7th International Conference on Seismology & Earthquake Engineering
18-21 May 2015

REDUCING EPISTEMIC UNCERTAINTY OF PROBABILISTIC SEISMIC HAZARD ANALYSIS USING MONTE CARLO SIMULATION

Erfan FIRUZI
Research Assistant, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
fkerfan@yahoo.com

Anooshiravan ANSARI
Assistant Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran
a.ansari@iiees.ac.ir

Keywords: Monte Carlo Simulation, Seismic Hazard, Epistemic Uncertainty, Tabriz

ABSTRACT

One of the significant concerns of conventional method of Probabilistic Seismic Hazard Analysis (PSHA) is management and treatment of uncertainties. These uncertainties originate from unavoidable reliance of PSHA on subjective decisions and using simplified assumptions and models in calculation. Monte Carlo simulation is actually a second approach for calculation of PSAH and provides a way for reducing such epistemic uncertainties. Monte Carlo simulation is a computational algorithm that relies on repeated random sampling for their results. This algorithm calculates seismic hazard by simulating of future pattern of ground shaking at the site. This method requires only information about past seismicity as minimum input data to generate a synthetic catalog. This simple method is a potent approach to bypass the need for identifying and quantification of parameters and models and as a result, decrease epistemic uncertainty of analysis. In this paper, a comprehensive comparison is made between the results of conventional PSHA and Monte Carlo simulation approach in order to reveal the influence of epistemic uncertainty on conventional PSHA and the power of Monte Carlo approach in controlling these uncertainties. To this end, a number of analyses have been carried out for a site in Tabriz city, Iran. It is turned out that Monte Carlo simulation introduces a way to reduce such kind of uncertainty.

1. INTRODUCTION

Evaluation of seismic hazard at an area is one of the most momentous subjects of earthquake engineering. The aim of seismic hazard analysis is determining probability of occurrence of specific level of ground shaking within a given future time interval. One of the substantial concerns of such calculation is manipulating of uncertainty induced by lack of precise information about source geometry and location, recurrence of seismic events at the source and influence of site effects. The proper way of dealing with and modeling of these uncertainties in analysis is a significant issue in seismic hazard; because, the results of seismic hazard can be influenced heavily by these uncertainties.

The first formulation for handling these uncertainties was proposed by Cornell (1968) and later enhanced by Mc-Guier (1976) in the general framework of PSHA. This method is now widely used and often seen as a general tool for seismic hazard analysis. This method is formed on the basis of total probability theorem (Musson, 2000). Although the basic formulation of this method included the aleatory uncertainty due to randomness of earthquake process, it does not incorporate additional sources of uncertainty that may be associated with the choice of particular model and model parameters. Indeed, the major difficulty of this method stems from reliance of this method on subjective decision that should be made by incomplete and uncertain information. Defining the most appropriate seismic source zones, selecting the most applicable recurrence model, and determination of seismic parameters like rate of occurrence λ_{min}, seismicity rate β, and the way of apportioning seismicity parameters to their corresponding seismic zones are some issues that rely on the view and opinion of experts and may result in uncertainty in the results of PSHA.

The primary focus of this paper is on the application of a powerful alternative approach to conventional PSHA based on Monte Carlo simulation method which is increasingly gaining popularity. This method is based on imitating nature of phenomenon by generating random variable or random processes according to specific data and models. By this algorithm a pattern of future ground shaking at the site is simulated. In other words, this method calculates seismic hazard by generating synthetic earthquake catalog by sampling of real catalog or specific models.

In proceeding, first, Monte Carlo simulation approach is introduced as a tool for probabilistic seismic hazard analysis. Then, benefits and limitation of this method is discussed. Eventually, the comparison of the results between conventional method of PSHA and Monte Carlo simulation for city of Tabriz is putted forward.

2. IMPLEMENTATION OF MONTE CARLO SIMULATION AS A TOOL FOR PROBABILISTIC SEISMIC HAZARD EVALUATION

Monte Carlo simulation is a potent tool for manipulating uncertainty in phenomenon with lots of degrees of freedom. This method has applied in various fields like mathematic, statics, econometric and any field which needs quantitative discipline. It is a computational algorithm that relies on repeated random sampling for their results. There are lots of Monte Carlo simulation algorithms that all of them follow same trend. In the first step, ranges of possible input are defined. In the second step, a number of possible input parameters are generated randomly based on particular probability distribution; then result of each input is calculated and stored. Finally, based on the stored results, probability of different outcome is determined.

With respect to the power of Monte Carlo simulation in dealing with problems with limited observed information and lack of knowledge about essence of process, this method makes its way in PSHA. The early development of this method in seismic hazard analysis represent in studies of Shapira (1983), Johnson and Koyanagi (1988). The more in depth investigation in this regard can be find in studies of Ebel and Kafka (1999), and Musson (2000). Within the framework of Monte Carlo, a synthetic catalog with thousands of years length is generated which represents a pattern of future earthquake in the region. By assessment the effect of each event in the synthetic catalog on the site, the annual rate of occurrence for different ground motion values can be calculated by merely counting the number of results exceeding a critical value. This simple formulation for estimation of annual rate of occurrence in an area has several superiorities over conventional method of PSHA described by Cornell (1968) that it will be discussed completely later.

In figure 1 general steps for calculation of probabilistic seismic hazard by Monte Carlo simulation method is represented. As it is clear, in the main loop of the algorithm magnitude and location of events of synthetic catalog is determined separately. Then with the aid of a ground motion prediction equation (GMPE) effect of simulated events is assessed on the site. It is noted that the scatter in GMPE should bring into account with a random variable based on log-normal distribution that adds to the result of GMPE. Eventually, based on the stored data, the annual rate of occurrence for different ground motion value is determined. As it is clear, the main challenging issue in this algorithm is the way of determining location and magnitude of events in synthetic catalog. In this paper for determining the location of synthetic events, the method of Ebel and Kafka (1999) is employed where events are generated with equal probability of occurrence in any direction within a circle with the radius of 30 Km around the original event. Also, parametric and nonparametric approaches are employed for determining magnitude of synthetic events and results have been compared. In parametric approach, magnitude of events in the synthetic catalog is determined by random sampling of Gutenberg-Richter recurrence model (1947) while in nonparametric approach magnitude of synthetic events is determined by random selection from the original catalog.

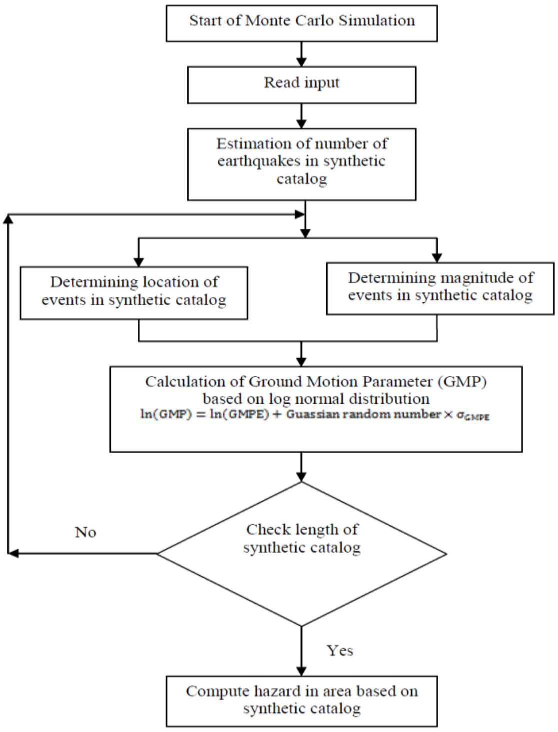

Figure 1. Algorithm of the general operation of the Monte Carlo Simulation for PSHA

3. BENEFITS AND LIMITATION OF MONTE CARLO SIMULATION METHOD IN COMPARISON WITH CONVENTIONAL METHOD OF PSHA

Conventional method of PSHA represented by Cornel (1968) comprises of four basic steps. In the initial step, all seismic sources which are capable of producing earthquake should be identified and characterized. In the next step, a recurrence model with its seismicity parameters should be designated to each seismic zone and with the aid of a ground motion prediction equation (GMPE), probability of exceeding different ground motion value is calculated. Finally, by using the total probability theorem, the spatial and size uncertainties and probability of exceeding different ground motion value is assembled (Cornell 1968).

The main problem in hazard assessments is that the different input parameters are not precisely known. The power of Monte Carlo simulation is to circumvent the need to these parameters. That is, the uncertainty in delineation of seismic sources and estimation of parameters and models can be excluded from calculation. It is the possible to enumerate the advantages of Monte Carlo simulation in comparison with conventional method of PSHA as follow:

- Elimination the need for delineation of seismic sources
- Exclusion the uncertainty of recurrence model and seismic parameters
- Omission the need for apportion of seismicity parameter among seismic sources
- Simple approach for determining of Design earthquake

Apart from these advantages, Monte Carlo approach for probabilistic seismic hazard analysis suffers from some issues. The most important one is that Monte Carlo method highly hinges on the quality of observed catalog. Similar drawback also exists in conventional PSHA, however, the influence of catalog quality is reduced by using a priori information about seismotectonic of the region. Another major problem of using Monte Carlo simulation for seismic hazard analysis is high computational cost of this method. In other words, Monte Carlo simulation encompasses a huge computation that takes lots of time. However, this issue is become less important by advances in parallel processing technology and using high speed computers.

4. APPLICATION OF SEISMIC HAZARD IN TABRIZ

To achieve a better understanding about capabilities of Monte Carlo simulation in dealing with uncertainties in seismic hazard of a region, a number of analyses have been carried out for an arbitrary site in Tabriz, Iran. Prior to Monte Carlo simulation, we have a general and quick review to the seismicity and seismotectonic of Tabriz region.

Seismicity: Tabriz city is one of the political and industrial cities in Iran and it comprises about 1.5 million inhabitants. From seismotectonic point of view, the Tabriz area is part of the complex tectonic system due to the interaction between Arabia, Anatolia and Eurasia and comprising the North Anatolian Fault, the East Anatolian Fault, the Caucasus Mountains, and the Main Recent Fault which bounds the Zagros Mountains. Part of the northward motion of Arabia is transferred to Anatolia by this complex system of faults. The North Tabriz fault (NTF) is a clear WNW–ESE trending strike-slip fault that runs for more than 100 km between the Lake Urumieh and the Talesh system. To the west, the NTF joins the EW trending right-lateral strike-slip Tasuj faults and the north-dipping Sufian reverse fault. The North Tabriz Fault is composed of several right-stepping segments associated with pull-apart basins, the most important being the Tabriz basin where the city of Tabriz is located (Moradi et al. 2011).

Earthquake catalog: The instrumental catalog for events within a radius of 150 Km around the site (46.29 E, 38.073N) was provided by the network of International Institute of Earthquake Engineering and Seismology (IIEES). This catalog encompasses events within the period of 1907-2012. The catalog was compiled with a more complete catalog supported by Iranian Seismological Center that covers the period of 1996-2012. Magnitude of all events in the resulting catalog homogenized into moment magnitude (Mw) by means of Scordolis (2006) and Shahvar et al. (2013) magnitude scale relations. The historical events in this regions were also compiled to the catalog from data set of Ambraseys and Melville (1982). To exclude the dependence events in the catalog the declustering algorithms of Reasenberg (1985) is used. The spatial distribution of these events is depicted in figure 2. In addition, in figure 3, time magnitude distribution of original catalog is presented.

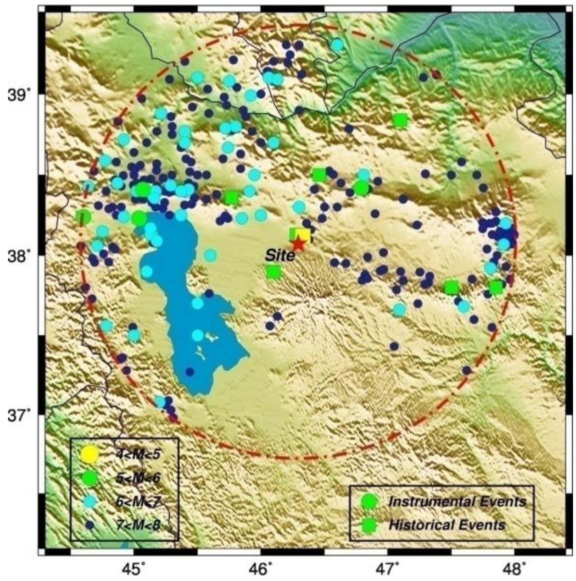

Figure 2. Distribution of instrumental and historical events in 150 Km around the site

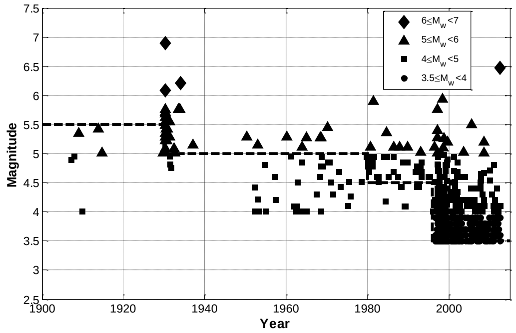

Fig. 3 Time magnitude distribution of instrumental catalog

In proceeding three different tests have been done for assessing the influence of the uncertainty on the results of conventional approach of PSHA and the power of Monte Carlo in dealing with these uncertainties.

4.1 UNCERTAINTY IN DELINEATION OF SEISMIC ZONES

To investigate sensitivity of conventional PSHA results to the uncertainty of different delineations of seismic sources, three different seismic sources have been considered, as it is depicted in Figure 4. In the first source model (SM1), just linear faults in 150 Km around of site are considered in calculation. The locations of these linear source models are consistent with map of major active faults of Iran. In the second source model (SM2), five area faults are depicted in a way that covers events around the site. Third source model (SM3) is a combination of first and second models. In fact, in this model, the area sources in the second models are ascribed as background seismicity zones for linear faults in the first model.

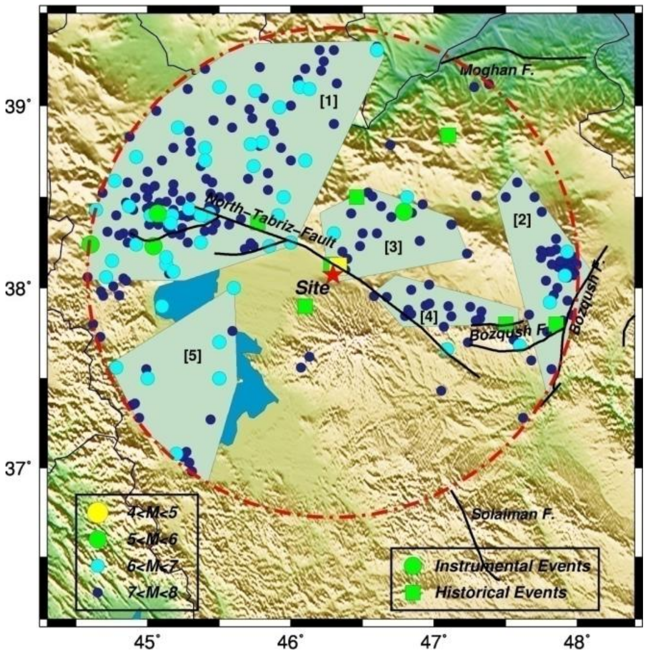

Figure 4. Different seismic zones models for Tabriz

Figure 5 represents the resulting hazard curves considering different source models. The resulting hazard curve of Monte Carlo simulation is also shown in this figure. Considering return period of 2475 years, the PGA obtained using SM2 is 54% of PGA using SM1. The difference between SM1 and SM3 is nearly 10%. It is noted that Tabriz region is a highly seismic area with known active faults. In such region, modeling defuse seismicity around active faults will result in 10% difference in PGA value. In areas with low seismicity where there are not any mapped active faults, the difference between reasonable source models is more pronounced.

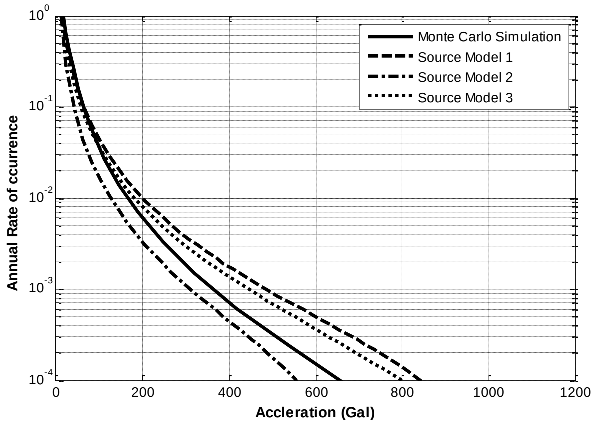

Figure 5. Hazard curve obtained by the conventional method for three different seismic sources (seismicity parameters derived via kijko and sellovel (1992) approach β=2.3, $\lambda_{4.0}$=3.5) and result of Monte Carlo simulation

4.2 UNCERTAINTY IN RECURRENCE MODEL AND SEISMICITY PARAMETER

In our second test, we assess the effect of using different recurrence models on the results of conventional PSHA. The uncertainty of recurrence models can be categorized into two different groups. The first type of uncertainty is due to availability of different recurrence models for use in PSHA. Simple Gutenberg- Richter, single and double truncated Gutenberg-Richter and characteristic earthquake models are more common models in PSHA. Decision about which model to use is usually a subjective judgment of expert and is a source of epistemic uncertainty. Another type of uncertainty is according to different methods of parameter estimation and the ways of considering different levels of catalog completeness. In this section, only the effect of this kind of uncertainty is considered. For this purpose, seismicity parameters of the area have been estimated in three different ways. In the first attempt, seismicity parameters are evaluated by method developed by Aki (1965). As the second approach of estimation, the method represented by Wichert (1980) is used and finally, the approach of Kijko and Sellovel (1992) is implemented. It should be noted that in estimation of seismic parameter variation of magnitude of completeness with time is considered, as depicted in Figure 3. Table 1 summarizes various values of β and λ_{min} calculated by different approaches.

Table 1. Result of seismicity parameters estimation by three different approaches

	β	**$\lambda_{4.0}$**
Aki (1965)	2.05	2.81
Wichert (1980)	2.45±0.115	3.70
Kijko and Sellevoll (1992)	2.30±0.09	3.5±0.13

Table 2 shows the sensitivity of results with variation of seismicity parameters estimated by three different ways. The results of parametric and non-parametric Monte-Carlo approach are also provided in this table. By considering return period of 2475 years and source model SM3, there is 16% difference between the results of Weichert (1980) and 4% difference between kijko and sellovel (1992) and Aki (1965). It is noted that this difference is only due to using different estimation method for calculation of seismicity parameters. The value of using non-parametric Monte-Carlo method is in eliminating epistemic uncertainty of model selection and parameter estimation.

Table 2. Results of seismic hazard in three specific return periods for different approaches of evaluating seismicity parameters

	Aki (1965)				Wichert (1980)				Kijko and Sellevoll (1992)				NP.M.C[b]
	SM1	SM2	SM3	P.M.C[a]	SM1	SM2	SM3	P.M.C	SM1	SM2	SM3	P.M.C	
475	0.406g	0.251g	0.370g	0.346g	0.351g	0.231g	0.329g	0.265g	0.381g	0.242g	0.374g	0.302g	0.280g
2475	0.711g	0.452g	0.653g	0.565g	0.602g	0.393g	0.554g	0.443g	0.647g	0.419g	0.676g	0.495g	0.468g
10000	0.791g	0.634g	0.897g	0.774g	0.791g	0.526g	0.732g	0.632g	0.858g	0.565g	0.812g	0.690g	0.642g

[a] Parametric Monte Carlo (P.M.C) simulation method

[b] Nonparametric Monte Carlo (NP.M.C) simulation method

4.3 UNCERTAINTIES IN APPORTIONING SEISMICITY RATE

In the third analysis, the impact of the way of apportioning seismicity rate on the conventional method of PSHA is addressed. Table 3 shows the difference of geometric and energetic approach for apportioning seismicity rate λ_{min}. As it can be seen in table 3, for the fault number 3 (figure 4), based on energy method parameter λ_{min} is nearly doubled.

Table 3. Distribution of parameter λ based on the area or energy of the faults

Fault No	Area apportioning	Energy apportioning
1	2.02	2.34
2	0.430	0.056
3	0.275	0.690
4	0.148	0.316
5	0.627	0.091

Figure 6 shows the sensitivity of the results of Conventional method of PSHA with respect to the way of distribution of λ_{min} for second source model. As it can be seen for return period of 475, acceleration of 0.242g is obtained based on distribution of λ_{min} according with the area of faults while based on the energy apportionment approach acceleration of 0.333g is derived. In other words, more than 37 percent difference in PGA value by using different methods of apportioning seismicity parameters among different seismic sources.

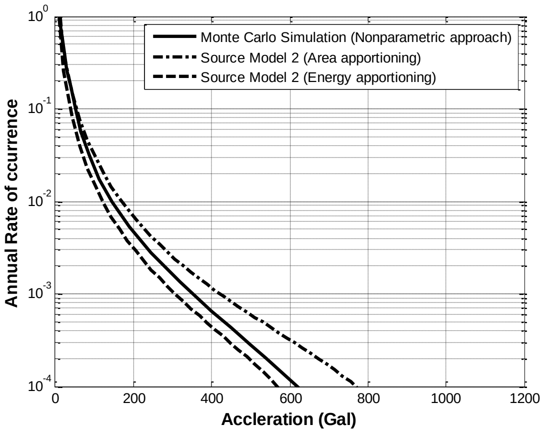

Figure 6. Hazard curve for the region based on source model 2 (apportioning of λ_{min} based on area and energy of the fault) and Monte Carlo simulation

CONCLUSIONS

The analyses in the previous section reveal that the result of conventional seismic hazard analysis is associated with different kinds of epistemic uncertainties. In Table 4, a summary table is presented to have a general comparison between the results of different conventional PSHA with non-parametric Monte Carlo simulation. In this table, the PGA values with return period of 2475 years are shown. Considering different source models, the difference between PGA values ranges from 10% for SM2 to 38% for SM1. Such differences are not so pronounced using different values of seismicity parameters. The similar range of difference could be also observed for different methods of seismicity rate apportioning. In real applications, it is a hard work to choose between different values of seismicity parameters or source models. The consequence of existence such uncertainty is obtaining different values for hazard levels for an identical location when hazard analyses are performed by independent experts. The value of Monte Carlo simulation for calculation of probabilistic seismic hazard is that such variations on the results are avoided. It circumvents the need for identifying and quantification of parameters and models, and automatically handles epistemic uncertainty in a very effective way.

Table 4. PGA values for 2475 years return period for different source models, seismicity parameters and apportioning methods

		PGA	Difference %
	Non-parametric Monte Carlo simulation	0.468g	0
Source models	SM1	0.647g*	38%
	SM2	0.419g*	10%
	SM3	0.595g*	27%
Seismicity parameters	Aki (1965)	0.452g**	3%
	Weichert (1980)	0.393g**	16%
	Kijko and Sellevoll (1992)	0.419g**	10%
Seismicity rate apportioning	Area apportioning	0.415g**	11%
	Energy apportioning	0.561g**	19%

[*] Results have been obtained based on the seismicity parameters of Kijko and Sellevoll (1992)
[**] Results have been obtained based on the source model 2 (SM2)

Although Monte Carlo simulation has strong advantages, there are some obstacles in application of that. Firstly, it involves extensive computation. Therefore, it is necessary to design program that optimize speed of run of program. Secondly, due to randomness essence of Monte Carlo, its result is not unique for high return period; however, this defect can be overcome by increasing the length of synthetic catalog. Finally, it should be noted that results of Monte Carlo heavily relies on the observed catalog. Hence, some expert judgments about the data set to be used are required for proper application of this method.

REFERENCES

Abrahamson NA and Bommer JJ (2005) Probability and uncertainty in seismic hazard analysis, *Earthq Spectra*, 21:603–607

Aki K (1965) Maximum Likelihood Estimation of b in the Formula LogN=a-bM and its Confidence limits, *Bull Seism Soc Am*, 43:237-239

Ambraseys NN and Melville CP (1982) A history of Persian earthquakes, Cambridge university press, London
Cornell CA (1968) Engineering Seismic Risk Analysis. *Bull Seism Soc Am*, 58:1503- 1606

Ebel JE and Kafka AL (1999) A Monte Carlo approach to seismic hazard analysis, *Bull Seism Soc Am*, 89:854–866.
Gutenberg B, Richter CF (1944) Frequency of earthquakes in California, *Bull Seism Soc Am*, 34:185-188

Han Sang-Whan and Choi Yeon-Soo (2008) Seismic Hazard Analysis in Low and Moderate Seismic Region- Korean Peninsula, *Structural Safety*, 30:543–558

Kijko A, Sellevoll MA (1992) Estimation of Earthquake Hazard Parameters from Incomplete Data Files. Part II. Incorporation of Magnitude Heterogeneity, *Bull Seism Soc Am*, 82:120-134

Moradi AS, Hatzfeld D and Tatar M (2011) Microseismicity and seismotectonics of the North Tabriz fault (Iran), *Tectonophysics*, 506:22–30

Musson RMW (2000) The use of Monte Carlo simulation for seismic hazard assessment in the UK, *Annali di Geofisica*, 43:1-9

Reasenberg P (1985) Second-order moment of Central California seismicity, 1969–1982, *Journal of Geophysical Research* 90:5479–5495

Shahvar M P, Zare M and Castellaro S (2013) A Unified Seismic Catalog for the Iranian Plateau (1900–2011), *Seismological Research Letters*, 84:233-249

Scordilis EM (2006) Empirical Global Relations Converting M_s and m_b to Moment Magnitude, *Journal of Seismology*, 10:225-236