Journal of Geotechnical Geology

Zahedan Branch,
Islamic Azad University

Journal homepage: geotech.iauzah.ac.ir

Evaluating and Analyzing of Earthquake Risk Assessment in Esfahan Nuclear Site

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ARTICLE INFORMATION

Received 24 May 2018
Revised 11 August 2018
Accepted 14 November 2018

KEYWORDS
Esfahan Nuclear Site; Earthquake catalogue; Kijko-Sellevol method; SHA; Kuh-Ghoruneh.

ABSTRACT

Esfahan Nuclear site is located in Esfahan province, South-East of Esfahan great city. In geological point of view, the study area almost located at the boundary between Zagros and Central Iran zones. The study area, experienced a wide variety of destructive earthquakes during historical and instrumental time span. In seismicity perspective, the western part of this area, on the high Zagros Mountains is more active than others. In this study, at first step we try to create a comprehensive earthquake catalog considering the independence of events based on Poisson's distribution. Then, the seismicity parameters will be calculated using different parameters such as seismic attenuation and seismotectonic states based on Kijko-Sellevol method. Results are persisting on a few active faults, especially Kuh-Ghoruneh located in distance 12 km to site with high horizontal and vertical seismic acceleration. According to these results, we conclude that the site located in the very seismically active region, which can be affected by future earthquakes.

1. Introduction

Due to long-term convergence between Arabian and Eurasian plates, as well as oceanic activities in Alp – Himalayan orogenic belt, there have occurred many destructive earthquakes which have had a harmful effect on the social, political and economic structures of the country. This kind of seismic activities may happen in the future. Such phenomena indicate that the robust and safe design and construction against earthquake has not been yet fully incorporated into structural engineering and extending the studies in this case is inevitable. Seismic Hazard Analysis (SHA) is, in fact, an analysis on earthquakes in time and location domain (Sitharam et al., 2018). Proper knowledge of seismic properties of an active region helps us to realize the active tectonics of study area (Mulargia et al., 2017). The determination of seismic parameters in SHA studies is of particular importance. In other words, these parameters represent the seismicity condition of a zone or fault and, describing the effect of an earthquake expressing in numerical quantity. Basically, SHA in a region, involves determining the ground motion parameters, while the evaluation of uncertainty for each parameter being accessible (Atkinson et al., 2014), because it directly related to the level of safety for a site.

Esfahan Nuclear Site, is one of the most sensitive facilities in Iran, located in the South-East of Esfahan city in approximate coordinate, 51.8E 32.5N. The case study is almost located at the interface between two seismotectonic regions of Iran, Zagros and Central Iran (Azarafza et al., 2014). The main aim of this paper is to investigate the background seismicity of the region, identify the effect of known faults and their mechanism and also study the specific seismic properties and finally evaluate the level of risk due to a forthcoming earthquake in the region. Therefore, at the first step, we should investigate the history of seismic events around the site. Then, seismic parameters, the return period and the probability of earthquake occurrence calculated in term of earthquake magnitude and are attributed to faults and main seismic sources. In order to evaluate the maximum level of strong ground motion parameters which include the maximum level of horizontal and vertical acceleration, we use deterministic and probabilistic approaches (Rodriguez-Marek et al., 2014). Since in both methods, at least one appropriate attenuation relation is required, we try to find a few acceptable attenuation relations from recent studies. In probabilistic approach, using a

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probabilistic model of seismic sources and assigning seismic parameters to them and also applying appropriate attenuation equation, we can find the maximum values of Earth strong ground motion and response spectrum of site. These parameters are also related to a beneficial lifetime of the building and possibility of earthquake occurrence over the defined basis for the site (Rob and Willford, 2007). In this study, the beneficial lifetime of the site was considered for 50 years. In general, the selected sensitive site and other related equipment should be classified based on the importance of them, in order to maintain their continuous operation over their lifetime against the risk of an earthquake. Overall, the categorization can be divided into four main groups (Ellingwood and Kinali, 2009):

- *Level Zero*: without importance (No site controlling presented against earthquake),
- *Level one*: necessary (using seismic construction level DBE (design Based Earthquake) without reduction coefficient and DBL (Design Basis Level) for enhancing coefficient),
- *Level two*: So important, include severe economic damage,
- *Level three*: Critical, damage and possible break down may cause a disaster.

In this study, level one and level two have been considered for the general nuclear site designing and to control the stability for this kind of sites, respectively.

Table 1 Faults property in radius 200 km around site and also calculated horizontal and vertical acceleration in different levels

Fault Name	M_w	Surface distance $_{min}$ (km)	PGA_v (84%)	PGA_v (50%)	PGA_h (84%)	PGA_h (50%)
Ardal	7.2	119	0.04	0.02	0.05	0.03
Chadegan	7.0	67	0.07	0.04	0.09	0.05
Chah Zangool	7.0	83	0.05	0.03	0.07	0.04
Dehshir	7.0	134	0.03	0.01	0.04	0.02
Dena	7.1	105	0.05	0.03	0.06	0.03
Dopolan	6.8	123	0.03	0.02	0.04	0.02
KuhLatif	6.8	156	0.02	0.01	0.02	0.01
KuhMil	7.1	64	0.09	0.05	0.11	0.06
KuhGhorooneh	6.6	12	0.74	0.39	0.80	0.42
Latan	7.2	86	0.05	0.03	0.07	0.04
Mafaroon	7.0	178	0.02	0.01	0.02	0.01
Maranjab	6.8	183	0.01	0.01	0.02	0.01
SabzKuh	6.9	131	0.03	0.01	0.03	0.02
ShahKuh	6.6	17	0.25	0.13	0.32	0.17
ZardKuh	6.9	163	0.02	0.01	0.03	0.02
Zefreh	7.1	56	0.09	0.05	0.11	0.06

2. Studied area

Seismological studies conducted all over the world, indicate that most of the earthquakes have occurred near active zones such as orogenic belt regions. One of seismically active and young belts is Alp - Himalaya orogenic belt. Iran is located exactly in the middle of this belt and has been experienced a lot of destructive earthquakes and thousands of human losses in recent decades (Mouthereau et al., 2012).

Esfahan region is located on the border between Zagros and Central Iran, constitutes of topographic structures far from the site and flat region in the middle and these topographic structures are increasing toward Charmal-va-Bakhtiari in the West. Existence of fluctuated structure and high altitude mountains are evidences for strong Alpine orogenic activities due to seismotectonic and geodynamics in Iranian plate (Mouthereau et al., 2012). Morphologic units in Esfahan and adjacent regions indicate dynamic activity of the Zagros crush zone in the Cenozoic era (Berberian and King, 1981). The Esfahan Nuclear site is exactly located in Central Iran and near the Zagros fault and thrust belt and Sanandaj-Sirjan zone. Therefore, the tectonic processes governing the geology of the region and its tectonic development depends on the orogenic activities in Zagros and its interaction by Iranian plateau structures in the last million years (Mouthereau et al., 2012). Within the study area, Moho depth is varying between 38 up to 43 km which increases toward the NW and decreases Eastward (Afsari et al., 2011). Also, based on derived geomagnetic maps of the area, the depth of basement varied toward Central Iran (Teknik and Ghods, 2017). The oldest rock units observed in this region are Lower-Jurassic Shales and Sandstones which have been cut by Jurassic Granodiorites (Agard et al., 2011).

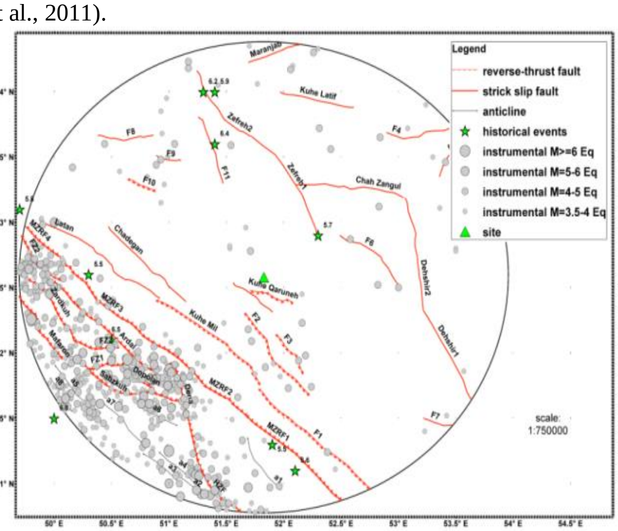

Figure 1. Distribution of historical and instrumental earthquakes in study area considering faults locations. In this paper, the region is divided into two segments, Zagros and Central Iran and all calculation conducted for both regions separately.

3. Material and Methods

3.1. Site Seismotectonic properties

According to seismogenic and seismotectonic properties, researchers have been considering seismotectonic zonation for Iranian plateau. The most famous zonation has been done by Mirzaei et al. (1998) which divided Iranian Plateau into 16 seismotectonic zones. According to this zonation, the study area located into the NW Zagros and Central Iran zones. Also, based on Tavakoli and Ghafori-Ashtiani (1999) zonation, the study area and region around (in radius 150 km), is located in zone #5 and next to the zones #3 and #4 (Tavakoli and Ghafori-Ashtiani, 1999).

A seismic source provide a crustal region, which is completely different from adjacent regions in seismicity and seismotectonically point of view due to difference in crustal movement and shortening (Mouthereau et al., 2012). These seismic sources are identified based on reflection and refraction geophysical methods in cooperation with geology and GPS data. In this way, various information such as seismotectonic data local quaternary geological history and historical-instrumental seismicity is can be used as additional constrains. Table 1 introduced the fault system around the study area (Mouthereau et al., 2012) which can be described as below:

- Basement faults with a NW-SE direction and reverse focal mechanism that can cause strong earthquakes,
- Same trend Faults parallel to Zagros which dominated with reverse mechanism and with NE fault plane direction. These kind of faults generate small to moderate magnitude earthquakes,
- The right-lateral strike-slip faults with NS direction which is formed by left-lateral rotation of the Arabian plate toward Eurasia (Jackson et al. 1995). Also a few scientists such as Walker and Jackson (2005) believed that this right-lateral rotation of faults is controlling the crustal deformations in the Zagros. Major faults like Dena fault system which involved in this group, can generate severe earthquakes (Walker and Jackson, 2004),
- Normal faults. Because the study area is located in a tectonic compressive system, the formation of a normal fault is not expected. Nevertheless, in the axis of anticlines, we can find them in small scale structures. This kind of faults has less priority in seismotectonic activities (Agard et al. 2011).

In the real Earth, the signature of fault's movement is covered or eliminated by alluvial deposits or human activities, respectively. Hence, by finding no signature of faults, we cannot conclude that no fault exists in study area. Most of the main faults in Zagros are not ruptured even after severe earthquake and this is not an evidence of inactivity of them. Detailed studies based on earthquake synthetic modeling indicate that most of the earthquakes in Zagros and adjacent region, occurred in Mb> 5.0, in the depth range of 10 to 20 km (Jackson and McKenzie, 1984). Also, the investigation of several earthquakes during a period from 1963 to 1983 indicate the occurrence of earthquakes at a depth of 6 to 13 km, which can be regarded as a sign of earthquake occurrence in Zagros sedimentary crust (Ni and Barazangi, 1986). The uncertainty in depth determination of an event, in particular for the earthquakes prior 1963 is relatively high, and in many cases was due to the lack of information or the impossibility of calculation. Therefore, in most cases the 33 km was considered as the depth of earthquakes. Therefore, the statistical analysis on the basis of such information cannot draw a correct image of earthquakes depth range for the study area. In order to find the most appropriate focal depths of earthquake, we used the results of earthquake relocation and parameters correction did by Maggie et al. (2002) and Engdahl et al. (2006). Based on these calculations, the focal depth of most earthquakes in the Zagros is lies at the depth of 10 to 15 km (Table 2). According to these results for the seismicity in Zagros and central Iran, a seism genic layer within 6 to 8 km thickness as an upper transition layer and 12 to 15 km as lower transition layer have been described (Maggie et al., 2002). Therefore, in order to improve our results, we consider 10 km as reference depth for seismic events in the study area. In Seismology, a variety of methods with different accuracy presented to determine the earthquake magnitude. The statistical studies carries out in the study area indicates that most of seismic events were recorded in the magnitude range of 3 to 4 and we have just a few earthquakes with magnitude larger than 5 (Fig. 1).

3.2. Seismicity and related parameters determination

Seismicity determination and seismic parameters calculation are just possible based on providing a reliable catalogue of occurred earthquakes. Therefore, based on the obtained information from earthquakes, the statistical properties of seismicity and related parameters are determined. For this purpose, at first step, it is necessary to collect all required information, and then process them. Most of the seismic parameter analysis is based on Poisson relation which is the most acceptable hypothesis in analytical seismology (Bommer et al., 2015). Magnitude-abundance relation for earthquake distribution is obtained by different methods such as Gutenberg – Richter relation (Reiter, 1991). In this equation, α and β are the constant coefficients, M_{max} is the maximum possible magnitude of an earthquake, and also return period of a new event has been considered (Gutenberg and Richter, 1944). The data used in this study has been extracted from the ISC database in a radius of 200 km around the site. In most studies, the earthquake magnitude threshold is considered as 4.0. But in this study, due to relatively low seismicity than the West and North part of the Zagros, the 3.5 is considered as the magnitude threshold in order to increase the number of earthquake and improve the stability of results.

Iranian plateau earthquakes can be divided into four groups:

- Historical earthquakes,
- Before 1964 (founding the WWSSN),
- From 1964 up to 1995 (expanding seismic networks in Iran),
- From 1995 up to now (Engdahl et al., 2006).

One of the main problems in catalogue creating is the historical earthquakes parameterization due to including a wide range of uncertainty. The earthquakes parameter determination since 20th century has become more precise, more complete and their uncertainties are better known after improving the seismic networks in the world and later in Iran. The approximate location of historical earthquakes considering the location uncertainty is depicted in Fig. 1. In SHA studies, the catalogue should be prepared based on one type magnitude scale (Reiter, 1991). The common magnitude scales are M_s (surface wave magnitude), m_b (body wave magnitude) and M_w (moment magnitude). M_w has been used more frequently than the other scales in seismological studies and also recent attenuation parameters are based on this magnitude. A comparison between Mw and the other type of magnitudes indicates their less sensitivity in severe earthquakes and become saturated during strong events (Scordilis, 2006). The major problem in preparing a catalogue for earthquakes in Iran is lack of seismic data based on Mw. Therefore, before processing the seismic parameters, it is necessary to convert all other scales into Mw. Recently, a few comprehensive conversion relations presented for different geological structures in Iran (Shahvar et al., 2013) and we use them in this paper.

The main assumption in earthquake catalogue preparation based on the Gutenberg-Richter is the consistency of seismic events distribution with the Poisson relation in statistical point of view. The basis of Poisson relation is the independence of earthquake in time and location domain for a specific region. Therefore, prior to start processing, it is necessary to examine the list of events based on this distribution model. In this way, for example, it is necessary to check the possibility of pre-shocks and aftershocks. Because most of the time, pre-shock and aftershock have been related to the main event and also to each other, consequently should be removed (Shahvar et al., 2013). One of the most suitable methods for the removal of the pre-shocks and aftershocks is moving time-location window procedure (Gardner and Knopoff, 1974). Another common method which has been used to control the dependence of events is Rosenberg connected window which was founded based on probabilistic rules (such as Omori law). Obviously, after implementing the mentioned methods on initial database, it will differ in term of the number of remaining events and we can consider this difference as uncertainty of study. In this study, both methods are used in our database development to create a comprehensive catalogue for the study area (Ansari et al., 2015).

4. Results and discussions

4.1. Evaluation of strong ground motion parameter

In the last section, a general image of the seismicity and seismotectonic of the study region was obtained. In this section, by analyzing risk assessment, the maximum ground acceleration in selected site will be determined based on calculated seismic parameters. Seismic risk assessment can be defined as the quantitative definition of ground motion in a specific region. In other words, in seismic risk assessment, we combine all available data such as distance, magnitude, focal mechanism, seismic wave speed and soil properties to predict a certain parameter of ground motion (e.g. acceleration). If there is a specific scenario for all the above mentioned factors, the SHA can be done in deterministic manner. In deterministic method, all the necessary parameters such as magnitude and rupture length are definitely selected (Zare et al., 2014). In this approach, the maximum believable magnitude of an earthquake is determined independent of specific time period based on maximum acceleration of seismic ground motion for the target zone. Mostly, this approach is considered in specific installation such as power plants and dams. In other hand, if we are interested to consider the uncertainties in above parameters, it is better to use the probabilistic approach. Over the past 20 years, the use of probabilistic theory in earthquake risk analysis has made it possible to incorporate existing uncertainties into the calculation. The uncertainties in this approach can be related to magnitude, location and earthquake occurrence rate. Probabilistic Seismic Hazard Analysis (PHSA) provides a framework to determine the uncertainties quantitatively and consider their effects in the calculation of risk assessment (Zare et al., 2014). This method can be described in four main steps. The first step is to identify the seismic source and it’s characteristic. In the second step, the seismicity or time distribution of the return of the earthquakes is determined. In this study, using the Kijko-Sellevoll method, seismicity parameters will be obtained and then based on seismic source length, the parameters related to each source will be determined (Kijko and Sellevoll, 1989). Also, it should be mentioned that all seismic sources are considered linearly. In the third step, the acceleration generated by the earthquake occurrence in each site is determined by means of attenuation relations and using any possible earthquake at any possible distance for each seismic source. Finally in the fourth step, the uncertainties in magnitude, distance, ground motion parameters are combined together to obtain the probability that it will exceed of a certain threshold (Kijko and Sellevol, 1992) (Fig. 2).

4.2. Evaluation of ground motion response spectrum

According to previous descriptions, finding the spectrum of site and accelerograms is the last step in our study (Fig. 3). In this regard, due to the importance of the intended structure, we use the probabilistic approach. Also, to select the accelerograms, four properties have been considered more precisely, including the target magnitude, distance between source and seismic station, earthquake focal mechanism and geological setting of the case study (Zare et al., 2014). The target magnitude is the mean value in a magnitudes interval which has more possibility for earthquake occurrence. The selected accelerograms should be within the target magnitude interval as much as possible. Choosing the magnitude interval is inevitable, because of the uncertainties in the target magnitude determination (Campbell 1986). In Figure 4, the results from separation analysis based on attenuation equation presented for 475 years return period and PGA parameter is illustrated. Separation analysis is providing a scenario in term of distance and magnitude of earthquake in seismic risk assessment. Generally, based on the presented results, the target magnitude is determined as 6.5 and we consider earthquakes with smaller magnitude.

The proximity to seismic source and near field effect are one of the interesting subjects that studying on it has been in progress yet. Usually at near distances from seismic source, seismic records have high energy pulses in medium to large periods where these pulses are dominant in waveform propagation direction perpendicular to slip and fault plane movement (Campbell, 1986). Based on Campell (1986) studies and US Nuclear Regulatory Commission (NRC) laws, in the absence of a real seismic source, the distance between accelogram and earthquake centroid which causes a rupture is considered about 30 km. Also, by increasing the distance, the effect of non-elastic attenuation will be increased and the probability of passing seismic waves through the rock units with different characteristic will be higher. For the study site, there are a few faults in near field structure. Based on separation analysis, the target distance for this study is less than 25 km (Fig. 4). Regarding the earthquake focal mechanism, it should be mentioned that characteristic of seismic waves in time and frequency domain is a function of radiation pattern, seismic moment and source mechanism, and the type of rupture in influenced by seismic wave frequency content. Therefore, the focal mechanism of the earthquakes which will be used asaccelerogram should be consistent with earthquakes occurred near the site. In this way, the dominant focal mechanism of an earthquake in the study area is reverse and strike-slip.

Based on site properties, ground parameters and their dynamic abilities, the waves can be attenuated or amplified while propagating through the structure beneath the station (Bommer et al., 2015). The most important effective feature is the shear wave velocity and also the vibrating periodicity of the Earth, which amplifies the amplitude of the vibrations of the waves adjacent to the natural vibrating period of the environment and weakens in the outside of it. To consider this case in seismogram selection, the shear wave velocity for the top 30 meter layer of the ground is considered 450 m/s.

In probabilistic approach, the spectral acceleration values obtained at design levels are used to estimate the response spectrum. Hence, at first, the maximum acceleration of strong ground motion in specific return period has been obtained. In Figure 5, the horizontal component of accelerogram for different return period to assess the seismic risk is illustrated. Based on building construction regulation against earthquake (standard 2800 regulation), the site spectrum should not be less than 80% of the standard thresholds (Fig. 6). The calculated values are based on the relation between acceleration spectrum and movements presented in EURO-CODE #8 (Iervolino et al., 2008).

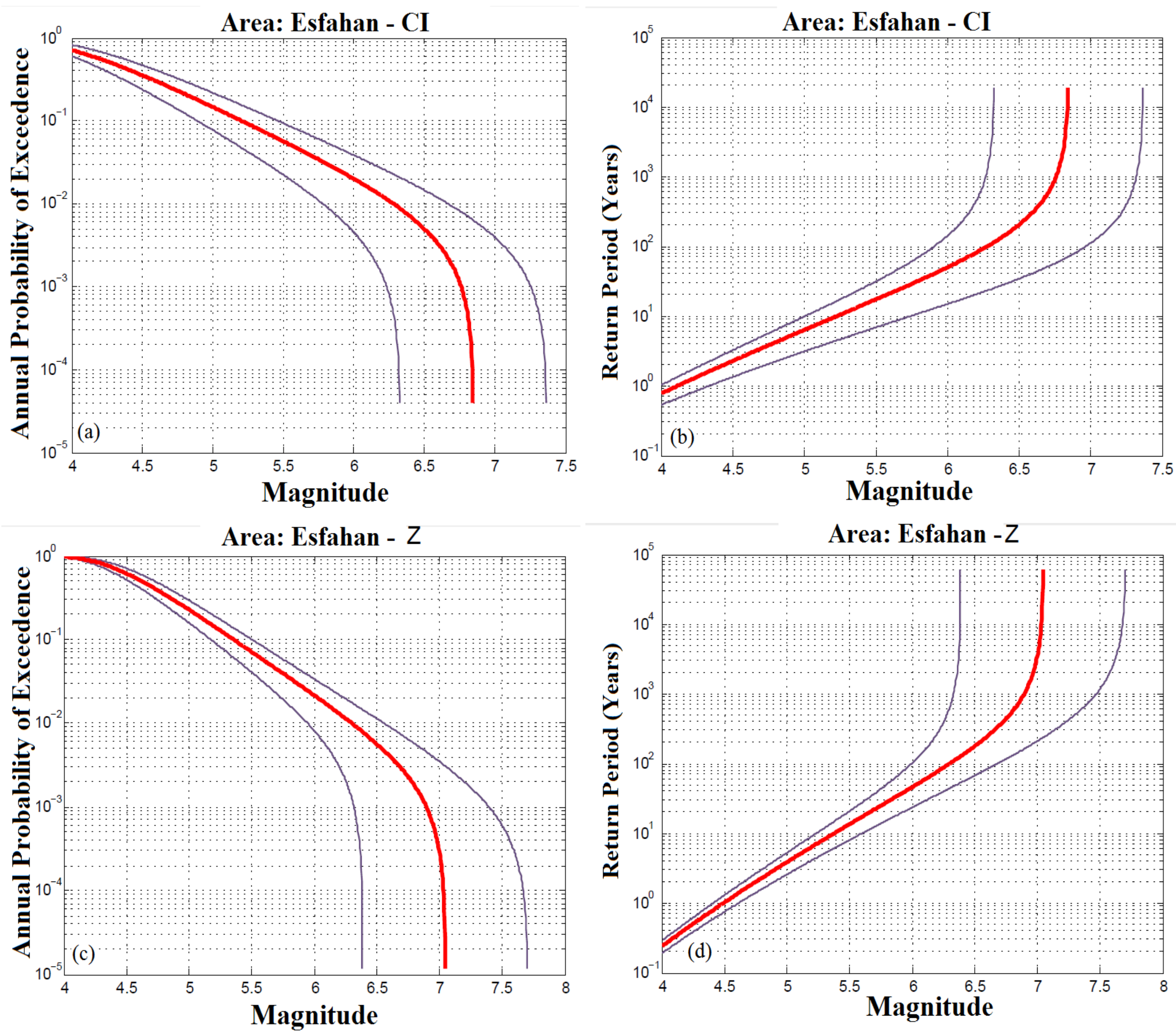

Figure 2. Possibility for the occurrence of an earthquake with different magnitude using Gardner Knopoff (1974) method (for CI and Zagros in Panel 1 and 3, respectively), The average annual return period for earthquake in different magnitude using Kijko-Sellevoll method (for CI and Zagros in Panel 2 and 4, respectively).

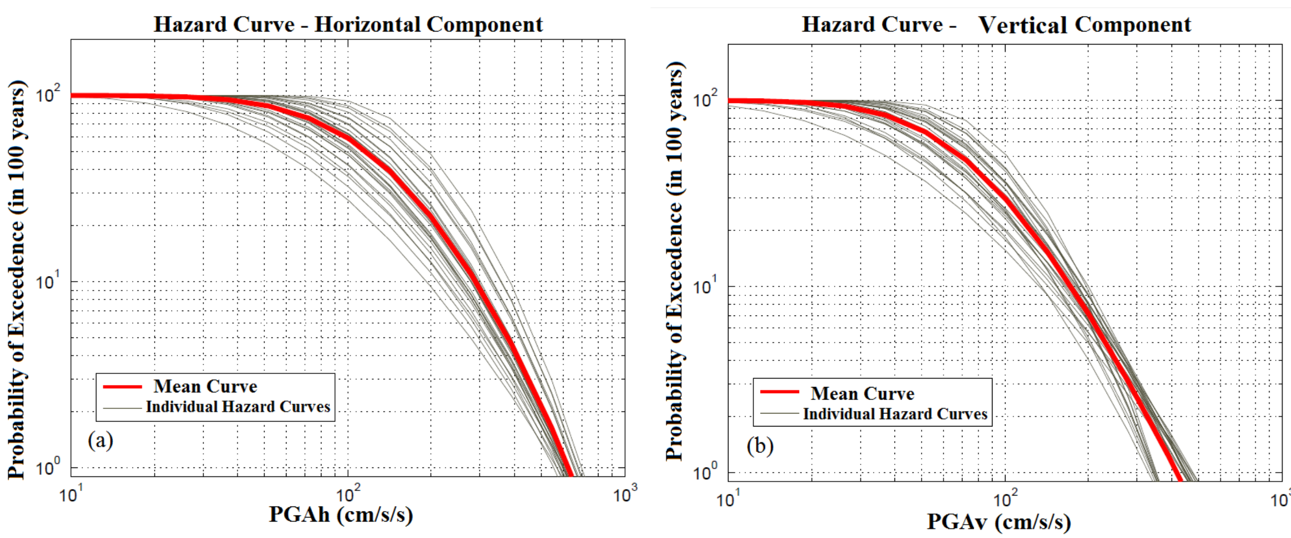

Figure 3. Possibility of experiencing maximum horizontal acceleration (first panel) and vertical acceleration (second panel) in study region

Table 2 Seismic parameters of historical earthquakes around site

Distance from site (km)	location	Depth (km)	Mag	Lat	Long	Year
177	Golpayegan	5	6.2	49.4	33.5	1316
195	Zagros	9	6.5	50.5	32.1	1666
190	Kashan	7	5.9	51.4	34.0	1755
188	Kashan	15	6.2	51.3	34.0	1778
170	Kashan	11	6.4	51.4	33.6	1844
136	Farsan	11	5.5	50.2	32.5	1853
119	Choghakhor	15	5.3	50.8	31.9	1874

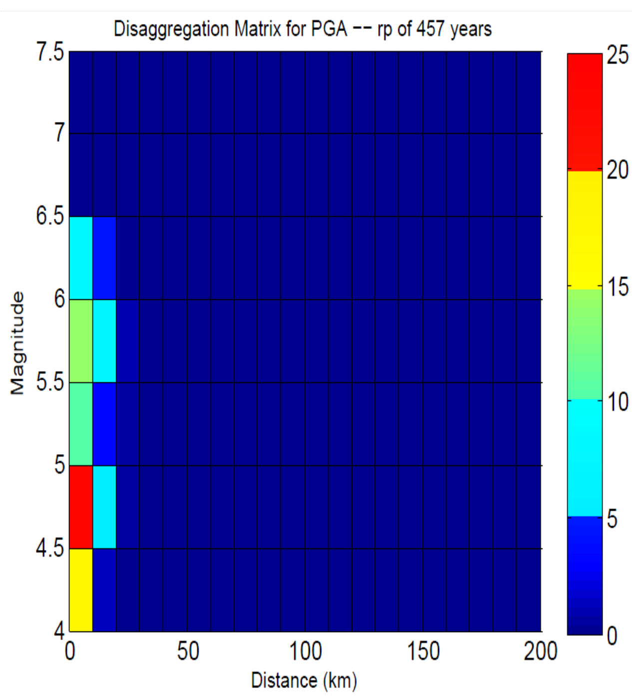

Figure 4. Analytical separation for 475 as return period (in maximum acceleration). The dominant scenario in distance and magnitude point of view is indicating by colorful cells

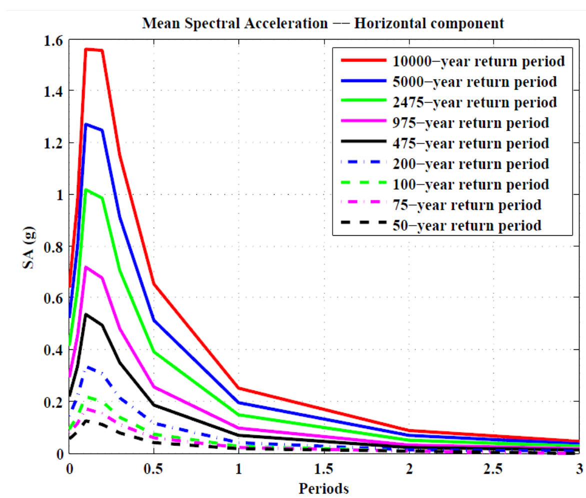

Figure 5. The average horizontal acceleration spectrum in different periods and five return periods

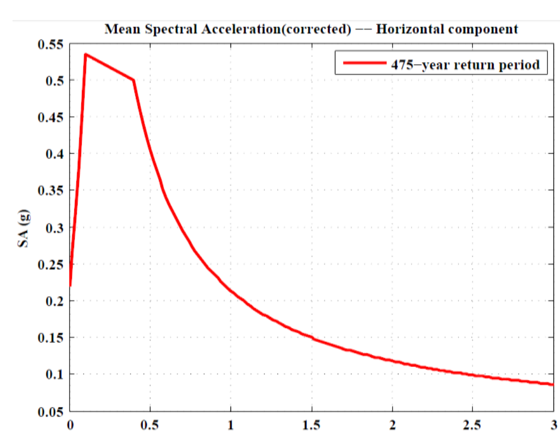

Figure 6. The corrected horizontal acceleration spectrum in different periods for 475 returns period

5. Conclusion

In this research, the Esfahan Nuclear Site which is located in the South of Esfahan city was investigated based on seismic risk assessment. The structure of the study area can be divided into two main geological blocks, Zagros and Central Iran. Hence, by dividing the region into two distinct boundaries, calculation was made for each region separately. For this purpose, by investigating the faults distribution in the region and evaluating the seismic events including historical and instrumental records over the time, at the first step, we tried to find the seismicity pattern considering the Poisson relation to prepare a comprehensive earthquake catalogue and then the related parameters have been obtained. In the next step, using the finalized results, the strong ground motion parameters are defined considering the site effects and seismicity background with probabilistic approach.

The presented results indicate that the closest fault to the site is KuhGhoruneh fault, located about 12 km from the site. This fault experienced a severe 6.6 magnitude earthquake in the past. Based on the calculated parameters, all values for horizontal and vertical component of acceleration in 50% and 84% seismic levels are related to this fault, which expresses the high seismicity and possibility of occurrence of destructive earthquakes in the future. Also, the results of analytical separation indicate the probability of a seismic event with a maximum magnitude of 6.5 in a distance of about 25 km from the site. In the following, the results indicate the maximum horizontal acceleration of 0.53g for 475 return periods in the site location which is significant compared with the other regions in the Iranian plateau. This value is decreasing for the shorter return period. For instance, for the earthquakes with 200 year return period, this value reaches to 0.35g.

Generally, based on the presented results, the Esfahan Nuclear Site can be evaluated in term of the risk level of future earthquakes at a high level. Therefore, it is recommended to consider and involve the level of risk in repairing, reconstructing and aging management of this susceptible nuclear site.

Acknowledgements

The authors wish to thank the Atomic Energy Organization of Iran and International Institute of Earthquake Engineering and Seismology for preparing requirement of studies.

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