Comparison of source-base estimate of peak ground acceleration (A_{max}) in Zagros by Bayesian method with non-source approach

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Abstract: Bayesian probability theory is an appropriate and useful method to estimate parameters in seismic hazard analysis. The analysis in Bayesian approaches is based on *a posterior* belief, also their special ability is to take into account the uncertainty of parameters in probabilistic relations and *a priori* knowledge. In this study, we used the program for seismic hazard Bayesian estimate which was elaborated by Alexey Lyubushin. Our study is the next in the sequence of applications of this software to seismic hazard assessment in different regions of the world. In this study, Bayesian approach has been used to obtain estimated seismic parameters. In order to reach this aim, 30 different source regions in Zagros seismotectonic province have been considered. The main assumptions are Poissonian character of the seismic events flow and properties of the Gutenberg-Richter distribution law. The a posteriori probability distribution functions of $M_{max}(T)$ and the tail probabilities $P(M_{max}(T)>M)$, that will occur in future time intervals of 10, 20, 50, 100 and 475 years are illustrated for source regions. The map of peak ground acceleration (PGA) zonation by probability level of 90% (in g) in rock bed for average return period of 50, 100 and 475 years is presented. According to the results, the maximum acceleration is estimated for the cities of Kermanshah, Ilam, Khorram Abad and Bandar Abbas which are related to NWZ1, NWZ2, NWZ3, NWZ7, NWZ8, SZ3, SH1, PG1 and PG2 sources. Finally, the results of this study are compared with obtained results of non-source approach.

Key words: seismic hazard, Bayesian approach, A_{max}, Zagros, PGA

1. Introduction

The Iranian plateau is a relatively wide zone of compressional deformation along the Alpine-Himalayan active mountain belt, bounded in the South

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by the Arabian plate and in the North by the Eurasian plate. The Iranian plateau is comprised of five main features, namely, the Zagros Mountains, the Kopeh Dagh, the Makran complex, the Alborz-Azerbaijani, and the central Iranian block. According to the five features, five seismotectonic provinces intended for Iran by *Mirzaei et al. (1998).* Seismicity map of Zagros seismotectonic province is demonstrated in Fig. 1. Zagros and its surrounding region have experienced repeated moderate to large magnitude earthquake during the previous centuries. The issue of earthquake hazard evaluations requires a profound and stable statistical and/or probabilistic technique which can offer outcomes with minimum uncertainties. Among statistical methods, Bayesian approach has an especial interest that comes from its power or ability to grow into the regarded uncertainty of parameters in fitted probabilistic laws and *a priori* given information (*Mortgat and Shah, 1979; Campbell 1982, 1983*).

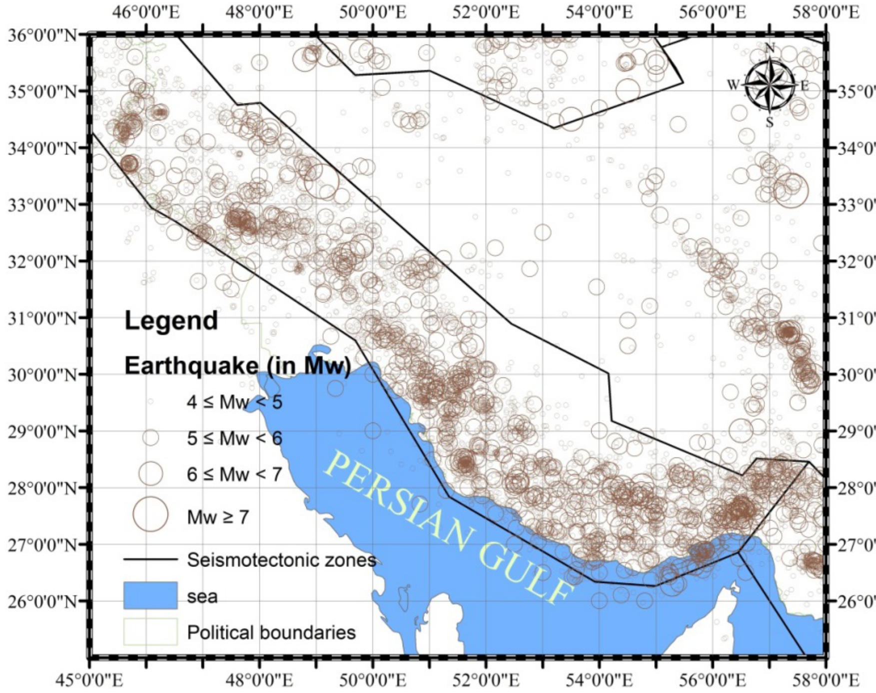

Fig. 1. Seismicity map of Zagros seismotectonic province and locations of earthquakes larger than M_w 4.

Bayesian techniques provide a rigorous means of combining prior information on seismicity whether it is judgmental, geological, or statistical with historical observations of earthquake occurrences (*Galanis et al., 2002*) and ready framework for the propagation of uncertainty through the risk models is supplied with probability distribution which represented through Bayesian approach (*Kelly and Smith, 2011*). Bayesian approach also provides conditions that we can insert uncertainty in our calculation. The present Bayesian approach was elaborated in the works *Pisarenko et al. (1996)* and *Pisarenko and Lyubushin (1997, 1999)*. Later, *Lyubushin and Parvez (2010)* modified creating maps of Bayesian estimates of peak ground acceleration statistics. The main computational code of the method which was elaborated by Lyubushin, has been applied to estimate seismic hazard in different regions of the world (*Lyubushin et al., 2002; Tsapanos et al., 2001; Bayrak and Türker 2016, 2017; Mohammadi et al., 2016; Salahshoor et al., 2018*).

In the present research, we have been using a procedure which was developed by *Pisarenko et al. (1996)* to evaluate earthquake hazard parameters for 30 different source regions of Zagros seismotectonic province. In previous studies, direct calculation of acceleration has been carried out, but in this study, at first we determine the sources very precisely and the parameters are obtained by Lyubushin and analysis of hazard is done by EZFrisk software. Whereas using attenuation relationship amounting to obtained PGA is very effective, *Akkar and Boomer (2010)*, *Akkar et al. (2014)* and *Zafarani et al. (2018)* therefore attenuation relationships have been used.

2. Data used and zonation

The catalogue of earthquakes is the most important prerequisite in this method. In this regard, for this study the seismic catalogue of *Shahvar et al. (2013)* is made updated in mid of 2019 by referring to USGS and ISC. An earthquake data set used in seismicity or seismic hazard assessments must be definitely uniform, in other words, it is essential to use the same magnitude scale. All data in this study are unified to the $\mathrm{M_w}$ scale (Fig. 1). To convert the scale of events from the magnitudes of $\mathrm{m_b}$ or $\mathrm{M_s}$ reported by ISC or USGS, the relationships provided by *Shahvar et al. (2013)* have been used. One of the most important assumptions used in the *Pisarenko et al. (1996)* method is the Poissonian character of events. So we only need the major events, and the associated events (i.e., foreshocks and aftershocks) are eliminated from the total data. For this purpose, we have used *Gardner and Knopoff (1974)* method.

Karimiparidari et al. (2013) developed a new seismotectonic zoning map for Iran. In this research, we utilized the regions which are defined by *Karimiparidari et al. (2013).* They updated Zagros seismotectonic province into 30 seismic regions (Fig. 2).

The next input in this approach is the selection of the appropriate attenuation law. *Akkar and Boomer (2010)*, *Akkar et al. (2014)* and *Zafarani et al. (2018)* attenuation models can be applied properly in Iran. In this regard, in this study, these three models are applied with the same weight.

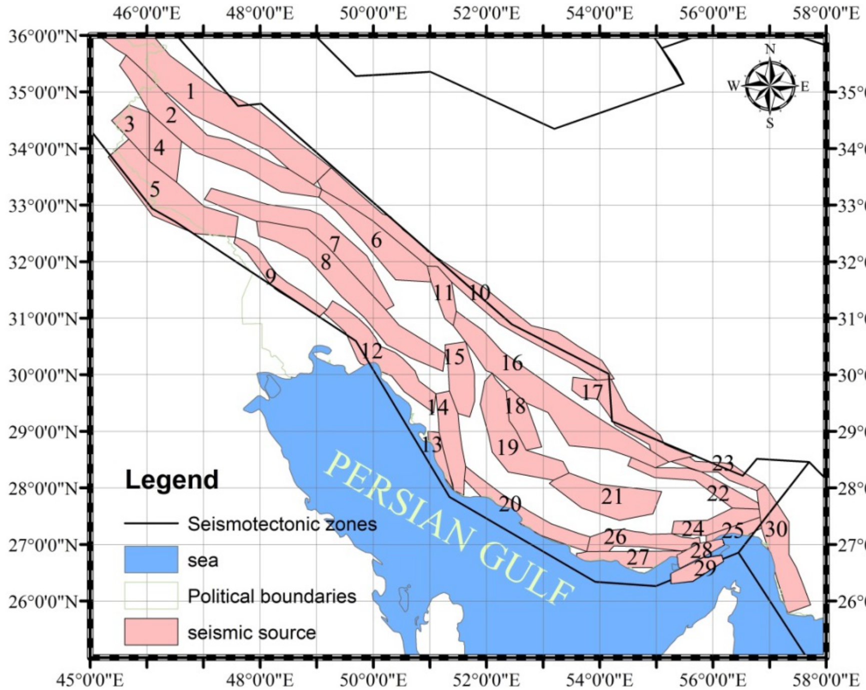

Fig. 2. Zoning of Zagros seismotectonic province and locations of 30 different source regions, 1-MZ1, 2-NWZ1, 3-NWZ7, 4-NWZ8, 5-NWZ6, 6-MZ6, 7-NWZ2, 8-NWZ3, 9-Ah1, 10-MZ2, 11-MZ5, 12-NWZ5, 13-KH1, 14-NWZ4, 15-SZ6, 16-SZ1, 17-MZ3, 18-SZ8, 19-SZ7, 20-SZ5, 21-SZ9, 22-SZ2, 23-MZ4, 24-SZ3, 25-SH1, 26-SZ4, 27-PG1, 28-PG2, 29-PG3, 30-SH2.

3. Method

The employed method is delineated in particular in papers (*Pisarenko et al. 1996; Pisarenko and Lyubushin, 1999; Tsapanos et al., 2001; Lyubushin et al., 2002; Lyubushin and Parvez, 2010*). However, we will give the main assumptions and key equations only.

Let R be a value of magnitude (M), which is a measure of the size of earthquakes that happened in a sequence on a past-time interval $(-\tau, 0)$:

$$\vec{R}^{(n)} = (R_1, \ldots, R_n), \quad R_i \geq R_0, \quad R_\tau = \max_{1 \leq i \leq n} (R_1, \ldots, R_n)\,, \tag{1}$$

where $i = 1, 2, \ldots, n$; and R_0 is the minimum cutoff value of magnitudes (M), i.e., determined by possibilities of registration system, or it may be a minimum value from which the value is written in Eq. (1) the statistically representative.

Two main assumptions for Eq. (1) were proposed. The first assumption is that Eq. (1) follows the G-R law of distribution:

$$\Pr\{R < x\} = F(x|R_0, \rho, \beta) = \frac{\mathrm{e}^{-\beta R_0} - \mathrm{e}^{-\beta x}}{\mathrm{e}^{-\beta R_0} - \mathrm{e}^{-\beta \rho}}, \quad R_0 \leq x \leq \rho\,. \tag{2}$$

Here, ρ is the unknown parameter that represents the maximum possible value of R, for instance, 'maximum regional magnitudes (M)' in a given seismogenic region. The unknown parameter β is the 'slope' of the Gutenberg-Richter law of magnitude-frequency relationship at small values of when the dependence (Eq. (2)) is plotted on double logarithmic axes.

The second assumption is that λ is an unknown parameter and a Poisson process with some activity rate or intensity λ in the sequence (Eq. (1)). If three unknown parameters (ρ, β and λ) can be written, the full vector is:

$$\theta = (\rho, \beta, \lambda)\,. \tag{3}$$

Apparent magnitude is a magnitude that is observed, i.e., those values that are presented in seismic catalogues. True magnitude is a hidden value and is unknown; it is defined by the formula:

$$\bar{R} = R + \varepsilon\,. \tag{4}$$

Let $n(x|\delta)$ be a density of probabilistic distribution of error ε where δ is a given scale parameter of the density and epsilon (ε) value is the error between the true magnitude (R) and the apparent magnitude ($\bar{R}$). We can estimate values of true magnitude taking into account the different hypotheses about the probability distribution of epsilon (for example, uniform) and about parameters of this distribution. Below, we shall use the following uniform distribution density:

$$n(x|\delta) = \begin{cases} 1/2\delta\,, & |x| \le \delta\,, \\ 0\,, & |x| > \delta\,. \end{cases} \tag{5}$$

Let Π be an *a priori* uncertainty domain of values of parameters θ:

$$\Pi = \{\lambda_{\min} \le \lambda \le \lambda_{\max},\ \beta_{\min} \le \beta \le \beta_{\max},\ \rho_{\min} \le \rho \le \rho_{\max},\}\,. \tag{6}$$

We should consider the *a priori* density of the vector θ to be uniform in the domain Π.

According to the definition of conditional probability, *a posteriori* density of distribution of vector of parameters θ is equal to:

$$f(\theta|\vec{R}^{(n)},\delta) = \frac{f(\theta,\vec{R}^{(n)}|\delta)}{f(\vec{R}^{(n)}|\delta)}\,, \tag{7}$$

but $f(\theta|\vec{R}^{(n)},\delta) = f(\vec{R}^{(n)}|\,\theta,\delta)f^a(\theta)$, where $f^a(\theta)$ is the *a priori* density of the distribution of vector θ in domain Π. As $f^a(\theta) = \text{const}$ according to our assumption and taking into consideration that:

$$f(\vec{R}^{(n)}|\delta) = \int_{\Pi} f(\vec{R}^{(n)}|\,\theta,\delta)\,\mathrm{d}\theta\,. \tag{8}$$

Then, we will obtain using a Bayesian formula (*Rao, 1965*). The Bayesian formula is as follows:

$$f(\theta|\vec{R}^{(n)},\delta) = \frac{f(\vec{R}^{(n)}|\,\theta,\delta)}{\int_{\Pi} f(\vec{R}^{(n)}|\,\vartheta,\delta)\,\mathrm{d}\vartheta}\,. \tag{9}$$

An expression for the function $f(\theta|\vec{R}^{(n)},\delta)$ should be used in Eq. (9).

To use Eq. (9), we must have an expression for the function $f(\theta|\vec{R}^{(n)},\delta)$. With the assumption of Poissonian character sequence in Eq. (1), and independent of its members, should give us:

$$f(\vec{R}^{(n)}|\,\theta,\delta) = \hat{f}(R_1|\,\theta,\delta)\ldots\hat{f}(R_n|\,\theta,\delta)\frac{\exp\left(-\bar{\lambda}(\theta,\delta)\,\tau\right)(\bar{\lambda}(\theta,\delta)\,\tau)^n}{n!}\,. \tag{10}$$

Now, we can calculate a Bayesian estimate of vector θ:

$$\hat{\theta}(\vec{R}^{(n)}|\,\delta) = \int_{\Pi} \vartheta f(\vartheta\,|\vec{R}^{(n)}, \delta)\,\mathrm{d}\vartheta\,. \tag{11}$$

An estimate of maximum value, ρ, is one of the computations of Eq. (11). We must obtain Bayesian estimates of any of the function to use a formula analogous to Eq. (11).

One of the computation in Eq. (11) contains an estimate of the maximum value of ρ. Using a formula analogous to Eq. (11), we must obtain Bayesian estimates for any of the functions. The most important are estimates of quantiles of distribution functions of true and apparent values on a given future time interval [0,T], for instance for quantiles of apparent values:

$$\widehat{\overline{\Upsilon}}_{\mathrm{T}}(\alpha|\vec{R}^{(n)}|\,\delta) = \int_{\Pi} \overline{\Upsilon}_{\mathrm{T}}(\alpha|\vartheta, \delta)\, f(\vartheta\,|\vec{R}^{(n)}, \delta)\,\mathrm{d}\vartheta\,. \tag{12}$$

$\widehat{\Upsilon}_{\mathrm{T}}(\alpha|\vec{R}^{(n)}|\,\delta)$ for α quantiles for true values is written analogously to Eq. (12). We must estimate variances of Bayesian estimates (Eqs. (11, 12)) using averaging over the density (Eqs. (9, 10)). For example:

$$\mathrm{var}\{\widehat{\overline{\Upsilon}}_{\mathrm{T}}(\alpha|\vec{R}^{(n)}|\,\delta)\} = \int_{\Pi} \Big(\overline{\Upsilon}_{\mathrm{T}}(\alpha|\vartheta, \delta) - \widehat{\overline{\Upsilon}}_{\mathrm{T}}(\alpha|\vec{R}^{(n)}, \delta)\Big)^2 f(\vartheta\,|\vec{R}^{(n)}, \delta)\,\mathrm{d}\vartheta\,. \tag{13}$$

First of all, we will set $\rho_{\min} = R_\tau - \delta$. As for the values of $\rho_{\max}$, they depend on the specific data in the series (Eq. (1)) and are produced by the user of the method. Boundary values for the slope β are estimated by the formula:

$$\beta_{\min} = \beta_0(1-\gamma), \quad \beta_{\max} = \beta_0(1+\gamma), \quad 0 < \gamma \le 1\,, \tag{14}$$

where β_0 is the "central" value and is obtained as the maximum likelihood estimate of the slope for the Gutenberg-Richter law:

$$\sum_{i=1}^{n} \ln\left\{\frac{\beta\,\mathrm{e}^{-\beta R_i}}{\mathrm{e}^{-\beta R_0} - \mathrm{e}^{-\beta R_\tau}}\right\} \to \max_{\beta,\,\beta\in(0,\beta_s)}\,. \tag{15}$$

Here, β_s is a rather large value.

For setting boundary values for intensity λ in Eq. (6), we used the following rational. As a consequence of normal approximation for a Poisson process for a rather large n (*Cox and Lewis, 1966*), the standard deviation of the value λ has the approximation value $\sqrt{n} \approx \sqrt{\lambda_\tau}$. Thus, taking boundaries at $\pm 3\sigma$, we will obtain:

$$\begin{aligned} &\lambda_{\min} = \lambda_0 \Big(1 - \tfrac{3}{\sqrt{\lambda_0\, \tau}}\Big)\,, \quad \lambda_{\max} = \lambda_0 \Big(1 + \tfrac{3}{\sqrt{\lambda_0\, \tau}}\Big)\,, \\ &\lambda_0 = \frac{\bar{\lambda}_0}{c_f(\beta_0, \delta)}\,, \quad \bar{\lambda}_0 = \frac{n}{\tau}\,. \end{aligned} \tag{16}$$

4. Results and discussion

In source-base approach, at first the sources are determined based on seismotectonic studies which in this study determined sources by *Karimiparidari et al. (2013)* have been used (Fig. 2). Then, within source data have been used and parameters have been obtained, using Lyubushin method. For each source, seismic parameters ($\mathrm{M}_{\max}$, λ and β) have been calculated using a sequence of magnitude values (Eq. (1)) of events of each source. This approach can be useful because a better estimation of source parameters values (*a posterior*) will be obtained, using seismotectonic information (*a prior*).

The next step is removing aftershocks, using Gardner-Knopoff method (*Gardner and Knopoff, 1974*), in order to provide a random nature of time moments sequence. In this province, 30 sources have been considered and for each source λ value, β value and $\mathrm{M}_{\max}$ are obtained, using Lyubushin method. In another word, in source-base approach will assign sequence of Eq. (1) magnitude values to itself, whereas the values of this sequence will accelerate in non-source approach. The posterior probability distribution functions $\mathrm{M}_{\max}(\mathrm{T})$ for 10, 20, 50, 100 and 457 years intervals in the future, have been presented in Fig. 3 for six sample sources. Also, tail probabilistic $\mathrm{P}(\mathrm{M}_{\max}(\mathrm{T}) \geq \mathrm{M})$ for 10, 20, 50, 100 and 457 years intervals in the future, have been presented in Fig. 4 for six sample sources. These graphs are useful probabilistic tools in analysis of earthquake hazard in the region.

For earthquake engineers, hazard maps at different levels of probability are much more important and more practical. We have estimated the peak ground acceleration in a grid of the size 40×40 nodes by latitude and

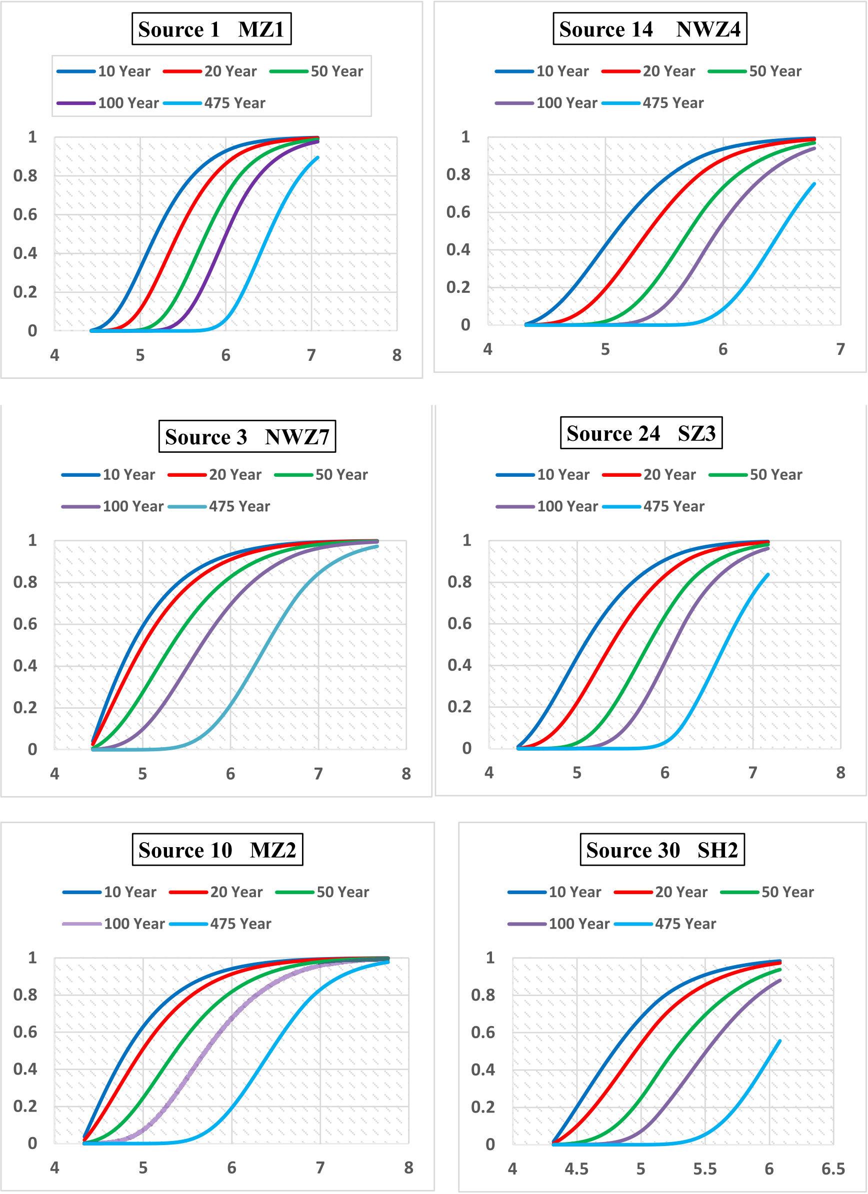

Fig. 3. A posteriori probability functions of $M_{max}(T)$ showing statistical characteristics of seismic hazard parameters for six sample sources in next T = 10, 20, 50, 100 and 475 years (horizontal axis, magnitude and vertical axis, Prob(M_{max} < M)).

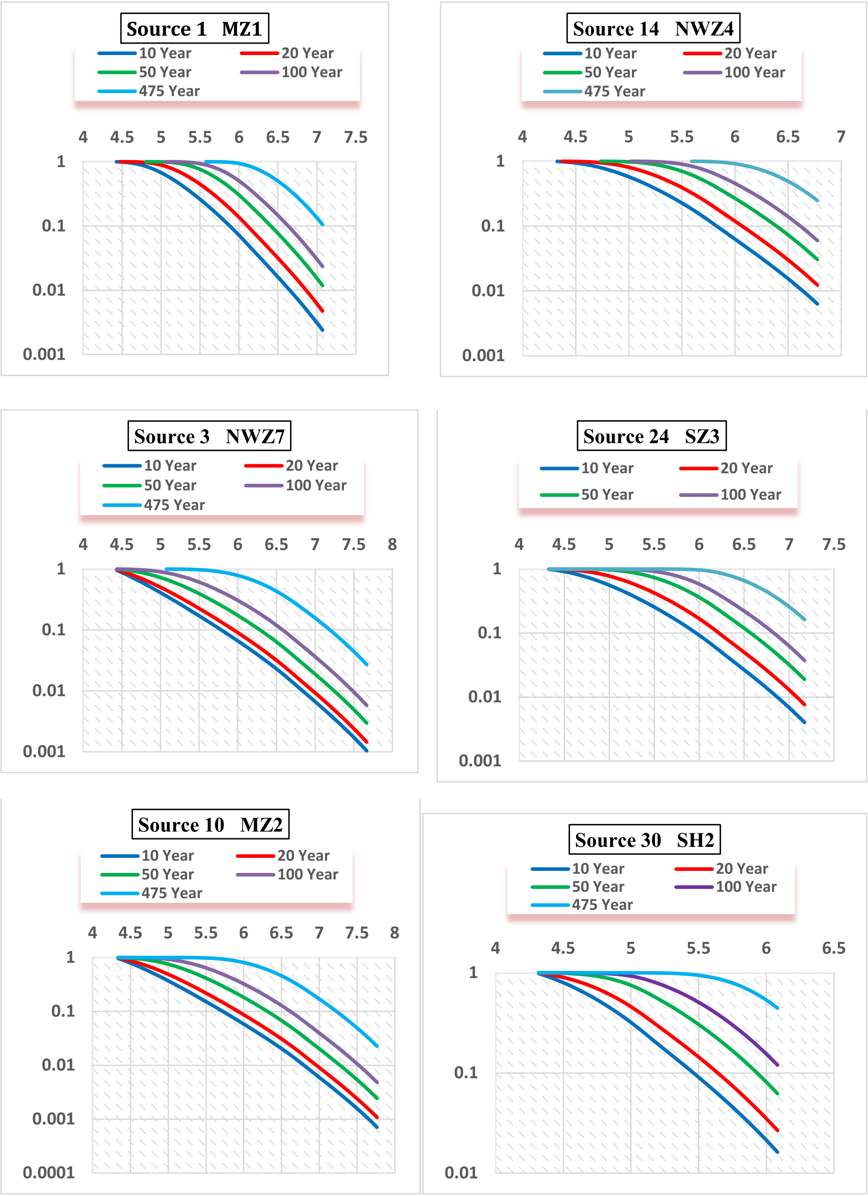

Fig. 4. 'Tail' probabilities $1 - \Phi(\mathrm{M}) = \mathrm{Prob}(\mathrm{M}_{\mathrm{max}}(\mathrm{T}) \geq \mathrm{M}))$ showing statistical characteristics of seismic hazard parameters for six sample sources in next $\mathrm{T} = 10$, 20, 50, 100 and 475 years, (horizontal axis, magnitude and vertical axis, $1 - \Phi(\mathrm{M})$).

longitude within rectangular 26° ≤ Lat ≤ 36°; 45° ≤ Lon ≤ 58°. The estimates were performed in the following way: zonation maps of peak ground acceleration by probability level of 90% (in g) in this province for average return period of 50, 100 and 475 years, using 3 attenuation relationships with equal weights and a normal earthquake catalogue has been presented, using EZFrisk software in Figs. 5, 6 and 7.

In this study, Bayesian method has been used to obtain seismic parameters in source regions. In calculation of PGA, more than using the seismic sources, a base seismic source on the seismotectonic province has been defined as homogenous. To calculate the acceleration of base seismic source, the same attenuation relationships have been used with seismic sources.

We exported data of sources and attenuation relationships to the software. One base source has been defined so as the borders of the base source are the dimensions of the studied region. Gridding in this software were 0.2° by 0.2°. The grid included 1600 nodes which are presented in Table 1 peak ground acceleration (PGA) and spectrum accelerations (SAs) in ten points of the grid according to mentioned numbers in zonation maps of PGA (Figs. 5, 6 and 7).

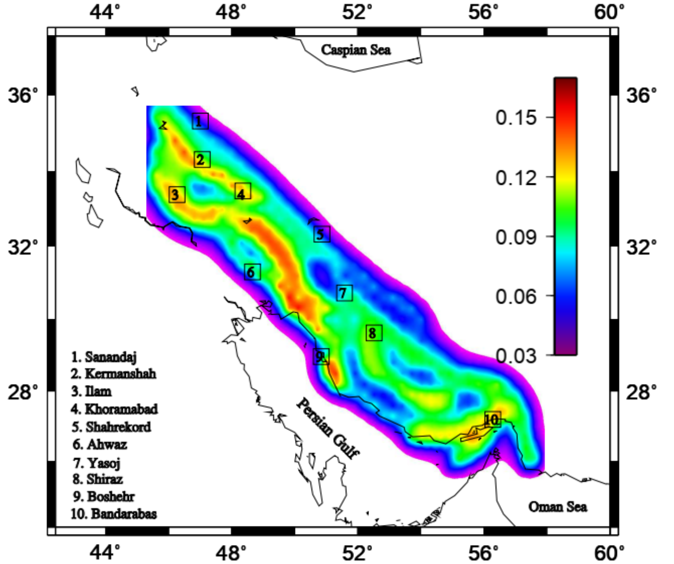

Fig. 5. Zonation map of peak ground acceleration by probability level of 90% (in g) in Zagros seismotectonic province for average return period of 50 years.

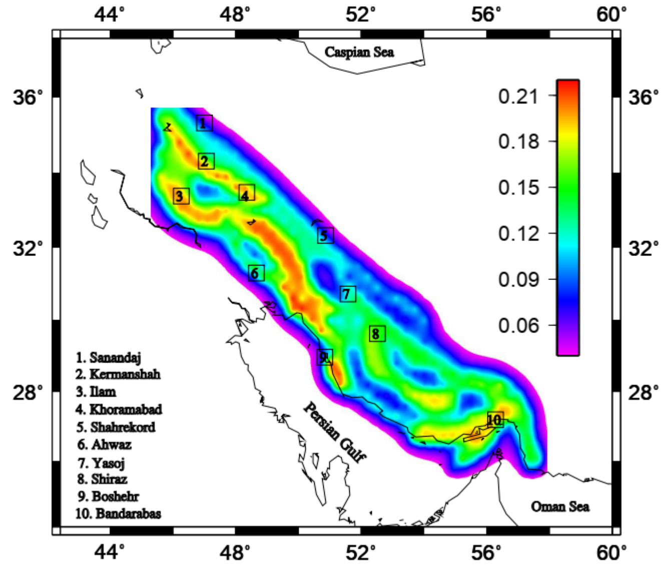

Fig. 6. Zonation map of peak ground acceleration by probability level of 90% (in g) in Zagros seismotectonic province for average return period of 100 year.

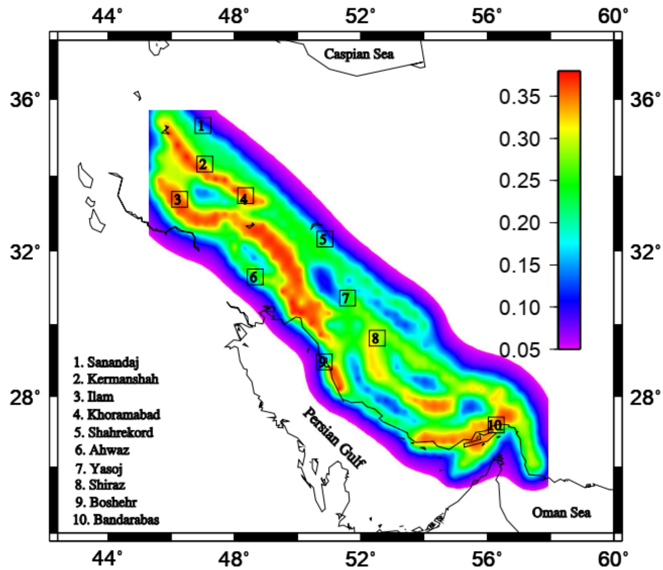

Fig. 7. Zonation map of peak ground acceleration by probability level of 90% (in g) in Zagros seismotectonic province for average return period of 475 year.

Table 1. Peak ground acceleration (PGA) and spectrum accelerations (SAs) in ten points of the grid according to mentioned numbers in zonation maps of PGA (Figs. 5, 6 and 7).

Num.	**lat**	**lon**	**0.01 s: 50 Yrs**	**0.01 s: 100 Yrs**	**0.01 s: 475 Yrs**	**0.2 s: 50 Yrs**	**0.2 s: 100 Yrs**	**0.2 s: 475 Yrs**	**2.0 s: 50 Yrs**	**2.0 s: 100 Yrs**	**2.0 s: 475 Yrs**
1	35.4	47.1	0.038	0.051	0.087	0.088	0.115	0.200	0.008	0.012	0.023
2	34.2	46.5	0.135	0.184	0.331	0.304	0.412	0.744	0.017	0.024	0.049
3	33.6	46.5	0.109	0.147	0.271	0.243	0.330	0.605	0.016	0.022	0.040
4	33.3	48.3	0.130	0.180	0.337	0.289	0.401	0.754	0.017	0.024	0.051
5	32.4	50.7	0.063	0.091	0.187	0.140	0.202	0.419	0.010	0.014	0.029
6	31.5	49.8	0.151	0.206	0.362	0.338	0.456	0.812	0.017	0.024	0.049
7	30.6	51.6	0.088	0.122	0.236	0.195	0.274	0.530	0.012	0.017	0.034
8	29.7	52.5	0.111	0.152	0.287	0.247	0.343	0.646	0.014	0.021	0.043
9	29.1	50.7	0.050	0.063	0.100	0.113	0.143	0.231	0.009	0.012	0.020
10	27.0	56.1	0.142	0.197	0.355	0.318	0.436	0.798	0.017	0.024	0.049

4.1. Comparison with non-source approach results

One means of differentiations of non-source approach is the arranging type of earthquake sources and calculation of the source parameters. In this approach, for each point of the grid, the corresponding parameters (ρ, β, λ) are calculated using a sequence including logarithm of acceleration values from adjacent events. β value and λ value are exactly the same concept of the similar values of seismicity parameters, with the difference that these values are obtained according to the acceleration values from the catalogue and the attenuation relations. In other words, magnitude values are substituted by the logarithm of peak ground acceleration values which are deduced from substituting magnitude and distance in attenuation relations. In this method, in order to obtain PGA, no regional sources based on seismotectonic studies are not applied. This can be very useful due to the lack knowledge of fault geometries. In order to estimate the parameter ρ-maximum possible value of $\mathrm{A}_{\max}$ due to the only 30 "main-shocks" events which have the maximum values of $\mathrm{A}_{\max}$ were taken for the analysis, thus, for each node of the grid, they have the same value of $n = 30$ in the Eq. (1) but different values of R_0 and $R_\tau = \max R_i$, $1 \leq i \leq n$ the *a priori* boundary value for ρ was taken as $\rho_{\max} = R_\tau + 0.5$.

In this study, we used the developed method of *Pisarenko et al. (1996)* with source-base approach for data of Zagros seismotectonic province and we compared the obtained results with results of non-source approach (the study of *Salahshoor et al., 2018*) which have been presented in Fig. 8. The estimated PGA values in Figs. 6 and 8 has been presented by probability level of 90% for return period of 100 years. In the study of *Salahshoor et al. (2018)* hasn't been used in calculations (based on Bayesian method) from source, in another word, each earthquake has been considered as a source of earthquake, but in present study, we have studied this concept considering the proper source. If there is a lack of data, especially in parts which have incomplete historical data or there are even little data, the estimation of source-base can compensate the shortage of data. Considering the values of PGA in Figs. 6 and 8 it is observed that results of both approaches are almost identical and whole when enough data in the region is available. Non-source approach shows more values of acceleration than source-base approach using only data limited to the sources to estimate. However, in the case when in one source we haven't enough data, despite existence of active fault, non-source approach estimates less acceleration than source-base approach. The reason of this effect is that source-base approach in

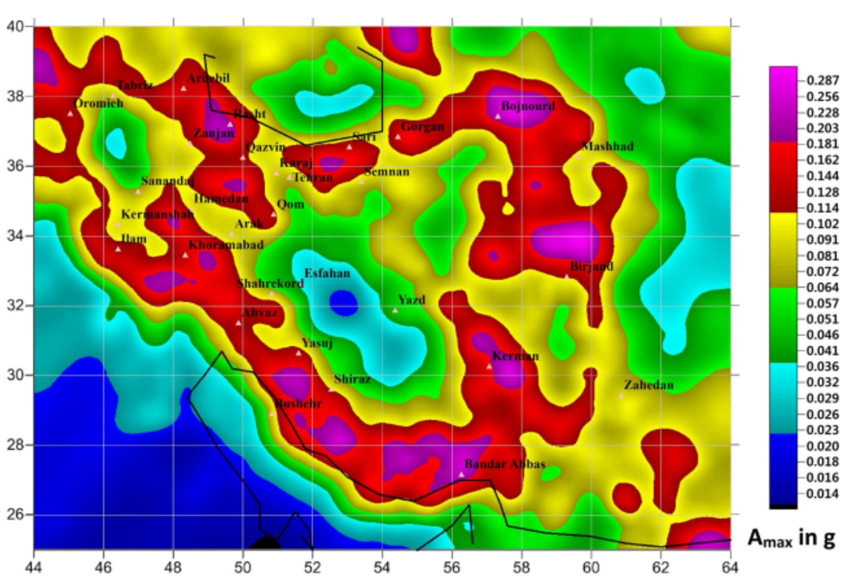

Fig. 8. The map of 90% quantile of distribution of A_{max} (in g) in the future time interval T = 100 years. The values are related to the ρ parameter (*Salahshoor et al., 2018*).

the region with poor data, poses proper seismic parameters for the sources, considering the specifications of seismotectonics of the region.

In a different study, *Mousavi Bafrouei et al. (2014)* presented the PGA applying the PSHA method. For return period of 475 years, reported the same results as found in this study and also what presented in *Karimiparidari et al. (2013)*, they have obtained a relatively higher values.

5. Conclusions

The condition of Bayesian method is repetition of earthquakes with a sameness of tectonic conditions. Considering the sort of fault of Sar-e-polzahab and horizontal faulting of bedrock, there isn't previous belief. Occurrence of a 7.3 earthquake at the end of Zagros mountain wasn't supposed and due to this reason, the source was not based on the number of earthquakes, but on existence of active fault. In the regions similar to Sar-e-polzahab, in which we haven't recorded any previous earthquakes and now a large earthquake has occurred, the data of seismotectonics of the fault is imported in the Bayesian relationships as an *a priori* belief and then we calculate the *posterior*. Smoothing and consideration to acceleration for the region which has fault, but hasn't earthquake, will be obtained by division of Zagros seismotectonic province (the regions with different tectonics) into parts with uniform tectonics.

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