Association of Earthquakes and Faults using Distance-Based Weighting Method

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SUMMARY:
Characterizing the frequency-magnitude behavior of faults is commonly approached by association of earthquakes and faults. There are few methods for associating events to active faults including energy and constant b-value methods. Choosing each method has a direct impact on the final results of PSHA. Weighting earthquakes based on their distance from the adjacent faults, which originates from fuzzy clustering algorithms, provides a method in association all events with different weight numbers to specific faults. The procedure is in such an order that the least distance from the fault, the most weight the event gets. The application of this method is described through a case study of events occurred through 150 km far from the metropolis Tehran which is located in Central Alborz, Iran. Based on the classic Gutenberg-Richter frequency-magnitude relationship, the process is applied to all events and major faults of the region in order to derive seismicity parameters for each fault. A comparison is made with common association methods.

Keywords: Association of Earthquakes, Seismicity parameters, Seismic Hazard Analysis

1. INTRODUCTION

One of the debates in the studies of seismic hazard assessment is about characterizing the frequency-magnitude behavior of seismic sources within the region of interest. Identification and delineation of potential sources of seismicity is the first step in any seismic hazard analysis. These sources are capable of producing potentially damaging ground motions which could dangerously influence the site. The source model which specifies the expected distribution of earthquakes within the range of distances is the key element in any seismic hazard analysis. For probabilistic methods the source model is often some combinations of area sources and specific faults, while for deterministic methods it is usually a specific fault. Most Earthquakes are caused by rupture of geological faults, but also by other events such as volcanic activity, landslides, mine blasts, and nuclear tests. The length or area of the fault rupture is used to determine an expected magnitude for the fault. This is an important factor since larger earthquakes occur much less frequently and tend to use up more stored energy (moment) than smaller earthquakes. Considering individual faults as major seismic sources of the region, significant earthquake activity can be directly associated with active faults. This requires that each fault be characterized by its own earthquake recurrence behavior. Faults having different degrees of activity differ significantly in the average recurrence intervals of significant earthquakes. Therefore, it is common to assign to the fault a certain proportion of the seismic activity which is assessed for the region containing the fault.

For purpose of deriving seismicity parameters of the region, the classic Gutenberg-Richter exponential frequency-magnitude relationship is usually used. But how are the occurred earthquakes apportioned among the faults? Various strategies may be chosen for the association of events and faults. There are few methods for apportioning seismicity parameters to active faults based on either source geometrical dimension or activity potential of sources such as energy and constant b-value methods. In the past two decades, these methods have increasingly been used in seismic hazard assessment in all most tectonically active areas of the world. In general, the basic strategies in association of earthquakes and faults are different and probably the main challenge for these methods is to make a step forward in characterizing the frequency-magnitude behavior of faults through a rational approach. The strength of one over the other is an exercise in inference. For instance, the apportionment based on the parameters of source configuration is easier to implement, whereas the activity potential of sources is reflected better through the energy apportionment. On the other hand, uncertainties will always exist and for efficient analysis they need to be explicitly accounted for. In fact, a significant degree of uncertainty related to the characteristics of past earthquakes over the entire time period of interest is inevitable in both methods. We have begun to understand the important role of uncertainty in seismic hazard analysis. However, there are still significant shortcomings in our treatment of uncertainty.

Regardless of region activity rate, it seems to be possible to estimate directly the required parameters describing the rates at which each individual fault has generated earthquakes of different magnitudes in the past, which are then taken as the expected probabilities to generate future earthquakes for use in the assessment of seismic hazard. If one wishes to estimate key parameters – the activity rate and the b-value – of each fault directly, rather than the apportioning process, the most robust way is to use fuzzy clustering algorithms.

The purpose of this paper is to propose and discuss a distance-based weighting method to extract seismicity around active faults of the region. Weighting earthquakes based on their distance from the adjacent faults, which originates from fuzzy clustering algorithms, provides a method in association all events with different weight numbers to specific faults. The procedure is in such an order that the least distance from the fault, the most weight the event gets. According to this method, all of the events are contributed in characterizing recurrence behavior of each fault and a rational and consistent framework for explicitly decreasing seismicity uncertainties is provided. The application of this method is described through a case study of events occurred through 150 km far from the metropolis Tehran which is located in Central Alborz,Iran. Based on the Gutenberg-Richter frequency-magnitude relationship, the process is applied to all events and major faults of the region in order to derive seismicity parameters for each fault. Finally, a comparison is made with common association methods.

2. ON THE SEISMICITY OF IRAN

The Iranian plateau has long been known as one of the seismically active areas of the world and it frequently suffers devastating and catastrophic earthquakes. Earthquake data of Iran show that most activity is concentrated along the Central Alborz and Zagros fold thrust belt. Less activity is observed in central and eastern Iran. Central Alborz corresponds to the E-W trending mountain range bounding the Caspian Sea to the South. It is an active mountain trend belonging to the Alpine-Hymalian seismic belt, connecting the Talesh and the Lesser Caucasus ranges to the west, and the Eastern Alborz structures to the East. Tehran lies on the southern flank of the Central Alborz, an active mountain belt characterized by many historical earthquakes, some of which have affected Tehran itself. Several high historical earthquakes occurred in this region demonstrates high seismic hazard in this region. The two most catastrophic ones were the 1957 Sangechal earthquake centered in the Alborz northeast of Tehran(Tchalenko, 1973), and the 1962 Buyin Zara earthquake centered outside the main range to the west of the capital(Ambraseys, 1963).

Several local and regional seismic hazard studies have been performed in order to estimate seismic activity all over the country. The latest version of seismic zoning map of Iran given in the Iranian Code of Practice for Seismic Resistant Design of Buildings Standard No. 2800 3rd Edition assigns four levels of seismicity for Iran in terms of zone factors. In other words, the earthquake zoning map of Iran divides Iran into 4 seismic zones (Zone 1, 2, 3 and 4). According to the present zoning map, Zone 1 expects the highest level of seismicity whereas Zone 4 is associated with the lowest level of seismicity.

2.1. Active Faults

The Alborz region is an active zone with a high density of active faults. The observed activity demonstrates the presence of numerous and large active faults. Geologically, an active fault is defined as a fault which has moved repeatedly in recent geological time and has the potential for reactivation in the future. Virtually all major faults in Iran are active and thus have great seismic potential. Focal mechanism solutions indicate dominance of thrust and strike-slip faults in Iran. It is believed that Tehran province belongs to Alborz and central Iran structural zones. The boundary between these zones matches on northern Tehran thrust fault. Alborz heights have thrusted on Tehran plain due to this fault. Geological studies indicate that Alborz and central Iran zones have many similarities, so that Alborz can be considered as central Iran`s marginal folds, although based on structure these zones are completely different. A rich historical and archeological record in Iran spans several thousand years, long enough to establish recurrence intervals of 1000 to 5000 yr on individual fault segments.

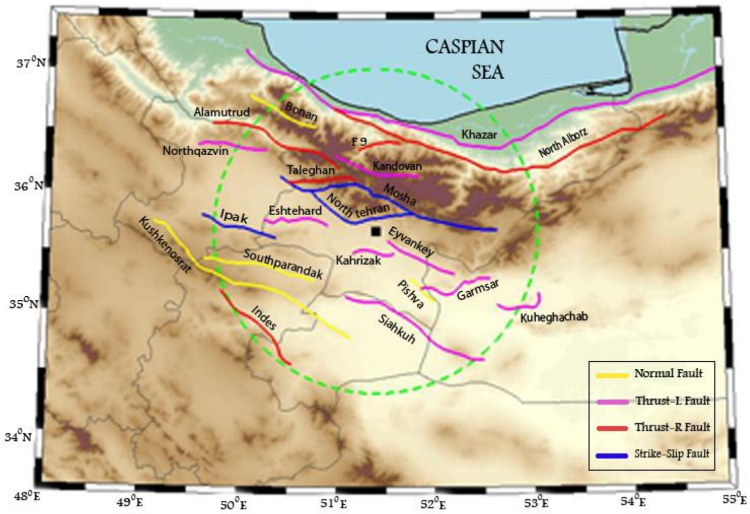

Figure 2.1. Map of active faults in the Alborz region

The region considered in this study includes the most important faults in the southern edge of Alborz, which their activity has been documented using both seismicity and field investigations. The geology of the Alborz Range in its central part is controlled largely by major thrust faults such as the North Alborz, Mosha and North Tehran faults. The Mosha Fault, which was first identified by Dellenbach et al. (1964), is the most prominent structure in the southern part of the Alborz. In addition, the Khazar fault which is located in the northern edge of the Alborz mountains is the longest active fault in the Alborz. The distribution of major active faults of the region is illustrated in Figure 2.1. The Figure shows a high density of active faults in the region which means that the source of earthquakes could be related to more than one fault. Moreover, some earthquakes in Iranian plateau occur on blind faults with no clear co-seismic surface rupture. The most accessible information relating to active faulting and blind faults comes from earthquake seismology. Since study of active faults has not been detailed enough in Iran, we cannot be certain that the area without active faults is completely free of earthquake risk. Furthermore, locating the active faults becomes complicated since many of the region`s earthquakes were not associated with surface faulting.

3. DATA

Iran's seismography network was inaugurated in 1957 when the Geophysics Institute of Tehran University was established. At present, 67 sites are working. Accelerography network of Iran has been launched from 1974. It has comprised 1041 sites up to now. About 7000 earthquakes have been recognized and recorded in history and by instruments. The earthquakes that have been reported before 1900 are called historical. The other earthquakes, which have been recorded by seismographs after 1900 are the instrumental events. Many relocation analyses were performed on instrumental part of catalogue (Niazi and Basford, 1968; Nowroozi, 1976; Ambreseys, 2001; Engdahl et al., 1998, 2006).

Two types of earthquake catalogs were used in this study; historical and instrumental. The historical part of the catalog was compiled from various literatures. The details of earthquake events for the period from 250 B.C. to 1505 A.D. were obtained from Ambreseys and Berberian Catalogues. On the other hand, primary source of instrumental earthquakes used in this study was obtained from the IIEES[1] website (http://www.iiees.ac.ir). Hence, the details of the past earthquakes and seismic sources were collected from an area which extend up to 300 km from Tehran city. A catalogue of 265 earthquakes with magnitudes more than M_w = 4.0 since 250 B.C is the basis of the present study.

3.1. Magnitude Conversion

Following the construction of new seismographs and different wave types, recorded at various distances, the magnitudes are reported in different scales. Region-specific earthquake magnitude scaling relations correlating different magnitude scales were achieved to develop a homogenous earthquake catalogue for different regions in unified moment magnitude scale. As a matter of fact, in order to work with a consistent measure of magnitude and creation of a homogenous earthquake catalogue, all events not already given in terms of Moment Magnitude (M_w) are converted to this scale. Many papers have been published in which the relationships between two or more magnitude scales have been examined and the problems of relationships between various magnitude scales have been discussed (e.g., Aki, 1967, 1972; Kanamori and Anderson, 1975; Noguchi and Abe, 1977; Chen, 1989; and Gusev, 1991). Of special interest is the representation of empirical relations obtained in these studies by a linear equation in some limited range of magnitudes. In this paper, we used the empirical global relations which were represented by E.M. Scordilis (2006).

3.2. Declustering the Catalogue

The context of earthquake catalogue is of much importance in the studies of seismic hazard analysis. In fact, the instrumental catalogues involve not only the main shocks but also foreshocks and aftershocks. The division between foreshocks, mainshocks, and aftershocks has a long and distinguished history in seismology. Within a pre-specified space-time domain, foreshocks are usually defined as earthquakes preceding a larger earthquake (mainshock), which is itself followed by an increase in seismicity of smaller earthquakes (aftershocks).

Existing approaches in the research of seismic hazard assessment are generally based on the Poisson model since events have no spatio-temporal correlation with preceding events. Aftershocks show a major deviation from a Poisson process. Therefore, the dependent events in the raw catalogue must be removed to ensure the Poissonian distribution of earthquakes. Consequentially, several methods have been suggested in the literature. (eg. Savage, 1972; Gardner and Knopoff, 1974; Reasenberg, 1985; Davis and Fohlic, 1991a, b; Molchan and Dmitrieva, 1992). Since the underlying physical processes are not fully understood, the qualifying time and space windows used to select foreshocks, mainshocks and aftershocks are more based on common sense than on hard science. For this study, the declustering algorithm of Gardner and Knopoff (1974) is adopted. Although this method is one of the oldest, it is the easiest to apply to an inhomogeneous catalogue. The result is illustrated in Fig. 3.1.

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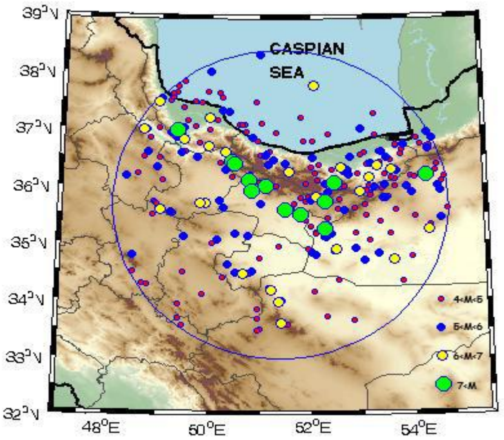

Figure 3.1. Map of events declustered through 300 km from Tehran

4. GUTENBERG –RICHTER PARAMETERS

There have been several efforts to estimate seismicity parameters for Iranian region based on both the historical as well as the instrumental earthquake catalog. Most researchers focused on some part or Iran or used different methodology for homogenization of catalogue as well as estimation or seismicity parameters. Nevertheless, the amount of information available for each individual seismogenic zone may be found insufficient for accurate statistical assessments of the seismicity parameters. The general form of the Gutenberg-Richter(1954) frequency-magnitude relationship is:

$$LogN(M) = a - bM$$

where N(M) is the cumulative number of earthquakes of magnitude greater than M, and a and b are constants. Based on this relationship, ‘a’ and ‘b’ are derived for the entire region. The results are given in Table 4.1.

Table 4.1. Gutenberg-Richter parameters

Parameter	Value
λ	2.52
b	-0.502

The b-value is indicative of the tectonic characteristics of a region. A higher b value means that a smaller fraction of the total earthquakes occurs at the higher magnitudes, whereas a lower b value implies a larger fraction (Bernice Bender, 1983). We may assume that the seismogenic zones all over the country will have the same value of b. This assumption may be considered to better represent the tectonic characteristics of the seismogenic zones in the investigated region. On the other hand, the seismo-tectonics may be of different character.

The next step is apportioning these parameters to the faults in order to reflect the seismicity of each fault. There are few methods for associating seismicity to seismic sources including energy and constant b-value methods. These apportioning could be done based on either the parameters of source configuration, i.e., length of sources, or activity potential of the sources. Choosing each method has a direct impact on the final results of PSHA.

5. DISTANCE-BASED WEIGHTING METHOD

Nowadays due to the yearly multiplying data comes always the claim for useful methods and algorithms that make the processing of these data easier. For the solution of this problem data mining tools come into existence, to which the clustering algorithms belong. Cluster analysis divides data into groups such that similar data objects belong to the same cluster and dissimilar data objects to different groups. In fact, the aim of clustering is to minimize a set of data points into self-similar groups such that the points that belong to the same group are more similar than the points belonging to different groups. The general case was developed by Jim Bezdek in his PhD thesis at Cornell University in 1973.

Application areas of fuzzy cluster analysis include for example data analysis and zone segmentation. Interestingly enough, it can be used for the purpose of deriving seismicity parameters in a seismic hazard analysis approach. When browsing through numerous papers on evaluating seismic parameters we can witness the dominant rule which the association of earthquakes and faults plays. Consequentially, it becomes apparent that fuzzy clustering is of vital benefit to the association approach. To implement the application of fuzzy clustering in estimating seismicity parameters around active faults a distance-based weighting method will be presented.

Weighting earthquakes based on their distance from the adjacent faults, which originates from fuzzy clustering algorithms, provides a method in association all events with different weight numbers to specific faults. The procedure is in such an order that the least distance from the fault, the most weight the event gets:

$$w_i = Min(\frac{10}{D_i}, 1)$$

where w_i is the weight which the event gets and D_i yields the distance of the i[th] event from the fault. This process is applied to all events and major faults of the region.

As mentioned above, different approaches can be attributed based on published literature. For this study, we adopted our new method through a case study of events occurred through 300 km far from the metropolis Tehran which is located in Central Alborz,Iran. Results from the application of this method and the comparison between the other approaches are illustrated is Fig. 5.1. and Fig. 5.2.

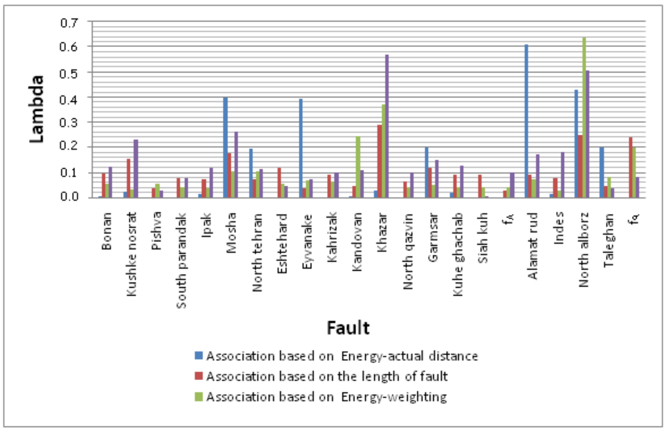

Figure 5.1. Estimation of Lambda

Another important seismicity parameter is the maximum magnitude which is the largest possible magnitude for a given seismogenic zone. In the probabilistic procedures, the value of Mmax is estimated purely on the basis of the seismological history of the area. Based on previous assessments we assumed that the maximum magnitude is 7.8. These estimations are based mainly on the limited seismic history and partially on the length of the mapped fault. In the case of the North Alborz fault we assumed Mmax=8.0 mainly due to the accumulated length of that fault system and due to its proximity to the population centers. We do not have any record of a strong earthquake (M>7.8) that has occurred in the past on that fault.

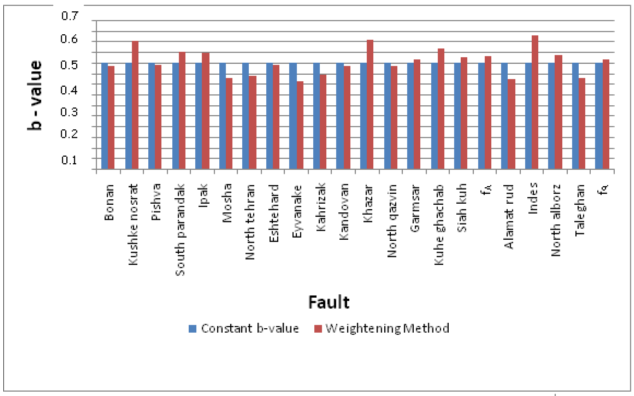

Fig. 5.2. Estimation of b-value

6. GROUND MOTIONS

The ground motion is determined from attenuation relations that relate the magnitude and distance from the site to the rupture. Typically ground motions tend to attenuate (or become smaller) as the waves travel away from the source. There are exceptions to this rule. For example, a wave may be amplified by soft sediments or by a deep basin. Earthquake records of ground shaking have been used to generate mathematical attenuation relations that describe how the ground motions attenuate with distance and for different sizes of earthquakes and different styles of faulting. Several different attenuation relations are used to generate the ground motions in the seismic hazard analysis(e.g. Boore et al., 1997; Sadigh et al. 1997; Abrahamson and Silva 1997; and Spudich et al., 1999). These relationships were derived empirically from recorded accelerograms due to earthquakes in different parts of the world. For our analysis we have used attenuation relations by Campbell and Bozorgnia (2003).

7. APPROACH AND RESULTS OF HAZARD ANALYSIS

For probabilistic seismic hazard assessment CRISIS (A Computer Program for Seismic Hazard Estimation) was used to calculate peak ground acceleration. This program is based on the assumption that the site acceleration has a Poisson distribution with a mean annual rate. The program can accommodate any attenuation relationships in digitized format and generate a table of peak ground accelerations and the cumulative distribution of the acceleration for each specified site. The PGA for the return periods of 475 years is illustrated.

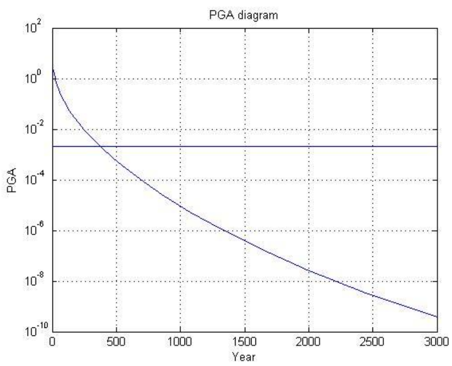

Figure 7.1. Estimation of PGA based on Energy-Actual distance

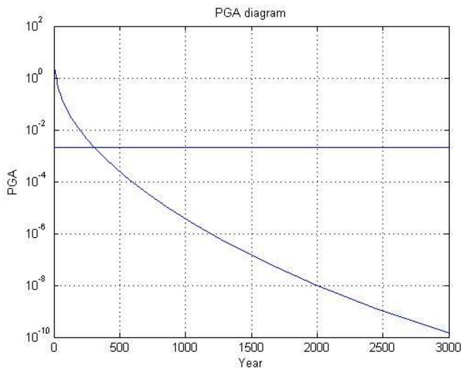

Figure 7.2. Estimation of PGA based on the length of the fault

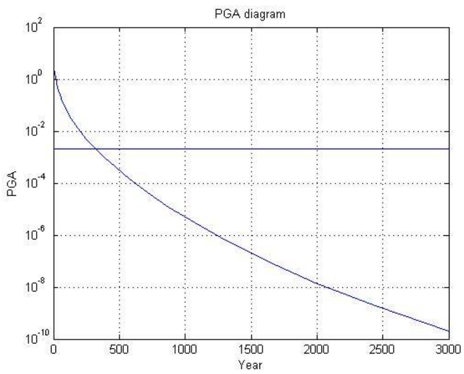

Figure 7.3. Estimation of PGA based on Energy-Weighting

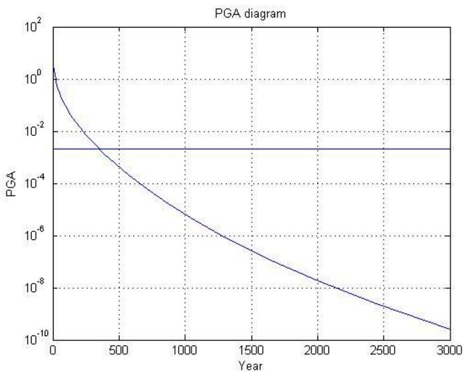

Figure 7.4. Estimation of PGA based on Weighting Method

8. CONCLUSION

In this study two major procedures in evaluation of seismic parameters for each fault has been carried out using the seismic data over an area having a 300 km radius around Tehran. Seismic parameters (lambda and b-value) have been evaluated from G-R relationship (Gutenberg and Richter, 1944). Three different association procedures were used in evaluating λ and a comparison has been made. Also, for b-value, we compared constant b-value method with weightening method. Finally, the Probabilistic seismic hazard analysis for Tehran city has been carried out. The hazard curves of mean annual rate of exceedance versus Peak Ground Acceleration (PGA) are generated. The quantified hazard in terms of the rock level peak ground acceleration values are mapped 10% probability of exceedance in 50 years. These values correspond to return periods of nearly 475 years (horizontal line in Figures).

REFERENCES

Bender B. (1983). Maximum likelihood estimation of b-value for magnitude grouped data. Bulletin *of the Seismological Society of America* **73:3**,831-851.

Bungum, H. (2006). Numerical modeling of fault activities. *Computers & Geosciences* **33**,808-820.

Douglas J. (2001). A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates. *ESEE Report* No. 01.

Kijko A. (2004) . Estimating of the Maximum Earthquake Magnitude, m_{max}. *Pure and Applied Geophysics* **161**,1-27

Kramer S. L. (1996). Geotechnical Earthquake Engineering. Prentice-Hall, Inc.

Nazari H., Ritz J-F, Salamati R., Shafaei A, Ghassemi A., Vernant P. (2006). Active transtension inside central Alborz: A new insight into northern Iran-southern Caspian geodynamica. *Geology* **34:6**, 477-480.

Nazari H., Ritz J-F, Salamati R., Solaymani S., Balescu S., Michelot J-L., Ghassemi A., Talebian M., Lamothe M., Massault M. (2008). Paleoseismological analysis in central Alborz,Iran. *50th anniversary earthquake conference commemorating the 1957 Gobi-Altay earthquake*.

Oncel, A. O., Alptekin O. (1999). Effect of aftershock on earthquake hazard estimation: An example from the North Antolian Fault Zone. *Natural Hazards* **19**,1-11.

Roshan A.D., Basu P.C (2010). Application of PSHA in low seismic region: A case study on NPP site in peninsular India. *Nuclear Engineering and Design*.

Scordilis E.M. (2006). Empirical global relations converting M_s and m_b to moment magnitude. *Journal of Seismology* **10**, 225-236.

Utsu, T. ; Relationships between Magnitude Scales. *International handbook of earthquake and engineering seismology*, Vol. 81A.

Wesson R. L., Bakun W. H., Perkins D. M. (2003). Association of earthquakes and faults in the San Francisco Bay area using Bayesian Inference. *Bulletin of the Seismological Society of America* **93:3**,1306-1332.