Seismic Hazards Assessment of North-west of Iran, Ardabil city

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SUMMARY:
A seismic hazard assessment is presented for the city of Ardabil in order to determine design earthquake and geotechnical hazards assessment. Ardabil is a city in northwest of Iran that some destructive earthquakes were reported due to existence of active faults. Seismicity parameters on the basis of historical and instrumental earthquakes are calculated using Tavakoli's approach and Kijko method. SEISRISKIII software has been employed for seismic hazard assessment. The study area was divided into a grid of 1×1 km^2 elements and sub-surface ground condition data from 150 borings was collected and analyzed. Site response analyses were carried out on each representative profile using 20 rock input motions. Distribution map of peak ground acceleration throughout the city were developed, providing a useful basis for land-use planning in the city.

Keywords: Seismic hazards assessment, PGA, Design Earthquake, Microzonation map

1. INTRODUCTION

Iran is one of the most seismic countries of the world. It is situated over the Himalayan-Alpied seismic belt and is one of those countries which have lost many human lives and a lot of money due to occurrence of earthquakes. Fig. 1 shows recent seismicity of Iran (Tavakoli and Ghafory-Ashtiany, 1999). The city of Ardabil in northwest of Iran, is a touristic city which existence of active faults, alluvium deposits of the region, and the occurrence of sever past earthquakes, all indicate the high seismicity of this region and they caused the probability of occurrence of sever earthquakes with magnitudes over 7 to be very high.
Iran's seismic code uses Eqn. 1.1 for the calculation of the earthquake equivalent static force (V):

$$V = \frac{A.B.I}{R} W \tag{1.1}$$

where A is the design basis acceleration over bedrock, B is the response factor calculated by simultaneous consideration of the amplifying effects of soil deposit and the structural response with respect to earthquake accelerogram, R is the reduction factor calculated by considering the nonlinear behaviour of the structure (resulting from the ductility property and the overstrength of the structure), I is the importance factor, and W is the weight of the structure.
The most important factor in this calculation is a reasonable value of the design basis acceleration over bedrock (A) that satisfies the scientific principles. The Iranian seismic code suggests the value of A=0.3g for the entire Ardabil. Considering, the availability of newer and more complement data and new scientific research, the need for performing hazard analysis for updating the corresponding results for a seismic city like Ardabil is now more than ever. The geotechnical hazard zoning maps developed in this study represent the behaviour of the region ground considered, mainly based on geotechnical data of the studied region.

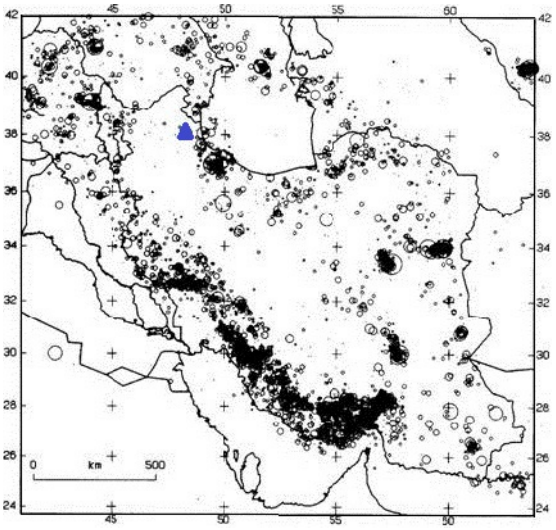


Figure 1. Recent seismicity map of Iran and location of Ardabil (Tavakoli, 1996)

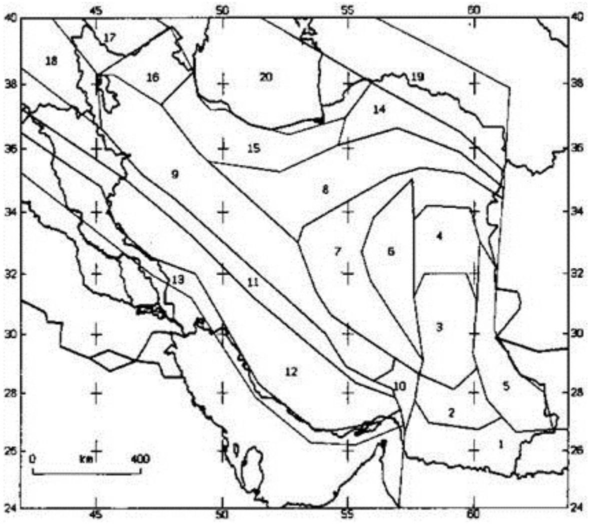


Figure 2. Seismotectonic provinces of Iran (Tavakoli, 1996)

2. SEISMOTECTONIC STRUCTURE OF ARDABIL

The seismotectonic conditions of the Ardabil region are under the influence of the condition of the Iranian tectonic plate in the Middle East. In order to understand the seismotectonic role of the region under study, the conditions of the tectonic plate of Iran should be studied. Several studies have been done on the seismotectonic structure of Iran in the past. Stocklin (1968), Takin (1972), Berberian (1976) and Nowroozi (1976) have suggested simplified divisions consisting of nine, four, twenty-three regions or seismotectonic provinces, respectively. Tavakoli (1996) proposed a new model of seismotectonic provinces using a modified and updated catalogue of large and catastrophic Iranian earthquakes. He has divided Iran into 20 seismotectonic provinces (Fig. 2).

The most significant faults in the vicinity of Ardabil those which fully or partially located within circle with radius of 200 km collected using Berberian (1976) map and local geological organization maps such as Geological and Mining Survey of Iran website (NGDIR, 2011) and major active faults map of Iran of IIEES (2007). The location of these faults can also be seen in Fig. 3 within study region. Note that M_{max} in this figure is calculated based on Nowroozi's relation (Nowroozi, 1985), Eqn. 2.1 to convert L (rupture length in meter) to M_s.

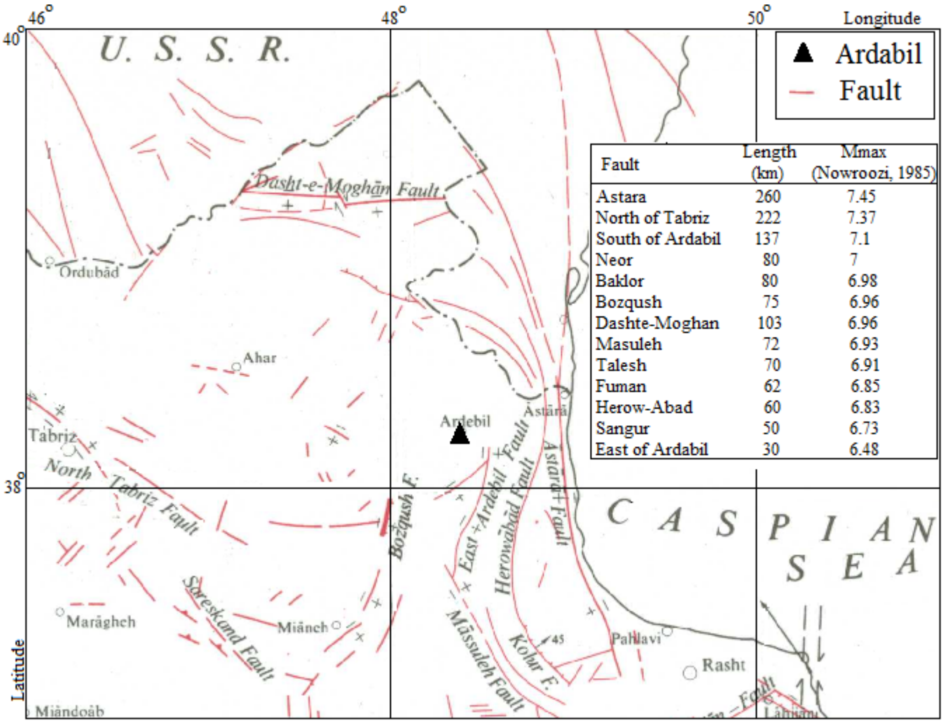
$$M_s = 1.259 + 1.244 \log(L) \tag{2.1}$$

3. SEISMICITY OF ARDABIL AND RELATED PARAMETERS

In general, 16 earthquakes with magnitudes greater than M_s=5.3 were reported over the time span of the studied catalogue, the maximum of which occurred in 1721 and 1990 with a magnitude of M_s=7.7 and recently Sarein, 1997 with a magnitude of M_s=6.1. The epicenter of this earthquake was in the Southwest of Ardabil, with 3000 casualties, more than three villages were destroyed completely.

3.1. Earthquake Catalogue

In order to collect information about earthquakes in this paper, a radial range was employed. For this purpose, a list of earthquakes was gathered and selected in a preliminary manner for a radius of 200 km around Ardabil. The results of investigations by Ambraseys and Melville (1982) and Berberian (1994) which are about historical earthquakes (before 1900) and IIEES (International Institute of Earthquake Engineering and Seismology of Iran), ISC (International Seismological Centre) which are



Fault	Length (km)	Mmax (Nowroozi, 1985)
Astara	260	7.45
North of Tabriz	222	7.37
South of Ardabil	137	7.1
Neor	80	7
Baklor	80	6.98
Bozqush	75	6.96
Dashte-Moghan	103	6.96
Masuleh	72	6.93
Talesh	70	6.91
Fuman	62	6.85
Herow-Abad	60	6.83
Sangur	50	6.73
East of Ardabil	30	6.48

Figure 3. Active faults of Ardabil and its vicinity (Berberian, 1976)

about historical earthquakes (before 1900) and IIEES, ISC which are about instrumental earthquakes (1900-2011) were used.

The final collective catalogue was prepared by eliminating the aftershocks, foreshocks, and the incorrect reported events from the data. Filtered data was evaluated in Poisson distribution. The method that was used for the elimination of foreshocks and aftershocks is the variable windowing method in time and space domains (Gardner and Knopoff, 1974).

3.1.1. Focal depth of earthquakes

In some earthquake cases the value of focal depth has been left blank indicating the lack of information regarding the earthquakes. Also, considering that most earthquakes in Iran are shallow, some of these values seem to be unreasonable. In this paper, the value of focal depth (h) is considered 10 km whereas it isn't specified by developers of attenuation relationships. It should be kept in mind that the variation of focal depth has minor effect on results.

3.1.2. The magnitude of earthquake

The magnitude usually used in seismic hazard analysis is M_S. Also m_b will be used in special cases. In this paper, IRCOLD relationship, Eqn. 3.1 is used to convert m_b in to M_S. This relationship is expressed as follows:

$$M_s = 1.2m_b - 1.29 \tag{3.1}$$

The correlation coefficient of this relationship is $R^2 = 0.87$

3.2. Determination of Seismicity parameters

Seismic hazard analysis needs determination of seismicity parameters and potential of earthquakes occurrence in the future. Parameters used in this paper are:

- Maximum expected magnitude (M_{max})
- b value of Gutenberg-Richter (1954) relationship
- Activity rate (λ)

The calculations for the evaluation of seismic parameters were done based on the occurrence of earthquakes and relationship between their magnitudes and frequencies. Gutenberg and Richter (1954) presented this logarithmic relationship for seismic hazard analysis. Eqn. 3.2,

$$\log \mathrm{N} = \mathrm{a} - \mathrm{b} \times \mathrm{M} \tag{3.2}$$

where N is the number of earthquakes having magnitudes greater than M, M is the earthquake magnitude, a and b are constants and they depend on the source area.

Two approaches are used to determine the seismicity parameters:

- Kijko method
- Tavakoli's approach

3.2.1. Kijko method

This method was used in this paper based on the double extreme distribution function of Gutenberg-Richter and the probabilistic method of maximum likelihood estimation. The assumptions considered in the Kijko (2000) method are as follows:

- The occurrence of earthquake is assumed independent from time and space domains to conform with the Poisson distribution.
- Uniform seismicity properties were assumed in the radius of 200 km around Ardabil.

Since the second assumption is somewhat uncertain, the seismicity study of Tavakoli (1996) was also used in this research through the logic tree method to improve the uncertainty.

Based on this method, three types of earthquakes were considered in this paper:

1) Historical earthquakes (before 1900) with magnitudes uncertainty from 0.3 to 0.5. (Period #1).
2) Instrumentally recorded earthquakes from 1900 to 1963 (the time of world seismography network installation) with uncertainty of 0.2. (Period #2).
3) Instrumentally recorded earthquakes from 1964 to 2011 with uncertainty of 0.1. (Period #3).

The obtained values of $\beta(b \times \ln 10)$ and λ for each case are shown in Table 1. Note that the calculated $\mathrm{M}_{\max}$ value using this method is 8±0.42 for Ardabil. In Fig. 4, the annual rate of occurrence, λ, for earthquakes with magnitude greater than 3.5 is presented.

Table 1. Seismicity Parameters for Ardabil

Beta = 1.02 ± 0.07 Lambda= 3.76± 0.4		
Data Contributions to the Parameters	Beta(%)	Lambda(%)
1)EXTREMES (Period #1)	27.1	8.8
2)COMPLETE (Period #2)	29.9	20.2
3)COMPLETE (Period #3)	43	71

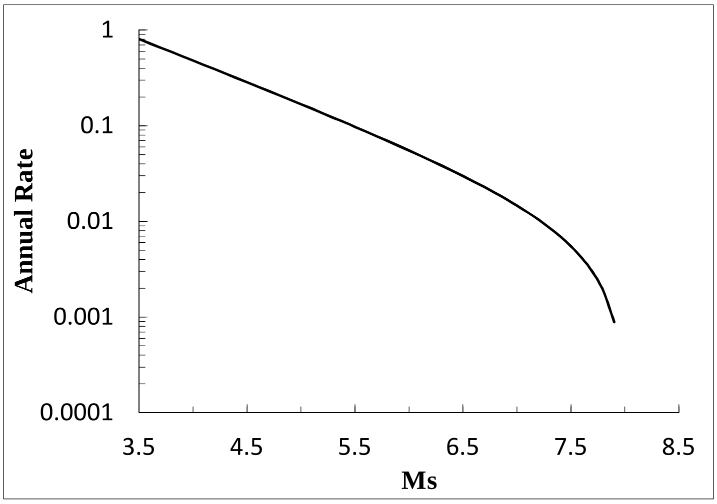


Figure 4. Annual rates estimated by Kijko (2000) method for Ardabil and its vicinity

3.2.2. Tavakoli's approach

Tavakoli (1996) has divided Iran into 20 seismotectonic provinces, as shown in Fig. 2 and earthquake hazard parameters have been evaluated for each seismotectonic. In this study, the maximum likelihood method (Kijko and Sellevoll, 1992) was applied. Suggested values for seismicity parameters for Ardabil (province No. 16 in Fig. 2) are shown in Table 2.

Table 2. Seismicity Parameters for Ardabil Province No.16 (Tavakoli, 1996)

Province No.	Span of time	Beta	M_{max}	Lambda (M_s=4.5)
16	1900-92	1.68±0.17	7.6±0.4	0.14

4. SEISMIC HAZARDS ASSESSMENT

Seismic hazard is the expected occurrence of a future adverse earthquake that has implications of future uncertainty; therefore, the theory of probability is used to predict it (Shah et al., 1976). The probabilistic approach, used in this study, takes into consideration the uncertainties in the level of earthquake magnitude, its hypo central location, its recurrence relationship and its attenuation relationship (Green and Hall, 1994).

The methodology of site effect microzonation adopted in this study falls into the category of Grade-3 zoning methods of Japanese TC4 Zoning Manual (1999). After dividing the city into a grid of 1×1 km^2, the steps for seismic hazard assessment can be summarized as follows:

(1) Modelling of seismic sources,
(2) Evaluation of recurrence relationship (i.e. frequency-magnitude relation),
(3) Evaluation of attenuation relationships for peak ground acceleration,
(4) Estimation of activity rate for probable earthquakes,
(5) Evaluation of basic parameters such as maximum magnitude,
(6) Evaluation of local site effects such as soil types, geotechnical characteristics of sediments, topographic effects, etc. (Shah and Dong, 1984; EERI, 1989; Reiter, 1990; McGuire, 1995; Abdalla, Mohamedzein and Abdel Wahab, 2001).

Steps 1 through 5 represent seismic hazard assessment for an ideal "bedrock" conditions while the inclusion of step 6 represents seismic hazard assessment for a specific site.

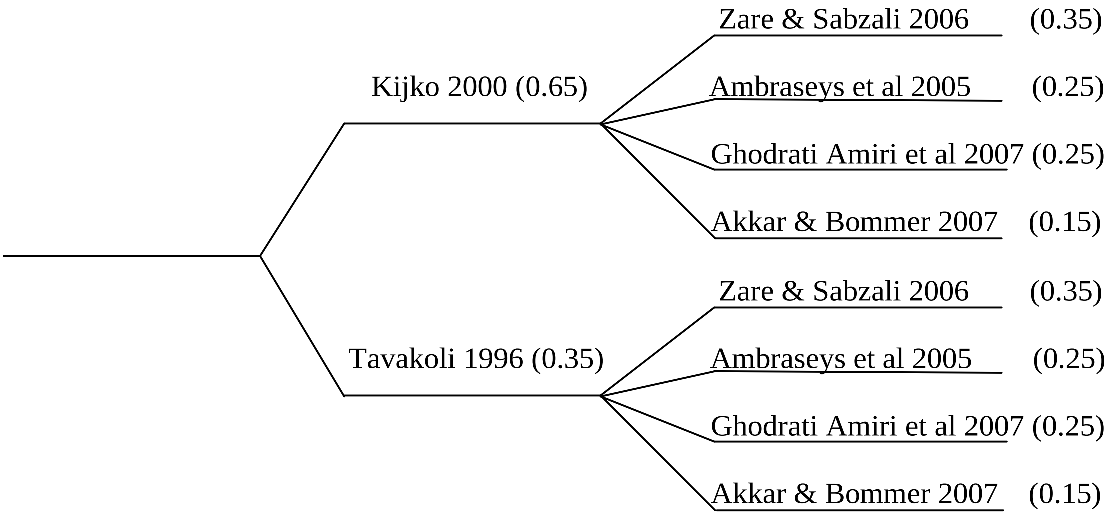


Figure 5. Applied logic tree

4.1. Logic Tree

Logic tree is a popular tool used to compensate for the uncertainty in PSHA. Logic tree reflects uncertainty by allowing the analyst to assign each parameter a range of values, along with an assessment of the probabilities that each of these is the correct value (Rabinowitz, Steinberg and Leonard, 1998).

Fig. 5 shows the logic tree that considered the uncertainty in attenuation relationships and seismicity parameters.

The reason for using the four different attenuation relationships from Douglas (2011) (such as: Ambraseys, Douglas, Sarma and Smit, 2005; Akkar and Bommer, 2007; Ghodrati Amiri et al., 2007; Zaré and Sabzali, 2006) rather than a single one in this paper is that Iran's data does not have the required accuracy. On the other hand, attenuation relationships like Ambraseys et al (2005) and Akkar and Bommer (2007) are global and data from other countries of the world have also been used in them and precision of data used in these relationships is very high.

Seismic parameters obtained by Tavakoli (1996) are calculated for each seismotectonic province and therefore compensate for the inaccuracy of the assumption made on uniformity of seismic properties in the region of 200 km radius around Ardabil. The time span used in Tavakoli's study was limited to 1927 to 1995. But using the logic tree method and employing seismic parameters, calculated in this paper with the time span from 1593 (the first reported earthquake in the history of the region by Ambraseys and Berberian) to 2011, improved the time span limitations.

4.2. Probabilistic Seismic Hazard Analysis

For Probabilistic seismic hazard assessment, in this paper, SEISRISK III software (Bender and Perkins, 1987) was used for PSHA. There are more advanced SHA programs than SEISRISK III software which can perform seismic hazard analysis more accurately. However it was preferred to use this software due to the lack of data and accuracy.

A mean seismic hazard curve for the region is drawn in Fig. 6. The output of curve is the anticipated Peak Ground Acceleration (PGA) in *g* with 10% Annual Probability of being Exceeded (APE) during life cycle of 50 years or for the ground motion return period of 475 years as follows:

$$\mathrm{APE} = 1 - \exp\left(-\frac{50}{\mathrm{T_r} = 475}\right) = 10\% \Rightarrow \mathrm{PGA}(10\%\mathrm{in}50\mathrm{years}) = \mathrm{PGA}\left(\frac{10\%}{50} = 0.002\right) = 0.31\mathrm{g} \quad (4.1)$$

This calculation provides bedrock design basis acceleration for the calculation of earthquake equivalent static forces in the return period considered by Iranian seismic code.

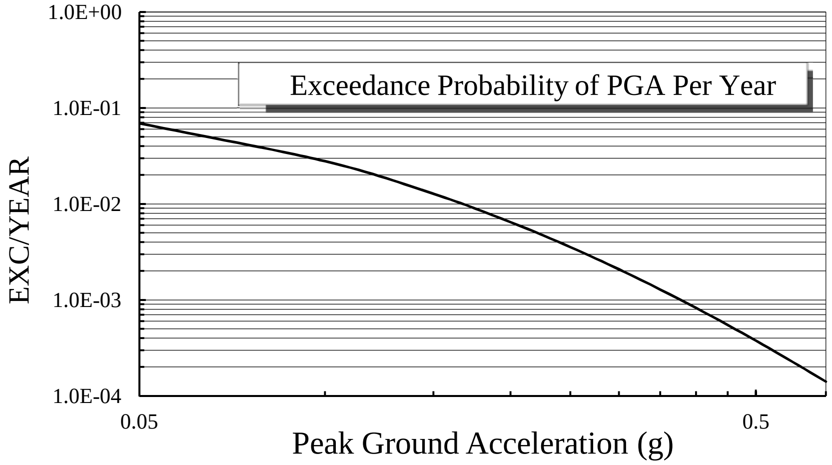


Figure 6. A mean seismic hazard curve for the region

5. GROUND DYNAMIC RESPONSE ANALYSIS

Most available reports on geotechnical site investigations conducted by national and local governments and public corporations were collected (The reports contains: SPT N-value, density, soil sort in each layer and water level). These comprised approximately 150 boreholes from 75 stations having limited depth (usually less than 30 m) and being unequally distributed in the investigated area. Fig. 7 presents the locations of the existing geotechnical data.

The ground conditions of the study were thus categorized according to shear wave velocity and depth of soil layers based on correlations between shear wave velocity and SPT N-value into 2 groups of 4 ground type groups of Iranian seismic code.

The nonlinearity of ground response is one of the important issues in assessment of site-specific effects, especially because of extremely dependence on Damping-Shear strain (D- γ). The nonlinear behavior observed in earthquake reports confirms it (Tokimatsu et al., 1982 and Chang et al., 1991). The equivalent linear model has not satisfactory results for a motion which has short period and long amplitude over deep soil profiles (TC4, 1993) for example Joyner and Chen (1975). Non-linear site response analysis was carried out to evaluate the site response of each of the representative geotechnical profiles to the 475 year seismic induced bedrock input motion. The Nera program (which stands for Nonlinear Earthquake Response Analysis) was used to model the site as a one-dimensional system of horizontal, homogeneous and isotropic soil layers consistent with actual ground conditions in most of the city where the ground surface and surface soil layers are either virtually horizontal or slope gently. The well-known shear modulus-strain and damping ratio-strain relations proposed by Seed and Idriss (1970) for sand and clays were used in the analysis. Since there are no recorded bedrock strong motion time histories for Ardabil city, twenty proper earthquake time histories were selected from available national and international databases. The selected ground Motion records were recorded during earthquakes with approximately the same magnitudes and distances as estimated by probabilistic method in section 5.1.

5.1. Design Earthquake

Following Frankel (1995) and current practice in PSHA, we consider response spectral acceleration or peak ground motion acceleration, u, from specific faults or source cells. From the kth source, S_k, having a limited range of magnitude, it is denoted that the conditional probability that u exceeds u_0, some reference ground motion, given the occurrence of an earthquake in this magnitude range in S_k, as $P[u > u_0|s_k]$. We denote the annual frequency of earthquakes with the same magnitude range in S_k as f_k. From the kth source, S_k, the annual mean number of exceedances at the site, h_k, can be calculated according to Harmsen et al. (1999) as below:

$$h_k = f_k P[u > u_0 | s_k] \tag{5.1}$$

The relative contributions of sources are often displayed in terms of a specified range of magnitude and distance. The combining process of contributions into an array of magnitude and distance ranges is called binning. Let us consider $h_i = \sum h_k$ where the sum is over k such that $S_k \in \text{bin}_i$, weigh the ith bin's contribution and k is an index over both location and magnitude. Given the distribution of potential seismic sources with well defined magnitudes and distances according to Frankel et al. (1996) and Harmsen et al. (1999) is:

$$\overline{M} = (\sum_i M_i h_i) \Big/ \sum_i h_i \quad \text{and} \quad \overline{R} = (\sum_i R_i h_i) \Big/ \sum_i h_i \tag{5.2}$$

where M_i is the $\overline{M}$ of sources in bin i and R_i is the $\overline{R}$ of sources in bin i. The sum over i includes contributions from all sources. $\overline{M}$ and $\overline{R}$ are independent of bin sizes and locations and other binning details. These parameters can be used for determining the design earthquakes (Bernreuter, 1992).

All selected acceleration time histories are scaled in order to conform to the rock response spectrum, using a coefficient (USACE, 1999) and normalized to the 475 year PGA estimated by PSHA.

5.2. Development of microzonation map of PGA

For each grid element, strong ground motion essential characteristic (PGA) was computed by subjecting their representative geotechnical profiles to the normalized 475 year bedrock input motions. Once the average results were obtained for each grid element, microzonation maps of the city were created showing the distribution of PGA values throughout the study area.

For the purpose of the study, seismic bedrock has been defined as rock-like media with shear wave velocities of over 700-800 m/s (Ishihara and Ansal, 1982; ICBO, 1997, 2003; BSSC, 2003; BHRC, 2005), which is suitable for ordinary low to medium-rise buildings (TC4, 1999). Five correlations between shear wave velocity and SPT N-value (Jafari et al., 1997, Jafari et al., 2002, Baziar et al., 1998, Lee, 1992, Hasancebi and Ulusay, 2007) were employed and averaged in order to determine shear wave velocity of each layer and average shear wave velocity ($\overline{v}_s$) for each grid element consistent with Ground classification of Iranian seismic code (Ground-type II: $375 \leq \overline{v}_s$ (m/s)<750, Ground-type III: $175 \leq \overline{v}_s$ (m/s)<375). It should be noted that use of correlation equations for N-values less than 2 or greater than 50 is not recommended due to generally poor accuracy (Ohta & Goto, 1978). These calculations indicates most grid elements of type III ($175 \leq \overline{v}_s$ (m/s)<375).

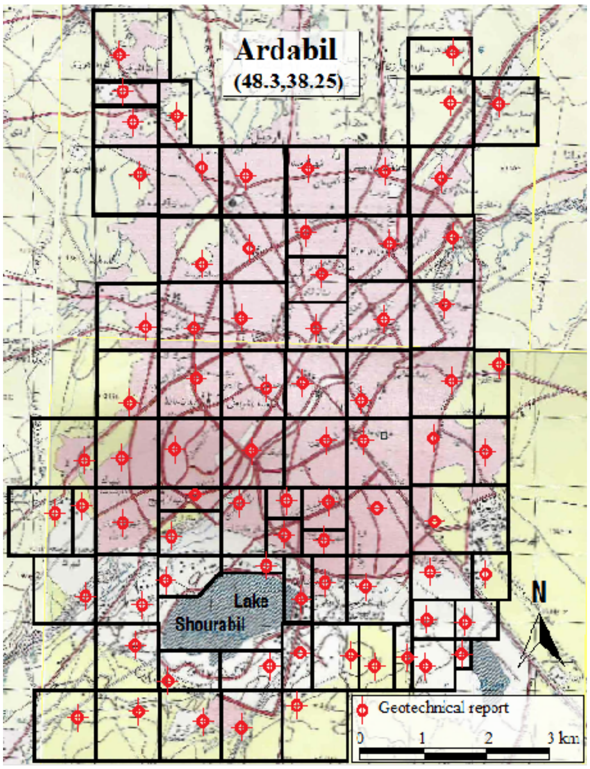


Figure 7. Location of geotechnical reports and study area limits

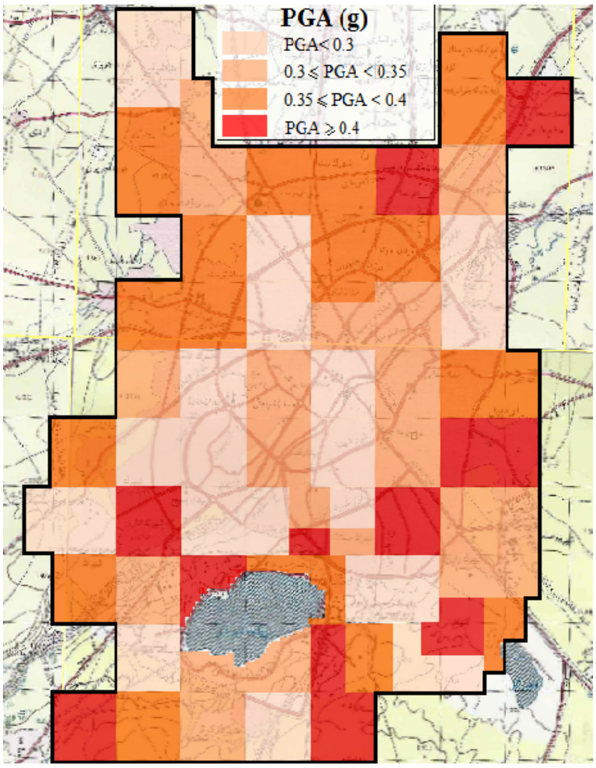


Figure 8. Distribution of PGA throughout the city for a return period of 475 years

Fig. 8 shows the distribution of the 475 year return period PGA on soil throughout the city. The PGA values vary from 0.3g to more than 0.4g. Almost 56% of the grid elements exhibit PGA values of 0.3g to 0.4g. Only 13% of them experience PGA values of more than 0.4g because of their considerable amplification potential caused by low to medium dense soil layers. The dense granular alluviums and some with high stiffness experience the lowest PGA of about less than 0.3g because the amplification potential of such sites is negligible.

6. CONCLUSIONS

In this paper, the seismic and geotechnical hazards analysis of city of Ardabil is performed. Important results of this analysis are expressed as follows:

(1) Assessment a full and up-to-date catalogue by using the information of historical and instrumental earthquakes.
(2) Digitizing seismic sources (faults) within 200km radius of region by international and local references and studies.
(3) Determining seismicity parameters of city of Ardabil.
(4) The mean seismic hazard curve for the whole city indicates that PGA over bedrock for the ground motion return period of 475 year is 0.31g which is a little more than 0.3 (which is suggested in Iranian seismic code).
(5) Determining Average shear wave velocity ($\overline{v}_s$) and ground-type for each grid element consistent with ground classification of Iranian seismic code, indicates most grid elements of type III($175 \leq \overline{v}_s$ (m/s)<375), which helps the designer to choose appropriate design spectrum in terms of ground type.
(6) Drawing the microzonation map of PGA can be useful in land-use planning in consideration of population density, building height and building importance.

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