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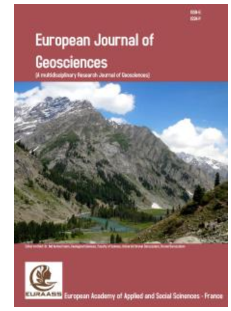

Research Article

Comparing the best-estimate uniform hazard response spectra to the observed data from the Mw 7.3 earthquake on November 12, 2017 in the Kermanshah areas of western Iran

Nadereh Amerian[a], Elham Shabani[b]*, Ramin Nikrouz[c]

[a]*M.Sc in Geophysics, Urmia University, Urmia, Iran*

[b]*Department of Seismology, Institute of Geophysics, University of Tehran, Tehran, Iran*

[c]*Department of Geology, Urmia University, Urmia, Iran*

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Abstract

In this study, synthetic catalogs based on the Monte Carlo simulations have been produced for probabilistic seismic hazard assessment (PSHA), in the Kermanshah region, West of Iran. Resultant seismic hazard zoning maps, hazard curves and three-dimensional deaggregation of seismic hazard are provided. In order to validate the estimated peak ground accelerations (PGAs), the deduced uniform hazard response spectra (UHRS) are compared with the recorded PGAs in some stations near to the large Mw 7.3 earthquake occurred in the western part of Iran near to Iraq border on 12 November 2017. Different ground motion prediction equations are tested and the results are compared.

Keywords:

Earthquake, Uniform Hazard Response Spectra (UHRS), Monte Carlo Simulation, PSHA, Acceleration, Iran, Kermanshah.

1. Introduction

Iran plate has a constant unique deformation due to its location between the Arabian and Eurasian plates and also the movement of the Arabian plate toward Eurasia. Some deformations caused by this movement and its compression forces emerge as earthquake events in the Zagros. The Zagros structural domain is located in the central part of the Arabia-Eurasia collision zone (e.g. Berberian, 1995).

Kermanshah is a province in the West of Iran near to Iraq and is located near to some active faults such as Zagros Main Recent Fault (MRF), Main Zagros Reverse Fault (MZRF), High Zagros Fault (HZF), Mountain Front Fault (MFF), Zagros Foredeep Fault (ZFF) and Balarud faults (Berberian, 1995). The history of occurred great earthquakes in this region, including a destructive earthquake on April 27, 2008, Ms=7 in Dinavar, earthquake on January 23,1909 Silakhor (Dorud) with Ms 7.4, and also the big recent one with Mw 7.3, 2017 Sarpole-Zahab, indicate that Kermanshah is one of the seismic parts of Iran and has been always exposed to extreme earthquakes.

Although it is not possible to accurately predict the occurrence of earthquakes, but making a reliable approximation of seismic hazard can minimize the economic and social losses of the future earthquakes. For this purpose, the information about the effect of expected

**Corresponding author:* E-mail: eshabani@ut.ac.ir (E. Shabani) Telephone: (+9821) 61118220.
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earthquakes based on the ground motion parameters during an earthquake is needed.

This study is motivated principally by the need to understand how similar are the results of seismic hazard assessment in Kermanshah, applying the Monte Carlo simulation based on the Musson method (2000), with the observed peak ground accelerations in seismic stations due to a large new earthquake. The advantages of applying the Monte Carlo simulation in seismic hazard analysis are its simplicity, controlling uncertainty, determining the contribution of each earthquake in the general hazard and as a result, ease in generating results of deaggregation and determining seismic design which can facilitate the hazard analysis process and at the same time, provide acceptable results.

In this study, 20 potential seismic sources within the interest region have been delineated. Then, according to the seismic parameters obtained for sources, synthetic catalogs of earthquakes are simulated using the Monte Carlo method, which are used to perform PSHA. Finally, resultant UHRS curves are evaluated with real peak ground accelerations recorded at some stations near to the location of a recent large event in the West of Iran, Mw 7.3 happened on 12 November 2017 known as the Sarpole-Zahab earthquake.

2. Methodology

2.1. Seismic hazard assessment

The purpose of seismic hazard assessment in a site is the logical evaluation of ground motion parameters caused by the earthquake event in potential seismic sources in a desired time. In PSHA, the seismic hazard of a certain site can be determined using total probability theorem. So that probability of exceedance of the ground motion parameter from a certain value, in a given time period, is computed in a double integral over earthquakes with all magnitudes for different distances to the site (Ebel and Kafka, 1999).

Common probability method for seismic hazard analysis encounters problems which mainly occur due to the lack of available seismic data in the potential seismic sources. In order to cope with problems of lack of seismic data, Shi and Gao (1993) introduced the concept of the spatial distribution function which displays the link of probabilistic distributions of magnitude and distance. In this regard, seismotectonic province is considered as a unit for statistical estimation of seismic parameters. Mean earthquake annual occurrence rate in seismotectonic subprovinces will be attributed to the magnitude intervals in the potential seismic source, for more details one can refer to Shabani and Mirzaei (2007).

In this study, the modified method is used to calculate the seismic parameters of potential seismic sources. The values of the distribution function for each of sources are presented in Table 2.

2.2. PSHA and Monte Carlo simulation

In the PSHA, seismic hazard is defined as the annual rate of exceedance of ground motion parameter (λ) from a certain value. The inverse of the annual frequency of exceedance is defined as the return period. The probability of occurring at least one exceedance of a certain level of ground motion (a_0), in the time interval t, i.e. $P(a \geq a_0)$, is related to the annual rate (λ) and defines as equation (1) (Ebel and Kafka, 1999):

$$P(a \geq a_0) = 1 - \exp(-\lambda(a \geq a_0).t), \quad (1)$$

for t=1 and a very small value of $\lambda(a \geq a_0)$, annual probability of an event is approximately equal to the annual rate of exceedance. Assuming the Poisson distribution of ground motion in a region and stable event process during the time, the seismic hazard can be estimated through counting numbers of events (N_T) that the ground motion parameter related to them is higher than the threshold $(a \geq a_0)$ in a site and time period (T) [Ebel and Kafka, 1999]. In fact, for seismic hazard analysis, the history of related seismic activity of a given site should be available. In the case of the presence of all events occurred in a region, from the largest event near to the study site to the smallest, such that a_k is the ground motion caused by k^{th} earthquake in a catalog, seismic hazard for a ground motion parameter can be estimated by equation (2):

$$\lambda(a \geq a_0) = \frac{T}{T_0}\left(\sum_K H(a - a_0)\right), \quad (2)$$

where, H is the Heaviside step function and T_0 is the catalog period (Ebel and Kafka, 1999). Relation (2) counts the number of events which their related acceleration (a) are larger than a certain level of a_0 i.e. $(a \geq a_0)$. The estimate of λ_T is correct if all earthquakes that can affect the site are present in the earthquake catalog. This means that the catalog should have a time period of several thousands or millions of years. Unfortunately, all available catalogs of historical earthquakes are too short to present long-term seismic activity. In addition, ground motions which are created by most past earthquakes are relatively unknown (Ebel and Kafka, 1999). The common method used for calculating the probabilistic seismic hazard is a method developed by Cornell (1968) and McGuire (1976) which is often called Cornell-McGuire method. The Cornell method is criticized for some reasons, such as lack of incorporating uncertainty in parameters of the recurrence relation, dependency to the hypothesis of the Poissonian earthquake occurrence and also determining the design earthquakes (Krinitzsky, 2002; Klügel, 2005).

A different but consistent method is presented which is based on the Monte Carlo simulation for solving some of these problems (Weatherill, 2009). In practice, the real performance of a system can be predicted and evaluated artificially by simulating the behaviour of that system. The Monte Carlo simulation method is a computing algorithm which is based on the random repetition of samples. Use of the Monte Carlo process in PSHA initially was introduced by Shapira (1983) and then by Johnson & Koyanagi (1988), in which seismic hazard is estimated in a site by random simulation of seismicity.

3. PSHA applying the Monte Carlo simulations in the Kermanshah region

A region bounded between 45°-48.50° E and 33 °-35.5° N is studied in order to do seismic hazard assessment in the Kermanshah (Fig. 1). Based on the division made by Mirzaei et. al (1998) and Tahernia et. al (2011), this area consists of parts of the Northern Zagros and the West-Central Iran seismotectonic subprovinces.

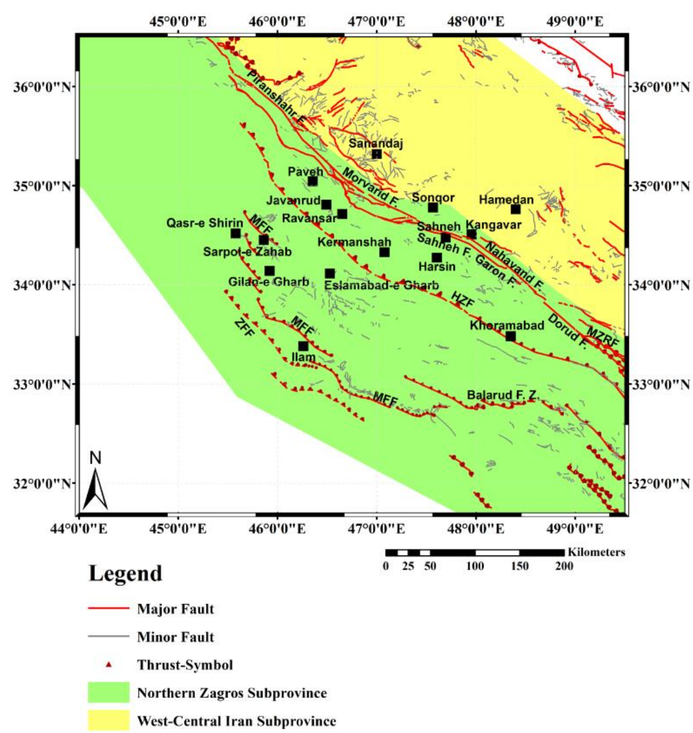


Figure 1. The study area is located in the Northern Zagros and West-Central Iran seismotectonic subprovinces.

3.1. Active faults in the studied region

Among the most important faults in the studied region, we can refer to the Zagros Main Recent fault system (MRF), with a strike slip mechanism, which consists of Dorud, Nahavand, Garon, Sahneh, Morvarid and Piranshahr faults [Berberian, 1995]. The occurrence of many major earthquakes in the studied area is caused by this system, including destructive earthquake on April 27, 2008, with magnitude 7 in Dinavar which occurred due to the motion of Sahneh fault, and the earthquake on January 23,1909 Silakhor (Dorud) with Ms=7.4, caused by the Dorud fault. Other important faults in the study area include Main Zagros Reverse Fault (MZRF), High Zagros Fault (HZF) with a thrust mechanism, Mountain Front Fault (MFF) with a thrust mechanism, which the earthquake on November 12, 2017 in Sarpole-Zahab (referred to Iran-Iraq border earthquake in USGS) with Mw=7.3 occurred because of the activation of Sarpol-Zahab basement fault from this system fault, Zagros Foredeep Fault (ZFF) with a reverse mechanism and Balarud faults. Fig. 2 shows the map of important faults in the studied area.

3.2. Seismicity in seismotectonic subprovinces

Seismicity parameters are calculated through recurrence relation in order to quantify the seismicity in a certain zone. In PSHA, it is assumed that the recurrence rule obtained from past seismic studies is valid and appropriate for predicting the seismicity of the future. The most famous recurrence relation is the Gutenberg-Richter (1944) recurrence relation which is defined as the equation (3):

$$\lambda_m = 10^{a-bM} = exp(\alpha - \beta M), \quad (3)$$

Where, λ_m is the annual rate of occurrence of earthquake with magnitude M or higher and *β=b.ln(10)* and *α=a.ln(10)* where *a* and *b* are constant parameters that show seismicity of the region. However, in practice, a truncated recurrence relation is commonly used which is defined as the equation (4):

$$\lambda_m = exp(\alpha - \beta m_{min}) \frac{exp[-\beta(M-m_{min})-exp[-\beta(m_{max}-m_{min})]}{1-exp[-\beta(m_{max}-m_{min})]}, \quad (4)$$

where, m_{max} is the maximum magnitude of the earthquake in each desired zone.

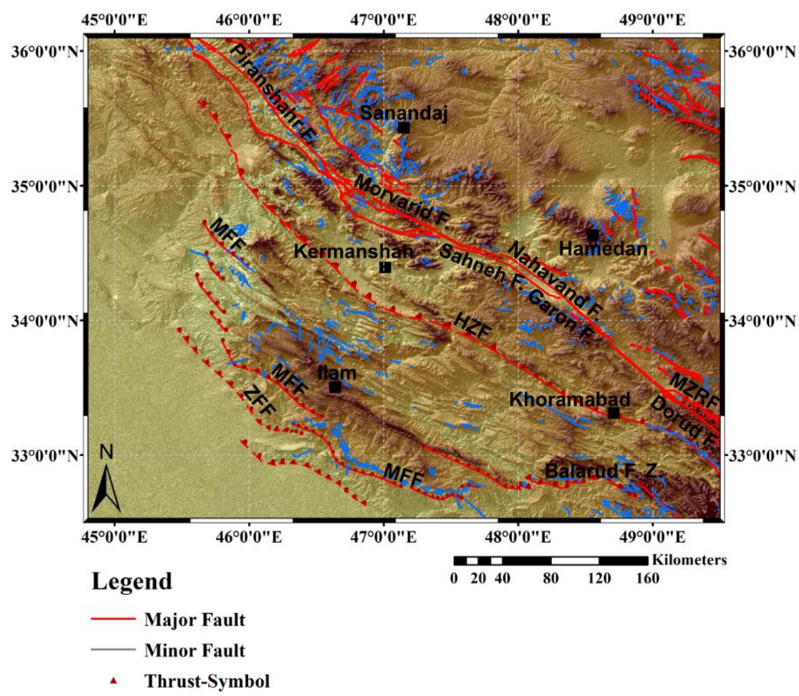


Figure 2. The map of faults along with Digital Elevation Model (DEM).

Finding seismicity parameters in subprovinces needs collecting and processing all seismic data. In order to collect the catalog of historical earthquakes in the study area, the catalog of Mousavi-Bafrouei et .al (2014) is used and updated, according to the International Seismological Center (ISC) and United States Geological Survey/National Earthquake Information Center (USGS/NEIC) as the first and second priorities, respectively. Then, the catalog is made uniform based on Mw using the relations presented by Mousavi-Bafrouei et .al (2015). Fig. 3 shows the seismotectonic map of the studied region.

In the next step, dependent events were identified and removed from the catalog using a window method introduced by Gardner and Knopoff (1974). The completeness of earthquake catalog is of great importance in seismicity studies and the estimation of seismic hazard parameters deduced from Gutenberg-Richter relation. In order to determine the completeness of the provided earthquake catalog, first, the magnitude-time curves have been used for the earthquakes in the North Zagros and West-Central Iran seismotectonic subprovinces in order to detect the time intervals with different magnitudes of completeness. After dividing the instrumental part of the earthquake catalog into smaller catalogs in terms of time, the magnitude of completeness was studied in each time interval. Finally, using the Kijko and Sellevoll method (1992) and soft-bound uncertainty model, seismicity parameters and a maximum magnitude of the earthquake in the Northern Zagros and West-Central Iran seismotectonic subprovinces were calculated. Table 1 shows calculated seismic parameters; λ is the annual rate of earthquake occurrences greater than minimum magnitude and maximum magnitude is the largest possible earthquake in each of the seismotectonic subprovince.

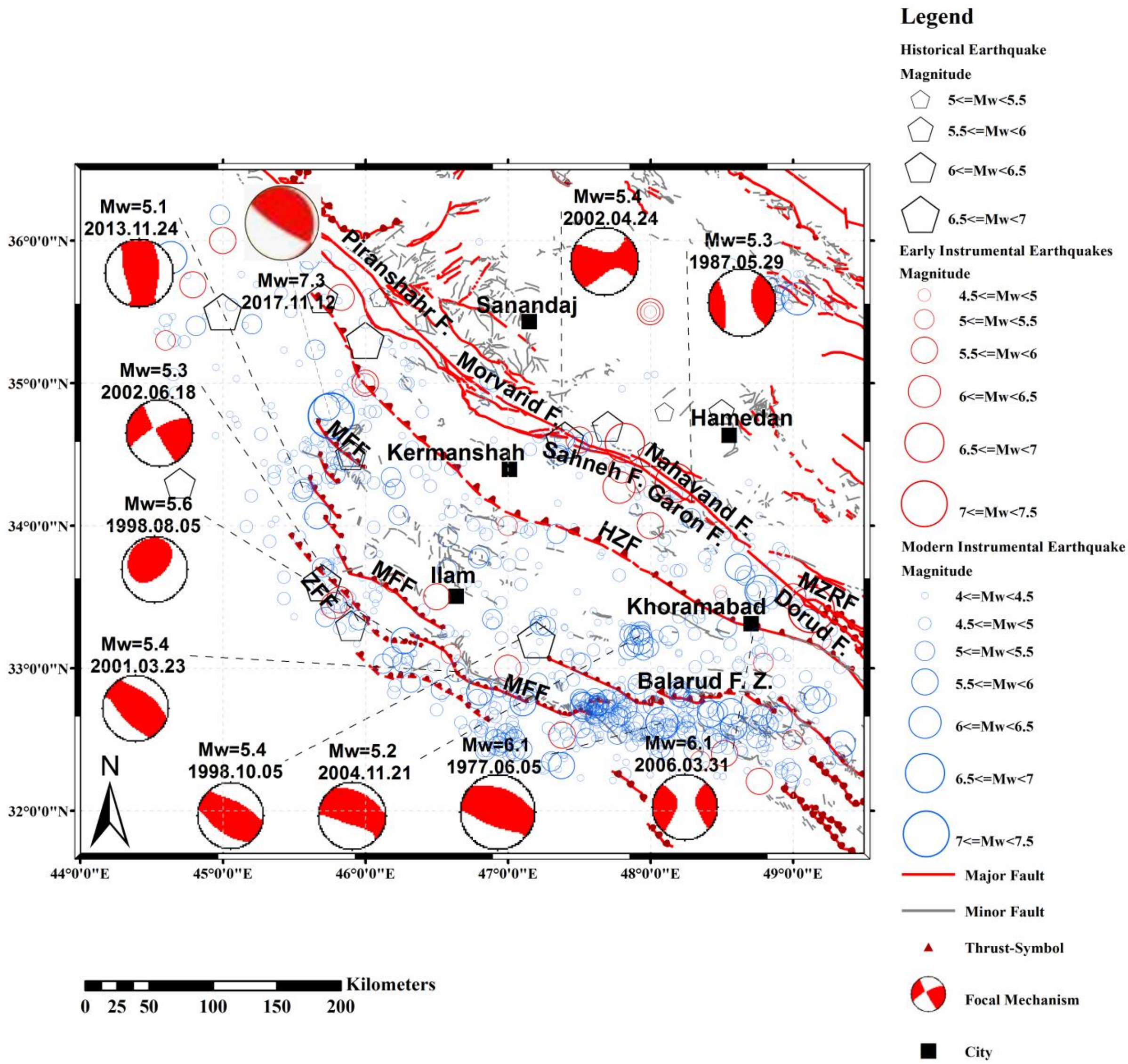


Figure 3. Seismotectonic map; including faults, epicenters and focal mechanisms of earthquakes in the study area.

Table 1. Seismicity parameters in each seismotectonic subprovince.

Seismotectonic subprovinces	β	b	λ	Minimum magnitude (Mw)	Maximum magnitude (Mw)
Northern Zagros	2.32 ± 0.03	1.01 ± 0.01	16.38 ± 0.62	4.3	**7.92 ± 0.22**
West-Central Iran	1.84 ± 0.08	0.80 ± 0.04	1.54 ± 0.020	4.1	**7.31 ± 0.21**

3.3. Modeling seismic sources

Inside a certain seismotectonic subprovince, due to the local changes in the tectonic site, the seismicity and maximum magnitude of an earthquake are varied; therefore, it is necessary to model the seismic sources and determine the maximum magnitude and seismicity parameters for each source. In this study, sources determined by Mousavi-Bafrouei et. al (2014) were reviewed and one the coordinates of a source (source number 5) is revised by the new information, and 20 seismic potential sources were determined in the study area (Fig. 4).

In this study, two methods are used in order to estimate the maximum magnitude of the earthquake in each seismic potential source. The first one, the maximum historical earthquake is increased by half a magnitude unit, and the second method is based on applying empirical relationships between the magnitude and fault parameters proposed by Wells and Coppersmith (1994). The larger one is selected as the maximum magnitude in the given source.

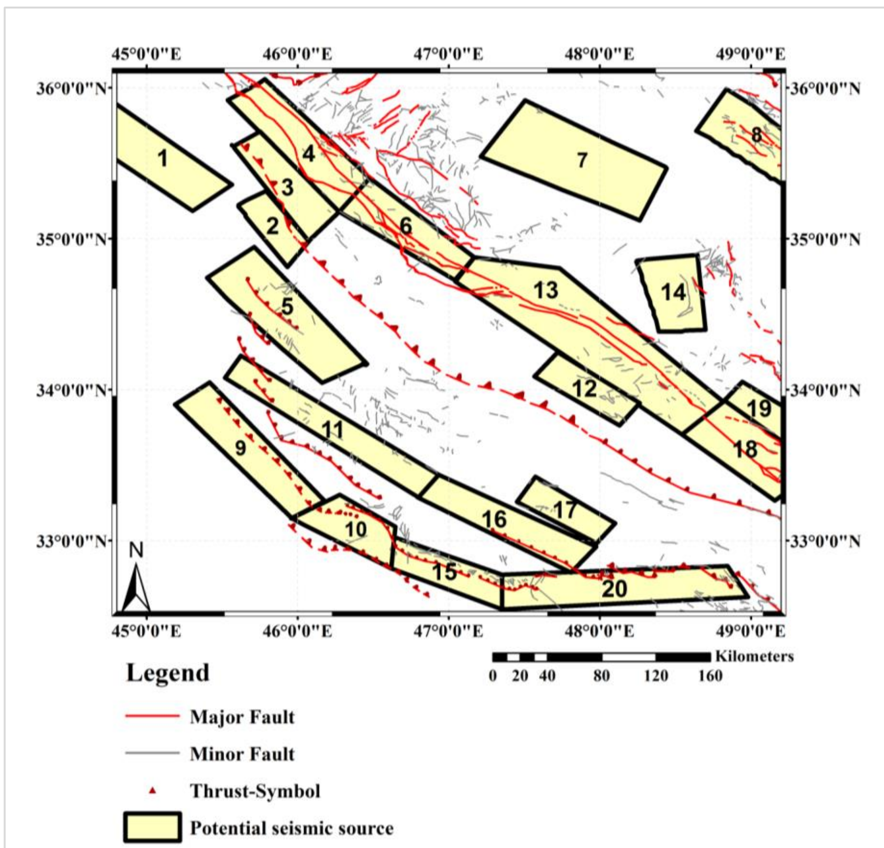


Figure 4: The map of seismic sources in the study area, according to Mirzaei et al (1998).

3.4. Seismicity parameters

The mean annual rate of occurrence of earthquakes in magnitude interval of ΔM in seismotectonic subprovince is as the equation (5) [Shi and Zhang, 1996]:

$$\lambda_{m_j} = \frac{2\lambda\, exp[-\beta(m_j - m_{min}) sh(0.5\beta\Delta M)}{1 - exp[-\beta(m_{max} - m_{min})]}, \quad m_{min} \le m_j \le m_{max}, \tag{5}$$

where, β and λ are seismicity parameters in each seismotectonic subprovince, m_j is the central value of the j^{th} magnitude interval, *sh* is hyperbolic sine function, ΔM is the width of magnitude intervals, m_{min} and m_{max} are the least magnitudes that can affect engineering structures (usually, Ms=4.0) and maximum expected magnitude in seismotectonic subprovince respectively. In order to show the heterogeneity of seismicity at the time and place and to avoid the underestimation of hazard of large earthquakes, the mean annual occurrence rate of earthquakes in seismotectonic subprovince should be shared in potential seismic sources using spatial distribution functions. For the i^{th} potential seismic source in the seismotectonic subprovince, the mean annual occurrence rate of earthquake is calculated as equation (6) [Shabani and Mirzaei, 2007; Shi and Zhang, 1996]:

$$\lambda_{l,m_j} = \frac{2\lambda\, exp[-\beta(m_j - m_{min}) sh(0.5\beta\Delta M)}{1 - exp[-\beta(m_{max} - m_{min})]} f_{l,m_j} \quad , m_{min} \le m_j \le m_{max}, \tag{6}$$

where $\lambda_{l,mj}$ and $f_{l,mj}$) are mean annual occurrence rate of earthquake and spatial distribution function of the jth magnitude interval in the lth seismic potential source, respectively. Further details on calculating the spatial distribution function are described in Shabani and Mirzaei (2007). Table 2 shows the values of the spatial distribution function and a maximum magnitude of each potential seismic source.

Table 2. The spatial distribution function and the maximum magnitude (Mmax) for each potential seismic source and the background seismicity in seismotectonic subprovinces.

Seismotectonic subprovince	Number/Name of source	The spatial distributon function	Maximum magnitude (Mw)
Northern Zagros	1	0.081	**7.5**
	2	0.037	**6.5**
	3	0.064	**7**
Northern Zagros	4	0.046	**7**
	5	0.074	**7.5**
	6	0.041	**6.5**
	9	0.082	**7.5**
	10	0.033	**6.5**
	11	0.030	**7**
	12	0.036	**7**
	13	0.115	**7.5**
	15	0.040	**7**
	16	0.070	**7.5**
	17	0.031	**7**
	18	0.107	**7.8**
	Background	0.240	**6**
West-Central Iran	7	0.070	**6**
	8	0.107	**7**
	14	0.070	**6.5**
	19	0.076	**6.5**
	Background	0.050	**5.5**

3.5. Hazard estimation applying Monte Carlo simulations

In this study, seismic hazard assessment applying the Monte Carlo simulation based on the Musson method (2000) is presented. Generally, this method follows the following steps (Musson, 2000): 1) The synthetic earthquake catalog is produced for duration of N years. 2) The highest ground motion in a year is selected. 3) For each event in the produced catalog, ground motion is calculated using attenuation relationships with random distribution in the site. 4) Steps 1 to 3 are repeated R times such that R×N must be 1000 times larger than the desired return period. Therefore, in order to the find annual probability of 10^{-4}, 100000 catalogs each with a duration of 100-year or 200000 catalogs each with a duration of 50-year can be used. And finally based on the above steps, 10000000 values obtained for maximum annual ground motion in the site. These values are arranged in the descending order, and in order to find the ground motion with annual exceedance probability of 10^{-4}, the 1001th motion selects. This value exceeds 1000 times than 10000000; therefore, it has a probability of 1 from 10000.

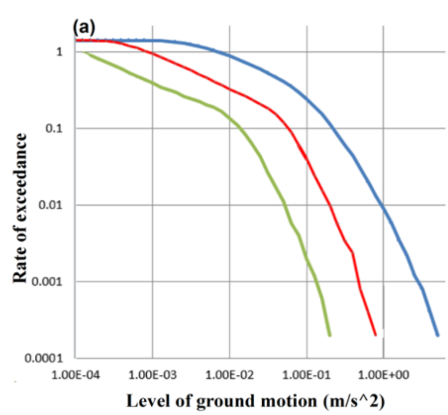
In this study, the EqHaz software (www.seismotoolbox.ca/EQHAZ.html) is used to estimate the seismic hazard assessment using the Monte Carlo simulation which analyzes the seismic hazard using three consecutive programs EqHaz1, Eqhaz2, and EqHaz3 [Assatourians and Atkinson, 2012]. In this study three ground motion prediction equations are used; Atkinson and Boore (2011), Campbell and Bozorgnia (2008) and Chiou and Yangs (2008), with equal weights.

Finally, to make a mean hazard curve, the number of exceeded ground-motions from threshold is counted and divided by the total duration. Fig. 5 shows mean hazard curves and Fig. 6 shows the seismic hazard zoning for the assumed source model shown in Fig. 4, the PGA and, spectral accelerations 0.5 and 0.2 Hz, for return periods of 50 and 475 years (%63 and %10 exceedance probability in 50 years) are presented.

3.6. Seismic hazard deaggregation

McGuire (1995) presented seismic hazard deaggregation, which separates the contribution of different factors in the mean annual exceedance rate of ground motion from a certain level in a site. Since in the seismic hazard analysis using Monte Carlo simulation, the contribution of each earthquake in the synthetic catalog has been clear in the total hazard, therefore, we can study the most important distance-magnitude combinations from a design point of view (Musson, 2000). Therefore, one advantage of using Monte Carlo simulation in PSHA is that it accelerates the generation of deaggregation results in each probability level. In the present study, three-dimensional deaggregation of seismic hazard has been conducted in order to determine the characteristics of scenario earthquake in the Kermanshah region. The results of magnitude-distance-epsilon three-dimensional deaggregation (epsilon = number of standard deviations of the logarithm of the ground motion from the calculated value using the attenuation relationship for certain M and R) with dimensions ΔR=5km and ΔM=0.2 for PGA and spectral accelerations 0.5 and 0.2 Hz, in return periods of 50 and 475 years are shown in Table 3 in the Kermanshah city. Fig. 7 shows the 3-D seismic hazard deaggregation for PGA in the return periods of 50 and 475 years.

In this study, an untraditional approach of applying uncertainty is used. In the traditional approach, a clear difference is considered between aleatory and epistemic uncertainty, however, it is known that this difference is somehow artificial (Bommer and Scherbaum, 2008). We assumed that the epistemic and aleatory uncertainties are equivalent.



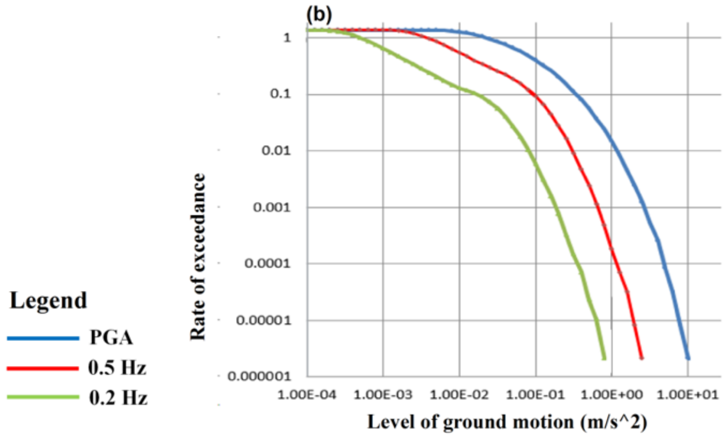


Fig 5. The mean hazard curve of the Kermanshah for PGA, and spectral accelerations 0.5 Hz and 0.2 Hz for two return periods of, a) 50 years and b) 475 years.

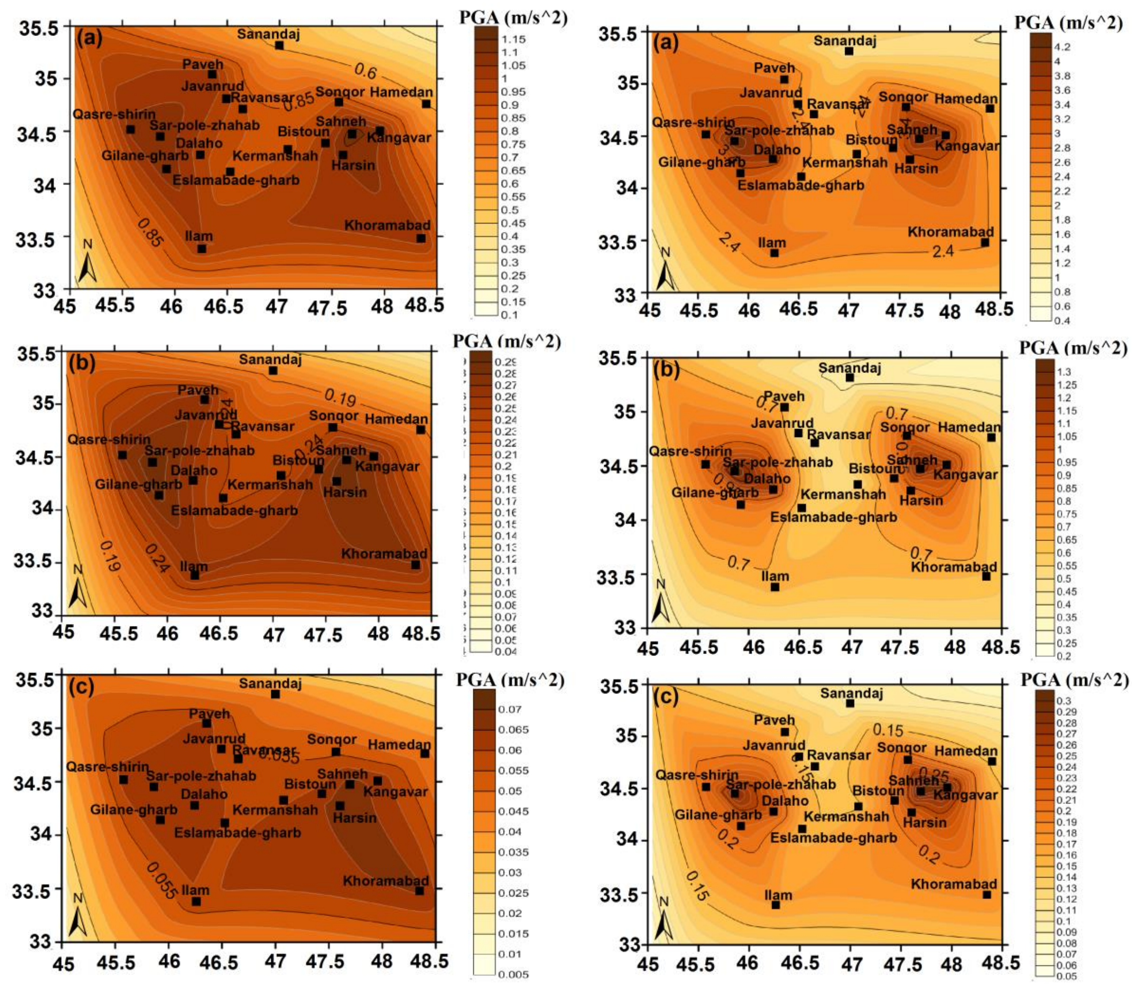


Figure 6. The seismic hazard zoning map of the Kermanshah region for, a) PGA, b) 0.5 Hz and c) 0.2 Hz for different return periods of 50 years and 475 years.

Table 3. Scenario earthquakes for PGA, and spectral accelerations 0.2 and 0.5 Hz in the Kermanshah city for return periods of 50 and 475 years.

Frequency	**PGA**		**0.5 Hz**		**0.2 Hz**	
Return period	50 years	475 years	50 years	475 years	50 years	475 years
Magnitude (Mw)	4.9	5.1	6.5	7.1	6.7	7.1
Distance (km)	7.5	7.5	62.5	42.5	72.5	52.5
Epsilon	0.67	0.57	0.61	0.70	0.68	0.73

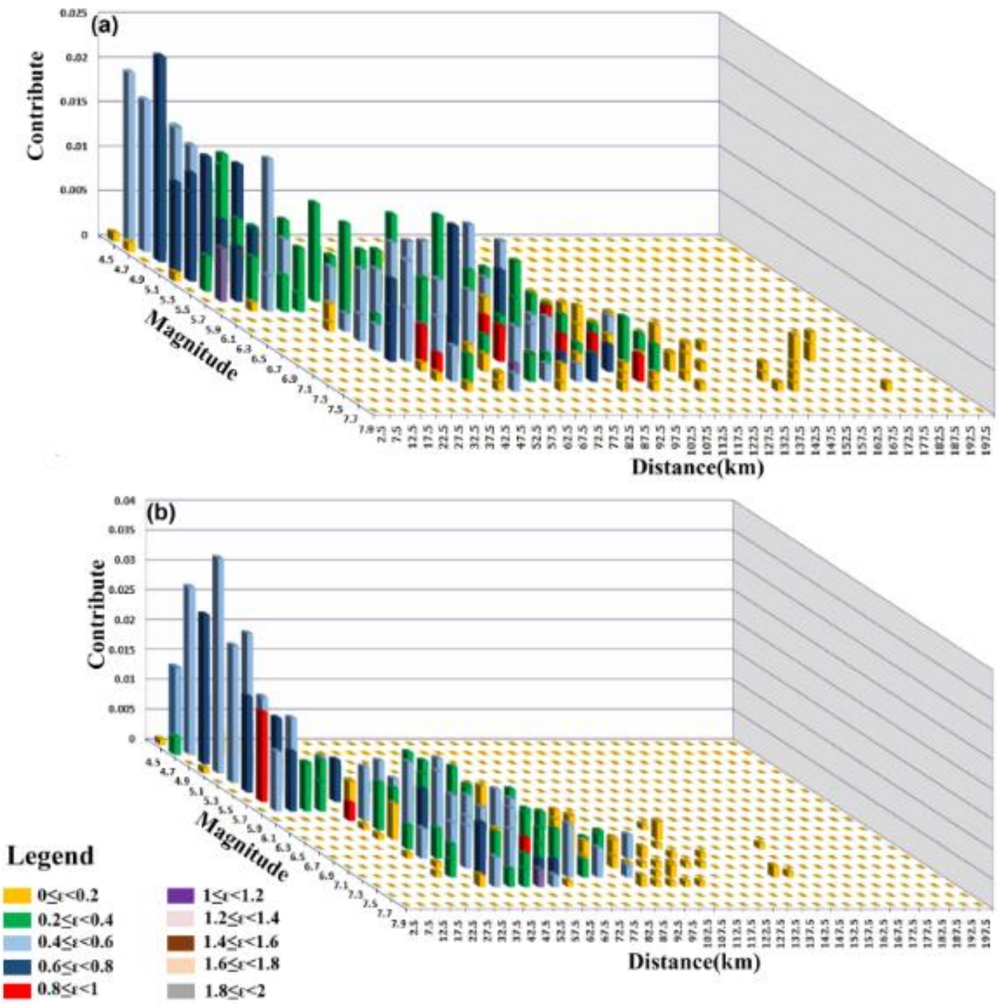


Figure 7. Magnitude-distance-epsilon deaggregation in the Kermanshah city for PGA in return periods of, a) 50 years and b) 475 years.

4. Validation of PSHA deaggregation results with the observed PGAs

The maximum predicted accelerations in PSHA are evaluated with peak ground observed accelerations in some seismic stations recorded the earthquake 12.11.2017 with Mw7.3 near the Iran-Iraq border. Three seismic stations of SPZ, KRD and KER2 are considered. As shown in Figs 8, 9 and 10, in each station, uniform hazard response spectra (UHRS) curves are calculated for three attenuation relationships; Atkinson and Boore (2011), Campbell and Bozorgnia (2008) and Chiou and Yangs (2008). These UHRS are depicted for each site per earthquake event rate with the magnitude of 7.3 which is simulated using Monte Carlo method for return periods of 475 and

2475 years.

Fig 11 shows a comparison made between maximum recorded acceleration in each of three mentioned stations during the Sarpole-Zahab earthquake and maximum predicted accelerations using attenuation relationships at the place of the three stations, in two return periods of 475 and 2475 years. Since attenuation relationships used in this study present the arithmetic mean of two horizontal components, therefore, the horizontal axis of the curves also shows the arithmetic mean of two horizontal components of recorded acceleration during the Sarpole-Zahab earthquake in each station. Regarding the three curves related to the Fig. 11, predicted accelerations related to each station in the return period of 475 years (contrary to the predicted accelerations in the return period of 2475 years) are consistent with recorded accelerations during the Sarpole-Zahab earthquake in that station. Fig. 12 indicates plots of acceleration versus distance show the difference between the observed acceleration and predicted acceleration using each of attenuation relationships for earthquake event rates with the magnitude of 7.3 in return periods of 475 years in the location of the earthquake epicenter.

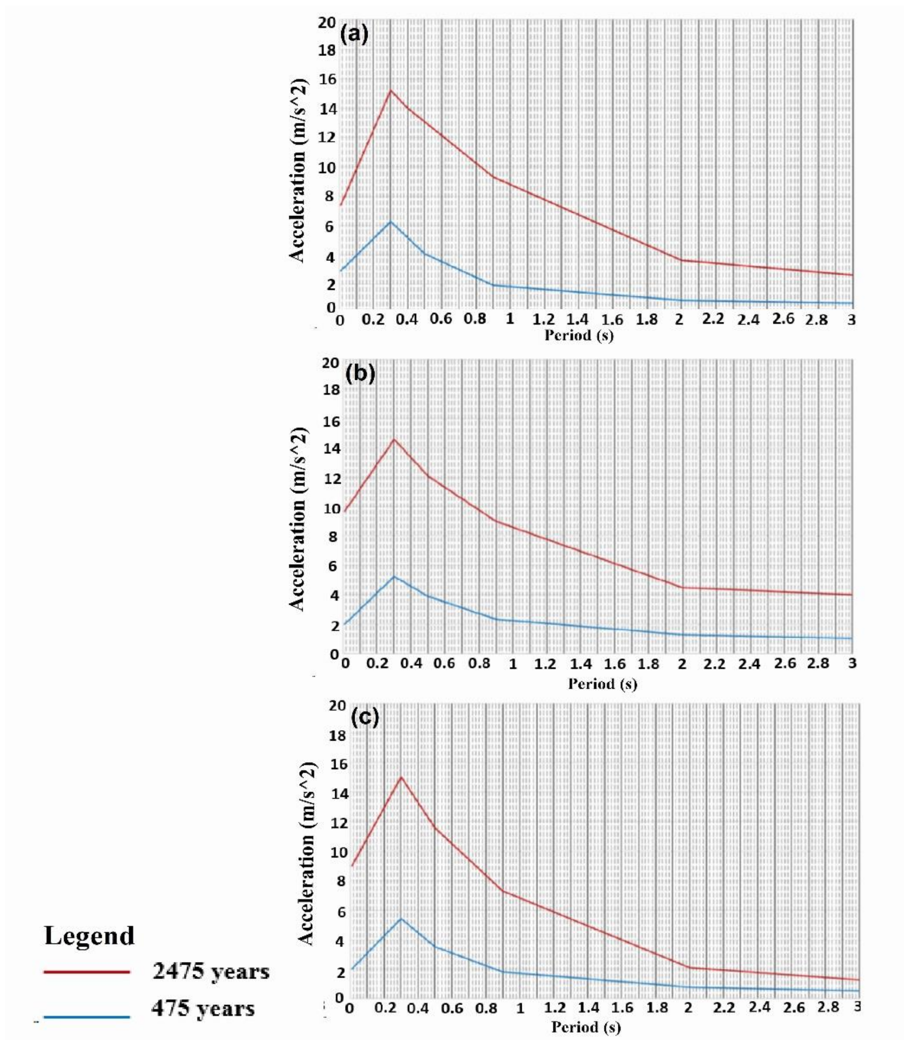


Figure 8. UHRS curves in SPZ seismic station, for different attenuation relationships; a) Atkinson and Boore (2011), b) Campbell and Bozorgnia (2008) and c) Chiou and Youngs (2008).

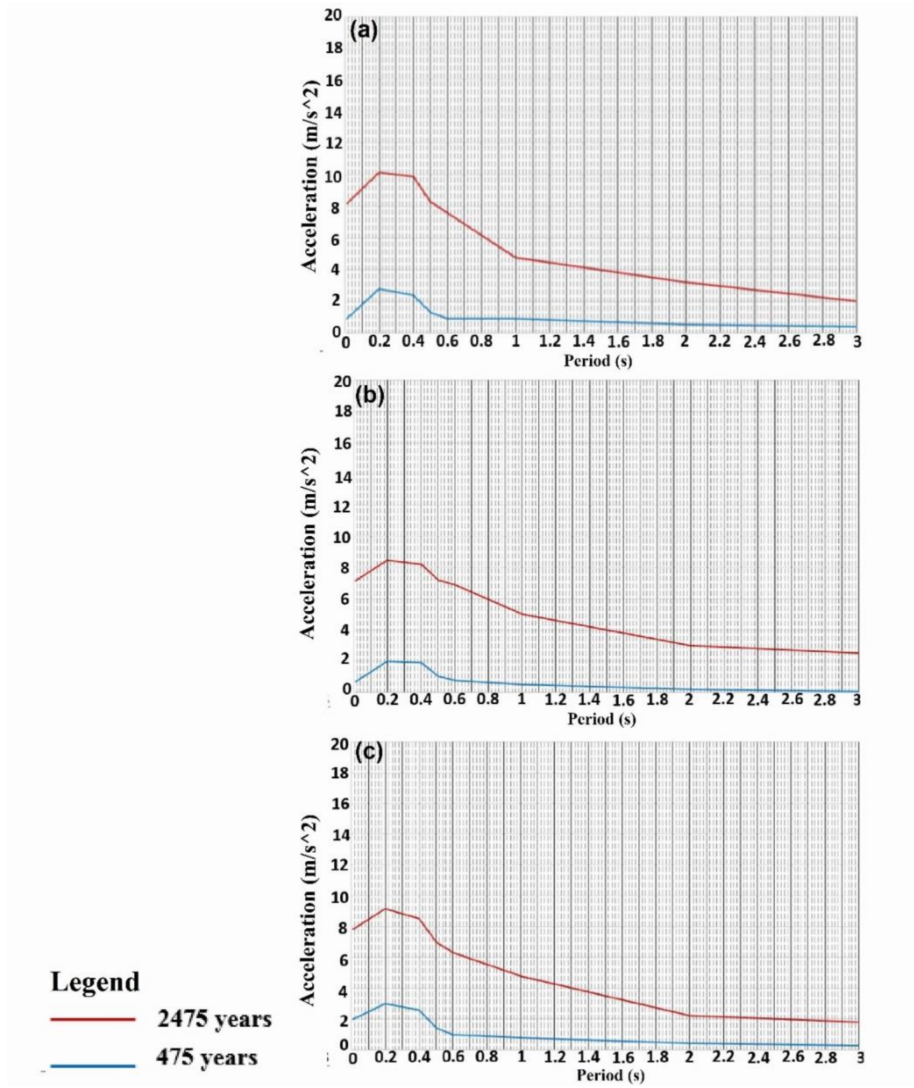


Figure 9. UHRS curves in KRD seismic station, calculated for different attenuation relationships; a) Atkinson and Boore (2011), b) Campbell and Bozorgnia (2008) and c) Chiou and Youngs (2008).

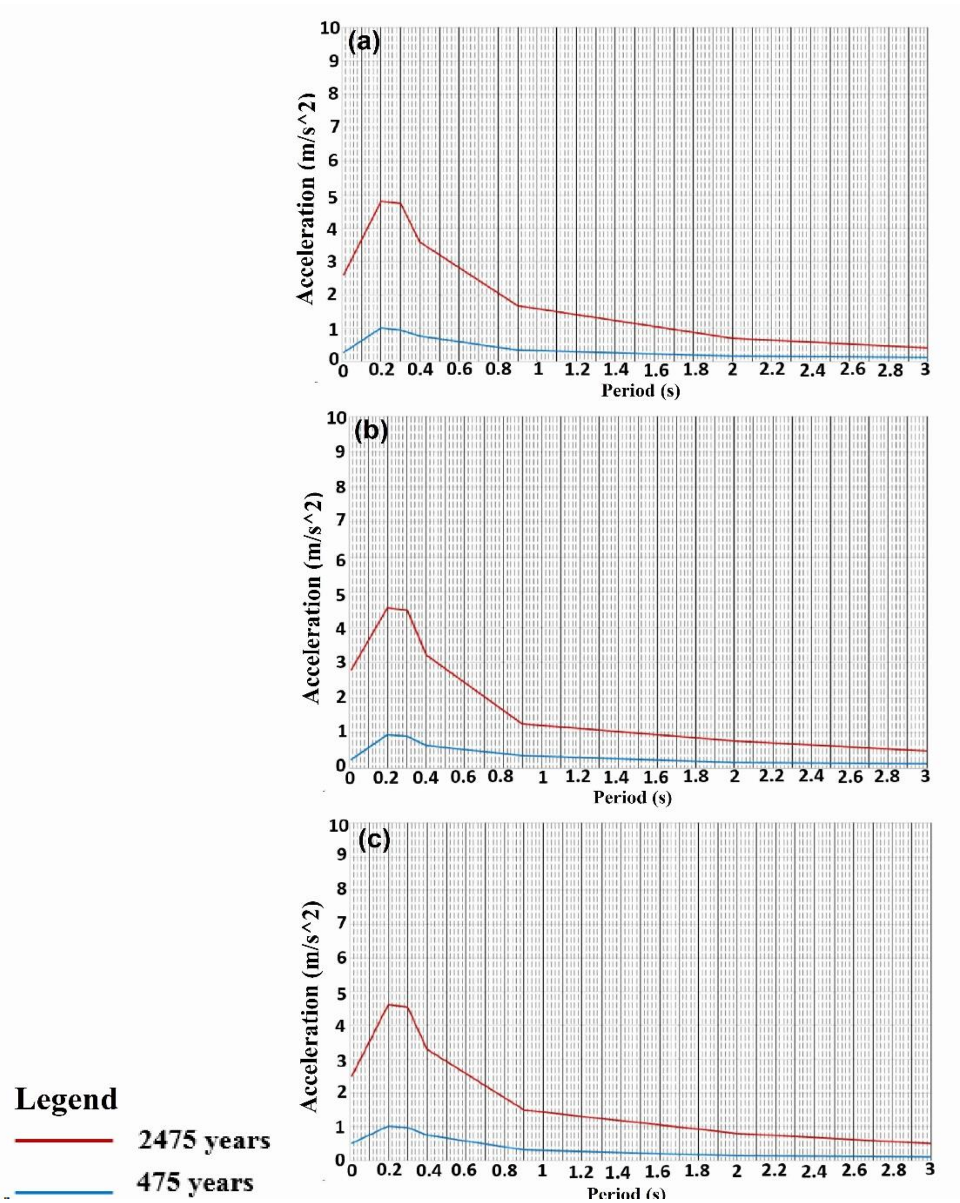


Figure 10. UHRS curves in KRM2 seismic station, calculated for different attenuation relationships; a) Atkinson and Boore (2011), b) Campbell and Bozorgnia (2008) and c) Chiou and Youngs (2008).

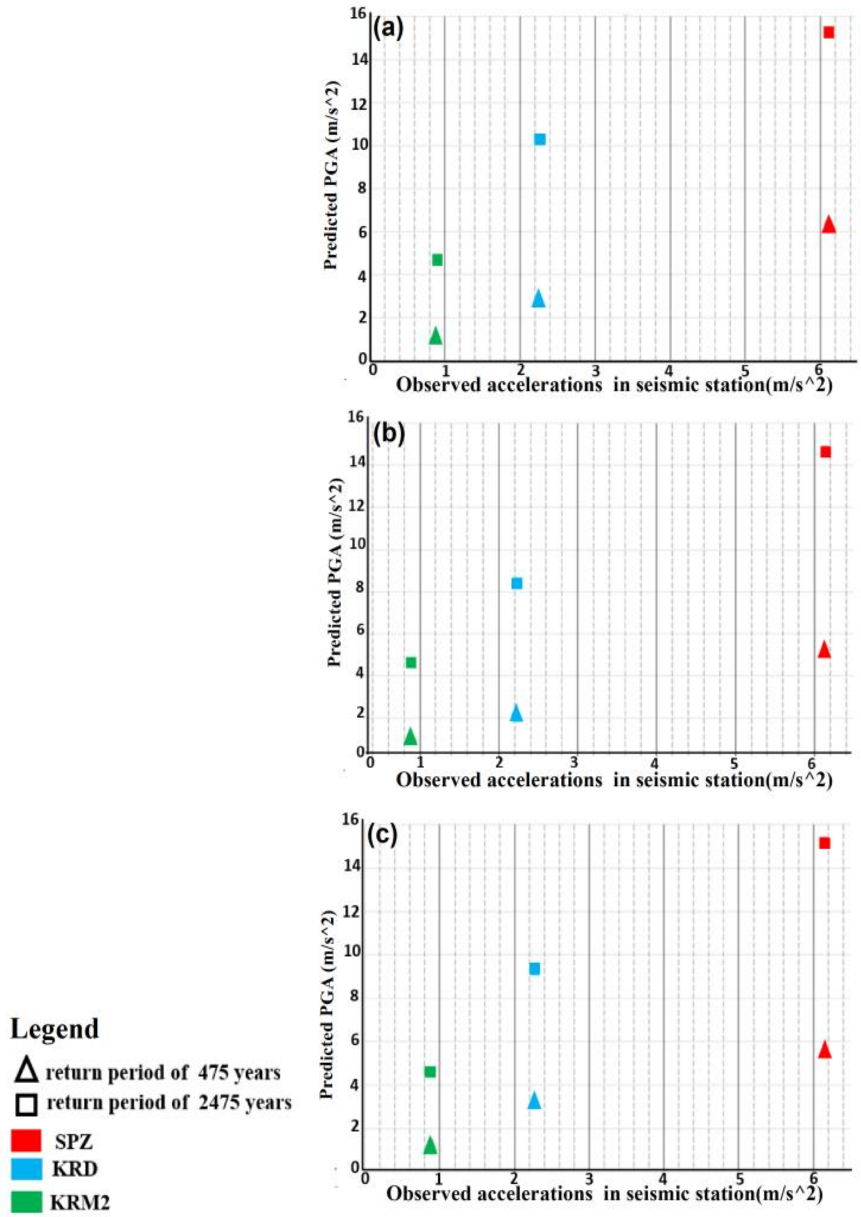


Figure 11. Comparing curves for maximum observed accelerations in three seismic stations during the earthquake of the Sarpole-Zahab with the maximum predicted accelerations using attenuation relationships; a) Atkinson and Boore (2011), b) Campbell and Bozorgnia (2008) and c) Chiou and Youngs (2008), at the same sites for the return periods of 475 and 2475 years.

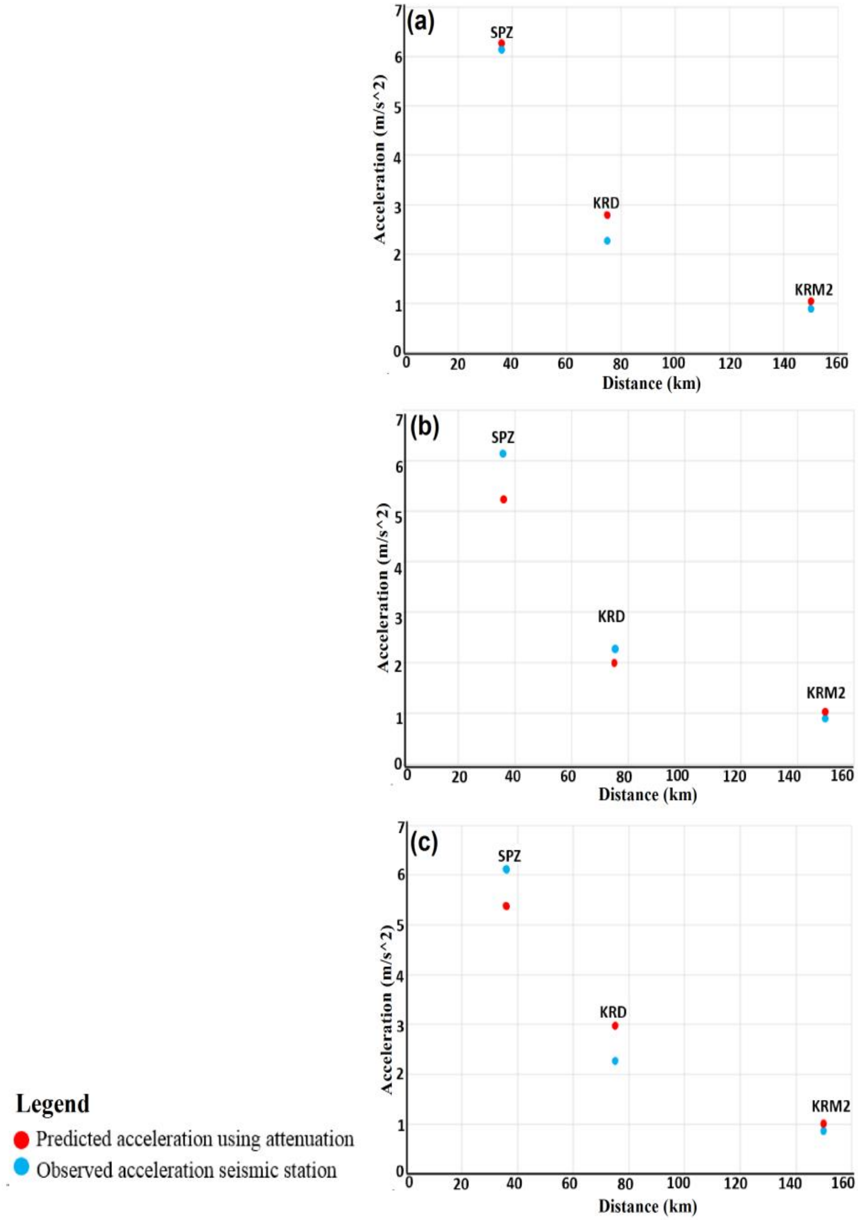


Figure 12. The difference between maximum observed acceleration during earthquake of Sarpole-Zahab in three seismic stations and the maximum predicted acceleration using attenuation relationships; a) Atkinson and Boore (2011), b) Campbell and Bozorgnia (2008) and c) Chiou and Youngs (2008).

5. Conclusions

Regarding the results and the hazard maps, in the return period of 50 years (%63 exceedance probability in 50 years) the Sahneh, Sarpol-Zahab and Harsin sites show the highest accelerations, and in the return period of 475 years (%10 exceedance probability in 50 years) the peak values are found in the Sarpol-Zahab and Sahneh sites. Dominant scenarios calculated for Kermanshah show similar distance 7.5 km for PGA in different return periods of 50 and 475 years. The most hazardous scenario earthquake related to the Kermanshah city is probably caused by sources of 5, 6, and 13. These sources have a maximum magnitude of 7.5, 6.5, and 7.5, respectively, which include Nahavand, Garon, Morvardi, and Main Zagros Front (MZF) faults. Final UHRS in locations of three seismic stations, SPZ, KRD and KER2, for seismic events with the magnitude of 7.3 in the return periods of 475 and 2475, years using three attenuation relationships, and comparing their maximum predicted accelerations with the maximum observed accelerations during the earthquake of Sarpole-Zahab Mw7.3 in each station, shows that the predicted accelerations in the return period of 475 years show closer values to the observed ones. In this return period, the maximum predicted accelerations using Atkinson and Boore (2011) have the least difference with the maximum observed accelerations in SPZ and KER2 stations, and the maximum predicted acceleration using Campbell and Bozorgnia (2008) relation has the least difference with maximum observed accelerations in KRD station.

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