

Original Research Paper

Probabilistic Seismic Hazard Deaggregation for Karaj City (Iran)

Hadi Jarahi

Department of Tunnel, Harazrah Consulting Engineers Group, Tehran, Iran

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Email: hadijarahi@gmail.com

Abstract: In this study the results of PSHA deaggregation for 5%-damped 0.2, 0.5, 2 and 4 s spectral accelerations, corresponding to Mean Return Periods (MRPs) of 50 and 475 yr for Karaj city was presented. The aim of this paper is to quantify the dominant events that have the most contribution on ground-motion exceedance from the above mentioned hazard levels. The scenario earthquakes are characterized by bins of Magnitude (M) and source-to-site distance (R). The results reveal that for Karaj city, the hazard is mainly controlled by near active fault.

Keywords: Deaggregation, Spectral Accelerations, Karaj City, Seismic Hazard Component

Introduction

Iran is one of the most seismic active countries in the world. During the last several decades several thousand people lost their lives, sever economic impacts and social damages were experienced. For example, during the 1990 Rudbar earthquake ($M_w = 7.3$) in northwest Iran, more than 40,000 people lost their lives, more than 500,000 became homeless, nearly 100,000 buildings were destroyed, three cities and 700 villages were demolished. Iran has been host to a long series of large damaging earthquakes, many of them occurring within the 20th century. There have been roughly 126,000 deaths attributed to 14 earthquakes of magnitude ~ 7.0 (one 7.0 earthquake/7-yr) and 51 earthquakes of 6.0-6.9 (one/2-yr) that have occurred in Iran since 1900. During this period nine (9) cities were devastated (one city/1 O-yr). Review of the historical seismic data shows that almost every part of the country has been hit by major earthquakes during the last century. Zagros, Alborz and Khorasan seismic regions are among the most seismically active regions of the country.

One of the advantages of PSHA is that it allows computation of the mean annual rate of exceedance at a particular site based on aggregated hazard of all possible range of magnitudes from potential seismic sources, occurring at many different source-to site distances. This integrating nature of PSHA leads to lose the concept of a single event threat for the site (McGuire, 1995). The so-called dominant events

(Bazzurro and Cornell, 1999) or design earthquakes (McGuire, 1995) are required to evaluate many characteristics of the ground motion, such as dynamic time history analysis, duration, nonstationary of motion and critical pulses (Cramer and Petersen, 1996). Design earthquakes can be chosen based on deterministic assumptions, such as the magnitude of the worst historical event reported and its best guessed location derived from known active structures. On the other hand, usually for the common case of a site, high-frequency hazard is dominated by frequent local earthquakes and low-frequency hazard is dominated by large magnitude earthquakes over a wide range of distances, therefore the selection of a unique earthquake scenario does not guarantee an equal seismic protection for the site under analysis (Sousa and Costa, 2009). In order to derive a seismic scenario consistent with the results of PSHA for a site and determine the relative contribution of events to the overall seismic hazard, the concept of deaggregation was introduced. The deaggregation process separates the contributions to the Mean annual Rate of Exceedance (MRE) of a specific ground-motion value at a site due to scenarios of giving magnitude M and distance R and often ϵ , the ground motion error term. The ϵ value is defined as the number of standard deviations by which the (logarithmic) ground motion generated by a given M-R pair deviates from the median value estimated by a prediction equation (Barani *et al.*, 2009). The seismic hazard deaggregation process has been performed by Bernreuter (1992) for the

first time and following this study, deaggregation methods and applications were extensively discussed and improved by Chapman (1995; McGuire, 1995; Cramer and Petersen, 1996; Bazzurro and Cornell, 1999; Harmsen *et al.*, 1999; Sokolov, 2000; Harmsen, 2001; Harmsen and Frankel, 2001; Montilla *et al.*, 2002; Halchuk and Adams, 2004), etc. In order to perform deaggregation of seismic hazard for Karaj city, probabilistic seismic hazard assessment is evaluated for the study area (yellow area in Fig. 1). Selecting this area allows to get involved in assessments and calculations all of the elements that could affect the seismicity of Karaj. The city of Karaj with highly dense population (about 5 million people) has not experienced a damaging earthquake since 1830, although it is located in an active seismic zone and surrounded by active faults with evidence of historical destructive earthquakes. The major aim of this study is the deaggregation of the hazard results in terms of magnitude, distance and epsilon, to investigate earthquake occurrences that have the most contribution to the resulting ground-motion hazard in Karaj. In this regard, 6 liner seismic sources are delineated in the study region and the quantified hazard values in terms of the Peak Ground Acceleration (PGA) over bedrock, are mapped for 63 and 10% probabilities of exceedance in

50 years on grid intervals of 0.1°, using the 4 Next Generation Attenuations (NGA). Then, based on obtained results of PSHA, deaggregation of the hazard is performed in terms of magnitude-distance pairs and epsilon for Karaj city.

Tectonic Setting

The study area covers the Alborz. Along the Alborz and the Central Iran seismotectonic provinces seismicity occur primarily in the upper crust, but some infrequent events occur in the mid-crust of the Alborz, where the South Caspian basin under thrusts the Alborz along the Khazar fault (JICA and CEST, 2000). Despite the relatively high elevation of Alborz Mountains, the Bougure anomaly has very small negative values and the crustal thickness is less than 35 km along the Caspian coast; therefore, it must be considered as mountains without root whose uplift is due to thrusting of allochthonous masses over each other in a compressional tectonic regime (Dehghani and Makris, 1983). Fault plane solutions of earthquakes in the study region indicate both thrust and strike-slip faulting, though the thrust faulting is prominent (Berberian, 2014; Abdi *et al.*, 2013).

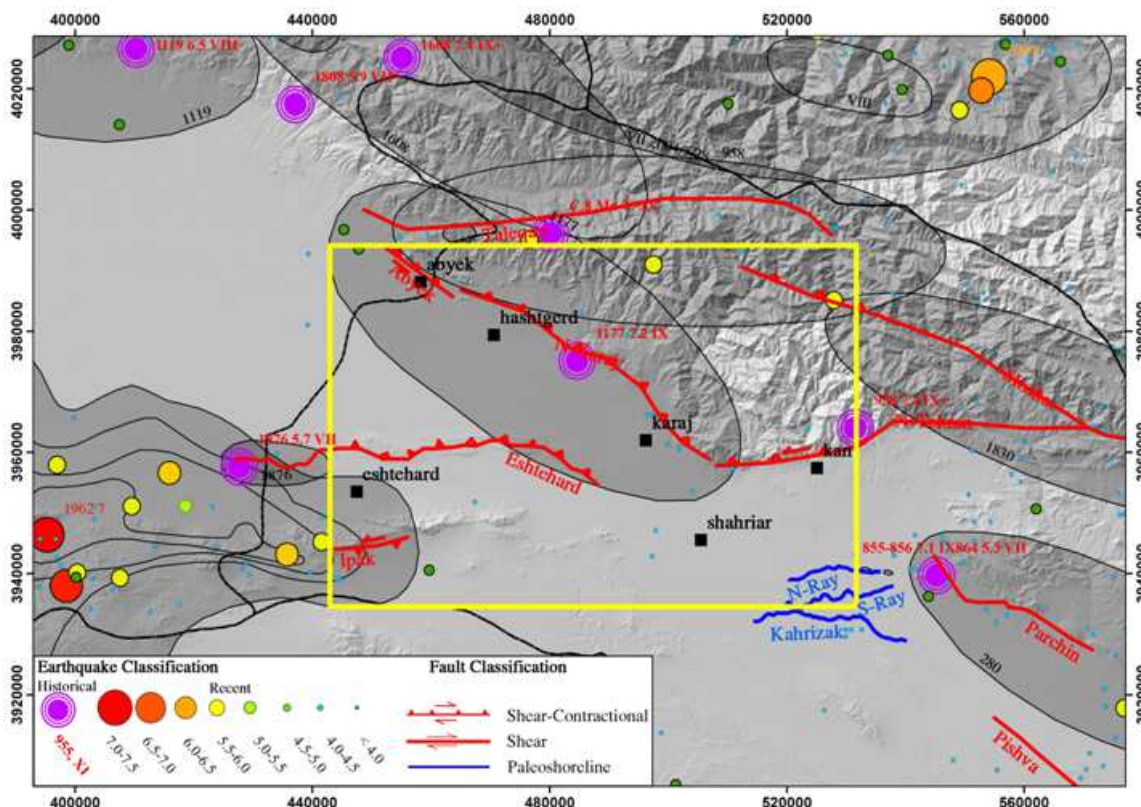


Fig. 1. Map of seismic sources of Karaj region. Elipsoids show the Meizoseismal area of earthquakes

Probabilistic Seismic Hazard Analysis

According to traditional methodology of PSHA (Cornell, 1968; Kijko, 2012), at first, potential seismic sources should be delineated and then seismicity parameters in each source will be determined. For regions with insufficient earthquake data, seismicity studies in potential seismic sources using the traditional method brings a noticeable uncertainty into results. To overcome such shortcomings, the traditional method has been modified by Shi *et al.* (1992) and developed by Ni (2012); therefore, inhomogeneity of seismicity in time and space could properly be regarded. In this study, the modified methodology of PSHA is applied. Three major steps of modified method are (Shabani and Mirzaei, 2007; Kijko, 2012):

- Delineation of seismotectonic provinces and evaluation of seismicity parameters
- Determination of potential seismic sources
- Dividing the interest region into a series of grid points and assessment of seismic hazard for every grid point

Seismotectonic province is defined as an area that under the present-day geodynamic regimes has a comparable tectonic setting and unified seismicity pattern (Ye *et al.*, 1995; Mirzaei *et al.*, 1998). According to Mirzaei *et al.* (1998), territory of Iran can be divided into five major seismotectonic provinces based on all available geophysical,

geological, tectonic and earthquake data. A uniform catalog of earthquakes containing historical and instrumental events covering the period from 400 BC to 2013 is used (Table 1). The earthquake database is mainly compiled from ISC for the modern instrumental time period (1964-2013) and the catalog of earthquakes provided by Ambraseys and Melville (1982) is the basic source of parameters for the historical (before 1900) and early instrumental (1900-1963) time periods. The catalog of earthquakes has been made uniform using the relationships between M_s and m_b for selected area.

Since we encountered an incomplete earthquake catalog in the study region, the procedures introduced by Kijko (2010), which permit incorporation of magnitude uncertainty to estimate seismicity parameters from incomplete data files, are applied to the uniform catalog of earthquakes for estimating the seismicity parameters. Results of the estimation of seismicity parameters in the selected area are presented in Table 2.

Figure 1 shows potential seismic sources in Karaj region. Further the meizoseismal area of historical events and paleoshoreline trace (Jarahi *et al.*, 2016) are shown. A total of 6 line sources and their corresponding M_{max} are chosen. For estimating M_{max} , used 4 tentative relationships between fault rupture length and earthquake magnitude (Zare, 1995; Wells and Coppersmith, 1994; Nowroozi, 1985; Ambraseys and Jackson, 1998). Then, by using logic tree (Fig. 2), that was match with tectonic setting of study area, value of M_{max} has been weighted and then estimated (Table 3).

Table 1. Event count for 1 Magnitude bins and 10 year bins

Date Range	Magnitude Range				Grand total
	4-4.9	5-5.9	6-6.9	7-7.7	
Historical					
(400-1900)		6	10	10	26
1900-1909		1			1
1910-1919					0
1920-1929		1			1
1930-1939		9			9
1940-1949	2	1			3
1950-1959	5	5	2	3	15
1960-1969	12	10	3	3	28
1970-1979	40	8			48
1980-1989	42	28			70
1990-1999	69	22			91
2000-2009	39	9			48
2010-2013	44	4	5		53
Grand Total	253	104	20	16	393

Table 2. Estimation of seismicity parameters from recorded earthquakes in the selected area

Parameter	Value
B	1.63±0.07 (b = 0.71±0.03)
λ	0.72±0.04 (for $M_{min} = 4.3$)
M_{max}	7.2±0.11 (for SIG (X_{max}) = 0.10)

Table 3. Seismicity Parameters of seismic source of study area. M_{max} calculated as the percentage weight of every relationship in front of it is inserted. In this process the four empirical relations use an event earthquakes associated with the fault as a factor in determining M_{max} is intended

Seismic source	M_{max}				Weighted
	1 (40%)	2 (20%)	3 (22%)	4 (18%)	
N-Karaj	6.8	7.6	6.9	6.8	7.0
Eshtehard	6.8	7.5	6.8	6.7	6.9
N-Tehran	7.2	7.8	7.1	7.0	7.2
Mosha	7.0	7.7	7.0	6.9	7.1
Abyek	6.5	7.4	6.7	6.6	6.7
Ipak	7.0	7.6	7.0	6.9	7.1

1- Zare (1995); 2- Wells and Coppersmith (1994); 3- Nowroozi (1985); 4- Ambraseys and Jackson (1998)

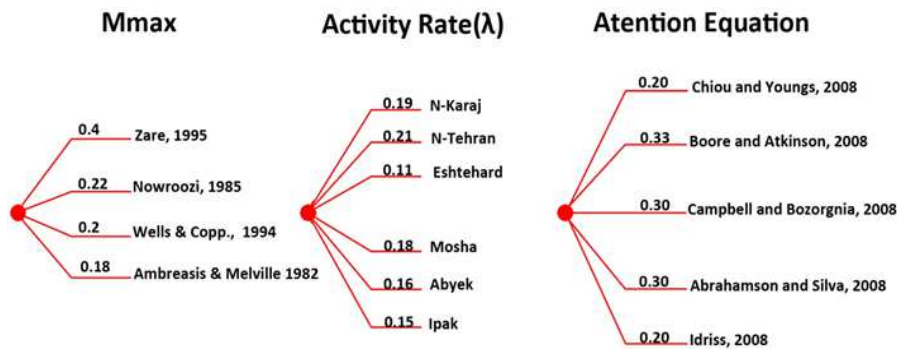


Fig. 2. The logic tree for weighting seismic parameters (Jarahi *et al.*, 2016)

Generally, in seismic hazard analysis, annual rate of earthquakes in active faults is calculated by definite integration on magnitude-frequency relation.

For the hazard analysis the EZ-FRISK program utilized to compute the hazard analysis of this study. The EZ-FRISK program calculates seismic hazard using the standard methodology for seismic hazard analysis mentioned above.

In the regions with high seismic activity, any seismic hazard assessment needs a set of attenuation equations which could appropriately represent the variable parameters of the strong motion in that region. For the Iranian plateau, there is a limited number of reliable strong ground-motion data to perform a specific attenuation relationship, especially in the near-source areas of large earthquakes. For example the Iranian strong-motion data have a total of only 4 recordings for magnitudes greater than 7.0 and distances less than 30 km (Shoja-Taheri *et al.*, 2010). Due to this reason, applying worldwide attenuation models for similar tectonic environment is appropriate. We have adopted for this study the attenuation relationship for rock ($V_s > 750$ m/s) developed by Boore and Atkinson NGA model (2008). The NGA project has resulted in the publication of five new ground-motion models to predict PGA, PGV and response spectral ordinates for periods 0.0 up to 10.0 s (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008; Idriss, 2008). The NGA database is one

of the largest databases of uniformly processed strong ground-motion recorded in shallow crustal earthquakes in active tectonic regions, including data recorded in the 1978 Tabas and 1990 Manjil earthquake that occurred, respectively, in central-east Iran and Alborz-Azerbaijan Seismotectonic provinces of Iran. Thus, these new equations might also be applied as ground-motion prediction in other parts of the world with the similar tectonic environment, such as the region encompassing the Iranian plateau. Shoja-Taheri *et al.* (2010) carried out a comprehensive study on comparison of the three NGA equations (Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008) as representative of all the NGA models, with the strong-motion data recorded in Iran and concluded that the three NGA models are generally applicable to the presently available Iranian dataset. Shoja-Taheri *et al.* (2010) also mentioned that the NGA model of Boore and Atkinson (2008) is somewhat more applicable for Iran than the other two models, since some of the details on the near source effects in it (e.g., effects of hanging wall and footwall, distance of the upper part of the fault rupture to the surface and so on) are excluded. Seismic hazard assessment has been performed for a grid of points with 0.1° interval in longitude and latitude in the study area. PGAs over bedrock, for Mean Return Periods (MRPs) of 50 and 475 yr, have been estimated and seismic zoning maps of the Karaj region was determined using EZ-FRISK computer program (Fig. 3).

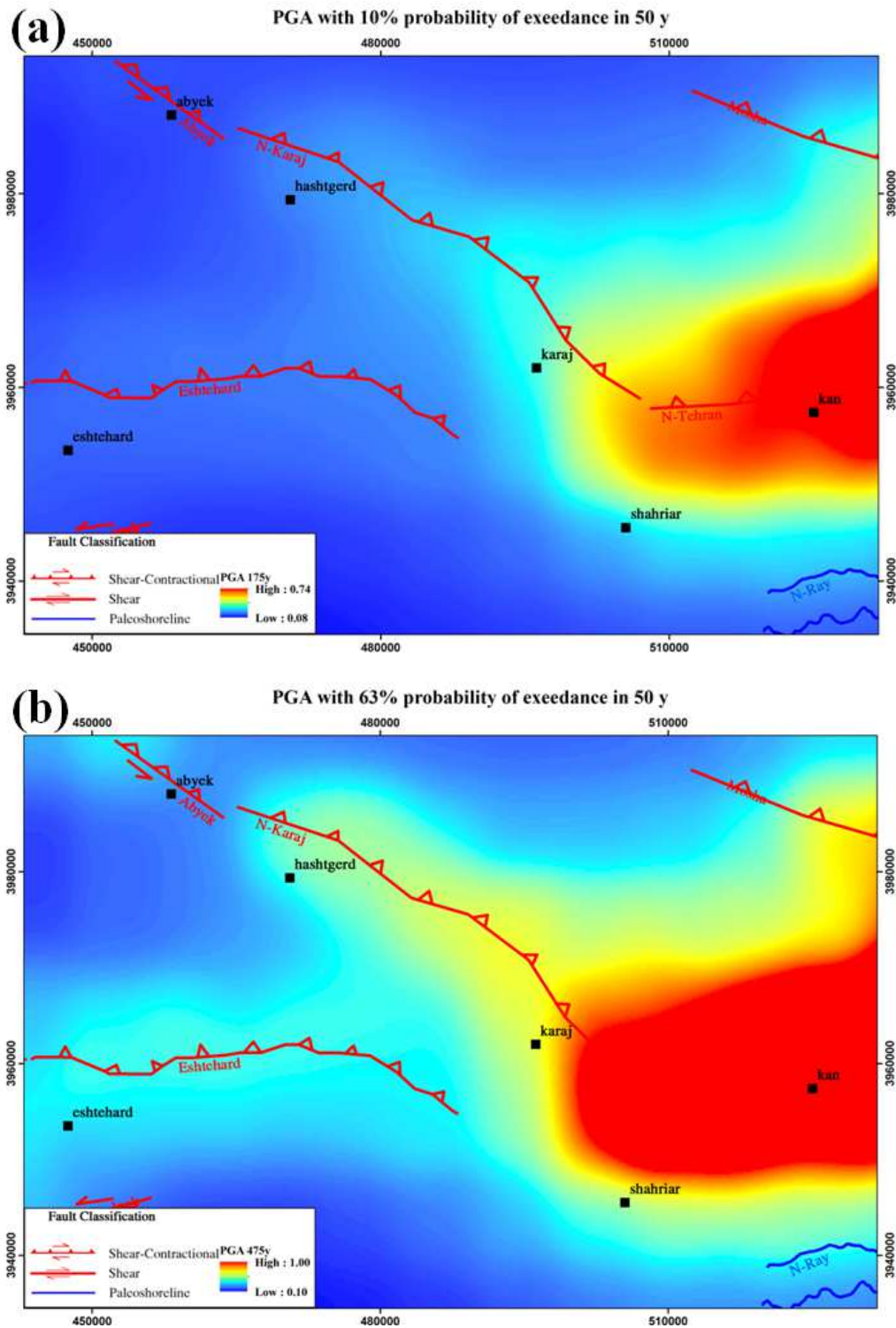


Fig. 3. Probabilistic seismic hazard map of Karaj region for peak horizontal acceleration on firm-rock site conditions for 10% (a) and 63% (b) probability of exceedance in 50 yr

The results show a good agreement with active faults and seismicity of the region. Sites with the highest level of PGA are mainly adaptable to N-Karaj, N-Tehran,

Mosha, Eshtehard and Abyek faults. The maximum PGAs at Karaj city are estimated to be 0.36 and 0.22 g for 475 and 50 yr return periods, respectively.

Seismic Hazard Deaggregation

For a specified spectral period and ground motion amplitude, the seismic hazard can be *deaggregated* to show the contribution to the annual frequency of exceedance by magnitude (M), distance (R) and the deviation parameter in the attenuation equation (ϵ). In general, deaggregating the hazard at high amplitudes indicates that large M , small R and large ϵ contribute most to hazard (these indications are reversed for low amplitudes of shaking). Low frequencies of shaking are usually associated with larger M and larger R than high frequencies. Attenuation equations that show lower dependence on M (or magnitude saturation at high amplitudes) generally show more contribution from lower magnitudes than those with high dependence on M (or no magnitude saturation). Finally, magnitude-dependent ϵ terms on attenuation equations (where ϵ decreases with increasing M) tend to shift the contribution to lower magnitude values.

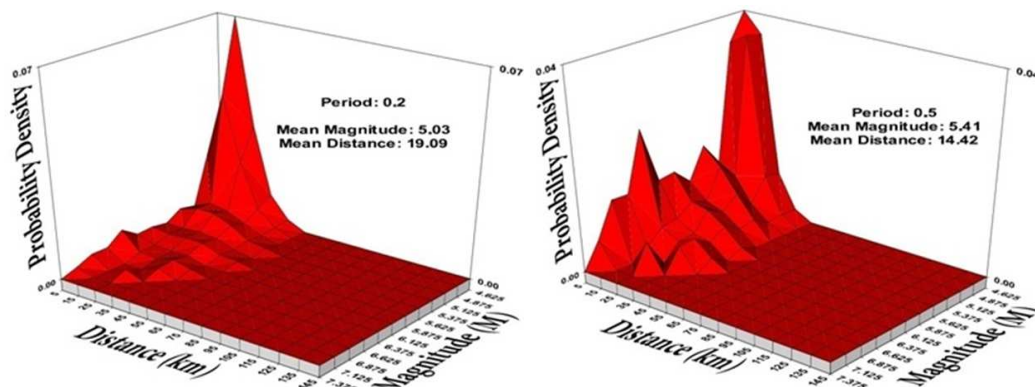
EZ-FRISK allows deaggregation by M , R and ϵ , as well as M - R , through plots and printed reports (Halchuk and Adams, 2004). EZ-FRISK code reports the deaggregation results in terms of Probability Density Function (PDF), which is obtained by dividing the Probability Mass Function (PMF) contribution of each bin by the bin's size, thus the PDF representation is independent of the bin's amplitude (Bazzurro and Cornell, 1999). The hazard can be simultaneously deaggregated in different types of bins. EZ-FRISK presents the result of seismic hazard deaggregation in terms of 1-D M , R and 2-D M - R bins. A detailed review

of different representations (PDF and PMF) and procedures (1-D, 2-D and 3-D deaggregation, geographical deaggregation in terms of latitude and longitude) can be found in Bazzurro and Cornell (1999). Usually, mean values of M and R are reported for identifying the dominant event, because each of them has its advantages and disadvantages. The mean values (M , R) are defined unambiguously and do not depend on the bin size, but they may correspond to a scenario that is not realistic, if there are two or more sources with significant contribution to the hazard.

Figure 4 and 5 (a through d) shows the M - R deaggregation plots of the 5%-damped linear elastic $S_a(T)$ values at periods of 0.2, 0.5, 2 and 4 s which correspond to MRPs of 50 and 475 yr. The results of computed controlling earthquakes have been summarized in Table 4. The 50 yr $S_a(0.2s)$ hazard for Karaj is controlled by almost nearby earthquakes of moderate magnitude. Larger and more distant events dominate the $S_a(4s)$ value for the same MRP. In particular, scenario earthquakes ranging from a magnitude $M = 5.2$ at $R = 13$ km for $S_a(0.2s)$, to a magnitude $M = 6.9$ at $R = 4$ km for $S_a(4.0s)$ has been determined to represent the relatively likely ground motion having a 63% chance of being exceeded in 50 yr. For less probable, extreme ground motions with a 10% chance of being exceeded in 50 yr, the scenario earthquakes ranging from a magnitude $M = 5.0$ at $R = 19$ km for $S_a(PGA)$, to a magnitude $M = 6.7$ at $R = 4$ km for $S_a(4.0s)$ are represented as dominant events (Fig. 4 and 5).

Table 4. M - R deaggregation results for 0.2, 0.5, 2 and 4 s spectral acceleration values corresponding to MRPs of 50 and 475 year

Period (s)	Return Periods (year)		Return Periods (year)	
	50	475	50	475
	Dis.(km)	Mag.	Dis.(km)	Mag.
0.2	19.09	5.03	13.31	5.29
0.5	14.42	5.41	9.44	5.91
2	6.3	6.54	4.94	6.73
4	4.38	6.75	4.65	6.9



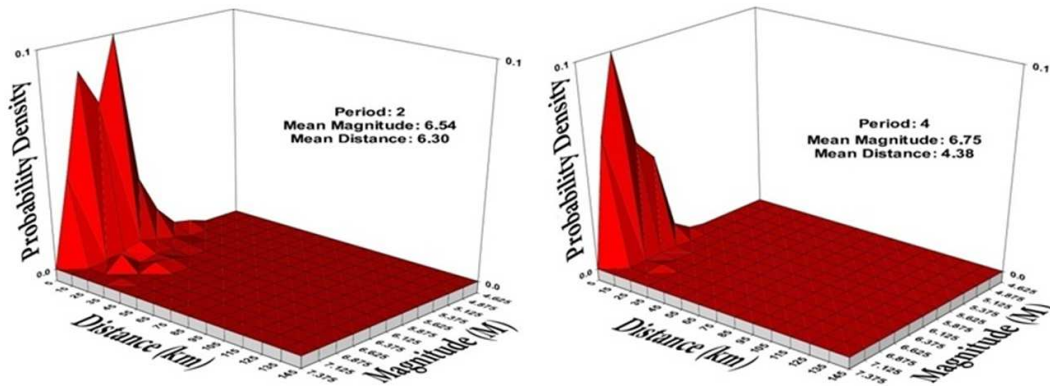


Fig. 4. Magnitude-distance deaggregation in 0.2, 0.5, 2 and 4 s, for 63% probability in 50 yr at Karaj

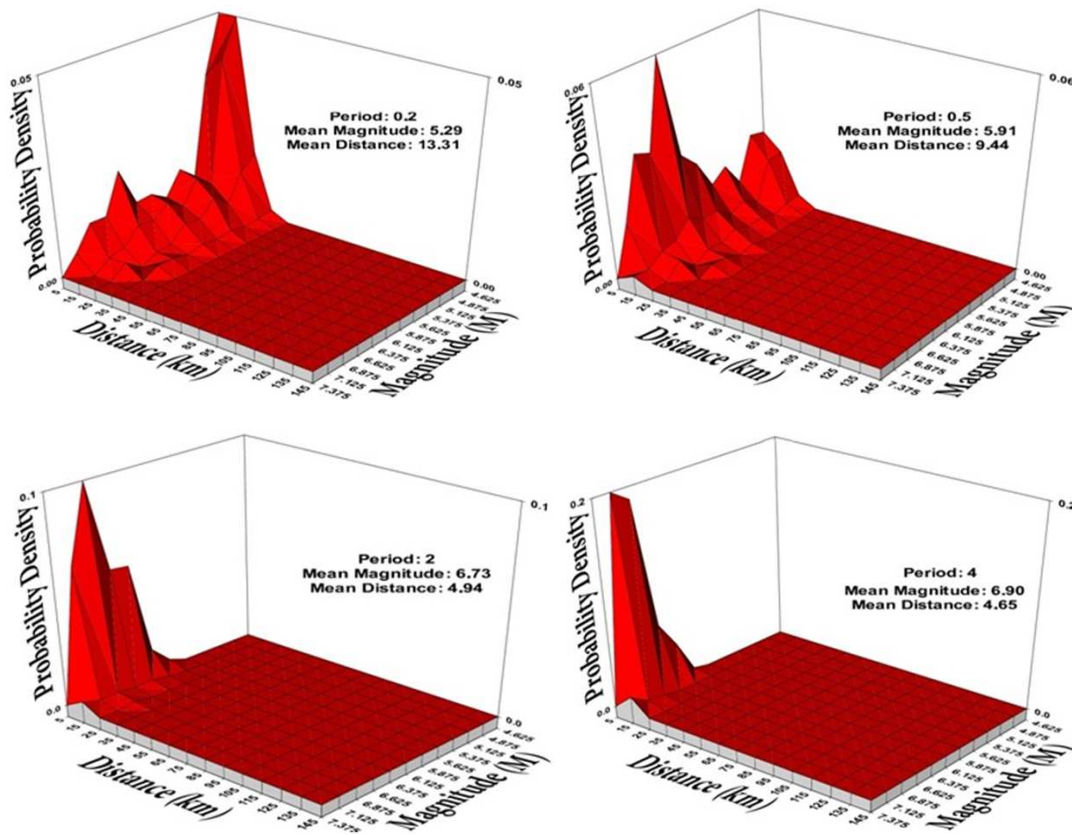


Fig. 5. Magnitude-distance deaggregation in 0.2, 0.5, 2 and 4 s, for 10% probability in 50 yr, at Karaj

It is worthwhile to mention again that a dominant event or a design earthquake is defined as a scenario which has the most contribution to the mean annual rate of exceedance of hazard from a specified level. A “dominant event” is not necessarily “the worst scenario” that can affect the site and it is obvious that because of the nature of the PSHA approach, no single event will ever be able to fully describe the seismic threat at the site. Figure 6 show the variation of mean values of M and R, with spectral periods of 0.2, 0.5, 2

and 4 s. The acceleration values deaggregated correspond to MRPs of 50 and 475 yr. For an MRP of 475 yr, mean magnitude and distance tend to increase with period. This trend was expected due to the fact that increasing of the mean magnitude and distance with increasing response period is a general behavior for uni-modal deaggregation plots (Harmsen *et al.*, 1999). An analogous behavior can be observed analyzing variation of mean magnitude and distance values for an MRP of 50 yr.

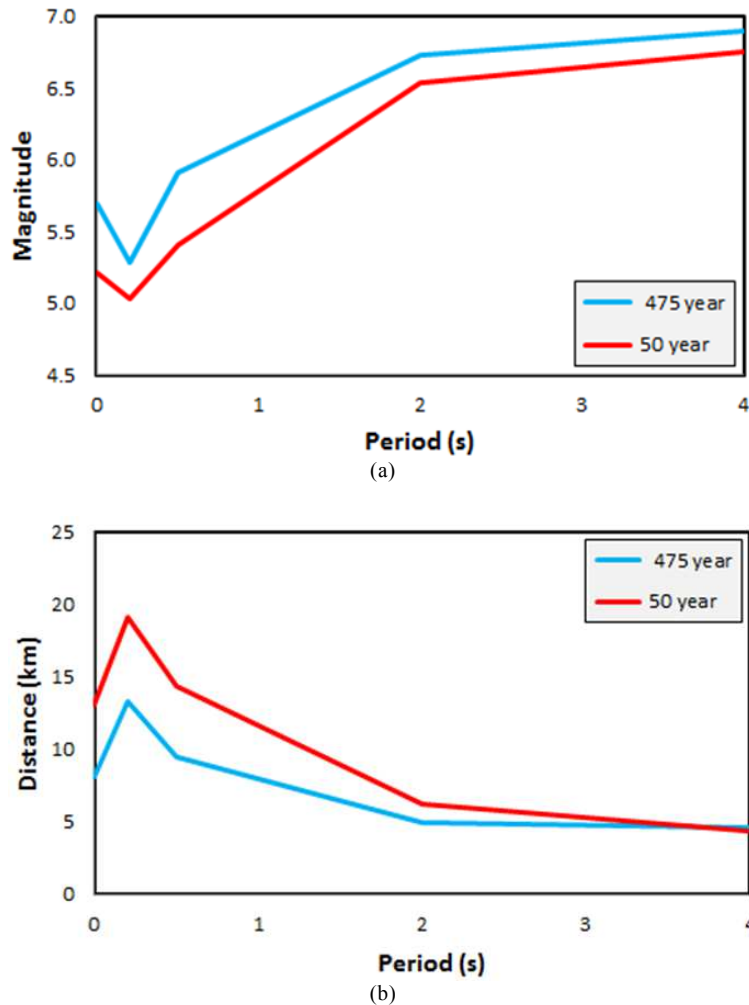


Fig. 6. Variation of mean values of M (a) and R (b) with spectral period for Karaj

For an MRP of 475 yr, variation of R is slightly with period and diagrams of mean distances seem close together. On the contrary, the existence of large difference between mean values of R for an MRP of 50 yr, especially for periods of greater than 0.5 s reveals that more than one seismic source contribute significantly to the site hazard for those spectral periods (Montilla *et al.*, 2002).

Conclusion

PSHA was evaluated in order to perform seismic hazard deaggregation for Karaj city. Generally, the trend of the deaggregation results with spectral period (T) shows that the mean rate of exceeding long-period spectral accelerations is controlled by earthquakes that are larger in size and farther from the site than those dominating the PGA and short-period spectral acceleration hazard. It was also observed that the larger the MRP, the greater the contribution from closer and higher magnitude events and, as the MRP increases, both

the mean values of “tend to increase. Particularly, since Karaj is located in a high seismicity region, nearby seismicity (5 km) has often the major contribution to the hazard. For an MRP of 50 yr, controlling earthquakes have the magnitude range between 5.0 and 6.7. Events with magnitude ranging from 5.2 to 6.9 have the most contribution to the hazard for an MRP of 475 yr and periods longer than 4 s, while the smaller magnitude ranging from 5.2 to 5.9 are dominant for shorter periods and PGA. Regarding deaggregation results at periods longer than 0.5, it could be concluded that events with most contribution to corresponding hazard levels are affected by the N-Karaj seismic source. At short periods (0.5>), N-Tehran seismic source is the most important seismic scenarios.

Data and Resources

Earthquakes catalog was searched using www.isc.com (Last accessed May 2016).

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Author's Contributions

Hadi Jarahi: Developed the conceptual idea, designed the study, collected data and made the interpretation.

Ethics

This article is original and contains unpublished materials. The corresponding author confirms that he has read and approved the manuscript and there are no ethical issues involved.

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