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EARTHQUAKE HAZARD ANALYSIS IN ALBORZ PROVINCE, IRAN

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ABSTRACT

Alborz Province is located west of Tehran Province on the South Alborz seismic belt. The city of Karaj, having a population of 2.2 million, is located in the South West of Alborz Mountain Belt in Northern Iran. The region is known to be a highly active seismic zone. This study is focused on the geological and seismological analyses within a radius of 200 km from the center of Karaj. There are identified five seismic zones and seven linear seismic sources. The maximum magnitude was calculated for the seismic zones using available correlations. The Kijko and Sellevoll (1992) method was used to calculate seismicity parameters, and the graphs of the return period and the probability frequency of recurrence of the earthquake magnitude in each zone were plotted for the 475-year return period. According to the calculations, the highest and lowest earthquake magnitudes of 7.6 and 6.2 were respectively obtained in Zones 1 and 4. In addition, the horizontal peak ground acceleration for the 475-year return period 0.42g and for 2475-year return period 0.70g also the vertical peak ground acceleration for 475-year return period 0.25g and 2475-year return period 0.44g was calculated using attenuation relationships Zare 1999, Ambraseys 1995, Boore, Joyner and Fumal 1981 in studying region. Moreover, the proposing a new seismotectonic model for Alborz Province and presenting the peak ground acceleration of seismic sources for this province are among the novelties of this study.

Keywords: Attenuation relationships, Earthquake, Hazard analysis, Magnitude, Seismic zones.

INTRODUCTION

A significance of seismic studies is that the correct seismic analysis of any type (seismic hazard analysis, seismic risk analysis, ground seismic response analysis, seismic site effects, and structural dynamic analysis) can offer useful economic parameters and avoid conservative design and implementation, which lead to an irrational increase in project costs and poor implementation, which in turn causes increased risk and possibility of destruction.

Alborz sedimentary–structural zone includes highlands north of Iranian Plate extending in an east-west direction from Azerbaijan to Khorasan in the form of a composite anticline. From a geomorphological point of view, the northern border of Alborz corresponds to hills consisting of Tertiary deposits and the Caspian coastal plain. From a geological point of view, the northern border of Alborz is bounded by the ancient Tethys geosuture formed by the collision of Alborz continental lithosphere and Turan lithosphere in the late Triassic Period. Most parts of the geosuture are, however, covered with plates moving from north to south. The southern bounds of Alborz are not very clear, and it seems there are no clear borders in southern Alborz, and a gradual transition had occurred from Central Iran to Alborz [1].

According to the seismotectonic map of Iran (Berberian, 1976), earthquakes in Alborz are shallow. There are also some intermediate earthquakes, and overall, the eastern Alborz is more earthquake prone than the western Alborz [2].

GEOGRAPHICAL LOCATION

Located in the south of Central Alborz highlands, Alborz Province is bounded by Mazandaran Province to the north, Markazi Province to the south, Tehran Province to the east, and Qazvin Province to the west. With an area of 5142 km2, it is located between the longitudes 50° 10’ and 51° 30’ and the latitudes 35° 31 and 36° 21. Alborz Province and its capital, Karaj, are located on the South Alborz seismic belt. The study area includes the eastern part of central Alborz in Tehran Province. Tectonically, it is part of the northern margin of the Iranian Plate. From the seismotectonic point of view, it is located on the seismic belt on the Iran-Turan convergent plate. Alborz Province is located in the east of this plate. The general direction of highlands in the region is east-west, along with some scattered reliefs. Baraghan River has created a deep valley with an east-west direction in the Alborz Mountains with nearly north-south branches. In the south of the plate, Shoor River flows from east to west after drainage from Eshtehard Desert. The river changes its direction from north to south and flows into Lake Houz Sultan after joining Sroud River. The province has a great diversity in terms of climate, with desert climate in the southern parts and semi-humid and humid climates in the northern parts.

MAJOR FAULTS IN THE STUDY AREA

A fault is a set of fractures in the Earth's crust that relative displacement occurs along their direction. The shear movement continues on both sides of the fault, from ground surface to large depths. Faulting and earthquakes occur due to the accumulation of stresses caused by the relative movements of tectonic plates and the movements within the upper mantle.

Most faults in Alborz follow the direction of existing folds with thrust mechanism and left lateral strike-slip [3]. In this zone, the number of faults sloping towards the Caspian Sea is almost equal to those with an opposite slope [4]. High-angle strike-slip faults are more inclined towards the Caspian Sea. The major faults in the northern areas of Alborz slope toward the south, and those in the southern part usually slope toward the north [5]. Strike-slip faults adjacent to the Central Iran Plateau are usually limited to the southern part of Alborz. A small component of normal displacement is clearly seen on some strike-slip faults. From seismotectonic point of view, almost all of the faults studied in this mountain range are active. The major faults in the study area include North Tehran fault, Taleghan fault, Mahdasht fault, Eshtehard fault, Eyvanaki fault, Mosha fault, and Rey fault. The major faults within a radius of 200 km from the study site were examined and are shown in Figure 1.

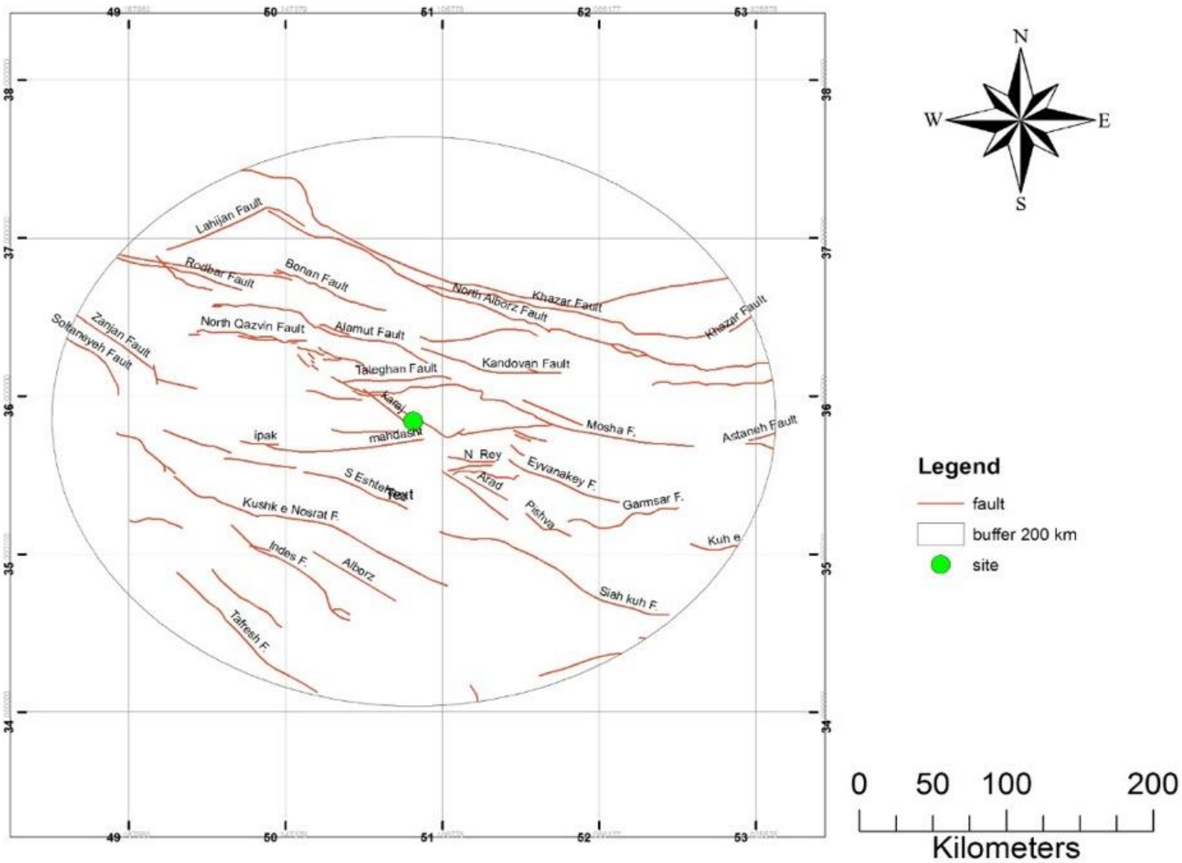

Figure 1. Major faults within a radius of 200 km from the study area.

SEISMIC LAYER

Determining the focal depth of earthquakes is essential for accurate interpretation of seismicity in regional tectonic studies and seismic hazard estimation. Despite the fact that existing global catalogs are used as sources of general information on focal depths, such catalogs are associated with a large error. Comparisons of focal depths by various seismological centers such as

NEIC, ISC, and those calculated through teleseismic waveform inversion show that the error in the calculated depths reaches up to 60 km [6-7-8]. Therefore, it can be argued that such catalogs are not a suitable and accurate tool for determining the depth of seismic events in the study area.

Regardless of the modeling method for body waves, which can be used to accurately determine (±3 km) the focal depth of earthquakes, the arrival times of seismic waves recorded in a dense and local seismological network offers the most appropriate method for determining the depth of earthquakes. The first method is mainly used for large earthquakes (often M> 5.5). Obviously, such a method can be applied to few earthquakes. Studies conducted in Iran using the teleseismic body wave modeling technique show that seismicity in the Iranian Plateau is essentially limited to the upper 20 km of the crust.

Nonetheless, it is necessary to determine the focal depth of all earthquakes in the study area to estimate the seismic hazard. To this end, a statistical study on the focal depth of the recorded earthquakes determines their distribution in the study area. Considering that most earthquakes reported in the study area have not been accurately relocated, they cannot be used to calculate the seismogenic layer. Hence, according to Maggi (2002), a depth of 15 km was considered the minimum depth for earthquakes occurring in the study area.

CALCULATION OF MAXIMUM MAGNITUDE (M_{MAX})

The maximum magnitude (Mmax) is usually estimated based on the general characteristics of seismic activity and geological similarities. In applied studies, Mmax is often estimated based on correlation of seismic magnitude and different fault parameters such as rupture, fracture surface area, maximum surface displacement, and seismic moment release rate. Multiple correlations have been proposed to relate these parameters and the earthquakes magnitude. Table 1 shows some correlations by different scholars [9].

Table 1. Correlations between the earthquake magnitude and different fault parameters.

No.	Proposed by	Correlation
1	Mohajer and Nowroozi (1978)	$Ms=5.4+LogL_R$
2	Zare (1995)	$Mw=3.66+0.91LnL_R$
Ms: Surface wave magnitude Mw: Moment magnitude		Lf: Fault length (km) L_R: Rupture length (km)

Correlations in Table 1 were used to calculate the maximum empirical magnitude, and the observed magnitudes for major faults in each zone were also reported. The results are given in Table 2.

Table 2. Maximum empirical magnitudes calculated from correlations in Table 1 and the observed magnitudes.

No.	**Fault**	**Fault Length**	**Zare (1995)**		**Mohajer and Nowroozi (1978)**		**Mmax**	**Observed Magnitude**
								Magnitude
			LR*0.37=Lf	Mw	L=0.5*Lf	Mw		
1	North Tehran	90	33.3	6.9	45	7.1	7	7.2
2	Mosha	200	74	7.6	100	7.4	7.5	7.1
3	Abyek	100	27	6.9	50	7.1	7	7.2
4	Taleghan	64	13.68	6.5	32	6.9	6.7	5.3
5	Alamutrud	100	37	6.9	50	7.1	7	7.6
6	Baijan	45	16.65	6.2	22.5	6.8	6.5	7
7	North Eshtehard	60	22.2	6.5	30	6.9	6.7	5.3
8	South Eshtehard & Eshtehard	80	29.6	6.7	40	7	6.85	-
9	Kandovan	76	28.12	6.7	38	7	6.85	-
10	Lar	25	9.25	5.7	12.5	6.5	6.1	4.5
11	Eyvanaki	80	29.6	6.7	40	7	6.85	7.6
12	Kahrizak	40	148	6.1	20	6.7	6.4	-
13	North Rey	165	6.105	5.3	8.25	6.3	58	7.1
14	South Rey	185	6.845	5.4	9.25	6.4	5.9	7.1
15	Garmsar	70	25.9	6.6	35	6.9	6.75	5.4
16	Pishva	34	12.58	6	17	6.6	6.3	-
17	Robat Karim	90	33.3	6.9	45	7.1	7	4.9

POTENTIAL EARTHQUAKE SOURCES

The analysis of earthquake hazard requires modeling of seismic sources. The earthquake source location is of great importance as the energy of waves decreases with distance. Different methods are available for earthquake source modeling taking into account the geological conditions. For instance, in some areas, the modeling of a seismic source involves an area where large earthquakes occur on the fault. Studies on seismic faults around the world show that the fault is not ruptured during a single earthquake, rather they break in the form of isolated pieces. In other words, fault zones are often divided into isolated parts. These parts are broken independently during different seismic events. The seismic depth is used to model the isolated sources. In the case of insufficient accuracy and inability to identify a fault as a seismic source in the seismic hazard analysis, the more conservative seismotectonic method can be used instead of active faults, in which the seismic sources are studied as wider seismic zone sources.

The concept of seismotectonics is practically used in the seismic hazard analysis for determining the seismotectonic source without any need for knowing or determining the exact details or location of seismic events. However, there are often problems in low-seismic areas, particularly in inter-plate areas where the tectonics theory is less useful in determining the seismotectonic sources. Considering the geological and seismological data, five seismic zones along with seven linear seismic sources were determined in the study area and are presented in Figure 2 [10].

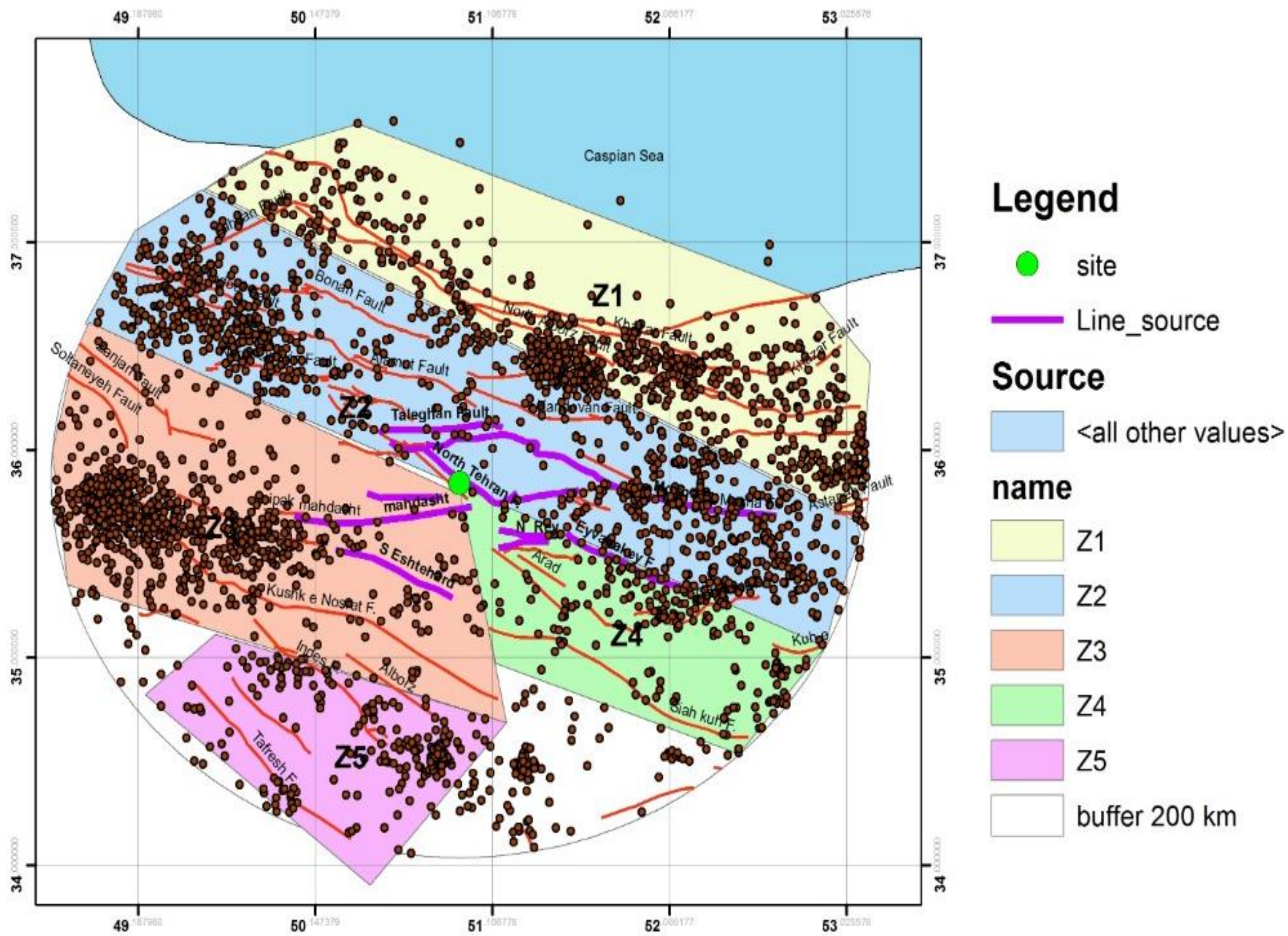

Figure 2. Seismic zones with linear seismic sources around the seismic site.

SEISMICITY PARAMETER ESTIMATION

The K-S method was used to achieve seismicity parameters within the scope of this study [11]. The methods presented by Kijko and Sellevoll allow the inclusion of the uncertainty of the earthquake magnitude and insufficient data in estimating the seismicity parameters. The results obtained from the analysis of seismicity parameters using the K-S method in seismic zones around the seismic site are reported in Table 3.

Table 3. Seismicity parameters around the seismic site.

Zone	Beta		Lambda for Mmin 4.0	Mmax	
z1	1.44	± 0.15	1.932	7.6	± 0.2
z2	1.69	± 0.14	1.88	7	± 0.2
z3	1.74	± 0.2	1.0108	7	± 0.2
z4	1.71	± 0.30	0.898	7.4	± 0.2
z5	1.76	± 0.30	1.048	6.7	± 0.2
Mahdasht	1.74	± 0.22	0.246	7	± 0.2
Taleghan	1.69	± 0.22	0.196	7	± 0.2
North Tehran	1.69	± 0.22	0.276	7	± 0.2
Rey	1.71	± 0.22	0.057	6.2	± 0.2
Eyvanaki	1.71	± 0.22	0.246	7.4	± 0.2
Mosha	1.69	± 0.22	0.614	7.4	± 0.2
Eshtehard	1.74	± 0.22	0.246	7	± 0.2

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

Due to the use of probability concepts during the last 20-30 years, there has been significant interest in uncertainty in the earthquake magnitude, location, recurrence rate, and ground motion characteristics in explicitly evaluating seismic hazards.

PSHA provides a framework to identify and quantify these uncertainties. The identified uncertainties are then orderly combined to give a more complete picture of seismic hazards. The PSHA method is significantly similar to the method well explained by Cornell (1968) and Algermissent (1982) [12].

ATTENUATION RELATIONSHIPS

Attenuation relationships are considered a core part of seismic hazard analysis. Despite efforts to discard doubtful information and use qualitative, weighted information, information dispersion will be inevitable. This dispersion can be attributed to the random nature of the failure mechanism, variability and multiplicity of seismic sources, seismic wave motion and path, and site conditions. Information dispersion around a mean value directly affects the seismic hazard analysis results; therefore, it should be properly considered in calculations. The standard deviation is conventionally used to reduce information dispersion [13-14]. The uncertainty in attenuation relationships can be considered in probabilistic calculations using the standard deviation from the desired mean. For example, using a given attenuation relationship, when it is assumed to calculate the probability of exceeding the ground motion parameter Y from the known value y due to an earthquake with a magnitude of m and a distance of r, this parameter is calculated as follows:

$$P[Y > y \mid M = m, R = r] = 1 - f_z(Z) \tag{1}$$

where fz(Z) is dependent on the standard deviation from the mean in the attenuation relationship on the one hand, and the probabilistic distribution of parameter Z is involved in its calculation on the other hand. The parameter Z can be calculated from the difference between the attenuation relationship for given m and r (representing the mean value) and the desired value (y) using the existing standard deviation in the attenuation relationship:

$$Z = \frac{y - \bar{y}}{\delta} \tag{2}$$

where $\bar{y} = f(m, r, C_i)$ and δ is the standard deviation of the attenuation relationship. Knowing the probabilistic distribution of Z, the probabilistic distribution function and, thereby, the required probability can be calculated. The ground motion parameters are generally assumed to have a normal logarithmic distribution, i.e., the logarithm of the desired parameter has a normal distribution. Using such an assumption, the attenuation relationships can be used in seismic hazard analysis calculations considering their uncertainty. It is noteworthy that the employed relationships can also be used for the Near Field sites.

SELECTED ATTENUATION RELATIONSHIPS

Selecting proper attenuation relationships plays a vital role in the reliability of final hazard analysis results. To this end, this study used three different attenuation relationships in calculations. After comparing the results from the above relationships by applying a logic tree and attributing appropriate weights for each relationship, the final results are summarized.

1. **ZARE ATTENUATION RELATIONSHIPS (1999)**

[15-16]

$$\log \mathrm{A} = \mathrm{aM} + \mathrm{bX} + \mathrm{C_i S_i} + (\sigma)\mathrm{p}$$

M: Magnitude (Mw) (3)

$$\mathrm{X}^2 = \mathrm{D}^2 + \mathrm{H}^2$$

X: Hypocentral Distance

H: Focal Depth

C_i : Site Class (C_1 : Rock, C_2 : Hard Alluvium, C_3 : Soft Alluvium, C_4 : Soft Soil), S_i : 0,1, P: 0 ,1

The standard deviation σ is calculated by inserting p=1 in the mean value when p=0.

2. **AMBRASEYS ATTENUATION RELATIONSHIPS (1995)**

$$\log \mathrm{a} = \mathrm{A} + B\mathrm{M_S} + \mathrm{Cr} + D\log r$$

[17]

$$r^2 = d^2 + h_0^2 \tag{4}$$

$$a \text{ is in } g, \text{for } 4.0 \le \mathrm{M} \le 7.4:$$

for horizontal PGA not including focal depth

$$A = -1.09,\ B = 0.238,\ C = -0.00050,\ D = -1,\ h_0 = 6.0\ and\ \sigma = 0.28,$$

for vertical PGA not including focal depth

$$A = -1.34,\ B = 0.230,\ C = 0,\ D = -1,\ h_0 = 6.0\ and\ \sigma = 0.27,$$

for horizontal PGA including focal depth

$$A = -0.87,\ B = 0.217,\ C = -0.00117,\ D = -1,\ h_0 = h\ and\ \sigma = 0.26$$

and for vertical PGA including focal depth

$$A = -1.10,\ B = 0.200,\ C = -0.00015,\ D = -1,\ h_0 = h\ and\ \sigma = 0.26.$$

3. BOORE, JOYNER AND FUMAL ATTENUATION RELATIONSHIPS (1981)

[18]

$$\ln Y = b_1 + b_2(\mathbf{M} - 6) + b_3(\mathbf{M} - 6)^2 + b_5 \ln \mathrm{r} + b_V \ln (V_S / V_A)$$

$$r = sqrt(r_{jb}^2 + h^2) \tag{5}$$

for strike-slip earthquakes $b_1 = b_{1SS}$

for reverse-slip earthquakes b_{1RS}

if mechanism is not specified b_{1ALL}

Y is the ground motion parameter (PGA, SA) in g

M is moment magnitude

r_{jb} is closest horizontal distance (km) to the vertical projection of the rupture

V_S is the average shear wave velocity to 30 m, in m/sec

CALCULATING DIFFERENT PROBABILISTIC HAZARD LEVELS

The PSHA was calculated using the methodology proposed by Russel A. Green and William J. Hall (1994). Tables 4 to 8 report the PSHA results for the horizontal and vertical peak ground accelerations on the seismic bedrock using the selected attenuation relationships and the results from combining the results of attenuation relationships using the logic tree.

THE RESULTS OBTAINED FROM ZARE ATTENUATION RELATIONSHIPS (1999)

Table 4 shows the PSHA results for horizontal peak ground acceleration on the seismic bedrock obtained from the Zare attenuation relationship (1999). The vertical peak ground accelerations are given in Table 5. The results are obtained for the combined seismic sources with return periods of 475 and 2475 years and damping of 5%.

Table 4. Horizontal peak ground acceleration.

Return period	H.PGA(g)
475	0.47
2475	0.85

Table 5. Vertical peak ground acceleration.

Return period	V.PGA(g)
475	0.29
2475	0.53

THE RESULTS OBTAINED FROM BOORE, JOYNER AND FUMAL ATTENUATION RELATIONSHIPS (1981)

The results are shown in Table 6. The results are obtained for the combined seismic sources with return periods of 475 and 2475 years.

Table 6. Horizontal peak ground acceleration.

Return period	H.PGA(g)
475	0.38
2475	0.56

THE RESULTS OBTAINED FROM AMBRASEYS ATTENUATION RELATIONSHIPS (1996)

These results are presented in Tables 7 and 8. The results are obtained for the combined seismic sources with return periods of 475 and 2475 years.

Table 7. Horizontal peak ground acceleration.

Return period	H.PGA(g)
475	0.36
2475	0.53

Table 8. Vertical peak ground acceleration.

Return period	V.PGA(g)
475	0.18
2475	0.30

THE RESULTS OBTAINED FROM COMBINING ATTENUATION RELATIONSHIPS

The PSHA results obtained from the above attenuation relationships were combined by applying a logic tree, and the results are reported in Tables 9 and 10. The coefficients of the above attenuation relationships for applying the logic tree are as follows:

Horizontal component: Zare (1999): 0.5, Boore (1981): 0.25, Ambraseys (1996): 0.25

Vertical component: Zare (1999): 0.6, Ambraseys (1996): 0.4

Table 9. Horizontal peak ground acceleration.

Return period	H.PGA(g)
475	0.42
2475	0.70

Table 10. Vertical peak ground acceleration.

Return period	V.PGA(g)
475	0.25
2475	0.44

CONCLUSIONS

The recent Malard Earthquake with a magnitude of 5.2 on the Richter scale and multiple earthquakes with magnitudes above 4 have increased the importance of seismic studies in the region. Seismic hazard studies are among the key preliminary urban development studies for preventing seismic vulnerability. The identification of seismic source zones is closely related to development infrastructure in any region. The results of these studies are widely used in vital projects such as water, gas, oil transmission lines, dam and airport construction, and residential development, and overlooking them may cause great damages. The earthquake hazard analysis based on the accurate location of seismic zones will provide more reliable results. The investigation of the region under study, its history of seismicity, and the recent earthquakes indicate the existence of seismic activity in the region. Considering the shallow depth of earthquakes, the intensity of earthquakes occurred in the region is high. Moreover, the calculation of β and λ parameters (ranging from 6.2 to 7.6) shows the seismicity of the region, indicating the need for observing safety measures in the constructions in the region. As mentioned earlier, the recent seismic activities and earthquakes in the region have doubled the importance of seismic studies and measures for strengthening seismic stations in the region. Moreover, the review of seismic catalogs show that the study area has been inactive over the past few decades and hence its sudden activity is quite significant.

Proposing a new seismotectonic model for Alborz Province and presenting the peak ground acceleration of seismic sources for this province are among the novelties of this study. The horizontal and vertical peak ground accelerations were also calculated by the selected relationships. The results indicated a high seismic hazard in this region which should be considered in calculations of vital structures.

Horizontal peak ground acceleration on the seismic bedrock with a return period of 475 years=0.42g

Horizontal peak ground acceleration on the seismic bedrock with a return period of 2475 years=0.70g

Vertical peak ground acceleration on the seismic bedrock with a return period of 475 years=0.25g

Vertical peak ground acceleration on the seismic bedrock with a return period of 2475 years=0.44g

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