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# Probabilistic seismic hazard assessment of Sanandaj, Iran

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**Abstract.** In this paper, the peak horizontal ground acceleration over the bedrock (PGA) is calculated by a probabilistic seismic hazard assessment (PSHA). For this reason, at first, all the occurred earthquakes in a radius of 200 km of Sanandaj city have been gathered. After elimination of the aftershocks and foreshocks, the main earthquakes were taken into consideration to calculate the seismic parameters (SP) by Kijko (2000) method. The seismotectonic model of the considered region and the seismic sources of the region have been modeled. In this research, Sanandaj and its vicinity has been meshed as an 8 (vertical lines) * 10 (horizontal lines) and the PGA is calculated for each point of the mesh using the logic tree method and the five attenuation relationships (AR) with different weighted coefficient. These calculations have been performed by the Poisson distribution of four hazard levels. Then by using it, four regional maps of the seismic hazard regions have been provided for Sanandaj and its vicinity. The results show that the maximum and minimum value of PGA for the return periods of 75, 225, 475, 2475 years are (0.114, 0.074) (0.157, 0.101), (0.189, 0.121) and (0.266, 0.170), respectively.

**Keywords:** probabilistic seismic hazard assessment; seismicity parameters; peak ground acceleration; Sanandaj, Iran.

## 1. Introduction

Many disasters have been occurred in Iran due to the occurrence of earthquakes, causing large economic and life losses. The specifications of some catastrophic earthquakes like Bouin-Zahra

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(1962), Dashte Baiaz (1967), Tabas (1978), Manjil_Roudbar (1990) and Bam (2003) demonstrate lack of our knowledge about the earthquakes. Sanandaj city is situated near the faults which are along the Zagros faults. Occurrence of several earthquakes in recent years (especially since 2000) proves that the faults of Zagros have been activated.

Sanandaj is the administrative centre of Kurdistan province in Iran, in which more than 500,000 people live in. The city has fundamental installations and attractive places for tourists and its many other potentialities for development can make it one of the significant centers of the country. Any strong earthquake may then make considerable damages in there. So, the importance of such studies is apparent.

The recent study, Probabilistic Seismic Hazard Assessment of the Kermanshah-Sanandaj Region of Western Iran, Peak Ground Acceleration values for Sanandaj city and its vicinity are estimated from 0.05 g to 0.15 g with 10% probability of being exceeded in 50 years (Shabani *et al.* 2007).

The study by Ghodrati *et al.* (2003), Peak Ground Acceleration in the Tehran renges from 0.27 g to 0.46 g for a return period of 475 years (Ghodrati *et al.* 2003).

The existence of active faults of Morvarid, Piranshahr, Dinvar, Sahneh, Nahavand, Garoun and the fault of the Zagros edge in the vicinity and the occurrence of severe earthquakes in the past show that the region has high seismicity and severe earthquakes are probable in the future. Fig. 1 represents the faults of the region.

The studied region encircles Sanandaj city with the radius of 200 km.

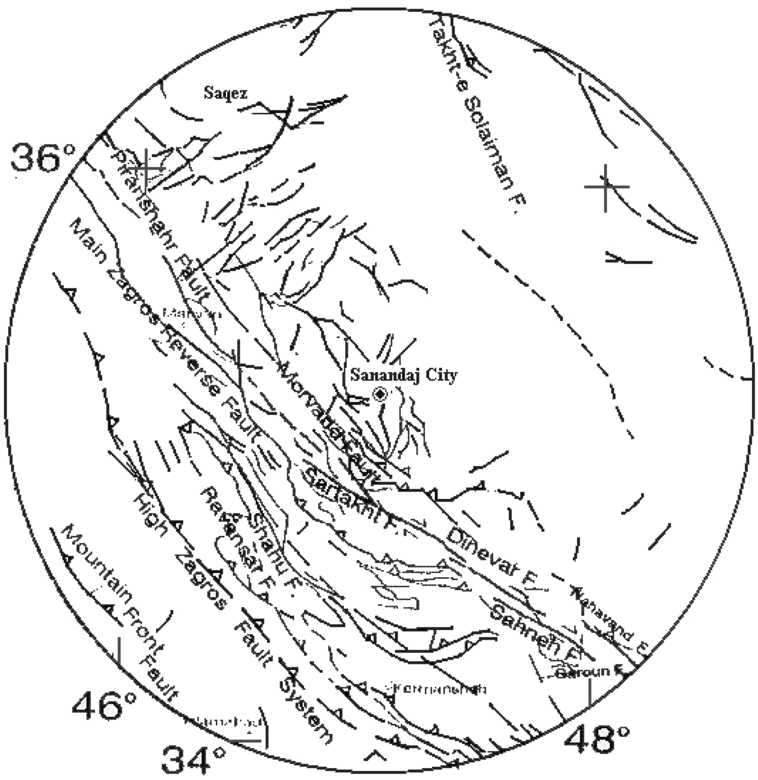


Fig. 1 Map of region faults (Hesami *et al.* 2001, 2003, Berberin *et al.* 1995, Tchalenko *et al.* 1974)

## 2. Geology and geotectonic

Based on geological and geotectonical references, Sanandaj is situated in the zone of Sanandaj-Sirjan band (as an independent region of the central Iran) and also located near to the zone of high Zagros.

According to geological studies, Sanandaj-Sirjan zone is the most active tectonic zone in Iran. The zone is influenced by the Mesozoic tectonic occurrences and severe foldings, faultings and Magmatism have been caused. But Cenozoic era appears as erosion without folding in the zone. In fact severe faulting and relative erosion caused in Mesozoic tectonic occurrences in Sanandaj-Sirjan zone have saved it from getting buried under Cenozoic deposits. Only so me shale and sandstone appearances are seen in small areas in west and east of Khomein located in the low parts of Sanandaj-Sirjan band. These are the youngest deposits of this zone. Besides, driving the oceanic crust of the high Zagros under the south active edge of central Iran (Sanandaj-Sirjan belt) has caused a Magmatic belt during Mesozoic and possibly tertiary. The Arabian plateau movement towards north and the subduction of its oceanic crust has closed the Alps Ocean of the high Zagros and finally has caused the collision of the central Iran and the Arabian plateau (Berberian *et al.* 1981). On the basis of the available information the thickest part of the crust is situated along Sanandaj-Sirjan (south west of the continental side of central Iran during Mesozoic) and also in the north east part of this zone (the continental side of Paleozoic and near Kopeh Dagh belt). The studied region is situated in the collided area of Iran, Arabia and Caucasus and is involved in motions which are caused by the transaction of these areas. Hence, it has unique seismotectonic specifications (Hesami *et al.* 2001, Berberian 1981).

## 3. The structure of the earth's crust

According to deep seismic profiles from reflexive method the crust's thickness under Sanandaj_ Sirjan belt (that is located next to Zagros) is 60 km. The existence of a stratum with low celerity of seismic waves in the middle of the two known surfaces as Moho (crust-mantle boundary) beneath the defined zone shows that the earth crust is situated beneath the high Zagros twice. This phenomenon can be explained by considering the Arabia crust beneath the central Iran. The Moho depth map that is provided on the basis of the gravity field also shows that the earth crust thickness in the vicinity of the studied region is about 50 km (Dehghani *et al.* 1983).

## 4. Active faults

As the ground motion along the faces of a fault usually accompanies with earthquakes, consideration of active faults is important for the seismotectonic studies. In this part, we describe those faults which are recognized as seismic sources in the studied region on the basis of the available evidences and resources. Table 1 represents the specifications of the active faults in a 200 km radius of Sanandaj.

Table 1 Specifications of the active faults in a 200 km radius of Sanandaj (Hesami *et al.* 2001, Berberin 1995, Tchalenko *et al.* 1974)

| No | Fault Name | Type of Faulting | Dip and Direction | Fault Length (km) | Min. distance (km) |
|---|---|---|---|---|---|
| 1 | Morvarid | Strike-slipe | High Angle to Vertical | 45 | 28 |
| 2 | Sartakht | Strike-slipe | High Angle to Vertical | 75 | 36 |
| 3 | Piranshahr | Strike-slipe | High Angle to Vertical | 130 | 58 |
| 4 | Dinavar | Strike-slipe | High Angle to Vertical | 44 | 69 |
| 5 | Sahneh | Strike-slipe | High Angle to Vertical | 47 | 91 |
| 6 | Nahavand | Strike-slipe | High Angle to Vertical | 100 | 121 |
| 7 | Garoun | Strike-slipe | High Angle to Vertical | 25 | 148 |
| 8 | Zagros mountain front | Reverse | Low to High Angle-NE | > | 135 |

## 5. Earthquake datas

Past earthquakes in the studied region can be divided into three categories:
1) Historical earthquakes, for the ones before 1900.
2) Inaccurate instrumental earthquakes; which have been recorded since 1900 till 1963 by seismographs.
3) Accurate instrumental earthquakes; which are the records that have been recorded from 1964 up to now (the time that the study has been performed) by seismographs.

Unfortunately the information of the historical earthquakes of Sanandaj city is too incomplete. According to the available information of the historical earthquakes, the oldest earthquake of the studied region is Goudin earthquake that has been occurred about 1600-1650 BC. The historical hill of Goudin which its history returns back to 5500 BC, is situated between faults of Nahavand and Sahneh. The place was vanished with its main buildings about 1600-1650. All available evidences show that this place has been destroyed by a severe earthquake (Berberian *et al*. 2001). The nearest historical city to Sanandaj was Dinvar, that has been destroyed twice by earthquake. The most severe historical earthquake with the magnitude of Ms7 has been occurred in this city, that made the city completely destroyed and more than 16000 people lost their lives. According to the researches this earthquake was probably accompanied with deformations on the surface of the earth (Ambraseys *et al*. 1982). Some sever earthquakes with the magnitudes of more than Ms6 have been recorded since 1900 either. The most severe earthquake of the region has occurred in the south of Sahneh with the magnitude of mb7.2 (Moinfar *et al*. 1994) and is known as Farsineh earthquake. According to official reports 1130 people died and 211 villages were destroyed. Field investigations show that the earthquake occurred on a buried fault, probably a continuation of the Nahavand Fault (Mirzaei *et al*. 2002).

## 6. Depth mechanism of the earthquakes

Using the mechanism of the epicenter of the occurred earthquakes is one of the approaches to study the active tectonic in the studied region. By using this method we can gather some information about the positions of the fault planes, the direction of the slip vector and principal

Table 2 The presented specifications for eight earthquakes in a radius of 200 km of Sanandaj city by CMT method (Harvard Seismology education 2007)

| No | Date | Time (GMT) | Lat. | Long. | Depth (Km) | Ms | Mb | Mw | Fault Plane 1 | | | Fault Plane 2 | | | Dis.To Site (km) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Strike | Dip. | Slip. | Strike | Dip. | Slip. | |
| 1 | 1990/6/24 | 9:45:56 | 36.08 | 48.91 | 15.0 | 4.6 | 5.1 | 5.3 | 234 | 69 | -163 | 138 | 75 | -22 | 193 |
| 2 | 1998/8/21 | 5:13:14 | 34.38 | 48.03 | 21.9 | 4.4 | 4.9 | 4.9 | 25 | 39 | -84 | 197 | 51 | -95 | 142 |
| 3 | 1999/1/15 | 19:14:14 | 35.27 | 44.97 | 33.0 | 4.5 | 5.0 | 5.1 | 128 | 29 | 86 | 312 | 61 | 92 | 185 |
| 4 | 2002/4/24 | 19:48:09 | 34.39 | 47.55 | 33.0 | 5.2 | 5.2 | 5.4 | 36 | 74 | 16 | 302 | 75 | 163 | 114 |
| 5 | 2002/6/22 | 2:58:29 | 35.82 | 48.97 | 15.0 | 6.4 | 6.2 | 6.5 | 295 | 29 | 99 | 104 | 62 | 85 | 188 |
| 6 | 2002/9/02 | 1:00:00 | 35.65 | 48.95 | 15.0 | | 5.1 | 5.2 | 105 | 34 | 71 | 308 | 58 | 103 | 181 |
| 7 | 2002/12/24 | 17:03:05 | 34.54 | 47.66 | 26.9 | 4.4 | 5.1 | 5.2 | 284 | 45 | 105 | 82 | 47 | 75 | 105 |
| 8 | 2006/6/06 | 17:03:12 | 35.97 | 46.06 | 25.2 | 4.9 | 5.0 | 4.8 | 313 | 41 | -168 | 214 | 82 | -49 | 113 |

stresses in the region. The depth mechanism of eight earthquakes in a radius of 200 km of Sanandaj city has been presented on the basis of the information of the Harvard University by Centroid Moment Tensor (CMT) method. The Table follows, contains the earthquakes of the studied region that their mechanism has been presented by the Harvard CMT Catalogue (Harvard Seismology education 2007). Among the eight earthquakes that their mechanisms have been presented, three of them are straight-slip. Four earthquakes have compressive mechanisms and one has tensile mechanism. Statistically, the main mechanism in the studied region can be assumed compressive up to straight-slip. In Fig. 2 the mechanism is represented.

## 7. Focal depth of the earthquakes

On account of few reliable earthquake data in the studied region, accurate information is not available about the depth of the ordinary earthquakes. Although focal depths have been reported for many of occurred earthquakes in the studied region, but due to small magnitude of most occurred earthquakes and weak arrangement of stations, they are not reliable. The main seismic activities (moderate and severe earthquakes) in this region generally have depth smaller than 20 km, according to the performed researches in the region of Zagros (Maggi *et al.* 2002). Besides, on the basis of various geological evidences, the mean depth of the seismic zone in the studied region is considered (8~12) km.

## 8. Seismotectonic of Sanandaj city

Based on seismotectonic, the studied region contains the seismotectonic units of Maraghe-Sirjan (including two tectonic zones: Sanandaj-Sirjan and Oroumiye-Dokhtar in the middle of Zagros and central Iran), the high Zagros, the driven folded thrust of Zagros and Central Alborz.

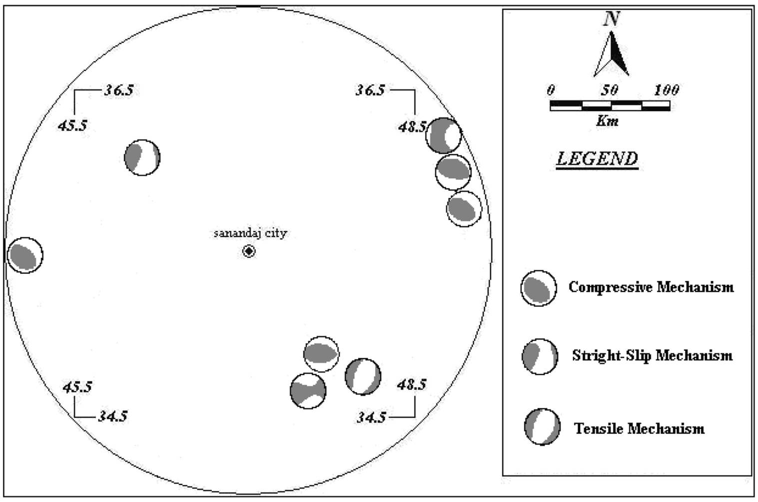


Fig. 2 The depth mechanism of eight earthquakes in the vicinity of Sanandaj by CMT method (Harvard Seismology education 2007)

## 9. Seismotectonic model of Sanandaj city

Based on the performed studies, the studied region is situated in the collided part of Iran, Arabia and Caucasus and mainly has got involved in vertical strike-slip and transitional motions. Structural elements of studied region consist of faults with north-west; south-east direction and reverse strike-slip reverse mechanism. Vertical component along these structures is mainly reversed (compressive) (Harvard Seismology education 2007, Hesami *et al.* 2001, Berberian 1981). Release rate analysis of seismic moment of earthquakes in the studied region shows that main part of energy releases along the strike-slip moving faults. But this is incompatible with the expected shortening of the region. So, this is the fact that increases the probability of moderate and severe earthquakes (Tchalenko *et al.* 1974). Most of the past earthquakes in the region were those have small depth and in many cases the bedrock is involved in deformations. The mean Moho depth is about 50 km and the depth of the seismic stratum has been assessed 8-12 km. (Maggi *et al.* 2002), According to focal mechanism of past earthquakes and tectonic evidences, the mechanisms of the reverse faults are predominant in the studied region but the effect of the reverse strike-slip faults can’t be ignored. Groups of young faults of Zagros as reverse strike-slip faults are most active faults of the region which encircle its young and principal deformations.

Based on the latest studies performed (Tavakoli 1996), Iran is divided into 20 seismotectonic provinces and earthquake hazard parameters were estimated for each of them. The studied region is situated in provinces 9-11-12-15 (zones of Maraghe-Sirjan, high Zagros, folded thrust belt of the Zagros and Central Alborz). Fig. 3 represents 20 seismotectonic provinces of Iran. Sanandaj city and its vicinity (the studied region) are located in the 9$^{th}$ seismotectonic province.

## 10. The assessment of seismic potential of faults in Sanandaj city region

Several methods are used to assess seismic potential of faults which can be divided into two categories. Initial evidences are used to estimate the magnitude of earthquakes in the first category where the length of surface rupture and maximum displacement are the most common parameters of evidences. Some other parameters like fault rupture or seismic moment are used also. The second category includes methods that try to assess the magnitude of earthquakes using secondary evidences like liquefaction and landslides. These methods are yet to be developed and experimented. Maximum earthquake magnitude has been assessed by the length of surface rupture in this study.

Nowroozi (1985) relationship was used to express the relationship between fault rupture and the earthquake magnitude (Eq. (1)). The relationship is based on studies about faults of Zagros, northern Alborz, north of Tabriz, Zafareh in north of Isfahan, Dehshir in south of Isfahan, Shahre Babak in Kerman and faults of Doroun and Dashte Baiaz in the region of Makran which have been ruptured by 10 earthquakes. The relationship is:

$$M_S = 1.259 + 1.244[\mathrm{Log}(L)] \tag{1}$$

Where $Ms$ is surface wave magnitude and $L$ is rupture length in meter.

Two models of faulting are used to calculate the maximum magnitude. In the first model 50% of fault length is ruptured during earthquake and in the second one the rupture is 50% to 100% of fault length. Final results will then be extracted using the logic tree mentioned in Fig. 4.

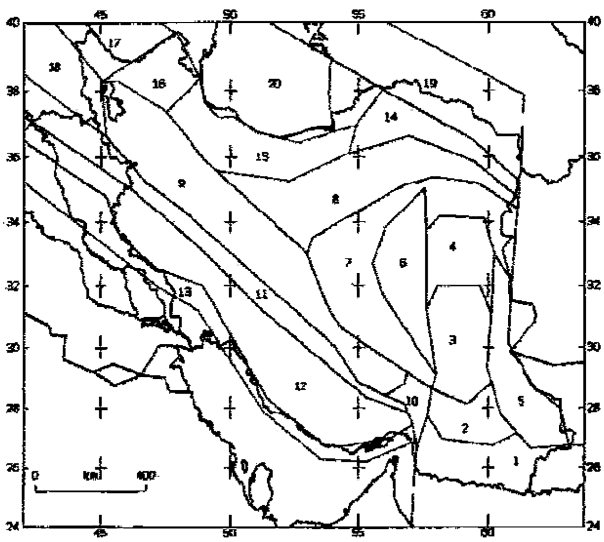

Fig. 3 Iran seismotectonic provinces (Tavakoli 1996)

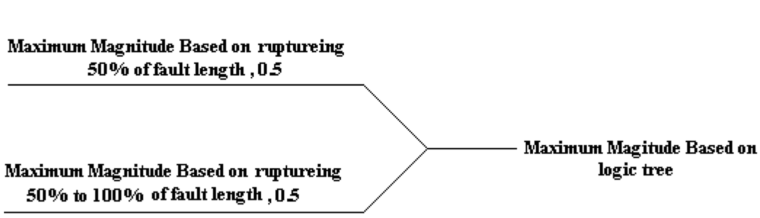


Fig. 4 The logic tree used in calculation of the maximum magnitude

Table 3 The maximum magnitude of the region active faults on the basis of 50% fault rupture

| No. | Fault Name | Fault length | Mmax |
|---|---|---|---|
| 1 | Morvarid | 45 | 6.7 |
| 2 | Sartakht | 75 | 6.9 |
| 3 | Piranshahr | 130 | 7.2 |
| 4 | Dinavar | 44 | 6.7 |
| 5 | Sahneh | 47 | 6.7 |
| 6 | Nahavand | 100 | 7.1 |
| 7 | Garoun | 25 | 6.4 |
| 8 | Mountain Front Fault | > | 7.5 |

Table 4 The maximum magnitude of the region active faults on the basis of 50% to 100% fault rupture

| No. | Fault Name | Fault length | Mmax |
|---|---|---|---|
| 1 | Morvarid | 45 | 7 |
| 2 | Sartakht | 75 | 7.2 |
| 3 | Piranshahr | 130 | 7.4 |
| 4 | Dinavar | 44 | 7 |
| 5 | Sahneh | 47 | 7 |
| 6 | Nahavand | 100 | 7.3 |
| 7 | Garoun | 25 | 6.7 |
| 8 | Mountain Front Fault | > | 7.5 |

Table 5 The maximum magnitude of the region active faults on the basis of the logic tree

| No. | Fault Name | Fault length | Mmax |
|---|---|---|---|
| 1 | Morvarid | 45 | 6.85 |
| 2 | Sartakht | 75 | 7.05 |
| 3 | Piranshahr | 130 | 7.3 |
| 4 | Dinavar | 44 | 6.85 |
| 5 | Sahneh | 47 | 6.85 |
| 6 | Nahavand | 100 | 7.2 |
| 7 | Garoun | 25 | 6.55 |
| 8 | Mountain Front Fault | > | 7.5 |

The maximum magnitude for the active faults of the studied region represented in Table 3 calculated by the first model of faulting. The amounts in Table 4 came out of using the second model of faulting and in Table 5 the final results have been calculated on the basis of the logic tree of Fig. 4.

## 11. The statistical specifications of the seismicity studies

Seismic hazard parameters (maximum expected magnitude of a region (Mmax), annual activity rate ($\lambda$) and seismicity coefficient of region (b)) describe a statistical model of any region as a numerical quantity. In order to assess these quantities, the seismic specifications of past earthquakes in a region should be studied and their effects on the site should be calculated. Therefore it is essential to gather earthquake data and analyze them statistically. These data are received from seismological stations and used for the analysis. The details that these data include, are date and time of occurrence, coordination of epicenter, magnitude, focal depth and the reporting center. There are some differences in determined parameters reported by deferent resources. These differences are due to the complicated specifications of earthquakes and possible errors in measurements of stations.

## 12. Selection of the type of earthquake magnitude

Earthquake magnitude is one of the important parameters to analyze and predict the strong ground motion. In fact the strength of an earthquake is assessed by magnitude scales. This parameter is estimated from the peak wave amplitude which is recorded by seismograms. Different types of magnitudes are defined considering type and period of waves and also distance from epicenter. This is indicated by the magnitude sign, $M$, and different subscripts. Since all magnitudes reported for historical earthquakes are in the form of surface wave, $Ms$, also instrumental earthquakes are based on surface wave, $Ms$, or body wave ($m_b$). Then, the magnitude of the surface wave, $Ms$, is used for all data. Using the relationship (Eq. (2)) presented by Iranian Committee of Large Dams (IRCOLD 1994), the magnitude of $m_b$ is converted into $Ms$:

$$M_S = 1.2m_b - 1.29 \tag{2}$$

## 13. Elimination of the foreshocks and aftershocks

In seismic hazard analysis of a region it is assumed that occurred earthquakes are location and time independents. It means that earthquakes occur successively in space and time along faults or in seismic regions. Therefore the occurrence time of an upcoming earthquake is independent from the last earthquake.

Regarding the mentioned limitations, foreshocks and aftershocks that are related to principal earthquakes should be eliminated from the data base. The most conmen method to eliminate aftershocks and foreshocks is to consider the time and location windows for their occurrences. Therefore in order to detach aftershocks and foreshocks from principal earthquakes and eliminate them from Catalogue, following conditions are followed:

- Their magnitudes must be less than the magnitude of the principal earthquake ($M$).
- The distance between epicenters of these earthquakes from the principal earthquake must be less than $S_{(M)}$.
- Time differences between these earthquakes and the principal earthquake should not be more than $T_{(M)}$.

$S_{(M)}$ and $T_{(M)}$ are experimental parameters. In this study Gardner and Knopoff (Gardner *et al.* 1974) method is used to eliminate aftershocks and foreshocks. The catalogue of principal earthquakes for the studied region is presented as an attachment.

## 14. Time distribution of peak earthquake magnitudes

In order to probabilistic seismic hazard study the earthquake catalogue in a 200 km region encircling Sanandaj has been gathered and processed to eliminate aftershocks and foreshocks.

According to historical earthquakes in the region the most severe earthquake occurred on April 27, 1008. The magnitude of the earthquake was 7 and its epicenter was located in 42 km from Sanandaj city. Fig. 5 represents the time distribution of peak earthquake Magnitudes of historical earthquakes and Figs. 6 and 7 represent the distribution for instrumental earthquakes occurred in a 200 km radius of Sanandaj city. The highest recorded magnitude of instrumental earthquakes in the studied region is 7.2 in the form of body wave (mb) (Moinfar *et al.* 1994). The earthquake occurred

Table 6 Time and location windows for elimination of aftershocks and foreshocks by Gardenr and Knopoff method (Gardner *et al.* 1974)

| Magnitude (*Ms*) | Distance (km) | Time (day) |
|---|---|---|
| 4 | 30 | 42 |
| 4.5 | 35 | 83 |
| 5 | 40 | 155 |
| 5.5 | 47 | 290 |
| 6 | 54 | 510 |
| 6.5 | 61 | 790 |
| 7 | 70 | 915 |
| 7.5 | 81 | 960 |
| 8 | 94 | 985 |

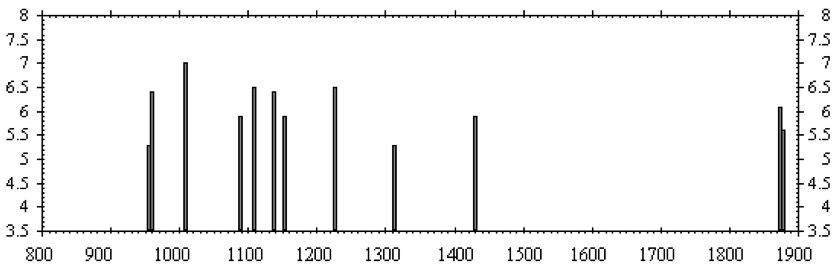


Fig. 5 Time distribution of peak magnitude of the historical earthquakes in a 200 km radius of Sanandaj city

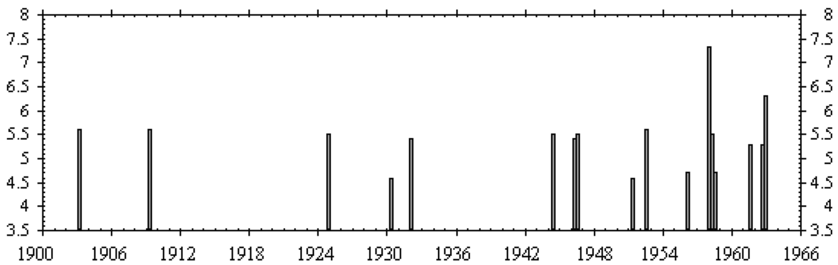


Fig. 6 Time distribution of peak magnitude of instrumental earthquakes (1900-1964) in a 200 km radius of Sanandaj city

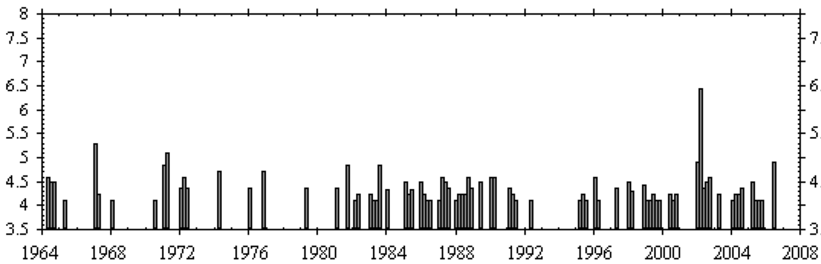


Fig. 7 Time distribution of peak magnitude of instrumental earthquakes (1964-2006) in a 200 km radius of Sanandaj city

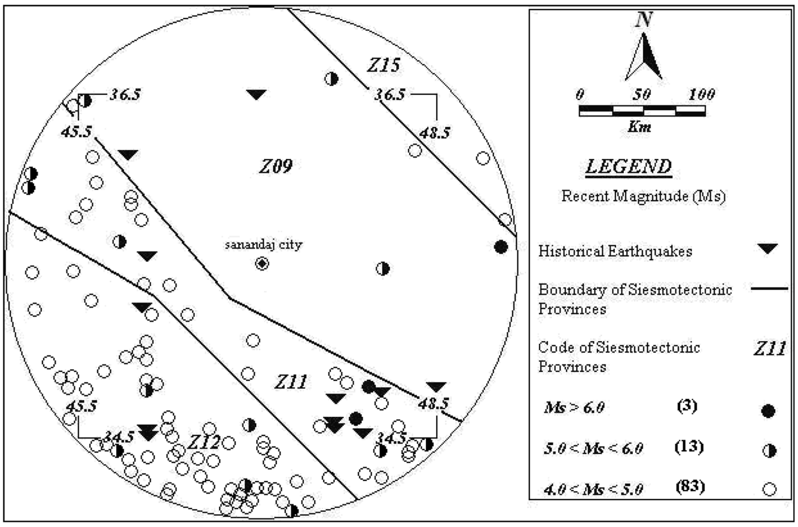


Fig. 8 The distribution of peak magnitude of historical & instrumental earthquakes in a 200 km radius of Sanandaj city

on December 13, 1957 in the region of Farsinj, 106 km far from Sanandaj city.

According to statistical analysis of instrumental earthquakes (from 1900 till 2006) in the region, 16% of earthquakes have magnitude greater than 5 ($Ms > 5.0$) and 84% of them are less than 5 ($Ms < 5.0$).

Fig. 8 represents the location of occurred earthquakes in a 200 km radius of Sanandaj city. The figure also represents boundaries of seimsotectonic provinces that are developed by Tavakoli (Tavakoli 1996) in the studied region.

The complete details of the earthquakes in a region of 200 km radius encircling Sanandaj city are attached.

## 15. Assessment of earthquake hazard parameters

Earthquake hazard parameters such as, maximum expected magnitude, *Mmax*, the rate of earthquake occurrence with different magnitudes (activity rate), $\lambda$, and b. The seismic hazard coefficients of the region (value of the Gutenberg and Richter (1954) relation) have been evaluated using maximum likelihood method (Kijko and Sellevoll 1992). Besides, the return period and the occurrence probability of each magnitude have also been calculated by the Kijko (2000) software. Regarding the importance of seismic hazard parameters, they are calculated using Tavakoli (Tavakoli *et al.* 1999) method, too. Then final results are came out by using the logic tree.

## 16. Selection of the assessment method of earthquake hazard parameters

Different methods are used in assessment of seismic hazard parameters. Selection of the proper method is done on the basis of engineering judgment, reliability of the seismic data and uncertainties in their report. Usually recorded earthquakes of any region in Iran only represent a part of occurred earthquakes in the region and many earthquakes are never recorded. Some reasons of insufficiency of earthquake data in Iran can be expressed as follows. In the case of historical earthquakes, historians might have not recorded some earthquakes or some records might have ruined or in some cases they might have been ignorant of some earthquakes because of the distance. And in the case of instrumental earthquakes, lack of seismographs was the most reason. The accuracy of recorded data also varies. Thus historical earthquakes are more uncertain and instrumental earthquakes which occurred in resent years are more accurate. Therefore, Kijko (2000) method is used to calculate the seismic hazard parameters. The method has the ability to analyze earthquake data of different accuracy. The parameters are also calculated by Tavakoli (1996) method due to the importance of the case.

## 17. Assessment of seismic hazard parameters with Kijko

In this study, the minimum magnitude (*Mmin*) is 4 in the form of surface waves (*Ms*). Kijko method is based on double truncated Gutenberg-Richter distribution function and the Maximum Likelihood estimation method.

In this paper three different categories of earthquakes are taken into consideration:

1. Historical earthquakes (before 1900) with the magnitude error of 0.5 (the first time period)
2. Inaccurate instrumental earthquakes (1900-1963) with the magnitude error of 0.2 (the 2nd time period)
3. Accurate instrumental earthquakes (1964-2006) with the magnitude error of 0.1 (the 3rd time period)

The calculation results of seismic hazard parameters from all historical and instrumental earthquakes by using Kijko method are as follows:

*Beta* = 2.22 ± 0.1 (*b* = 0.96 ± 0.05)
*Lambda* = 0.92 ± 0.09 (for *Mmin* = 4.00)
*Lambda* = 0.30 ± 0.03 (for *Ms* = 4.50)
*Mmax* = 7.66 ± 0.37 (for *SIG* (Xmax) = .20)

Besides, the seismic hazard parameters of historical and instrumental earthquakes are calculated separately. Calculation results of the seismic hazard parameters for each of three time periods are represented in Table 7 for comparison.

Table 7 The result values of the calculated seismic hazard parameters in different time periods by Kijko method

| Catalogue | Parameter | Value | Data Contribution to the Parameters (%) | | |
|---|---|---|---|---|---|
| | | | Period#1 | Period#2 | Period#3 |
| 20th Century Earthquakes Data | Beta | 2.03 | | 23.4 | 76.6 |
| | Lambda (for Ms=4) | 1.08 | | 17.2 | 82.8 |
| Historical Earthquakes Data | Beta | 2.27 | 100 | | |
| | Lambda (for Ms=4) | 0.42 | 100 | | |
| Historical and 20th Century Data | Beta | 2.22 | 53.6 | 17.7 | 28.7 |
| | Lambda (for Ms=4) | 0.92 | 10.8 | 15.3 | 73.9 |

## 18. Return period analysis of earthquakes

After calculating the seismic hazard parameters, the return period of earthquakes in the studied region are calculated. Fig. 9 represents the return period of earthquakes of different magnitudes for Sanandaj city and its vicinity.

According to this analysis, an earthquake with the magnitude of 6 occurs in the studied region every 100 years. For return periods of 75, 225, 475, 2475 years which are the introduced hazard levels in the Prestandard and Commentary for The Seismic Rehabilitation of Building (FEMA 365, 2000), the earthquake magnitudes are assessed 5.9, 6.4, 6.7 and 7.25, respectively.

As it is mentioned previously, the seismic hazard parameters of the studied region are calculated by Tavakoli (Tavakoli *et al.* 1999) method, too. As Sanandaj city and its vicinity are situated in the 9$^{th}$ seismotectonic province seismic hazard parameters of this province are shown in Table 8.

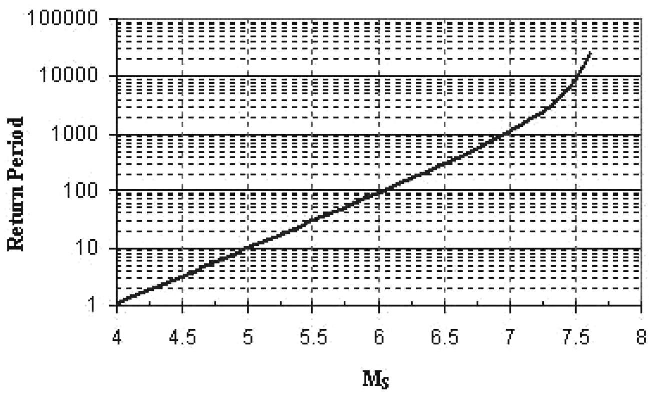


Fig. 9 The relationship between the return period and the magnitude by using Kijko method

Table 8 Estimated earthquake hazard parameters for the tectonic province of Sanandaj city by Tavakoli method (Tavakoli 1996)

| Province No. | Span of time | Beta | M max | Lambda (Ms = 4.5) |
|---|---|---|---|---|
| 9 | 1922-1995 | 1.94 ± 0.16 | 7.3 ± 0.3 | 0.27 |

## 19. Strong ground motion parameters in the region of Sanandaj city

Different parameters are involved in ground motion. These parameters are the peak velocity, the peak acceleration, the maximum displacement and other parameters which are present in the frequency content of the records. The peak horizontal ground acceleration and respond spectrum are two index parameters representing the nature of the strong ground motion. Both parameters are highly dependent to the earthquake magnitude, epicenter distance and geological specifications.

## 20. The peak horizontal ground acceleration

In this paper in order to assess the parameters of the ground motion, the peak ground acceleration over the bedrock (PGA) is calculated by probabilistic seismic hazard analysis. The peak ground acceleration over the bedrock (PGA), is represented by, A, in Iranian Code of Practice for Seismic Resistant Design of Buildings (BHRC 2005) that is used to directly calculate the base shear exerted to the buildings by earthquake.

## 21. Earthquake hazard analysis

The strong ground motion is assessed by the earthquake hazard analysis. This analysis can be performed by two methods: deterministic method and probabilistic method. In Defining method, a controlling earthquake is usually considered by the magnitude and the distance from the structure. This earthquake causes the peak strong ground motion in the studied region. In the probabilistic method, the peak strong ground motion is assessed by a model including geological information, seismicity and attenuation information for different time periods and hazard levels.

## 22. Basic steps in the assessment of the earthquake hazard analysis by probabilistic method

The steps for seismic hazard assessment for an ideal "bedrock" condition can be summarized as follows:

(1) Modeling of seismic sources, (2) evaluation of recurrence relationship, (3) elevation of attenuation relationship for peak ground acceleration, (4) estimation of activity rate for probable earthquakes, (5) evaluation of basic parameters such as maximum magnitude (Abdalla *et al*. 2001, Ghodrati Amiri *et al*. 2003).

Numerous seismic hazard forecasting models were developed within the last several decades. The simplest widely used model is the Poisson model with the assumptions that seismic events are spatially and temporally independent and the probability that two seismic events will take place at the same location and at the same time approaches zero (Kayabali 2002).

It is mentioned previously that the occurrence relationship of Gutenberg and Richter and Poisson model are used as the function of the probability prediction of the earthquake occurrence in the future.

## 23. Seismic sources model in the region of Sanandaj city

There are different ideas to select seismic sources model. The point sources model is not very accurate because of the uncertainty in the location of the earthquakes and inadequate data of past earthquakes. In the case of the regional sources model, there isn't enough information about different regions in Iran. Consequently, assuming the same seismicity parameters, the model of linear sources is used and it is also assumed that the seismic power of all the active faults in the region is equal.

## 24. Selection of the proper attenuation relationship

Attenuation relationships are one of the most important elements in the seismic hazard analysis which represent the relationship between peak ground acceleration, the distance from the surface epicenter of the earthquake and the magnitude. Selection of the most proper model among the various attenuation models of the strong ground motion is done based on following criteria:

- The relationship can be applicable for the studied region.
- The distance of the site or sites from the seismic sources must be in the determined maximum and minimum range of the relationship.
- The earthquake magnitude scale of the region is as the same as the magnitude scale in the relationship.
- The maximum and minimum values of earthquake magnitudes in the region are the same as the magnitudes from relationship.
- The focal depth of earthquakes of the region must be in the range of the attenuation relationship.
- The soil type of the studied region and the attenuation relationship must be the same.

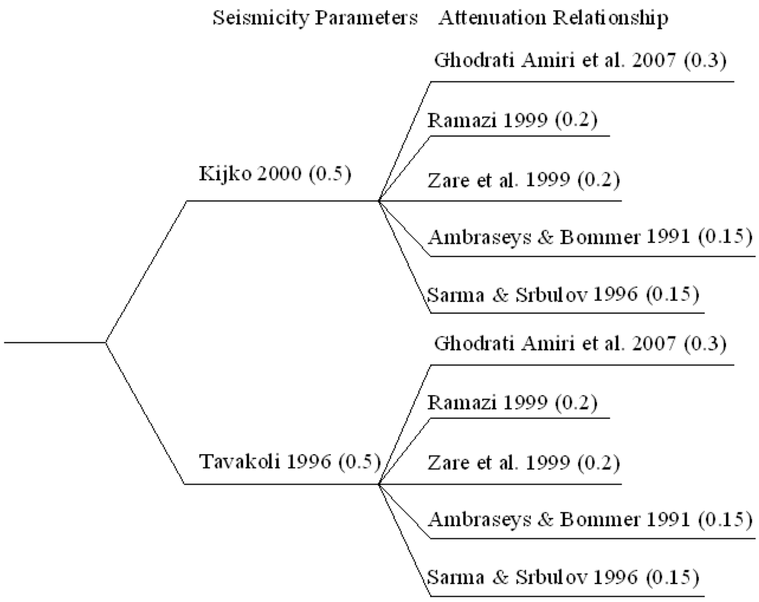


Fig. 10 Logic tree coefficients used in calculations

- The mechanism of the most seismic sources of the studied region must be the same as the mechanism of the attenuation relationship.

In this study, after assessing different attenuation relationships according to mentioned conditions, five attenuation relationships Ghodrati Amiri *et al.* (2007), Ramazi (1999), Zare *et al.* (1999), Ambraseys and Bommer (1991) and Sarma and Srbulov (1996) with the related coefficient of the logic tree 0.3, 0.2, 0.2, 0.15 and 0.15 are chosen respectively.

As Ghodrati Amiri *et al.* (2007), Ramazi (1999) and Zare *et al.* (1999) relationships are merely for Iran then they are thought over to be more accurate for the calculation of the strong ground motion in Iran. Consequently higher weighted coefficient is given to them. But the highest weighted coefficient is given to Ghodrati Amiri *et al.* (2007) because it is recent. Ambraseys and Bommer (1991) and Sarma and Srbulov (1996) which are for the Middle East and global respectively, are given the same coefficient. Ambraseys and Bommer (1991) relation is for the Middle East and ought to be more accurate than the global relation of Sarma and Srbulov (1996), but as the global relation is recent, then, they are given the same weighted coefficient.

## 25. Seismic hazard assessment in the region of Sanandaj city by the probabilistic method

In this Research the structure of Sanandaj city and its vicinity is subdivided into a grid of 8×10, total of 80 sites, with eight vertical and ten horizontal lines that the distance between every two subsequent vertical lines is 1.66 km and the distance between every two subsequent horizontal lines is 1.82 km. Probabilistic seismic hazard analysis is then carried out for each site. In order to analyze the seismic hazard regarding the region faults, the seismic sources of the region are modeled and with the required parameters for the seismotectonic model, the calculated seismicity parameters by each of the two methods and peak values of the strong ground motion that have been calculated for each of attenuation relationships are introduced separately to SEISRISK III (Bender *et al*. 1987). The program outputs are mixed by logic tree coefficients as shown in Fig. 10. Then final result, as peak ground acceleration over the bedrock (PGA) is calculated for 80 sites of Sanandaj city (the points of the introduced mesh), based on 50%, 20%, 10%, and 2% probability of being exceeded during life cycles of 50 years or the return periods of 75, 225, 475 and 2475 years respectively, that are introduced hazard levels in the Seismic Rehabilitation Code for Existing Buildings in Iran (FEMA 365, 2000). Iso-acceleration zoning map of of Sanandaj city structure for each hazard level is represented in Figs. 11 to 14. Figures show that the south western parts of Sanandaj city have the highest peak ground acceleration.

The comparison of the calculated values in this study in the return period of 475 years with the proposed design acceleration of the Iranian Code of Practice for Seismic Resistant Design of Buildings (BHRC 2005) (A = 0.3 g) shows that the proposed values of the 2800 manual are conservative. The difference between the results of the present study and the design value of the 2800 manual is because the Iranian Code gives the PGA for a large area including many places including many cities and a lot of villages. It may be the greatest PGA calculated for different parts of that area. But, this study is for limited region with its special conditions, so the PGA obtained is more precise for the studied region.

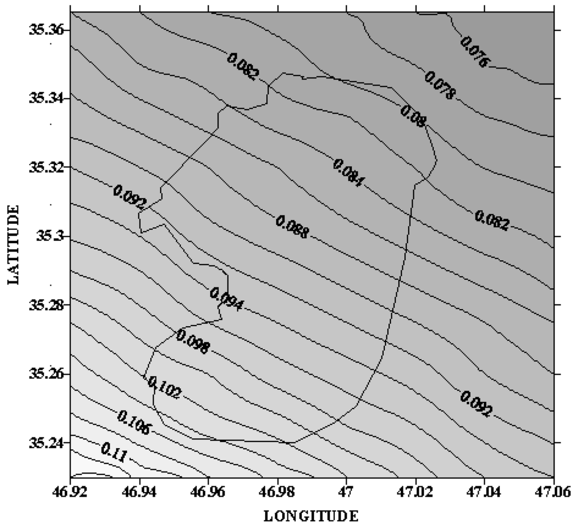


Fig. 11 Final zoning map (PGA over bedrock) of Sanandaj and its vicinity using logic tree for 75-year return period and the border of Sanandaj (thick line)

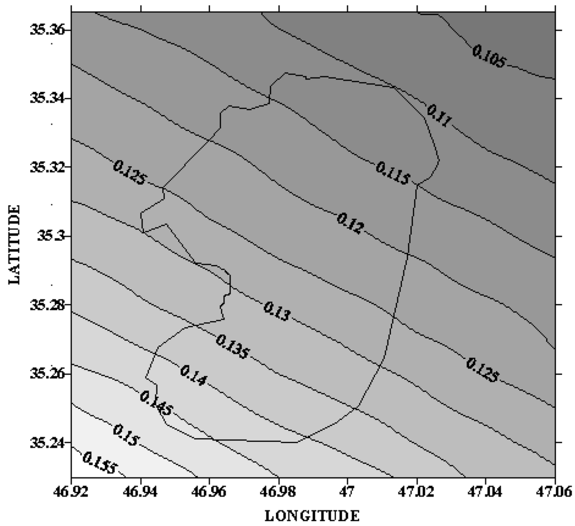


Fig. 12 Final zoning map (PGA over bedrock) of Sanandaj and its vicinity using logic tree for 225-year return period and the border of Sanandaj (thick line)

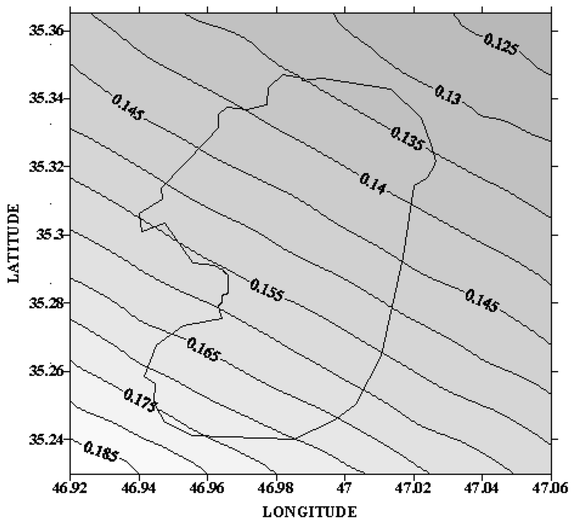


Fig. 13 The Final zoning map (PGA over bedrock) of Sanandaj and its vicinity using logic tree for 475-year return period and the border of Sanandaj (thick line)

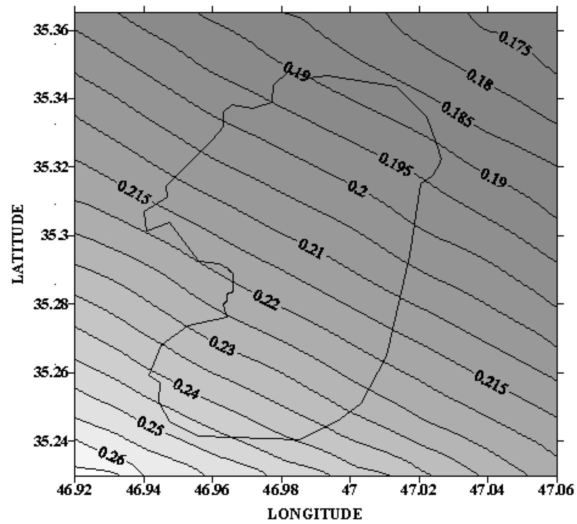


Fig. 14 Final zoning map (PGA over bedrock) of Sanandaj and its vicinity using logic tree for 2475-year return period and the border of Sanandaj (thick line)

## 26. Conclusions

In this study, zoning maps of the peak horizontal ground acceleration over the bedrock in different parts of Sanandaj city is presented according to four hazard levels that show PGA values for 50%, 20%, 10%, and 2% probability of being exceeded during life cycles of 50 years (Fig. 11 to Fig. 14). The maximum and minimum values of PGA for the return periods of 75, 225, 475, 2475 years are (0.114, 0.074) (0.157, 0.101), (0.189, 0.121) and (0.266, 0.170), respectively.

The results also show that the south western part of Sanandaj city has the highest and north eastern part of Sanandaj city has the least amount of Peak Ground Acceleration over the bedrock (PGA).

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