi_{j,k}^*(t) dt \]  

(13)

An applied method, namely SBC on earthquake signals, has been used for signals in electrical engineering in previous studies [42].

In this paper, the mentioned method has been used for analyzing earthquake records for the first time in which the MER is divided into two parts of high and low frequencies. Low and high frequencies of earthquake record are called approximation and detail, respectively. In DWT, low frequencies of earthquake record are applied and the detailed part is ignored. Another SBC is applied for the approximation part divided into two parts of approximation and detail.

In Fig. 1, decomposing the Sefidrood Dam record in Iran using DWT is shown. In the first level of MER, two signals A1 and D1 have been obtained, in which A1 and D1 represent approximation and detail, respectively. Comparison between figures and MER shows that A1 is more similar to MER. Then, two signals A2 and D2 are obtained from A1. The Signal A2 is more similar to A1. This process continues for five levels.
4. Data bank

In this study, 28 earthquake records have been used; these occurred in Iran from 1981 to 2013 as shown in Table 2 [43]. The value of earthquake intensity of these records was varied from 4.5 to 7.2 on the Richter scale. Distances to the center of earthquake recording station were between 6 and 56 km. These recorded earthquakes were classified into four categories in terms of shear wave velocity of soils. Shear wave velocity ranged from 165 to 1363 meters per second, respectively. These earthquakes are selected based on Chandler’s classification [44]. According to this classification, the accelerograms are divided into three sets based on the ratio PGA/PGV in which PGA and PGV show the peak ground acceleration and velocity of the earthquake, respectively. The ratios (PGA/PGV) for the different earthquakes adopted in this paper are given in Table 2. According to the Chandler’s classification, all three types of earthquake sets have been used and studied in this paper. Hence, these earthquakes are good representative to support a comprehensive analysis.

5. Strong ground motion with discrete wavelet transform

In this study, SGM parameters have been determined in four kinds of soils with different magnitudes using DWT. For this purpose, at first these parameters are obtained from MER. Then, the MER is decomposed using DWT and its high and low frequencies are obtained. Accordingly, two signals including detail and approximation of MER are obtained. An approximate signal is used as a NER and SGM parameters of NER are calculated again. In the next level using DWT, the approximation signal obtained in previous level is decomposed again and two new signals including approximation and detail are obtained. The approximation signal obtained in this level is a NER and SGM parameters are calculated again. This process continues over five levels and the results obtained for the mentioned parameters are compared with MER. Results showed that for all parameters, the calculation error is less than 10% until the third level. For some of the parameters until the fourth or fifth level, the error can be ignored. In this study, the Daubechies 4 has been used for high and low frequencies of the earthquake record. Wavelet denoising method is used for decomposing the earthquake record. In this method, the number of points in every level does not decrease and just its noises are omitted. In Table 3, some descriptions are presented for the signs applied in figures and their specifications.

Table 4 presents error indices characteristics and also the method of their determination. Here $E_i$ indicates the difference between the SGM parameters of NER and MER in each level.
6. The main Steps of methodology

In main steps of calculating SGM parameters using wavelet transform are as follows:

a) Determining SGM parameters of MER
b) Decomposing MER using DWT according to equation (13) and separating the approximation and detail signal of MER
c) Considering approximation signal (A1) as a NER
d) Determining SGM parameters of NER
e) Decomposing of NER (A1) with DWT and determination of approximation record (A2)
f) Considering approximation signal (A2) as a new NER and determining SGM parameters
g) Conducting steps e to f during 5 levels and determining SGM parameters in each level
h) Comparing SGM parameters in each level with initial value in step a
i) Determining error indices in all levels respect to initial value in step a

7. Results and discussion

In this section, SGM parameters are divided into terms of characteristics describing ground in Table 2, and will be explained separately. In these figures, the parameters are investigated in all 28 earthquakes as well as the same parameter with 5 decomposed levels with denoising wavelet transform. All the abbreviations of the considered parameters have been listed in the Appendix section.

Figs 2–5 indicate the parameters of PGA, PGV, PGD, and PVA, that can show ground motion amplitude. Figs 6–14 indicate the parameters of $a_{\text{RMS}}$, $v_{\text{RMS}}$, $D_{\text{RMS}}$, ASI, VSI, SMA, SMV, $I_h$, and $S_e$, able to describe the amplitude and frequency content of ground. Figs 15–18 indicate parameters, representing three characteristics of amplitude, frequency content, and duration of SGM. These parameters include $I_a$, A95, $I_c$, and CAV.

7.1 Amplitude parameters

Fig. 2 indicates PGA of MER and earthquakes decomposed into five levels, and Table 5 represents statistical indices of these values. According to Table 5, their average error calculated from different methods is 0.39%, 1.26%, 5.95%, 33.56%, and 135.13%, respectively. In addition, the regression value in these five levels is 1, 0.99, 0.99, 0.95, and 0.85. Therefore, if the acceptable error is considered less than 10%, the wavelet decomposed in the third level can be used. Fig. 2 shows that only for earthquakes numbers 13 and 14, in which their shear wave velocity is very low, can PGA decomposed in the fifth level be used.
Table 5 represents PGV statistical indices for MER and earthquakes decomposed into five levels and Fig. 3 represents this parameter for all earthquakes and also five decomposed levels. Based on Table 5, the average error corresponding to levels 1 to 5 determined according to different approaches is 0.01%, 0.02%, 0.14%, 0.57%, and 1.95%, respectively. The regression coefficient for levels 1 and 2 is 1. This parameter is 0.99 for levels 3 and 4 and also 0.89 for level 5. If acceptable error is considered less than 10%, wavelet decomposed in the fourth level can be used for calculating this parameter. It should be noted that the fourth level of decomposition means that we have decomposed high and low frequencies of MER four times using DWT. Fig. 3 shows that for very low PGVs (less than 0.05 m/s), the wavelet decomposed in the fifth level can be used.

Fig. 4 indicates PGD of MER and earthquakes decomposed in five levels and Table 5 represents statistical indices of these values. According to Table 5, the average error calculated from different methods and regression value for levels 1 and 2 are 0 and 1, indicating the high accuracy of results for these two levels. In addition, the average error for levels 3, 4, and 5 is 0.01%, 0.03%, and 0.37%, respectively. Furthermore, for these levels regression value is 1, 1, 1, 0.99, and 0.91, respectively. Fig. 4 shows that for all earthquakes (except earthquake number 26), PGD decomposed in the fifth level can be used.

7.2 Frequency content

Table 5 represents PVA statistical indices for MER and earthquakes decomposed into five levels and Fig. 5 represents this parameter for all earthquakes and also five decomposed levels. According to Table 5, the average error calculated from different methods is varied increasingly and the regression value in levels 1 to 5 is for PVA are 1, 0.99, 0.99, 0.86, and 0.49, respectively. This index is 0.02, 0.05, 0.21, 1.26, and 4.39 for these levels. Fig. 5 shows that for all earthquakes, PVA decomposed in the third level can be used and the wavelet decomposed in the fourth and fifth levels are not very good.

7.3 Amplitude and frequency content parameters

Table 5 represents $a_{RMS}$ statistical indices for MER and earthquakes decomposed into five levels. According to Table 5, their average error determined according with different approaches is 0.05%, 0.09%, 0.61%, 3.31%, and 7.08%, respectively. Regression coefficient for levels 1 and 2 is 1. This index is very desirable for levels 3 and 4 as it is 0.99 and 0.91. For level 5, the regression value is 0.83. If acceptable error is considered less than 10%, the wavelet decomposed in the third level implemented
three times can be used. Fig. 6 shows that only for earthquakes 13 and 14 in which their shear wave velocity is very low can $a_{RMS}$ decomposed in the fifth level be used.

Table 5 represents $V_{RMS}$ statistical indices for MER and earthquakes decomposed into five levels and Fig. 7 represents this parameter for all earthquakes and also five decomposed levels. Based on Table 5 the average error calculated from different methods is 0%, 0%, 0%, 0.02%, and 0.36% for levels 1 to 5, respectively, and for levels 1 to 3 the regression value is 1. In addition, it is 0.99 and 0.64 for levels 4 and 5. According to regression and error values it can be claimed that for calculating $V_{RMS}$ of earthquakes except earthquakes with high shear wave velocity (more than 750 m/s), the wavelet decomposed in fifth level can be used.

Table 5 represents $D_{RMS}$ statistical indices for MER and earthquakes decomposed into five levels according to Table 5. Their average error determined according to different approaches and regression coefficients for levels 1 to 3 is 0 and 1. The average error for levels 4 and 5 is 0.01% and 0.20%, respectively. The regression coefficient in these two levels is 1 and 0.84. Fig. 8 shows that for all earthquakes (except for number 26), $D_{RMS}$ decomposed in the fifth level can be used.

According to Table 5 the average error of ASI determined according to different approaches is 0.0%, 0.08%, 0.81%, 10.84%, and 61.92%, respectively. The regression coefficient in these five levels is 1, 1, 0.99, 0.99, and 0.93. Fig. 9 shows that for all earthquakes, ASI decomposed in the third level can be used. It should be noted that fourth level of decomposition means that we have decomposed high and low frequencies of MER four times using DWT.

Table 5 represents VSI statistical indices for MER and earthquakes decomposed into five levels and Figure 10 represents this parameter for all earthquakes and also five decomposed levels. According to Table 5, their average error determined according to different approaches is 0.0%, 0.04%, 0.23%, 1.45%, and 5.83%, respectively. The regression coefficient in these five levels is 1, 1, 0.99, 0.99, and 0.91. Based on Fig. 10, except for earthquakes 13 and 14 that have low shear wave velocities and wavelet decomposed in the fifth level, the fourth level wavelet can be used for calculating VSI.

According to Table 5, the average error of SMA determined according with different approaches is 0.22, 1.93, 15.41, 33.76 and 76.31 percent, respectively and regression coefficient of SMA in levels 1 to 5 is 1, 0.99, 0.96, 0.91 and 0.70. Fig. 11 shows that for all earthquakes, SMA decomposed in third level can be used.

Table 5 represents SMV statistical indices for MER and earthquakes decomposed into five levels and Fig. 12 represents this parameter for all earthquakes and also five decomposed levels. According to Table 5, their average error determined according to different approaches is 0%, 0.01%, 0.13%, 0.33%, and 1.21%, respectively. The
regression coefficient in levels 1 and 2 is 1. The value of this index is 0.99 for levels 3 and 4. In addition, it is 0.91 for level 5. If acceptable error is considered less than 10%, the wavelet decomposed in the fourth level can be used for calculating SMV. It should be noted that the fourth level of decomposition means that we have decomposed high and low frequencies of the main earthquake wave four times using DWT.

According to Table 5, their average error of $I_H$ determined according to different approaches is 0%, 0.04%, 0.06%, 0.32%, and 4.03%, respectively. The regression coefficient of $I_H$ in levels 1 to 5 is 1, 1, 1, 0.99, and 0.84. Fig. 13 shows that except for earthquakes 9, 26, and 27 that have high shear wave velocity, the fifth level wavelet can be used for calculating $I_H$.

Table 5 represents $S_E$ statistical indices for MER and earthquakes decomposed into five levels. According to Table 5, their average error determined according to different approaches is 0%, 0%, 0%, 0.02%, and 0.18%, respectively. The regression coefficient in these five levels is 1, 1, 1, 0.99, and 0.89. Fig. 14 shows that except for earthquakes 3, 10 and 26 that have peak values, the fifth level wavelet can be used for calculating $S_E$.

Table 4 represents $I_a$ statistical indices for MER and earthquakes decomposed in 5 levels and Fig. 15 represents this parameter for all earthquakes and also five decomposed levels. According to Table 5, the average error determined according with different approaches is 0%, 0.1%, 1.15%, 7.16%, and 18.57%, respectively. The regression coefficient in these five levels is 1, 1, 0.99, 0.96, and 0.83 and based on Fig. 15, as the $I_a$ value is lower, the wavelets decomposed in the fourth and fifth levels can also be used, while for high values of $I_a$ only the third level decomposed wavelet can be used.

According to Table 5, the average error of A95 parameter determined according to different approaches is 0.79%, 1.56%, 9.37%, 35.53%, and 111.90%, respectively, and the regression coefficient of A95 in these five levels is 1, 0.99, 0.99, 0.95, and 0.85. As the A95 parameter is related to 95% of the Arias intensity, if the Arias intensity value is lower, wavelets decomposed in the fourth and fifth levels can also be used, while for high values of Arias intensity only the third level decomposed wavelet can be used. Fig. 16 shows that for all earthquakes, A95 decomposed in the third level can be used.

According to Table 5, their average error of $I_c$ determined according to different approaches is 0.01%, 0.36%, 1.82%, 12.23%, and 30.79%, respectively. The regression coefficient of $I_c$ in these five levels is 1, 1, 0.99, 0.96, and 0.84. Furthermore, Fig. 17 indicates $I_c$ of MER and earthquakes decomposed into five levels. If acceptable error is considered less than 10%, wavelet decomposed in the third level can be used for calculating this parameter. It should be noted that the third level of decomposition means that we have decomposed high and low frequencies of the main earthquake wave three times using DWT.
Fig. 18 indicates CAV of MER and earthquakes decomposed into five levels and Table 5 represents statistical indices of these values. The regression coefficient in these five levels is 1, 1, 0.99, 0.96, and 0.84, respectively. According to Table 5, the average error determined according to different approaches is 0.10%, 1.18%, 10.16%, 57.67%, and 197.23%, respectively. According to Fig. 18 it can be claimed that for using this parameter in evaluating the failure of structures, the third level decomposed wavelet can be used.

The high and low frequencies are separated at each level using DWT. As a rule, at the first level, the largest frequencies with the lowest effect are eliminated. On the other hand, although the high frequencies are eliminated for higher levels at each level, the elimination of the high frequencies will remove a number of accelerogram data. According to the results of this study, it is clear that errors are insignificant until the third level. In other words, up to this level, the high frequencies have been eliminated three times and this is the reason of the occurred errors.

The studied strong ground motion parameters (peak ground motion acceleration, peak ground motion velocity, Arias intensity, Housner intensity and etc.) are used to select some suitable earthquakes for dynamic analysis of structures. Therefore, eliminating the largest frequencies in each level reduces the number of accelerogram. It can decrease the required time for dynamic analysis especially for unconditionally stable methods such as Linear Newmark method. In addition, by reducing the number of accelerogram, the responses of the structure cannot be computed at eliminating time. It should be noted that it does not affect the maximum responses of the structures which are important [22].

8. Conclusions

Based on the results obtained in this paper, it can be concluded that DWT can be used to calculate SGM parameters. DWT in the third level can be used to calculate all parameters of SGM with less error. The mean percentage of error indices in all parameters are 0.09%, 0.39%, 2.71%, 11.5%, and 38.67%, respectively in levels 1 to 5, respectively. Calculation time reductions due to the application of DWT are 1%, 4%, 8%, 9%, and 10%, respectively, for first to fifth levels, respectively. The mean regression in 1 to 5 levels is equal to 1, 1, 0.99, 0.96, and 0.82, respectively. The Application of DWT method to calculate strong ground motion parameters is for the first time and there is no similar work in this field. The high and low frequencies are separated at each level by DWT. As a rule, at the first level, the largest frequencies with the lowest effect are eliminated. On the other hand, although the high frequencies are eliminated for higher levels at each level, the elimination of the high frequencies will remove a number of accelerogram data. According to the results of this study, it is clear that errors are insignificant until the third level. In other words, up to this level, the high frequencies have been eliminated three times and this
is the reason of the occurred errors. These errors are the weak points for the wavelet theory. The studied strong ground motion parameters are used to select some suitable earthquakes for dynamic analysis of structures. Therefore, eliminating the largest frequencies in each level reduces the number of accelerogram. It can decrease the required time for dynamic analysis especially for unconditionally stable methods such as Linear Newmark method. These characteristics are categorized as strong points for the wavelet theory. In addition, by reducing the number of accelerogram, the responses of the structure cannot be computed at eliminating time. It should be noted that it does not affect the maximum responses of the structures which are important. In addition, some applications of the strong ground motion parameters in earthquake and structural engineering are listed as follows:

The PGA parameter is commonly used in structures design. It should be noted that for an earthquake with very high PGA and frequency content that has long strong ground motion duration, the damage value is greater than the damage value due to an earthquake with short strong ground motion duration. The PGV parameter is an important tool for detecting the amount of damage or ground vibration intensity. It should be noted that the maximum velocity gives a more precise characteristic for evaluating the damage respect to the maximum acceleration. The PGD parameter is used to determine the values of damages. The PVA parameter is used to predict the average periods of earth motions for stiff and rocky grounds. The Arias intensity is used as a criterion for measuring the magnitude of ground motion. This parameter mainly represents the amount of energy applied to the structure and is measured by the transient (unstable) earthquake waves to determine the magnitude of earthquake motion.

The characteristic intensity is defined as a criterion that is linearly related to the structural damage index due to the maximum change in structural deformation and absorbed hysteretic energy.

The cumulative absolute velocity is used to indicate the potential of structural damage. In other words, this parameter is an indicator for the energy applied to a structure by an earthquake and is directly related to the structures damage.

The Housner intensity shows the capacity of the ground motion to damage structures. It can be estimated as an average rate of total input seismic energy per unit of mass during earthquake motion.

For the signals of the main earthquake and five decomposed levels for the earthquakes used this paper, conducted in different kinds of soils, it can be claimed that:

(i) for stiff soils (with shear wave velocity less than 175 m/s), nearly all of the MER parameters can be replaced by DWT parameters decomposed in fifth level;
(ii) for rock and hard rock soils (with shear wave velocity more than 750 m/s), DWT in the third level can be used for calculating most parameters and the wavelet decomposed into four and five levels cannot be appropriate.

In addition, for the other parameters mentioned in Table 1 and their error and regression had been investigated in five decomposed levels in Section 7, we can make the following claims.

1. In all parameters that describe only ground motions amplitude:
   - for PGA, the error value of the third level is less than 6%;
   - for PVA, the error value of the third level is less than 1%;
   - for PGV, the error value of the fourth level is less than 2%;
   - for PGD, the error value of the fifth level is less than 1%.

2. For all parameters describing ground frequency content and amplitude:
   - for SMA the error value of the second level is less than 2%;
   - for a_{RMS} and ASI, the error value of the third level is less than 1%;
   - for S_E, I_H, SMV, V_{RMS}, the error value of the fourth level is less than 1%;
   - for VSI, the error value of the fourth level is less than 2%;
   - for D_{RMS}, the error value of the fifth level is less than 1%.

3. For parameters which describe three characteristics of ground motion:
   - for I_a, the error value of the fourth level is less than 10%;
   - for I_c, the error value of the third level is less than 2%;
   - for A95, the error value of the third level is less than 10%;
   - for CAV, the error value of the second level is less than 2%.

A. Appendix

Table A1 presents list for abbreviations of all considered studied parameters.

Acknowledgments

We would like to thank the Road, Housing and Urban Development Research Centre of Iran for providing earthquake records for this study.
References


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Table 3. The abbreviations of signals decomposed in every level
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Fig. 2. PGA of MER and NER of decomposition with DWT

Fig. 3. PGV of MER and NER of decomposition with DWT

Fig. 4. PGD of MER and NER of decomposed with DWT

Fig. 5. PVA of MER and NER of decomposition with DWT

Fig. 6. $a_{RMS}$ of MER and NER of decomposition with DWT

Fig. 7. $V_{RMS}$ of MER and NER of decomposition with DWT

Fig. 8. $D_{RMS}$ of MER and NER of decomposition with DWT

Fig. 9. ASI of MER and NER of decomposition with DWT

Fig. 10. VSI of MER and NER of decomposition with DWT

Fig. 11. SMA of MER and NER of decomposition with DWT

Fig. 12. SMV of MER and NER of decomposition with DWT

Fig. 13. $I_h$ of MER and NER of decomposition with DWT

Fig. 14. $S_E$ of MER and NER of decomposition with DWT

Fig. 15. $I_c$ of MER and NER of decomposition with DWT

Fig. 16. $A_{95}$ parameter of MER and NER of decomposition with DWT

Fig. 17. $I_v$ of MER and NER of decomposition with DWT

Fig. 18. CAV of MER and NER of decomposition with DWT
Table 1. Ground motion characteristics by SGM parameters

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Table 2. Information of earthquakes

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Table 4 The abbreviation of error indices

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Table 5. Error indices for SGM
Table A1. A list for abbreviations of all considered studied parameters.

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<td>Strong ground motion</td>
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<td>MER</td>
<td>Main earthquake record</td>
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<td>Discrete wavelet transform</td>
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Fig. 1. Schematic view of DWT of the Sefidrood Dam earthquake record
Fig. 2. PGA of MER and NER of decomposition with DWT
Fig. 3. PGV of MER and NER of decomposition with DWT
Fig. 4. PGD of MER and NER of decomposed with DWT
Fig. 5. PVA of MER and NER of decomposed with DWT
Fig. 6. $a_{\text{RMS}}$ of MER and NER of decomposition with DWT
Fig. 7. $V_{\text{RMS}}$ of MER and NER of decomposition with DWT
Fig. 8. $D_{\text{RMS}}$ of MER and NER of decomposition with DWT
Fig. 9. ASI of MER and NER of decomposition with DWT
Fig. 10. VSI of MER and NER of decomposition with DWT
Fig. 11. SMA of MER and NER of decomposition with DWT
Fig. 12. SMV of MER and NER of decomposition with DWT
Fig. 13. $I_{th}$ of MER and NER of decomposition with DWT
**Fig. 14.** $S_E$ of MER and NER of decomposition with DWT
Fig. 15. $I_a$ of MER and NER of decomposition with DWT
Fig. 16. A95 parameter of MER and NER of decomposition with DWT
Fig. 17. $I_c$ of MER and NER of decomposition with DWT
Fig. 18. CAV of MER and NER of decomposition with DWT
Biographies:

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