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# Probabilistic analysis of seismic hazard in Ardabil Province with R-CRISIS

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**Abstract**

In this article, the methods and software used for seismic hazard analysis are presented. Ardabil province is part of the Western Alborz tectonic unit-Azerbaijan. Azerbaijan region is considered one of the tectonically active regions. The main activity of this region is the result of the movement of the Arabian block, which affects the north-western corner of Iran, the Caucasus Mountains and eastern Turkey by 3 cm per year. This research was conducted to determine the seismic hazard of Ardabil province using a probabilistic method. After determining the characteristics of seismic sources, the seismicity or time distribution of the earthquake event was investigated and a regression relationship was used to determine the seismicity of each seismic zone. Determining the ground motion resulting from an earthquake event of any possible magnitude in the site, which may occur at any possible point of each source area, was done using attenuation relationships. Finally, the uncertainty in the location of the earthquake and its magnitude were combined in determining the ground motion parameters to determine the probability in which the ground motion parameter occurs in a certain period. The calculations were performed using the R-CRISIS software utilizing the Gutenberg-Richter seismicity model. This study revealed that the north and southwest faults of Ardabil province are the most active source in terms of seismic hazard. The maximum value of the magnitude of the earthquake for Ardabil province for the return period of 475 years was obtained at 8.2-8.8.

Keywords: earthquake hazard, probabilistic forecasting, earthquake catalog, seismic attenuation
2020 MSC: 65C20, 86A15

## 1 Introduction

Earthquakes are natural hazards with a random nature that can cause damage to all kinds of structures and lifelines. Therefore, the effects of future earthquakes cannot be determined exactly, and these effects can only be partially predicted with probabilistic methods. Earthquake hazard analysis includes research and methods by which the effects of future earthquakes can be estimated on the site. These effects mainly include ground motion parameters. Earthquake hazard analysis is an essential and integral part of the seismic design of structures, earthquake risk analysis, loss and damage estimation and related insurance calculations. Earthquake hazard analysis is necessary to prepare seismic maps that provide important information for the design of structures. In fact, earthquake hazard analysis is

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a quantitative estimate of the hazards of ground motion in a particular location. In the hazard analysis, parameters such as distance, magnitude, attenuation relationships, local soil conditions, etc. are used and a certain parameter of ground motion is predicted at the site. There are two deterministic and probabilistic methods for seismic hazard analysis [20].

Ardabil province is located in a cold region and in the northwest of the Iranian plateau, with an area of 17800 square kilometres, 1% of the total area of Iran. This province is a part of the triangular plateau of Iran located in the east of the Azerbaijan plateau, about two-thirds of which has a mountainous texture with a large height difference, and the rest is made up of plain and lowlands [14, 4]. In the study area (cities of Ardabil province), the existence of geological formations with heterogeneous resistance, the location of the city on an alluvial plain with less resistance than the thick bedrock, being surrounded by numerous faults and the occurrence of many destructive historical and ancient earthquakes, create damaging conditions against the vibrational forces resulting from the earthquake [10]. Therefore, it seems necessary to perform an earthquake hazard analysis for this province. Some of the studies available in the literature on this topic are summarized below.

Karimi and Reiazi Rad estimated the seismic hazard of the Ardabil city in a deterministic approach. Considering the faults and empirical relationships, they obtained the parameters of the strong ground motion in the considered site. The region considered in this study, Ardabil City is a part of the tectonic unit of Western Alborz - Azerbaijan. According to the results of this study, the largest seismic source around Ardabil is the Yamchi fault with a length of 21 km and the smallest one is the Chokhoryurd fault with a length of 3 km; The longest distance from the fault to the site is the East Ardabil fault and the shortest distance is the Janaqord fault. Also, the maximum potential is related to the Sarein fault at a distance of 21 km from the site, which causes a 0.2g ground motion in the considered site [13].

Other studies have been done to estimate the hazard of earthquakes in Iran, among them, we can mention the research of Tavakoli and Ghafory-Ashtiany in 1999, which used the method of probabilistic risk analysis for the area of Iran, the maximum acceleration of the earth for the return period of 75 and 475 years old, and since they have prepared an earthquake hazard zoning map for the whole of Iran, then based on that data, Ardabil city is located in a high hazard area [22]. The earthquake (standard 2800) has also placed Ardabil city in the region with high relative hazard [6]. Bafroi et al. in 2014 in order to evaluated the levels of strong motion on the bedrock for the maximum acceleration and spectral values in the area of Iran. Earthquake hazard estimation has been done by the modified probabilistic method, based on the results of their study for the return period of 475 years in bedrock, the maximum acceleration value in Ardabil city is estimated between 0.25-0.15 and 0.25-0.35 in terms of g [17].

Khodavardi and Porzeinali investigated the zoning and deterministic estimation of the hazard of earthquakes in Ardabil City using attenuation relations and fuzzy logic. For this purpose, the number of 20 potential earthquake sources of the surface type within a radius of 150 km from the city has been determined and the values of horizontal peak ground acceleration on the surface of the seismic bedrock for the centre of networks with dimensions of $1000 \times 1000$ meters on the surface of Ardabil city using the conventional deterministic method and fuzzy inference system was obtained. According to the results obtained from both methods, source No. 7 can be considered the main factor in causing devastating earthquakes in the future compared to other sources, whose main fault is the Bezgosh fault and is located very close to Ardabil city. The changes in the horizontal peak ground acceleration at the surface of the bedrock have been obtained using the attenuation relations is 0.24g to 0.43g. The changes of the horizontal peak ground acceleration at the surface of the bedrock using fuzzy logic are also 0.25g to 0.43g. As a result, it can be said that the horizontal peak ground acceleration in this region is 0.43g [16].

Esfandyari et al. assessed the vulnerability of cities from surrounding faults using the TOPSIS method in a GIS environment. In this research, the vulnerability of Ardabil city to the hazard of earthquakes, from five important faults around the city, has been studied. Based on the results obtained, on average, 0.69 Square Kilometers of the city's area due to the earthquake caused by the investigated faults have a very high vulnerability rating, and 4.08 Square Kilometers of the city's area is in the area of high vulnerability. In general, based on the studies, the Doyle (Talash west slope) fault scenario causes the most damage to the region, and the Sareyn fault scenario causes the least amount of damage [10].

Alizadeh et al. analyzed the probabilistic seismic hazard of Ardabil City using geological maps based on the existing faults. Also, they used earthquake data recorded by the instruments and Matlab, Zmap, Kijko and Ez-frisk software. The seismic hazard map for PGA (Peak Ground Acceleration) was prepared on bedrock with 1% damping for a return period of 50 and 475 years in gridded points at $0.1^\circ \times 0.1^\circ$ and $0.05^\circ \times 0.05^\circ$ intervals. According to the acceleration rate for the city of Ardabil, this area is divided into 4 micro-zones. The results show that the acceleration values in this range for PGA vary from 0.19 in the north to 0.21 in the southwest and the city of Ardabil can be introduced as one of the cities with moderate hazard in seismicity analysis [2].

Nouri et al. developed site-specific design spectra for the central parts of Ardabil city. Preparation of site-specific spectra for alluvium and design of tall and special structures are needed. Due to the placement of the city of Ardabil on the alluvium and the development of construction in the central part of the city, preparing site-specific design spectra is inevitable and worthwhile. In this paper, according to the geotechnical boreholes and tests to a depth of 40 meters in different parts of the city, besides probabilistic hazard analysis, site-specific spectra for central part of the city are developed Through the probabilistic hazard analysis, design acceleration of 0.32g is obtained for earthquakes with a return period of 475 years, which is 6% higher than that proposed by Building Design Codes for Earthquakes-Standard 2800. Design spectra are obtained using three methods of ground response analysis, statistical analysis of different earthquakes and uniform hazard spectra. The soil types in most parts of the studied area are classified as type III of the standard 2800 classification. Comparison of the obtained spectrum with the proposed spectrum of standard 2800, showed that in the range of constant acceleration, the values of site-specific design spectra are 25% higher than those proposed by the standard 2800 [18].

It seems that to consider the combined effect of multiple seismic sources in the site and the uncertainties in various parameters, it is necessary to perform a hazard analysis using a probabilistic approach in Ardabil city. Also, it is necessary to consider a wider area such as Ardabil province and parts of the surrounding provinces due to the existence of seismic sources affecting the region. In order to perform deterministic and probabilistic seismic hazard analysis, and facilitate and minimize errors, specialized and new software must be used.

### 1.1 Probabilistic seismic hazard

Concepts of probabilities have been used to consider the uncertainty in the magnitude, location and rate of earthquake events and changes in the characteristics of the ground motion in earthquake hazard analysis [9]. The purpose of the probabilistic earthquake hazard analysis method is to investigate and consider these uncertainties. In order to assess the vulnerability of a structure against an earthquake, the probability or the rate of an earthquake exceeding the target acceleration range must be obtained. This analysis finally leads to the earthquake hazard curve at the site, which can be used to obtain the design spectrum of the site, which is the basis for the seismic design of special structures against earthquakes [20].

The probabilistic earthquake hazard analysis consists of four steps: Seismic source zoning, Selection of recurrence relationships, determining attenuation relationships and obtaining the exceedance probability of the ground motion parameter in a certain period [15].

### 1.2 Hazard computation algorithm

To compute seismic hazard, the territory under study is first divided into seismic sources according to geotectonic considerations [9, 11]. In most cases, it is assumed that, within a seismic source, an independent earthquake-occurrence process is taking place. For each seismic source, earthquake occurrence probabilities are estimated by means of statistical analysis of earthquake catalogues.

In the more general case, earthquake occurrence probabilities must stipulate the probability of having $s$ events $(s = 0, 1, \ldots, N_s)$ of magnitude $M_i$ in the following $T_j$ years at a given source $k$. We will denote these probabilities as $P_k\left(s, M_i, T_j\right)$ and they completely characterize the seismicity of source $k$.

Seismic hazard produced by an earthquake of magnitude $M_i$ at a single point source, say the $k$th source and for the next $T_j$ years, can be computed as:

$$P_r\left(A \geq a \middle| M_i, T_j, k\right) = 1 - \sum_{s=0}^{N_s} P_k\left(s, M_i, T_j\right)\left[1 - P_r\left(A \geq a \middle| M_i, R_k\right)\right]^s \tag{1.1}$$

Where $P_r\left(A \geq a \middle| M_i, R_k\right)$ is the probability that intensity $a$ is exceeded given that an earthquake of magnitude $M_i$ occurred at source $k$, that is separated from the site of interest by a distance $R_k$.

Seismic hazard, contained in the above equation, is more easily expressed in terms of non exceedance probabilities in the following manner:

$$P_r\left(A \leq a \middle| M_i, T_j, k\right) = \sum_{s=0}^{N_s} P_k\left(s, M_i, T_j\right)\left[P_r\left(A \leq a \middle| M_i, R_k\right)\right]^s \tag{1.2}$$

But seismic sources are usually points, lines, areas or volumes, so a spatial integration process must be carried out to account for all possible focal locations. We will assume that the spatial integration process leads to N sources. So finally, if earthquake occurrences at different sources are independent from each other, we obtain that the non-exceedance probability of intensity a in the next $T_j$ years due to earthquakes of all magnitudes located at all sources, can be computed with [19]:

$$P_r\left(A \leq a|T_j\right) = \prod_{k=1}^{N} P_r\left(A \leq a|T_j, k\right) \tag{1.3}$$

$$P_r\left(A \leq a|T_j\right) = \prod_{k=1}^{N} \prod_{i=1}^{N_m} P_r\left(A \leq a|M_i, T_j, k\right) \tag{1.4}$$

$$P_r\left(A \leq a|T_j\right) = \prod_{k=1}^{N} \prod_{i=1}^{N_m} \sum_{s=0}^{N_s} P_k\left(s, M_i, T_j\right) \left[P_r\left(A \leq a|M_i, R_k\right)\right]^s \tag{1.5}$$

Finally,

$$P_r\left(A > a|\, T_j\right) = 1 - \prod_{k=1}^{N} \prod_{i=1}^{N_m} \sum_{s=0}^{N_s} P_k\left(s, M_i, T_j\right) [P_r\left(A \leq a|\, M_i, R_k\right)]^s \tag{1.6}$$

## 2 Description of the study area

Ardabil province is located in a cold region and in the northwest of the Iranian plateau, with an area of 17800 square kilometers, 1% of the total area of Iran. This province is a part of the triangular plateau of Iran located in the east of the Azerbaijan plateau, about two-thirds of which has a mountainous texture with a large height difference, and the rest is made up of plain and lowlands. The highest point of the province is Sablan peak with an approximate height of 4811 meters. This province is located in the geographical coordinates of 47 degrees 30 minutes to 48 degrees 55 minutes east longitude and 37 degrees 45 minutes to 39 degrees 42 minutes north latitude. This province is bordered by the Republic of Azerbaijan from the north and northeast, Zanjan province from the south, and Gilan province from the east and southeast. This province, with its elongated shape in the north-south direction and due to special geographical conditions, has a lot of environmental diversity. This expansion in the latitude axis along with its plains and mountains in a harmonious combination with the Caspian Sea has given the province a special position. Almost all of this province, with the exception of a small part of it, is located in the watershed of the Caspian Sea (Fig. 1). The high mountains of Sablan and Bezgosh and the western slopes of Talash mountains are considered high areas of the province [14, 4]. It seems necessary to estimate the hazard of earthquake and its impacts on this province.

### 2.1 Geological features of the region

The region can be divided into three areas based on engineering geology:

The first area: The materials that make up this area are very diverse and include all kinds of small silty grains to all kinds of coarse grains and young stone layers such as marls and stone clays with gypsum veins. The fine grains in this area are mostly sand type with high density. Due to the presence of gypsum veins in this area, the amount of sulfate in the soil exceeds the permissible limit. In different parts of this area, stone outcrops can be observed.

The second area: The materials that make up this area are coarse sand grains. The layers of this area have medium to high density and in some specific areas, it is very difficult to perform drilling due to contact with stone layers.

The third area: This area, like the first area, has a lot of diversity according to the type of sediments so in this area, all kinds of silty and sandy compositions can be observed. This variety shows different sedimentation activities in this area.

Also, the sediments of the region can be studied in three general sections:

A) Sablan pyroclastic sediments: In the west and southwest of Ardabil, the former Quaternary sediments are covered by clastic sediments of Sablan volcanic origin. These sediments can be seen as mudflows with large and abundant debris of Sablan lava in an argillaceous field alternating with layers of ash. These sediments were probably formed simultaneously with the explosive activity of Sablan during a post-glacial period with heavy seasonal rains (Fig. 2).


Figure 1: The map of Ardabil province

Figure 2: Pyroclastic deposits

B) Alluvial terrace of young sediments: these sediments include a series of porous limestone or pumice. These young sediments are placed on the old Neogene sediments. In addition, travertine can also be seen in this part of the sediments, which are used as building materials (Figs. reff3, 4).

Figure 3: Alluvial terrace

Figure 4: Stone outcrops

C) Neogene clastic and pyroclastic sediments: These sediments include Neogene and Neogene pyroclastic sediments. These sediments include layers of light yellow marl and grey sandstone with thin layers of chalk. It seems that this area was associated with intense volcanic activity at the end of the Neogene, and except for conglomerate and sandstone sediments, other sediments were formed in a calm environment.

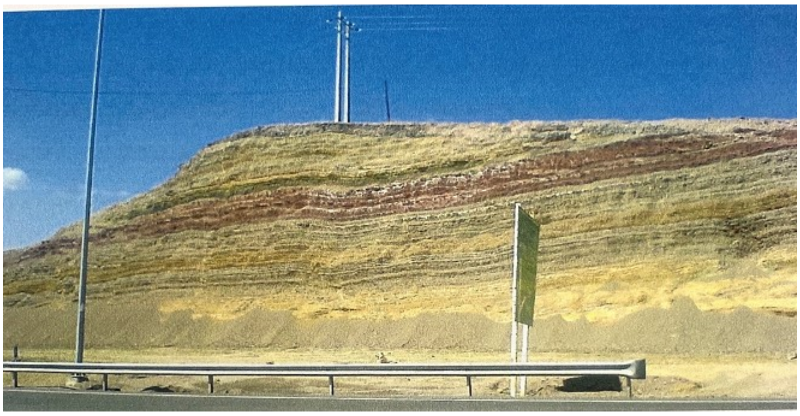

Figure 5: Neogene clastic and pyroclastic sediments 1

Figure 6: Neogene clastic and pyroclastic sediments 2

Due to the presence of dense or medium-density coarse-grained layers and taking into account the geotechnical records of the surrounding areas and taking into account caution, due to the low depth of the excavations, the investigated area is classified in group 3 in terms of land type classification.

### 2.2 Tectonic structure of the region

In general, the state of Azerbaijan, one of the sedimentary structural units of Iran, has a thick crust, which can be considered due to its proximity to the junction of the Eurasian and Iranian plates, which forms the northern limit of the Iranian continental plate and is exposed to stress forces caused by the collision of these two continental plates. Historical earthquakes and earthquakes that occurred in the 20th century and the resulting casualties and even mountain falls can be attributed to crustal movements and the accumulation of energy and its sudden release.

From the tectonic point of view, the Azerbaijan region is one of the very young regions of Asia and is located in the earthquake belt known as the Alpine-Himalayas earthquake belt. This belt, which starts from the middle of the Atlantic Ocean, after passing through the Alps of Turkey, Azerbaijan, Iran, Pakistan, Afghanistan-Northern India, and Tibet, reaches the Philippine Islands region and creates a wide strip. In fact, this tape can be removed and considered as the fusion of the earth's plates. The study of the historical earthquakes of Azerbaijan and also the earthquakes of the current century in Azerbaijan show that the physical movements of the crust of Azerbaijan still exist. The studies of mountain movements and landslides in Azerbaijan also show that, in addition to earthquakes, the slight movements of the earth are also manifested in the landslides and even cracks in the mountains of the region. The warm waters of Ardabil, Khalkhal, etc., are another sign of new tectonic activities in the region. All these evidences indicate the fact that every part of Azerbaijan is always potentially at risk of destruction, and a day will come when the so-called peaceful areas of Azerbaijan will experience destructive movements of the earth, as we have sometimes witnessed these bitter events.

Ardabil province is also a part of the tectonic unit of Western Alborz - Azerbaijan. The huge level difference between the surface of the Caspian Sea and the vast lands under investigation shows that during the Quaternary period, this part of the earth's crust rose a lot and more earthquakes occurred in the boundary between the Caspian Sea and Talash-Baghrodagh. In the discussed area, faults with activity in the Quaternary period are the most important tectonic elements with the possibility of earthquakes.

### 2.3 Active faults in Ardabile Province and its vicinity

In this part, the major faults in the province and its surroundings will be introduced. Although some of these faults are located outside the province, they have been investigated due to their effect on the seismicity of the province. The faults of the province can be divided into three categories according to their location: the faults of the southeastern part of the province, the northern faults and the western faults which are located outside the border of the province and south of Sarab and are stretched towards Ardabil province. The trends of these faults are different and their characteristics are as follows.

Tabriz Fault: This fault has caused devastating earthquakes several times since ancient times and most of the historical earthquakes in Tabriz region have been attributed to it. This fault can be followed in the northwest-southeast direction (120-125 degrees) from the north of Misho Mountain to the southwest of KokDaragh (Garachman road to the Miyaneh) and its length is 180 km or more. The slope of the fault is towards the north, and northeast and its value is more than 70 degrees. Its northeastern block, more or less everywhere, has moved upwards compared to the southwestern block, and in fact, it has been pushed on the block on the other side of the fault. The effect of the fault on the alluvium of the area is well known, and its maximum vertical displacement is estimated to be about 80 meters in the Sufian area. The closest distance from the south-eastern end of the fault to Sareyn is about 90 km and to Ardabil is about 120 km. The maximum length of the fault that has moved in a seismic event has been reported to be at least 50 or 70 km, which caused devastating earthquakes in 1721 AD and 1780 AD. The magnitude of both mentioned earthquakes is estimated to be $Ms = 7.7$, which reflects the high seismogenic power of the fault [5, 3].

Talash Fault: Caspian Sea subsidence has occurred along this fault, which is north-south, and Baghrou Mountain is more than 2,500-2,000 meters higher than the shores of the Caspian Sea. Such a special shape (Hiran neck) undoubtedly shows the pattern of the fault.

The length of the Talash fault is at least 170 km, no historical or 20th-century earthquake event can be related to the movement of this fault. However, several earthquake centres have been located within its 5 km radius, which may reflect the movement of the Talash fault. Considering the current shape of the Caspian Sea, Talesh-Baghro Mountains and also the proximity of the earthquake centre to the fault, it seems that this fault has most likely caused historical earthquakes and earthquakes of the 20th century. The 1980 earthquake with a magnitude of $M_b = 4.6$, whose centre was in the Caspian Sea, had a push mechanism towards the west; the closest distance from the fault to the centre of Ardabil is about 73 km.

Bezgosh Fault: In the easternmost slopes of Bezgosh Mountain, as well as in its south, there is a fault that has a gentle bend towards the south and the earthquake of 1879 due to the movement of a small part of this fault destroyed Nir in the north to the Miyaneh in the south.

Marlstone rocks have been pushed by this fault on the Quaternary alluviums by the Germi River, and therefore the fault is of compressional type. From the length of the fault, only about 2 km can be seen in the outcrops and its continuation is hidden under the alluvium of the Germi River. The general fault south of Bezgosh is about 58 km, but only a small part of it was moved in the earthquake of May 22, 1979. The centre of an earthquake of the 20th century is also located next to this fault, whose dependence on the movement of the fault is not clear. The closest distance of this event to the centre of Ardabil is measured about 30 kilometres [1].

Masuleh thrust Fault: which is in the northwest-southeast direction, and its eastern block is pushed on the western block. No sign of its movement during the Quaternary period is known. The epicentre of any historical or 20th-century earthquake is not located within a few tens of kilometres. The length of this fault is about 90 km [5, 3].

Figure 7 shows the map of active faults in Ardabil Province and its vicinity. By considering the range of geographical coordinates of the region, the complete characteristics of the faults in the region have been obtained. The area of $300 \times 350\ km^2$ has been investigated in this research.


Figure 7: Active fault zones in the Ardabil Province and its vicinity (Water and Wastewater Company)

## 2.4 Seismicity of Ardabil province and its vicinity

There is significant seismic activity for Ardabil and its surroundings in the form of historical and instrumental earthquakes. In recent years, many earthquakes have occurred in the area with longitude coordinates of 46-51 degrees and 35-40.5 degrees latitude with a magnitude greater than 2.5.

Several earthquake catalogues and historical sources describe the 893 Ardabil earthquake as a destructive earthquake that struck the city of Ardabil, Iran. The magnitude is unknown, but the death toll was reported to be very large. The USGS, in their "List of Earthquakes with 50,000 or More Deaths", give an estimate that 150,000 were killed, which would make it the ninth deadliest earthquake in history.[22] The 1997 Ardabil earthquake occurred on 28 February with a moment magnitude of 6.1 and a depth of 10km and a maximum Mercalli intensity of VIII (Severe). The strike-slip earthquake occurred in northern Iran, near the city of Ardabil. The earthquake occurred at 12:57 UTC (4:27 p.m. Iran Standard Time) and lasted for 15 seconds. At least 1,100 people were killed, 2,600 injured, 36,000 homeless [21, 12]. Also, from the devastating earthquakes before the 20th century (historical earthquakes), we can also refer to the 1593 Sarab earthquake with a surface wave magnitude (Ms) of 6.1 at 37.80 North and 47.50 East; Earthquake of 1844 in the coordinates of 37,40 North and 48,00 East with a surface wave magnitude of 6.9; The 1863 Hir-Ardabil earthquake at coordinates 38.20 North and 48.60 East with Ms = 6.1; Earthquake of 1879 in Bezgosh-Garmroud at coordinates 37.80 North and 47.90 East with $Ms = 6.7$; And the Khalkhal-Sangabad earthquake of 1896 at coordinates 37,800 North and 48,400 East with $Ms = 6.7$ [3].

In terms of seismicity, the studied area is one of the areas with high seismicity, which is surrounded by a chain of faults. Based on the results obtained from the studies, the focal depth of most of the earthquakes that have occurred is low and close to the earth's surface, and the formations of the studied area do not have the same resistance, so the density of faults follows the trend of the resistance of the formations, and the highest density of faults happened in the formations with high axial pressure resistance [10].

Fig. 8 shows the seismicity of Ardabil and its surroundings in the instrumental period. Other details about magnitude, focal depth and geographic coordinates of earthquakes with magnitude greater than 2.5 are given in Appendix A. Historical earthquakes have been collected from Tehran Geophysics Institute and Iran Earthquake History book [3]. Also, the epicenters of instrumental earthquakes are shown in the Fig. 9. Table 1 shows the historical earthquakes and their magnitudes.

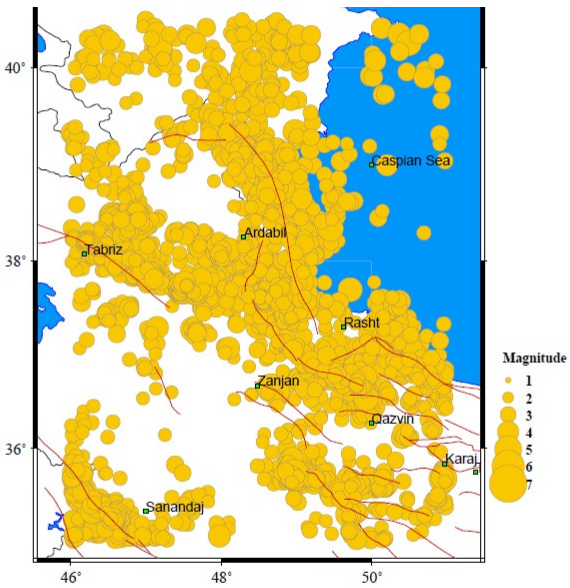


Figure 8: Seismicity map of the region 2006-2023 (Tehran Geophysics Institute)

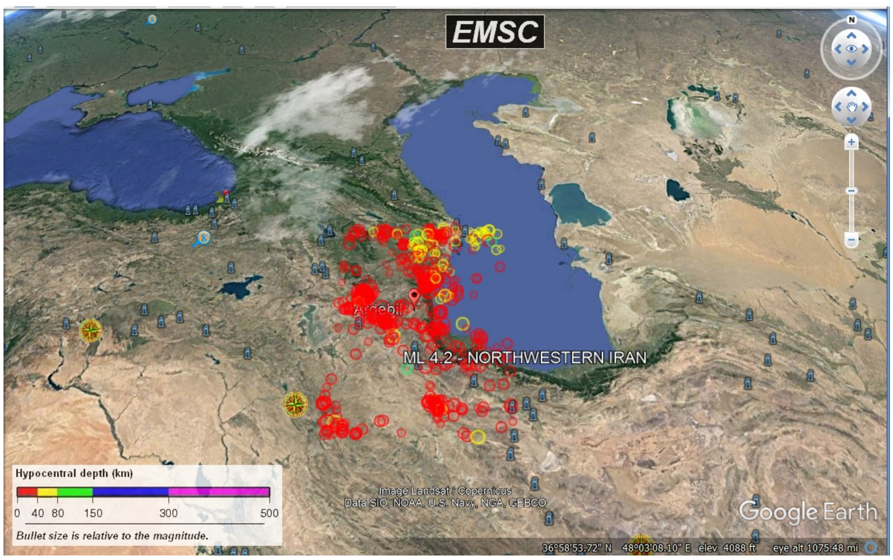


Figure 9: Regional Earthquake Hypocenter 2004-2023 (EMSC)

Table 1: Historical earthquakes of region

| No. | Date | Epicenter | | Magnitude | Ref. |
|---|---|---|---|---|---|
| | | Lat. | Long. | | |
| 1 | c.1.8 Ma | 36.11 | 50.78 | 7 | BER |
| 2 | c.11000 BP | 33 | 47.6 | 7 | BER |
| 3 | c.4500 BP | 36.7 | 49.98 | 6.5 | BER |
| 4 | c.3000-2800 BP | 36.82 | 49.48 | 7 | BER |
| 5 | 427 | 40.5 | 46.5 | 6.5 | ULM |
| 6 | 840 | 31.3 | 48.8 | 6.5 | AMB |
| 7 | 855 | 38.1 | 46.3 | 5.3 | ULM |
| 8 | 858 | 38.1 | 46.3 | 6 | AMB |
| 9 | 864 01 | 35.7 | 51 | 5.3 | AMB |
| 10 | 872 06 22 | 33.2 | 47.2 | 6.8 | AMB |
| 11 | 893 01 06 | 37.7 | 47.5 | 7.7 | ULM |
| 12 | 956 | 34.8 | 48.1 | 5.3 | AMB |
| 13 | 957 | 41.5 | 49 | 5.5 | ULM |
| 14 | 986 11 | 36.2 | 48.1 | 6.1 | ULM |
| 15 | 987 11 | 34.8 | 48.5 | 5.9 | ULM |
| 16 | 1008 04 27 | 34.6 | 47.4 | 7 | AMB |
| 17 | 1042 11 04 | 38.1 | 46.3 | 7.6 | AMB |
| 18 | 1052 | 31.5 | 50 | 6.8 | AMB |
| 19 | 1052 | 36.6 | 50.3 | 6.8 | BER |
| 20 | 1085 05 | 30.6 | 50.3 | 5.8 | BER |
| 21 | 1085 05 | 30.7 | 50.3 | 5.8 | AMB |
| 22 | 1087 11 | 34.8 | 48.5 | 5.9 | AMB |
| 23 | 1107 09 | 34.6 | 47.4 | 6.5 | AMB |
| 24 | 1119 12 10 | 35.7 | 49.9 | 6.5 | AMB |
| 25 | 1122 | 40.3 | 46.3 | 6.1 | ULM |
| 26 | 1139 09 30 | 40.3 | 46.2 | 7.3 | ULM |
| 27 | 1177 05 | 35.7 | 50.7 | 7.2 | AMB |
| 28 | 1226 11 18 | 35.3 | 46 | 6.5 | AMB |
| 29 | 1235 | 40.6 | 46.2 | 5.7 | ULM |
| 30 | 1250 | 41.6 | 47.2 | 5.7 | ULM |
| 31 | 1273 01 18 | 38.13 | 46.28 | 6.5 | BER |
| 32 | 1308 | 39.4 | 46.2 | 6.1 | ULM |
| 33 | 1310 | 35.6 | 46.1 | 5.3 | AMB |
| 34 | 1316 01 05 | 33.5 | 49.4 | 6.2 | AMB |
| 35 | 1430 | 34.5 | 48 | 5.9 | AMB |
| 36 | 1430 | 32.2 | 46.4 | 5.3 | AMB |
| 37 | 1457 | 31.9 | 46.9 | 6.1 | AMB |
| 38 | 1485 08 15 | 36.7 | 50.5 | 7.2 | AMB |
| 39 | 1495 | 34.5 | 50 | 5.9 | AMB |
| 40 | 1593 | 37.8 | 47.5 | 6.1 | AMB |
| 41 | 1608 04 20 | 36.4 | 50.5 | 7.6 | AMB |
| 42 | 1639 | 36.6 | 50 | 6.1 | ULM |
| 43 | 1641 02 05 | 37.9 | 46.1 | 6.8 | AMB |
| 44 | 1666 | 32.1 | 50.5 | 6.5 | AMB |
| 45 | 1668 01 14 | 41 | 48 | 7.8 | ULM |
| 46 | 1678 02 03 | 37.2 | 50 | 6.5 | AMB |
| 47 | 1717 03 12 | 38.1 | 46.3 | 5.9 | AMB |
| 48 | 1721 04 26 | 37.9 | 46.7 | 7.7 | AMB |
| 49 | 1780 01 08 | 38.2 | 46 | 7.7 | AMB |
| 50 | 1803 | 36.33 | 48.95 | 5.3 | BER |
| 51 | 1808 12 16 | 36.4 | 50.3 | 5.9 | AMB |
| 52 | 1828 08 09 | 40.7 | 48.4 | 5.7 | ULM |
| 53 | 1832 08 03 | 40.6 | 48.6 | 5.4 | ULM |
| 54 | 1844 05 13 | 37.6 | 47.8 | 6.9 | AMB |
| 55 | 1851 04 09 | 40 | 47.3 | 6.2 | AMB |
| 56 | 1853 06 11 | 32.6 | 50.3 | 5.5 | AMB |
| 57 | 1859 06 11 | 40.7 | 48.5 | 6 | ULM |
| 58 | 1861 02 28 | 39.4 | 47.8 | 5.6 | ULM |
| 59 | 1861 05 24 | 39.4 | 47.5 | 6 | AMB |
| 60 | 1862 12 19 | 39.3 | 47.8 | 6.1 | AMB |
| 61 | 1863 12 30 | 38.2 | 48.6 | 6.1 | AMB |
| 62 | 1867 07 23 | 40.6 | 46.3 | 6.2 | ULM |
| 63 | 1868 03 18 | 39.6 | 47.6 | 6 | AMB |

| | | | | | |
|---|---|---|---|---|---|
| 64 | 1872 01 28 | 40.6 | 48.7 | 6 | ULM |
| 65 | 1872 06 | 34.7 | 47.7 | 6.1 | AMB |
| 66 | 1875 03 21 | 30.5 | 50.5 | 5.7 | AMB |
| 67 | 1875 08 07 | 40.7 | 48.7 | 5.4 | ULM |
| 68 | 1876 09 28 | 33.1 | 49.7 | 5.8 | AMB |
| 69 | 1876 10 20 | 35.8 | 49.8 | 5.7 | AMB |
| 70 | 1878 05 04 | 41.6 | 48.1 | 5.7 | ULM |
| 71 | 1879 03 22 | 37.8 | 47.8 | 6.7 | AMB |
| 72 | 1880 | 32.02 | 50.65 | 5.3 | BER |
| 73 | 1880 07 04 | 36.5 | 47.5 | 5.6 | AMB |
| 74 | 1883 05 03 | 37.9 | 47.2 | 6.2 | AMB |
| 75 | 1896 01 02 | 37.7 | 48.32 | 5.3 | BER |
| 76 | 1896 01 04 | 37.8 | 48.4 | 6.7 | AMB |

## 3 Modeling probabilistic seismic hazards of the region

In this study, the software R-CRISIS was used, which can calculate the results of probabilistic seismic hazard analysis in the form of outputs with different characteristics (such as exceedance probability curves, stochastic event sets). This program calculates the seismic hazard by considering earthquake occurrence probabilities, attenuation characteristics and the geographical distribution of earthquakes. Calculation locations (places where seismic hazard is supposed to be calculated) must be defined by the user as a site grid. All seismic sources in R-CRISIS are assigned seismicity parameters by the modified Gutenberg-Richter seismicity model. As many Ground Motion Prediction Models (GMPMs) as needed can be added to the R-CRISIS project, and combinations between user-defined models and existing models are allowed. In the hybrid GMPM model, all selected attenuation relationships for the CRISIS project can be added. Also, a relative weight should be assigned to each added attenuation relationship. Appropriate attenuation relationships for the region were used as a combined model. Then, the total magnitude of the ground motion could be determined using the probabilistic assessment. After performing a probabilistic hazard analysis, hazard maps can be generated, drawn and exported [12, 19].

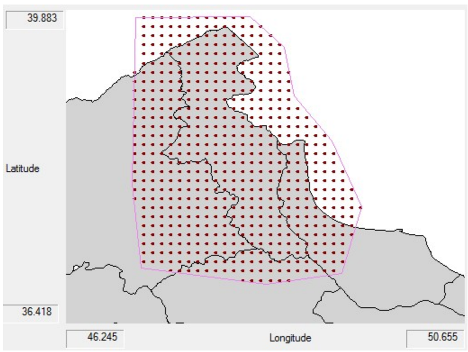


Figure 10: Hazard analysis area - Ardabil, East Azerbaijan, Gilan and Zanjan provinces

### 3.1 Defining the geometry of seismic sources

This study was conducted to obtain the seismicity of the region using national and international earthquake catalogs. Instrumental data from the site of the Mediterranean Seismological Center (EMSC), USGS and Institute of Geophysics of Tehran University were used to collect the number of earthquakes with a magnitude of 2.5 or more in Ardabil province and its vicinity between 1963-2023. The data were combined and compared in terms of time and place of occurrence, and duplicate data were removed. We tried to remove the aftershocks related to the main events so that the real seismicity rate of the region or the return period of the events can be displayed more realistically and the uncertainties are reduced.

In this project, we consider linear sources. After a seismic source is added to the R-CRISIS project, the coordinates of the fault vertex must be entered. In the case of linear sources, the rupture length parameters must also be defined [19]. The specifications of the sources are listed in Table 2.

Table 2: Characteristics of regional faults

| Fault name | Name of the segment | The longitude of the beginning | The latitude of the beginning | The longitude of the ending | The latitude of the ending | Depth | Fault type |
|---|---|---|---|---|---|---|---|
| Sangavar | Sangavar-1 | 48.5483 | 38.23 | 48.457 | 38.029 | 20 | RL |
| Sangavar | Sangavar-1 | 48.4567 | 38.0286 | 48.466 | 38.005 | 20 | RL |
| Sangavar | Sangavar-1 | 48.4662 | 38.0054 | 48.282 | 37.749 | 20 | RL |
| Sangavar | Sangavar-1 | 48.282 | 37.7487 | 48.25 | 37.649 | 20 | RL |
| Talesh | Talesh-1 | 48.1787 | 39.4885 | 48.743 | 38.737 | 20 | R |
| Talesh | Talesh-1 | 48.7433 | 38.7366 | 48.897 | 37.829 | 20 | R |
| Talesh | Talesh-1 | 48.897 | 37.8286 | 49.229 | 37.175 | 20 | R |
| Bozqush | Bozqush-1 | 47.8598 | 37.4382 | 48.2155 | 38.2358 | 20 | SS |
| Dasht-e- Moghan | Dasht-e- Moghan-1 | 47.0694 | 39.2425 | 47.425 | 39.324 | 20 | SS |
| Dasht-e- Moghan | Dasht-e- Moghan-1 | 47.4247 | 39.324 | 47.65 | 39.282 | 20 | SS |
| Dasht-e- Moghan | Dasht-e- Moghan-1 | 47.6501 | 39.2815 | 47.661 | 39.244 | 20 | SS |
| Dasht-e- Moghan | Dasht-e- Moghan-1 | 47.6643 | 39.2625 | 48.085 | 39.269 | 20 | SS |
| Dasht-e- Moghan | Dasht-e- Moghan-1 | 48.1161 | 39.3037 | 47.814 | 39.326 | 20 | SS |
| Masuleh | Masuleh-1 | 48.6869 | 37.3038 | 48.415 | 37.5999 | 20 | R |
| Masuleh | Masuleh-1 | 49.0107 | 36.93.18 | 48.687 | 37.304 | 20 | R |
| Masuleh | Masuleh-1 | 48.4799 | 37.4849 | 48.424 | 37.529 | 20 | R |
| Dasht-e- Moghan | Dasht-e- Moghan-1 | 48.1161 | 39.3037 | 47.814 | 39.326 | 20 | SS |
| Kalibar | Kalibar-1 | 47.066 | 39.103 | 47.725 | 39.078 | 20 | SS |
| Tabriz | Tabriz-1 | 47.065 | 37.657 | 47.319 | 37.501 | 20 | R |
| IRQ10 | IRQ10-1 | 47.257 | 37.694 | 47.570 | 37.646 | 20 | SS |
| IRQ10 | IRQ10-2 | 47.748 | 37.712 | 47.921 | 37.774 | 20 | SS |
| IRQ11 | IRQ11-1 | 47.286 | 37.807 | 47.648 | 37.823 | 20 | SS |

*SS: Strike-Slip, R: Reverse, RL: Right Lateral

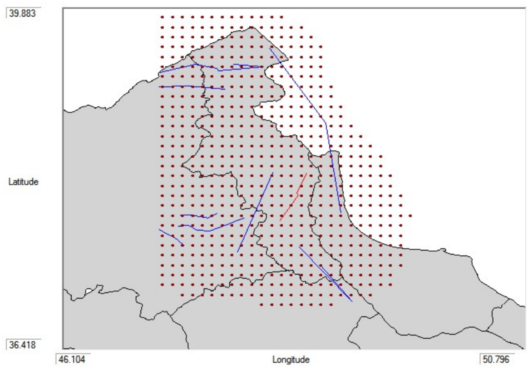


Figure 11: Seismic sources defined in R-CRISIS

### 3.2 Calculation of the recurrence relationships of seismic source zones

All seismic sources in R-CRISIS must be assigned seismicity parameters; a modified Gutenberg-Richter seismic model was assigned to each source. This model is associated to Poissonian occurrences and so, the probability of exceeding the intensity level as in the next $T_f$ years, given that an earthquake with magnitude M occurred at a distance R from the site of interest, is described by:

$$Pe\left(a, T|M, R\right) = 1 - \exp\left[-\Delta\lambda\left(M\right)T.p_1\left(a|M, R\right)\right] \tag{3.1}$$

where $Pe(a|M, R)$ is the exceedance probability of the hazard intensity level a, given that an event with magnitude $M$ occurred at a distance R from the site of interest, and $\Delta\lambda(M)$ is the Poissonian magnitude exceedance rate associated to the magnitude range characterized by magnitude $M$.[15] The Gutenberg-Richter plot are shown for sources in in Fig. 12.

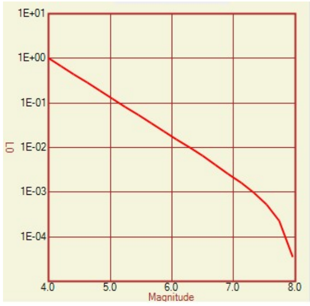


Figure 12: Gutenberg-Richter plot

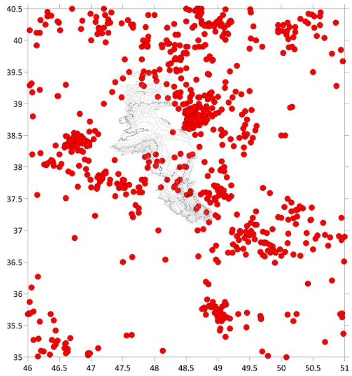


Figure 13: Evevnts obtained from the catalog in Surfer software

### 3.3 Ground motion prediction models (attenuation relationship) used in the analysis

The Azerbaijan region is the continuation of Alborz, the border of Caucasus and Anatolia that is, Sablan and Bezgosh, where three formations meet, each of which has a different structure and seismic regime. It is not easy to decide the area attenuation relations. Then we use several attenuation relations. For the hybrid attenuation model, Campbell's relationship [7] was defined with a coefficient of 2 and the rest of the relationships include Tavakoli and Pezeshk [23], Campbell and Bozorgnia [8] NGA with a coefficient of one.

Table 3: Attenuation relations used in the model

| **Reference** | **Magnitude range** | **Distance range** | **Spectral period range** |
|---|---|---|---|
| Campbell (2003) | 5.0-8.2 | 1-1000 km | 0.01-4.0 s |
| Campbell and Bozorgnia (2014) NGA-West2 | 3.0-8.5 | 0-300 km | 0.0-10.0 s |
| Campbell and Bozorgnia (2008) NGA | 4.0-8.5 | 0-200 km | 0.0-10.0 s |
| Tavakoli and Pezeshk (2005) | 5.0-8.2 | 0-1000 km | 0.0-4.0 s |

## 4 Probabilistic earthquake hazard analysis for the region

Different softwares such as Shake91 (1992), EZ-FRISK (1997), Ordonez (2009), CRISIS2007 (2007) and SEISRISK III (1987) are used to estimate the seismic hazard [19]. In the present study, the R-CRISIS V20 software developed by Ordaz was used to perform the probabilistic seismic hazard analysis. The geographical coordinates of the study area were determined as 26.0-31.0 North and 46-51 East, taking Ardabil Province as the center. Seismic parameters were assigned to each source based on the modified Gutenberg-Richter model. Then appropriate attenuation relations were selected for the region and total ground motion magnitudes and seismic hazard were computed for the specified probability of exceedance by probabilistic approach.

Figs. 14 and 15 shows the hazard maps of the region with a period of $T = 0.2$s and 1s. Fig. 16 shows the magnitude map (more than 5.5) based on the exceedance probability of 10% using the attenuation relationships Campbell's (2003), Tavakoli and Pezeshk (2005), Campbell and Bozorgnia (2008 , 2014) NGA for 475, 1000 and 2475 years.

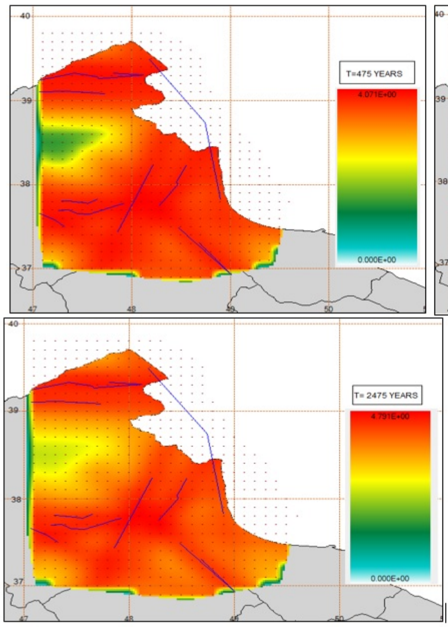


Figure 14: The seismic hazard maps of the region with a period of $T = 0.2$ sec for 475, 1000 and 2475 time frames

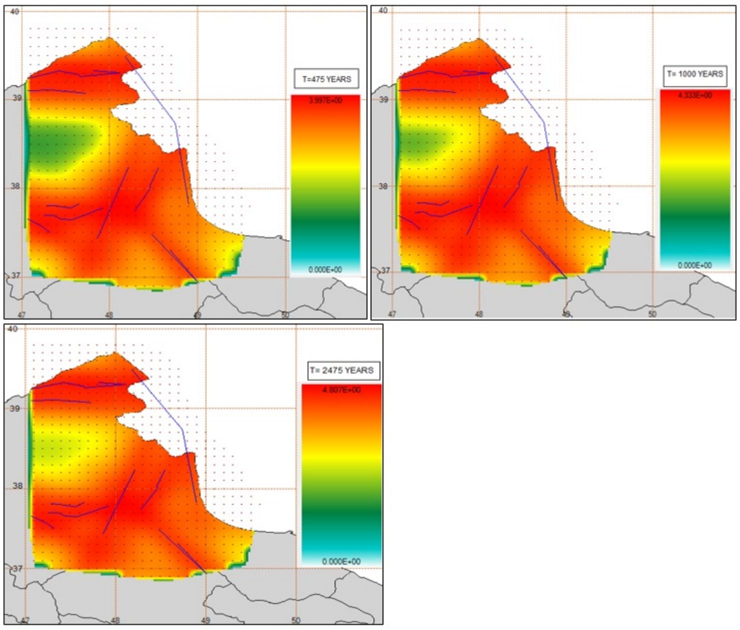


Figure 15: The seismic hazard maps of the region with a period of $T = 1$ sec for 475, 1000 and 2475 time frames

## 5 Conclusions

The study also reveals that north and southwest faults of Ardabil province are the most active sources in terms of the seismic hazard and that the seismic hazard of the southwest and north of the region are greater compared to other parts. According to the type and mode of activity of these faults, these areas of the province can be considered as having a relatively high seismic hazard. If the project is close to active faults, it is recommended to consider necessary safety precautions for the project structures. Also, the maximum moment magnitude value in these areas for 475 years was found to range between 8 and 8.8 using the model proposed. It is suggested that important centers and buildings should be built in areas with a smaller majority, which will be better in terms of the development of the province in the future and the use of R-CRISIS software is recommended due to its advantages such as simplicity, high flexibility and speeding up the earthquake hazard analysis process, which can save a lot of time. According to the history of

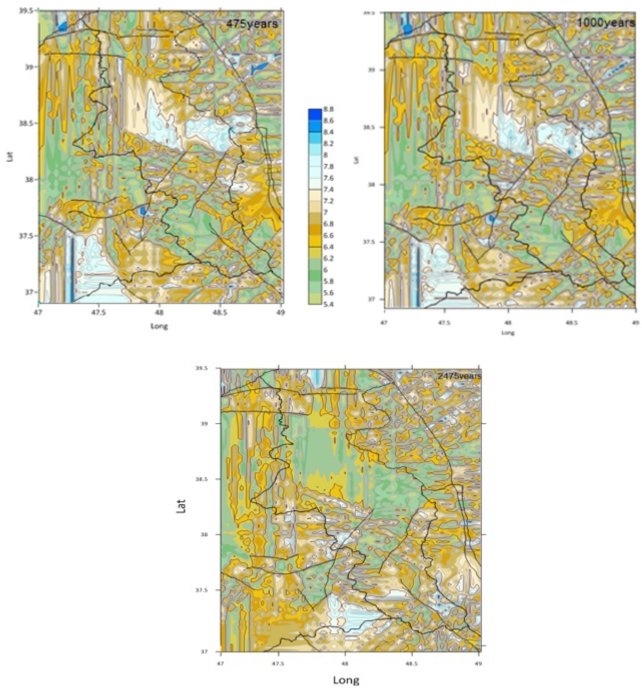


Figure 16: The magnitude map based on the exceedance probability of 10% using the attenuation relationships Campbell's (2003), Tavakoli and Pezeshk (2005), Campbell and Bozorgnia (2008 , 2014) NGA for 475, 1000 and 2475 years (Sufer software)

earthquakes in the region and the results of the risk analysis, the occurrence of a severe earthquake between Ardabil, East Azarbaijan and Gilan provinces in the near future seems certain.

The maximum value of the magnitude of the earthquake for Ardabil province was obtained in the range of 8.8-7.6 and the maximum acceleration 0.22 and 0.65g was obtained with the introduced hybrid attenuation model. According to the study, the magnitude of most of the earthquakes in the northwestern region of Iran in the investigated time periods are in the range of 6.8-6.8 and 6.8-6.4. The most dangerous earthquakes occur during periods of 475 and 1000 years in the vicinity of the Moghan, Bozgush and Tabriz faults in East Azarbaijan and Zanjan provinces and central Ardabil with a magnitude of 8.6-8.8. The seismic hazard of these areas should be investigated more closely in future studies. Also, during the period of 2475 years, 8.6-8.8 earthquakes will occur on the border between Ardabil province with Gilan and East Azerbaijan, and the occurrence of severe earthquakes in the southeast of East Azerbaijan in the period of 2475 years seems more likely.

Most of the populated areas of Azerbaijan such as Ardabil, Tabriz, Salmas, Khoy and Zanjan were built in very active tectonic areas and next to active, young and powerful faults. Therefore, informing the people of these areas and even other areas that are less hazard, with this phenomenon and how to deal with this natural event, whether from the point of view of construction engineering, including building construction, oil and gas pipelines, highways, water and sewage networks, telecommunications and The underground cable network, airports, ports, railway network, and in terms of examining safety and educating everyone about earthquakes, to reduce the amount of damage and casualties, it is a basic duty for earthquake specialists.

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