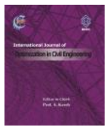
INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2018; 8(1):103-115



APPLICATION OF WAVELET THEORY IN DETERMINING OF STRONG GROUND MOTION PARAMETERS

A. Heidari*, †, J. Raeisi and R. Kamgar
Department of Civil Engineering, Shahrekord University, Shahrekord, Iran

ABSTRACT

Cumulative absolute velocity (CAV), Arias intensity (AI), and characteristic intensity (CI) are measurable characteristics to show collapse potential of structures, evaluation of earth movement magnitude, and detection of structural failure in an earthquake. In this paper, parameters which describe three characteristics of ground motion have been investigated by using wavelet transforms (WT). In fact, in this paper, a series of twenty eight earthquake records (ER) are decomposed to a pre-defined certain levels by the use of WT. The high and low frequencies are separated. Since higher frequencies do not have any significant effect on the ER, then the low frequencies of ER have been used. For this purpose, each ER is decomposed into 5 levels. Then, for low frequencies of ER, the CAV, AI, and CI are calculated for each level and the results are compared with the values of CAV, AI, and CI which have been computed for the original ER. The results indicate that the value of error is less than 1 percent in the first and second level and this value is less than 10 percent for the third level. In addition, this value is more than 15 percent for the fourth and fifth levels. If the acceptable value for error is considered to be less than 10 percent, it is recommended to use the third level of decomposition for determining these parameters, since the value of error is low and also, the required time is reduced.

Keywords: arias intensity; cumulative absolute velocity; characteristic intensity; wavelet transform; earthquake record.

Received: 20 March 2017; Accepted: 5 July 2017

1. INTRODUCTION

The study of strong ground motions, seismic parameters, their characteristics, their effects, and their relation with the failure of the structures have been studied by a number of researchers. Parameters that can be used in the earthquake-resistant design are low and are

---

*Corresponding author: Department of Civil Engineering, Shahrekord University, Shahrekord, Iran
†E-mail address: heidari@eng.sku.ac.ir (A. Heidari)

concerned directly to the structural analysis methods which are used in current practice. When a parameter is selected to describe the motion of the earth, it is important for features such as earthquake source, propagation path, and site conditions to be evaluated [1]. Time history analysis is considered as the most important tool for performance-based seismic design. In the seismic analysis, the most significant concern is relationship between severity index, and the actual damage. As a result, seismic performance can be performed with more precision [2]. The structure damage can be well presented by pseudo-acceleration, Arias intensity, and input energy for a series of earthquakes [3]. Ground motion parameters are obtained based on equations which can predict the ground motion by traditional regression analysis. These equations predicted the ground motion parameters in terms of independent variables including strength of earthquake, the focal length of rupture surface, site conditions, seismic wave propagation, and the characteristics of the earthquake source [4]. Stochastic methods can be used to predict strong ground motions [5]. The stochastic process is a collection of random vectors in which time plays a very important role. Information of strong ground motion for the Nepal earthquake indicated that acceptable attenuation relationship can be obtained by a two-level regression. And this obtained attenuation is useful for the assessment of forthcoming large earthquakes [6]. A series of ground motion parameters was used in assessment of seismic hazard and also in predicting the effects of earthquakes for areas of Kazakhstan subjected to earthquake [7].

Considering the concept of wavelet transform, many researchers studied this field. Wavelet transform is a new tool for signal analysis, and also can provide signals in time and frequency domains at the same time. Application of wavelet processing for seismic waves, separation and compression of waves are important issues in seismic engineering. By creating a wavelet network and replacing original signals with the detailed ones, the computational time is decreased [8]. The fast wavelet transform is used to develop a method in order to determine the dynamic responses of a structure. Two types of low-pass and high-pass filter are used for decomposing of acceleration [9]. Also, wavelet transform method helps to investigate the process of decomposition of produced wave [10]. To solve this problem, signal processing as well as wavelets and filter banks are used. The acceleration record is filtered by the aforementioned method, and then the number of points of record will be decreased [11].

In this paper for the first time, CAV, AI, and CI are determined by wavelet theory. For this purpose, some of strong ground motion parameters are obtained by SeismoSignal [12] software and then, the earthquake wave is decomposed into 5 levels and the characteristic of each earthquake is determined based on these levels.

2. THE STRONG GROUND MOTION PARAMETERS

Three main characteristics of ground motion are amplitude, frequency content, and duration of strong ground motion which are used in earthquake engineering applications. To determine these characteristics, many formulas have been proposed. Of them, some formulas describe only one of the aforementioned characteristics. These characteristics are described briefly in the following section.

Some parameters such as acceleration, velocity, and displacement are determined to show the amplitude of the ground motion. Amplitude parameters only describe the maximum amplitude from the time history of earth movement.

Frequency content parameters describes the distribution of earth movement amplitude in different frequencies. As frequency content of earthquakes are largely affected by those movements, it will be impossible to determine the characteristics of that movement if its frequency content has not been considered.

The strong ground motion duration of earthquake are computed by parameters which show the potential of earthquake in order to destruct the structures. The strong ground motion duration depends on the required time to release cumulated strain energy along fault.

2.1 The cumulative absolute velocity

The area under the graph of the absolute value of the acceleration is used to illustrate the potential of structural damage, and is called the cumulative absolute velocity. This parameter is calculated by the following equation:

$$CAV = \int_0^{t_{total}} |\ddot{x}(t)|\, dt \tag{1}$$

where $|\ddot{x}(t)|$is considered as the absolute value of the acceleration time history, and ttotal is the total duration of the ground motion. As low-amplitude accelerations usually do not result in structural damages, different kinds of CAV are developed in order to omit these low-amplitude accelerations from the time integration of Eq. (1) so that long period characteristics of the ground motion have represented better [13].

2.2 The arias intensity

Arias intensity [14], is a tool to determine the cumulative ground motion intensity that is determined according to the time integral of squared acceleration, as follows:

$$I_a = \frac{\pi}{2g}\int_0^{t_{total}} [\ddot{x}(t)]^2 dt \tag{2}$$

where g represents the acceleration of gravity. As it can be seen from the Arias acceleration equation, the acceleration amplitude, frequency content, and duration of strong ground motion can be determined by this equation. This unique feature is for arias intensity which makes it different from the other ground motion parameters. This is the main characteristic of ground motion parameter.

2.3 The characteristic intensity

The Park index as an indicator to compute the characteristic intensity is defined as follows [15].

$$I_c = (a_{RMS})^{\frac{3}{2}}.\sqrt{T_d} \tag{3}$$

This parameter is a tool that is linearly related to the failure of structures, and absorbed energy. Where T_d represents the duration of earthquake, and (a_{RMS}) is related to the root mean squares of acceleration. It is applicable for earthquakes with moderate intensity and is calculated as follows:

$$a_{RMS} = \sqrt{\frac{1}{T_d}\int_0^{T_d} [\ddot{x}(t)]^2 dt} = \sqrt{\lambda_0} \tag{4}$$

It should be considered that integration on the duration of the phase of strong earthquakes (T_d) is according to Parceval's theorem to determine the overall severity of ground motion in the time, and frequency domains.

3. WAVELET TRANSFORM

Multi-level WT is carried out to decompose a signal with lower resolution, to control the scale of the displacement, and also to shift it. This conversion is performed by applying both a high-pass filter, and a low-pass filter. Wavelet transform (WT) is used as an advanced mathematical tool in signal processing. Ability of wavelets has been applied in different sciences such as geophysics, meteorology, and earthquake engineering. The basic idea of WT has been taken from both Fourier transform (FT), and short time Fourier transform (STFT) [16]. FT method only determines frequency content of signal, and is not able to localize time- frequency along signal. Attempts to solve the problem of FT resulted in the introduction of the STFT method. However, STFT isn't able to localize time- frequency of signal exactly due to its structural nature. WT method is an application method in analyzing signal that localizes time- frequency well. Mentioned transform can transfer signal or time series to a three-dimensional space including time, scale (or frequency) and magnitude.

Some important features of discrete wavelet transform are as follows:

1. In each scale or failure of curvature using orthogonal wavelets for this particular scale, wavelet function is proportional to the width.
2. Wavelet spectrum is produced in a separate process, and shows a brief of original signal.
3. Given its orthogonal properties, it is not complicated reconstruction.
4. Discrete wavelet eliminates redundant information in order to identify better processes in the signal wavelet coefficients).

The continuous wavelet transform (CWT) for a signal f (u) ∈ L^2can be determined using the following equation [16]:

$$Wf(\lambda,\tau) = \int_{-\infty}^{+\infty} f(u)\, \frac{1}{\sqrt{\lambda}}\psi^*\left(\frac{u-\tau}{\lambda}\right) du. \tag{5}$$

where λ and τ represent scale and shift parameters for integral functions, respectively. In this equation, if λ and τ parameters have discrete values, obtained transform will be called a discrete wavelet transform (DWT). In equation (5), ψ (u) ∈ L^2 represent mother wavelet, and * represents a complex conjugate. The mother wavelet is moved by shift parameter (τ), and is dilated by scale parameter (λ). These basic functions are convoluted with f (u) function to compute the wavelet coefficients $Wf(\lambda, \tau)$ [17].

In this method of wavelet transform, the number of points didn't reduce, and just high and low frequencies have been separated from each other which is called wavelet de-noising. It's clear that the signals obtained from main data can't be without noises [18]. Generally, signals need to be recovered from noisy records using data analysis. The main feature of this transform is that the time needed for calculations are reduced, while the approximations of calculations aren't decreased.

In this study, applied WT namely the Daubechies is used [16]. Daubechies wavelet is defined as a family of orthogonal wavelets defining a DWT, and is characterized by the highest number of vanishing moments for some given supports. For every wavelet kind of this category, there is a scaling function that makes an orthogonal multiresolution analysis.

4. THE DATA BASE

In this study, 28 ER are used. These earthquakes have occurred in Iran from 1981 to 2013, and are shown in Table 1. For these earthquakes, the value of intensity is varied from 4.5 to 7.2 on the Richter scale. Distance between the center of earthquake and recording station is between 2.5 to114 km. These selected earthquakes are classified into four categories based on the shear wave velocity, and vary from 165 to 1363 meters per second.

Table 1: Information about selected earthquakes [19]

Number of earthquake	Earthquake ID	Date of occurrence	Number of earthquake	Earthquake ID	Date of occurrence
1	Tabl	2008/9/10	15	Jangal	2010/7/30
2	Sadeh	2008/3/9	16	Ziveh	1998/7/9
3	Meimand	1994/6/20	17	Namin	1998/7/9
4	Kolour	2006/11/5	18	Boushehr 5	2004/3/2
5	Mousian	2008/8/27	19	Borazjan	2004/3/2
6	Doubaran	2003/11/28	20	Arkvaz-malekshahi	2001/3/23
7	Marak	1997/5/10	21	Minoudasht	2004/10/7
8	Torbate-heidarieh	1997/5/10	22	Ramian	2004/10/27
9	Avaj	2002/6/22	23	Bandargaz	2004/10/07
10	Ahar-varzaghan	2012/8/11	24	Gorgan	2004/10/07
11	Abgarm	2002/6/22	25	Zarat	1994/3/30
12	Fin 1	2006/6/22	26	Roudbar2	1990/8/20
13	Noshahr	2004/5/28	27	Babamonir	2011/3/5
14	Roudsar	2004/5/28	28	Ghir	1985/2/2

5. METHODOLOGY

The main records of earthquake are at first loaded in SeismoSignal software, and the parameters of CAV, AI, and CI are computed. Then, the earthquake records are decomposed by wavelet transform into five levels with Daubechies 4. Then aforementioned parameters are recalculated, and compared.

6. ANALYSIS OF THE RESULTS

The abbreviation, and features of signals decomposed in wavelet transform are presented in Table 2.

Table 2: The abbreviation of signals that are decomposed for each level

Name	Abbreviation	Feature (main record or the high and low frequencies of earthquake wave are separated)
Main record	*Ea*	Main earthquake wave
Level 1	*Ea1*	decomposed in one level
Level 2	*Ea2*	decomposed in two levels
Level 3	*Ea3*	decomposed in three levels
Level 4	*Ea4*	decomposed in four levels
Level 5	*Ea5*	decomposed in five levels

Figs. 1, 2 and 3 indicate the results of CAV for selected earthquakes which are decomposed into 5 levels. Figs. 4, 5 and 6 show these variation for the AI. Figs. 7, 8 and 9 depict this variation for the CI. It can be seen from Fig. 1 that the value of *Ea* has no difference with the *Ea1* and *Ea2*. The mean difference of CAV in the first level of decomposition with main signal is less than 0.001, and for second level of decomposition is less than 1 percent.

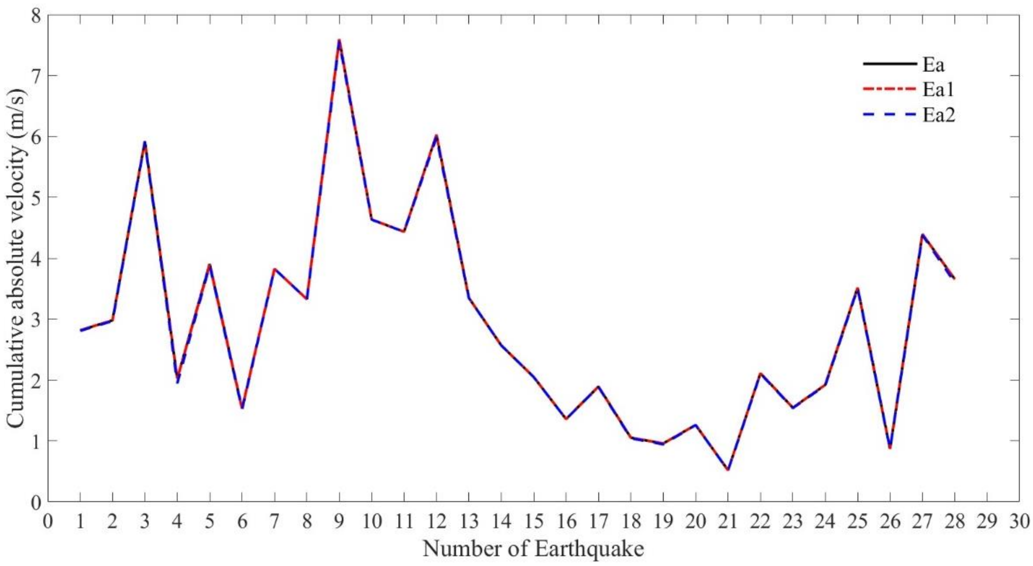


Figure 1. The cumulative absolute velocity for *Ea*, *Ea1 and Ea2*

Fig. 2 shows the comparison between the values of CAV for *Ea3* and *Ea*. It shows that the results of *Ea* and *Ea3* are very close. Mean difference between *Ea* and Ea3 is less than

10 percent.

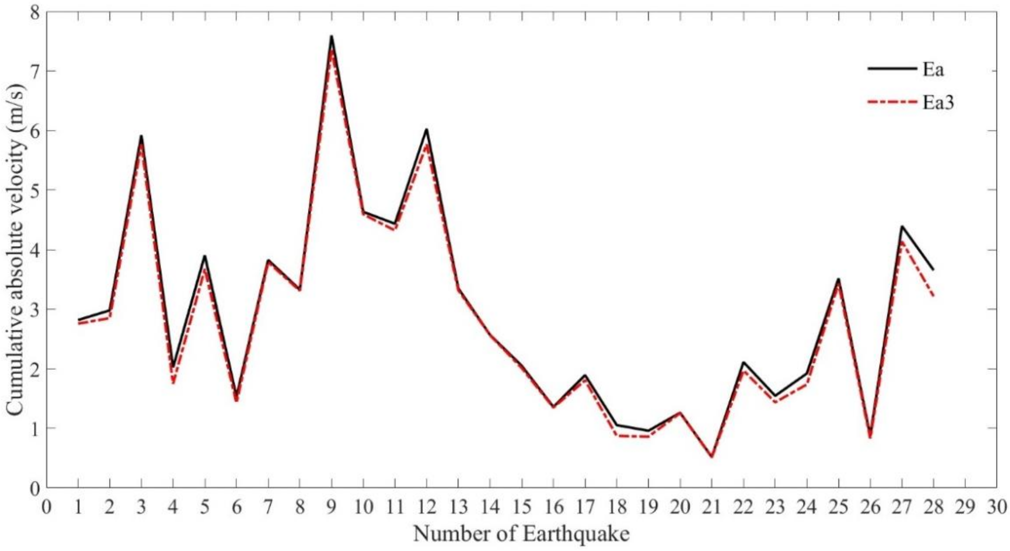


Figure 2. The cumulative absolute velocity for *Ea* and *Ea3*

According to Fig. 3, the difference between *Ea*, *Ea4* and *Ea5* is more than 20 percent, and the wavelet decomposed in fourth and fifth levels is not significant.

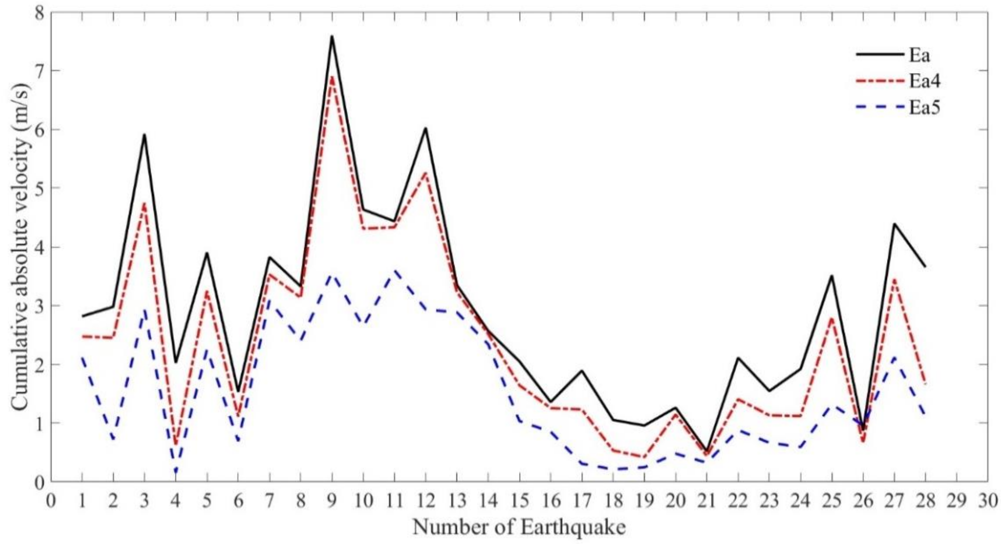


Figure 3. The cumulative absolute velocity for *Ea , Ea4 and Ea5*

As Fig. 4 shows, *Ea* has no difference with the *Ea1* and *Ea2*. The mean difference of AI for the first level of decomposition with the main signal is less than 0.0001, and for the second level of decomposition is less than 1 percent.

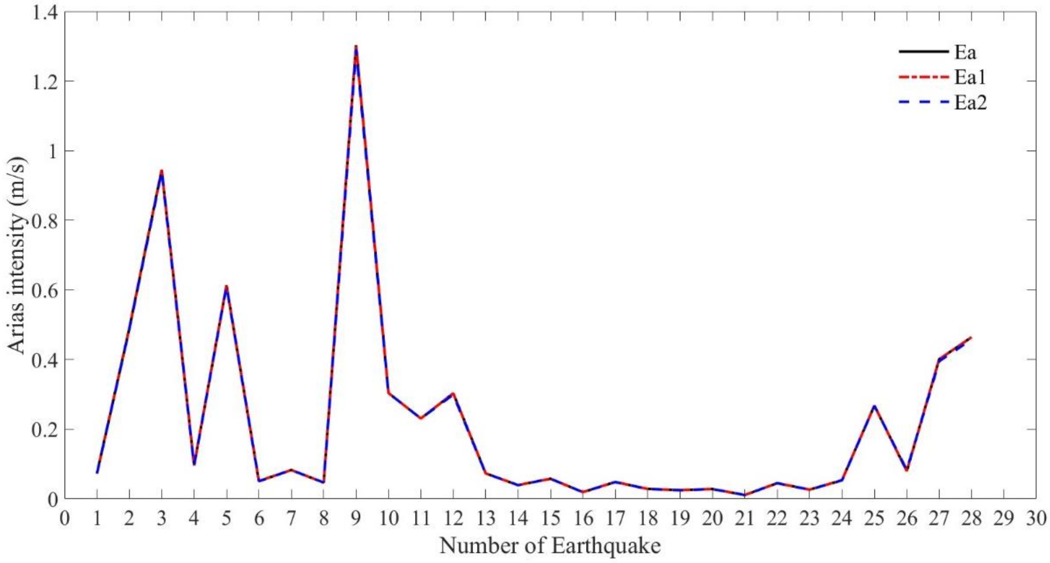


Figure 4. The arias intensity for *Ea*, *Ea1* and *Ea2*

As it can be seen from Fig. 5, the comparison between *Ea* and *Ea3* indicates that for some signals the difference is negligible while for the others signal, the difference is less than 10 percent of the initial value. Therefore, *Ea3* can be used instead of *Ea*. And this value is very close to the real value.

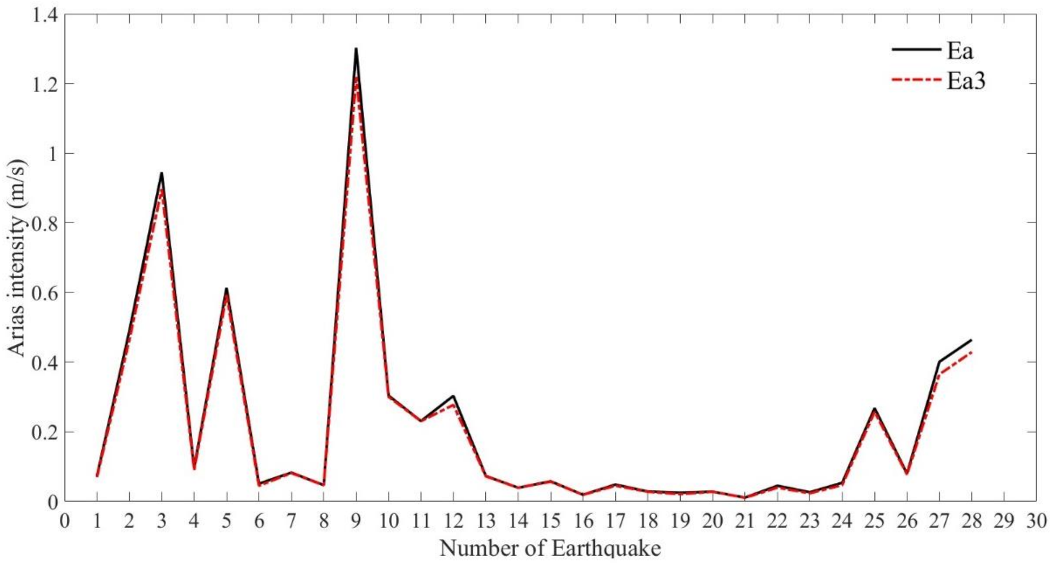


Figure 5. The Arias intensity for *Ea* and *Ea3*

As it can be noted from the Fig. 6, the difference between *Ea* , *Ea4* and *Ea5* is more than acceptable value. And the wavelets decomposed in the fourth and fifth level are not very excellent.

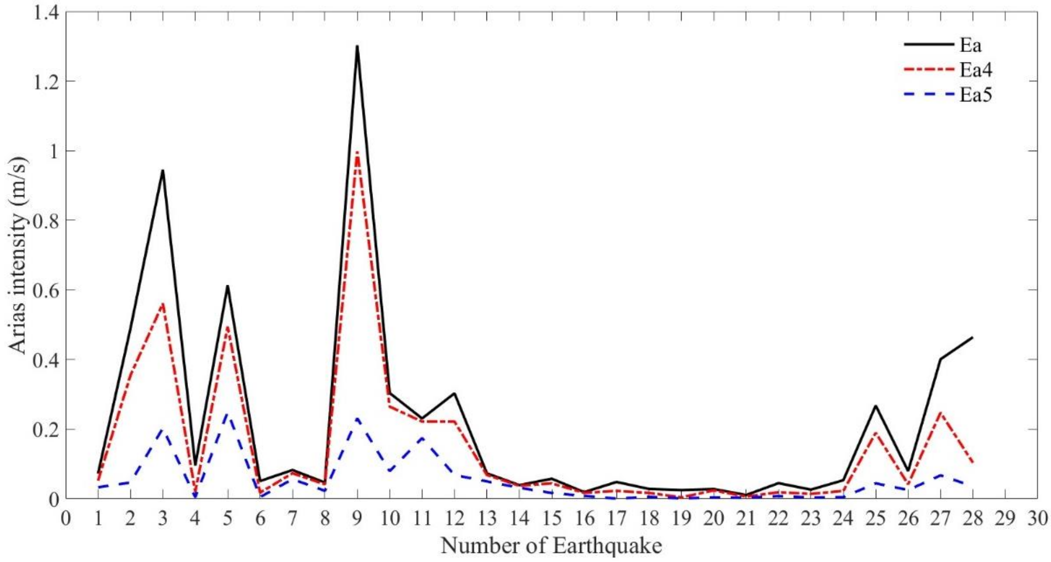


Figure 6. The Arias intensity for *Ea*, *Ea4* and *Ea5*

As Fig. 7 shows, *Ea* has no difference with the *Ea1* and *Ea2*. The mean difference of CI in the first level of decomposition with main signal is less than 0.01, and for the second level of decomposition is less than 1 percent.

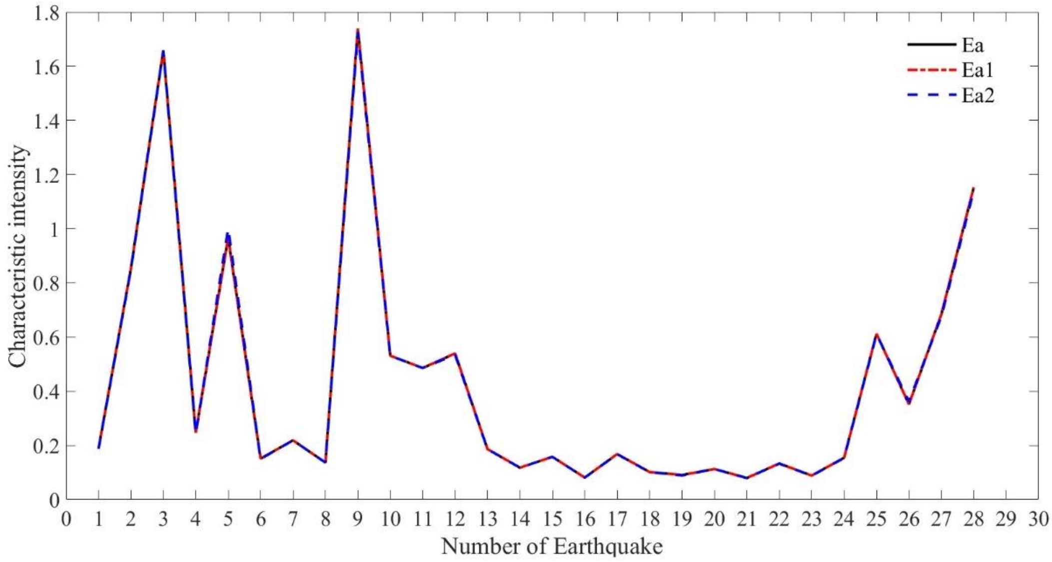


Figure 7. The characteristic intensity for *Ea*, *Ea1* and *Ea2*

As it can be seen from Fig. 8, the comparison between *Ea* and *Ea3* shows that for some signals the difference is negligible while for the others signal the difference is less than 10 percent of initial value. Therefore, it can be found that the *Ea3* can be used instead of *Ea* because this value is very close to the main value.

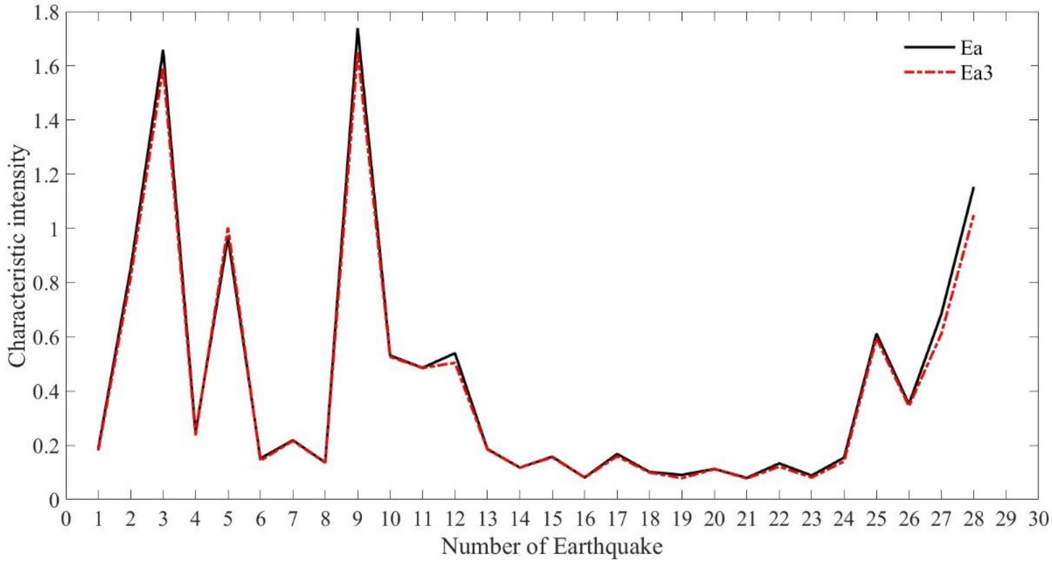


Figure 8. The intensity characteristic for *Ea* and *Ea3*

According to Fig. 9, the difference between *Ea*, *Ea4* and *Ea5* is more than acceptable value, over 15 percent, and therefore decomposition of the wavelets for the fourth and fifth levels is not significant.

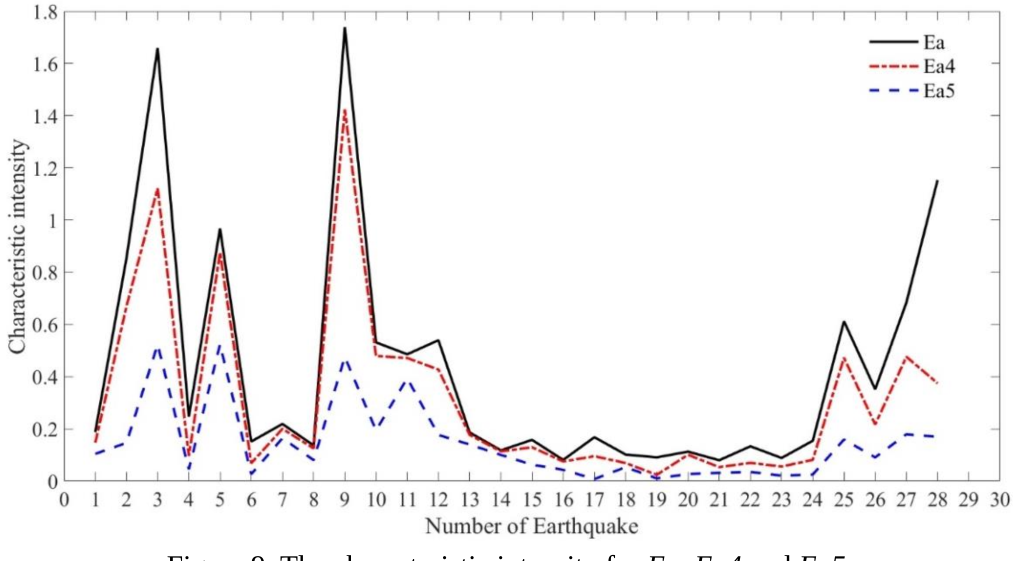


Figure 9. The characteristic intensity for *Ea*, *Ea4* and *Ea5*

7. ERROR INDICES

Then, for each levels of decomposition by wavelet, error indices including the mean absolute error, root-mean-square error, sum of squared errors, and mean square error are initially defined, and calculated to check the ability of the wavelet transform.

7.1 The mean absolute error

The mean absolute error (MAE) indicates the average error for a given set. The index is expressed by the following equation.

$$MAE=\frac{1}{\mathrm{N}}\sum_{i=1}^{N}|E_i| \tag{6}$$

7.2 The root-mean-square error

The root-mean-square error (RMSE) represents the average error rate. The difference value is derived from differences between experiments, and models. Equation (7) indicates this index.

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i)^2} \tag{7}$$

7.3 The sum of squared errors

The sum of squared errors (SUM) indicates the sum of squares error. This error can be calculated as follows:

$$SSE=\sum_{i=1}^{N}(E_i)^2 \tag{8}$$

7.4 The mean square error

The mean square error (MSE) is also used and defined as follows:

$$MSE= (RMSE)^{2} \tag{9}$$

Table 3 shows the values of error indices for the cumulative absolute velocity while Table 4, and 5 show these values for the arias, and characteristic intensity, respectively.

Table 3: Error indices for cumulative absolute velocity

Error indices	*Ea1*	*Ea2*	*Ea3*	*Ea4*	*Ea5*
MAE	0.0006	0.0127	0.1205	0.546	1.3851
SSE	0.0001	0.0140	0.7089	13.625	79.7519
MSE	0.000006	0.0005	0.0253	0.4866	2.8433
RMSE	0.0026	0.0224	0.1591	0.6976	1.6877
Regression	1	0.99995	0.99838	0.96722	0.84457

Table 4: Error indices for arias intensity

Error indices	*Ea1*	*Ea2*	*Ea3*	*Ea4*	*Ea5*
MAE	0.00006	0.0015	0.0119	0.0715	0.1685
SSE	0.000001	0.00015	0.014	0.4523	2.5071
MSE	0.00000003	0.000009	0.0004	0.0162	0.0895
RMSE	0.0001	0.0031	0.0223	0.1271	0.2992
Regression	1	0.9999	0.9997	0.996	0.8338

Table 5: Error indices for characteristic intensity

Error indices	*Ea1*	*Ea2*	*Ea3*	*Ea4*	*Ea5*
MAE	0.0001	0.0034	0.0197	0.1187	0.285
SSE	0.000005	0.0016	0.0323	1.1876	5.2896
MSE	0.0000001	0.00005	0.0012	0.0424	0.1961
RMSE	0.0004	0.0076	0.0339	0.2059	0.4428
Regression	1	0.99998	0.9988	0.94929	0.83952

7. RESULTS

The results of this paper can be summarized as follow:
1. The mean value of error for *Ea1*, *Ea2*, *Ea3*, *Ea4*, and *Ea5* are respectively 0.0001, 0.0031, 0.098, 0.388, and 1.553.
2. The mean value of regression for *Ea1*, *Ea2*, *Ea3*, *Ea4*, and *Ea5* are respectively 1, 0.999, 0.999, 0.971, and 0.839.
3. The percentage required time which is reduced to compute calculating of *Ea1* to *Ea5* is respectively 1, 4, 8, 9, and 10.

Therefore, based on the above-mentioned results, the *Ea3* can be used instead of *Ea*.

Acknowledgment: Authors would like to express their deepest gratitude to the Road, Housing, and Urban Development Research Centre of Iran for sharing the earthquakes data.

REFERENCES

1. Nolasco L, García S, Ovando-Shelley E, Castillo MA. Neural estimation of strong ground motion duration, *Geofis Int* 2014; **53**(3): 221-39.
2. Ye L, Ma Q, Miao Z, Guan H, Zhuge Y. Numerical and comparative study of earthquake intensity indices in seismic analysis, *Struct Des Tall Spec Build* 2013; **22**(4): 362-38.
3. Elenas A. Correlation between seismic acceleration parameters and overall structural damage indices of buildings, *Soil Dyn Earthq Eng* 2000; **20**(1): 93-0.
4. Douglas J. Earthquake ground motion estimation using strong-motion records, a review of equations for the estimation of peak ground acceleration and response spectral ordinates, *Earth Sci* 2003; **61**(1): 43-04.
5. Boore DM. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, *Bull Seismol Soc Am* 1983; **73**(6A): 1865-94.
6. Prajapati S, Dadhich H, Chopra S. Isoseismal map of the 2015 Nepal earthquake and its relationships with ground-motion parameters, distance and magnitude, *J Asian Earth Sci* 2016; **133**(1): 24-37.
7. Silacheva N, Kulbayeva U, Kravchenko N. Catalogs of ground motion parameters for earthquake-prone regions in Kazakhstan, *Geodesy Geodyn* 2014; **5**(1): 20-6.

8. Salajegheh E, Heidari A. Optimum design of structures against earthquake by wavelet neural network and filter banks, *Earthq Eng Struct Dyn* 2005; **34**(1): 67-82.
9. Salajegheh E, Heidari A. Time history dynamic analysis of structures using filter banks and wavelet transforms, *Comput Struct* 2005; **83**(1): 53-68.
10. Heidari A, Salajegheh E. Time history analysis of structures for earthquake loading by wavelet networks, *Asian J Civ Eng* 2006; **7**(1): 155-68.
11. Heidari A, Salajegheh E. Wavelet analysis for processing of earthquake records, *Asian J Civ Eng*; **9**(5): 513-24.
12. http://www.seismosoft.com/seismosignal.
13. Wang G, Du W. Empirical correlations between cumulative absolute velocity and spectral accelerations from NGA ground motion database, *Soil Dyn Earthq Eng* 2012; **43**(1): 229-36.
14. Arias A. *A Measure of Earthquake Intensity*. In: Hansen RJ, editor. Cambridge, MA: MIT Press; 1970, pp. 438-483
15. Park YJ, Ang AHS, Wen YK. Seismic damage analysis of reinforced concrete buildings, *J Earthq Eng*; **111**(4): 740-57.
16. Daubechies I. The wavelet transform, time–frequency localization and signal analysis, *IEEE Trans Inf Theory* 1990; **36**(5): 961-5.
17. Noh HY, Lignos DG, Nair KK, Kiremidjian AS. Development of fragility functions as a damage classification/prediction method for steel moment-resisting frames using a wavelet based damage sensitive feature, *Earthq Eng Struct Dyn* 2012; **41**(4): 681-96.
18. Taswell C. The what, how, and why of wavelet shrinkage denoising. *Comput Sci Eng* 2000; **2**(3): 12-9.
19. Http://www.bhrc.ac.ir.