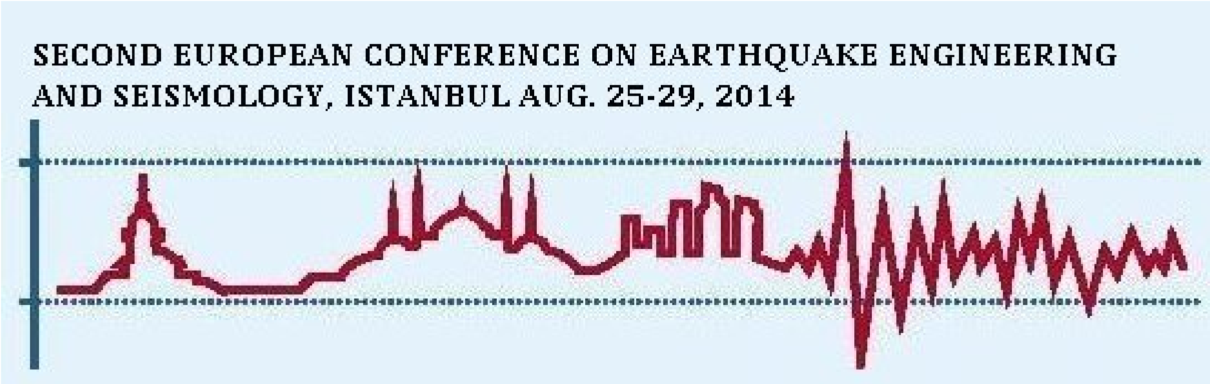

DESIGN AND DEVELOPMENT OF A GIS-BASED SEISMOTECTONIC SOURCE MODEL FOR IRAN

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ABSTRACT

Iran is located in a seismically active region and exposed to seismic activity from many seismic sources and active faults. Probabilistic seismic hazard assessment is the basis for many pre and post-earthquake risk management issues. Definition and parameterization of active faults and seismic sources are among the most important aspect for reliable PSHA studies. In this paper an effort in designing and development of a GIS-based database representing active faults and seismic sources zones is presented. A GIS-based database has been conducted which provides facility to update and complete information from latest researches. It facilitates efficient organization of faults characteristics such as strike, dip angle, fault length, fault mechanism, horizontal and vertical slip rates and includes all publically available researches on seismotectonic and active faults of Iran. The database also contains information on historical earthquakes, field observations and photographic images, satellite images, geo-referenced images and published articles for all known faults within Iranian territory. The GIS-based system used to conduct this database provides facility for various visualization of geographical and attributes information. In this study also two alternative seismic source models with their seismotectonic parameters are proposed. The geological and tectonic maps of Iran, maps showing smoothed frequency of earthquakes; fault orientations and cumulative distribution of seismic moment have been prepared and used as tools to determine the boundaries of these two seismotectonic models. The seismicity parameters such as a-value, b-value and maximum magnitude are determined for each seismotectonic provinces.

INTRODUCTION

Iran is part of the Alpine Himalayan orogenic belt that extends over more than 10,000 km from west Europe to Southeast Asia (e.g. McKenzie, 1978; Stöcklin et al., 1968). Due to the northward motion of the Arabia plate that collides with Eurasia, Iran is actively deforming and becoming one of the most seismically active regions of the world and frequently suffers catastrophic and devastating earthquakes such as Silakhor (Ms=7.4, 1909), Salmas (Ms=7.4, 1930), Buyin Zahra (Ms=7.2, 1962), Dasht-e-Bayaz (Ms=7.4, 1968), Khorgu (Ms=7, 1977), Tabas (Ms=7.7, 1978),Rudbar-Manjil (Ms=7.2, 1990), Birjand (Ms=7.3, 1997), Fandog (Mw=6.6, 1998) and Bam (2003). Several destructive earthquakes have been responsible for serious economic damage and loss of life in the recent decades in different parts of Iran. In order to mitigate seismic risk in Iran, detailed investigation for preparing faults database as the main causes of earthquakes is required.

As an initial step towards proper assessment of seismic hazard, identification of active faults and their geometric properties are essential in seismically active regions. Several studies have been

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performed in recent years, aiming at mapping active faults in Iran. Examples are maps provided by of IIEES (2003) and NGDIR (2002) which represent images of geographical distribution of active faults in Iran and in some cases brief descriptions of their characteristics. However, such maps at best reveal some kind of analogue visualization and in addition, the various scales and geographic coordinate systems used to conduct such maps result in significant errors in geographical location and shape of these faults.

In order to compile a digital detabase of active faults in Iran, in this study, all infromation on active faults that have been identified to date (2012) in the Iran's seismically territory are coleected by studying all publically available researches conducted in the last couple of decades. Using raster SRTM data file, representin topographic map in 3 second resolution, attempts are made to remove or decrease geographic errors associated with the location and position of reported faults. One of The main objectives of this study is to prepare a complete digital fault information system. We attempt to extract and collect the geometric characteristics as well as other information representing fault activity such as strike and dip angles, fault length, fault mechanism, horizontal and vertical slip rates and also information on historical earthquakes field observations and photographic images, satellite images, geo-referenced images and published articles for all known faults within Iranian territory. In order to manage and access this database, a GIS-based user-friendly tool is used which provides facility for better organization of geographical and attributes information and constant data updating. Due to the high seismicity of Iran and the importance of large earthquakes with long return period, reliable data on past earthquakes has significant impact on seismic hazard assessment. A historical and instrumental earthquake catalogue is compiled from different sources for events with $Mw \geq 4.0$.

The first step in a probabilistic seismic hazard assessment is definition of seismotectonic sources that affect the site of interest. The seismic source model of Iran is defined as an area bounded by geological, seismological and geodetic features as well as distribution of future earthquakes in time, size and space which show differences of one province from its neighboring provinces. The seismotectonic structure of Iran was studied by several investigators in the past .Stoklin (1968), Takin (1972), Berberian (1976) and Mirzaei (1998) have suggested simplified divisions consisting of only nine, four, four and five regions, respectively. Nowroozi (1976), Nogol Sadat (1994), Tavakoli (1996) and Zaré (2010) suggested more elaborated division and have divided Iran into 23, 23, 20 and 18 seismotectonic provinces, respectively. Recently, Karimiparidari et al (2011) proposed 29 seismotectonic provinces with different specification. The seismic boundaries should be established through analysis of seismic history, relocated epicenter for the past several decades, tectonic environments, active faults, regional geomorphology, and plate boundaries. However, most previous studies on seismic sources modeling rely on single aspect of such characteristics and ignoring other aspects such as geological, seismological, tectonic features and also seismicity distribution. In the present work, efforts are made to develop two set of seismic source models for Iranian territory based on the topographic and tectonic maps and presented active faults map as well as geographical (spatial) distribution of historical and instrumental earthquakes maps and distribution of released cumulative seismic moment maps in raster-layers shapes.

TECTONIC SETTING OF IRAN

Identifying a region tectonic is essential in determining of seismotectonic models and seismic hazard assessment. Therefore, the first step in any seismic hazard study is the reliable identification of active faults and their geometrical and seismic activity characteristics. The areas of high seismic activity in Iran coincide in general with the Alpine mobile belts, which border the Arabian and Indian plates to the south, and the Turan plate of Central Asia to the north. The Iranian mountain ranges have long been known as part of the Alpine–Himalayan system of western Asia. They form the folded belts between Arabian Plate in the south and southwest, and the Turan Plate in the northeast that leads to continuous thickening and shortening of the continental crust. Also strike-slip faulting and subduction of Oman oceanic lithosphere beneath the Makran are the results of this convergence and causing lots of destructive earthquakes in Iran territory.

Based on geodetic data, convergence between the Arabian and the Eurasian plates is estimated at around 21mm/yr at a longitude of 52°E (e.g., McClusky et al. 2003; Vernant et al. 2004a). [7] The Arabia-Eurasia convergence is accommodated differently in eastern and western Iran. East of 58°E, most of shortening is accommodated by Makran subduction zone (19.5±2mm/yr) and less by the Kopet-Dag (6.5±2mm/yr). West of 58°E, the deformation is distributed in separate fold and thrust belts. At the longitude of Tehran, Zagros and the Alborz mountain ranges accommodate 6.5±2mm/yr and 8±2mm/yr respectively. The right-lateral displacement along the Main Recent Fault in the northern Zagros is about 3±2mm/yr, smaller than what was generally expected.

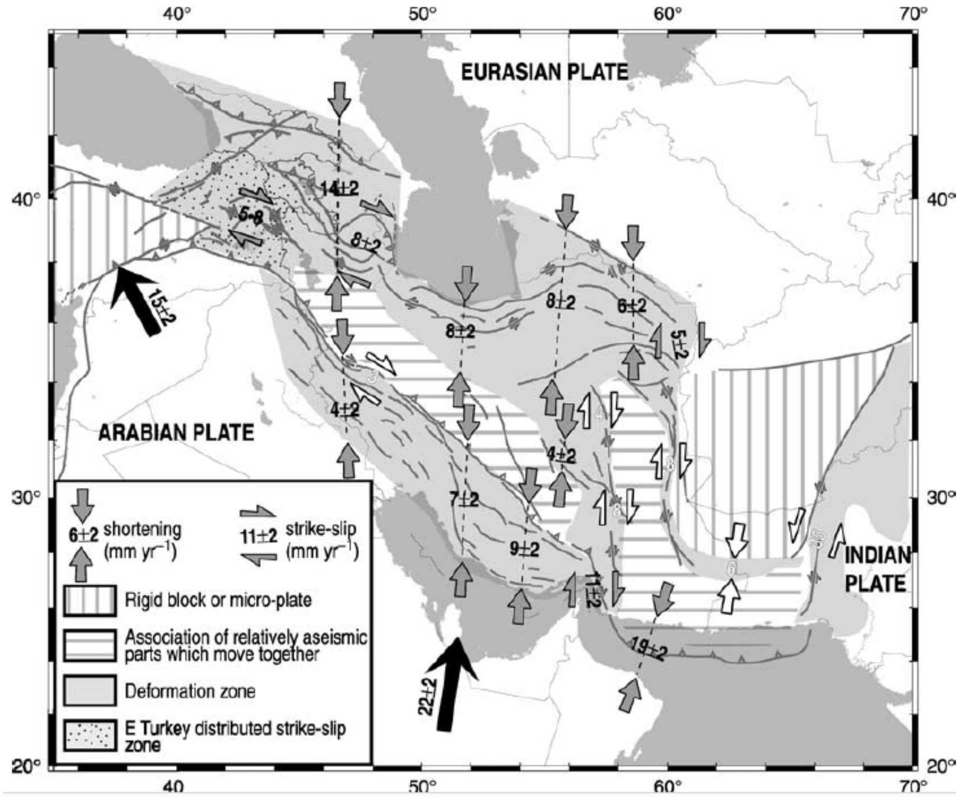

Figure 1. GPS horizontal velocities (Vernant et al. 2004a)

The Central Iranian Block is characterized by coherent plate motion (internal deformation < 2mm/yr). East of 61°E sites show very low displacement relative to Eurasia. The kinematic contrast between eastern and western Iran is accommodated by strike-slip motion along the Lut Block. To the south, the transition zone between Zagros and Makran is under transpression with right-lateral displacement of 11±2mm/yr. (Figure 1)

PREPARATION OF IRAN FAULTS DATABASE

In this study the fault database has been prepared by studying many publically available researches conducted in the last couple of decades. Many of such articles refer to maps of field studies in various scales which have been further geo-referenced in order to implement them in the GIS-based database. Once analogue maps are geo-referenced faults traces (lines, routes) are digitized and collected in GIS shape-files. The customized GIS tool is also equipped with facility to relate images and articles to each data entered to the database. At the end combining the recorded (registered) images extracted from numerous articles we prepared a complete and updated map of all Iran’s fault that has have been identified up to now. Using SRTM (3 second) digital topographic map, geographical locations of known faults were compared with visible trains on the DTM map and where necessary location correction are made. Figure 2 represents geographical location of all faults collected in the database.

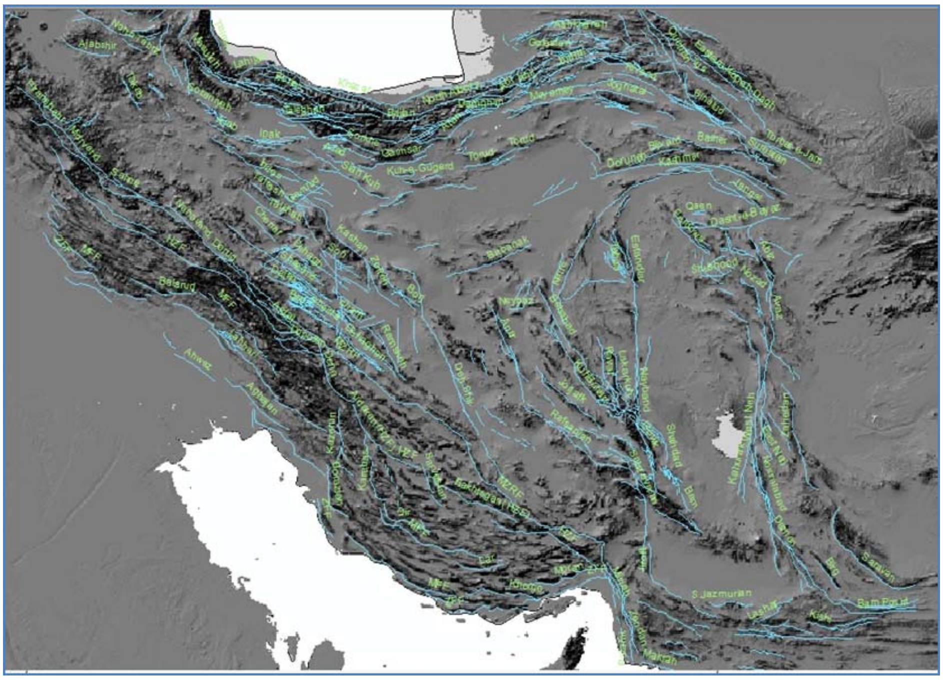

Figure 2**.** Geographical location of active faults in Iran

One of the main objectives of this study is preparation of a digital database of active faults in Iran. GIS-based system used to conduct this database provides facility to update and add information based on newer researches. It also allows provides user-friendly facilities for end users to better access and visualize faults characteristics and where necessary to examine such information against other geographic information in raster or vector format. User could access fault information such as name, strike and dip angles, fault length, fault mechanism, horizontal and vertical slip rates, etc. The user could also see information on historical earthquakes field observations and photographic images, satellite images, seismotectonic geo-referenced images and published articles for all known faults.

TEMPORAL AND SPATIAL DISTRIBUTION OF IRAN'S SEISMICITY

Iran is one of the most seismically active areas in the world. The seismicity database available for Iran can be divided into three periods such as many other regions in the world. 1) the pre-historic and historical data up to the beginning of the twentieth century, 2) the instrumental data (1900-1963) development's period of seismographic instruments in quantity and quality, results in a variety of seismicity data and 3) the modern instrumental data (1964 up to now) which contains the most complete and homogenous data. To evaluate the seismic activity in this study we collect a comprehensive catalogue of all historical and instrumental earthquakes of Iran from 400B.C. up to 2011. In this paper the ISC (International Seismological Center), USGS (U.S. Geological Survey), IIEES (International Institute of Earthquake Engineering and Seismology) and Harvard seismic catalogue were used for instrumental events. For historical events, data provide by Ambraseys and Melville (1982) and Berberian (1995) are used. The compiled catalogue is de-clustered using the proposed algorithm by Gardner and Knopoff (1974) to remove dependent shocks. Where necessary magnitude conversion relationships are used to convert reported magnitude to Mw.

There are uncertainties associated with majority of the data and assumptions used in seismic hazard studies which contribute to the uncertainty of the final results. In order to incorporate uncertainties associated with input data involved in developing seismic hazard models, various representation of past seismicity are examined against known tectonic features. In order to picture spatial spreading of past seismicity in the studied are, geographical smoothing processes are performed on regional seismicity using the approach proposed by Zolfaghari (2009). The proposed approach provides practical facility for better capture of spatial variations of seismological and tectonic characteristics, which allows better treatment of their uncertainties. In this study spatial distribution of earthquake epicenters, earthquake ruptures and seismic moments have been prepared for definition seismic source boundaries. In smoothing process earthquakes are contributed base on their location, magnitude and their tectonic features. In this study we used Normal distribution models as proposed by Zolfaghari (2009) for smoothing observed seismicity. For small earthquakes (Mw<5.5) we used a symmetric Normal distribution function with circular contours with the correlation distances of 15 km to smooth the number of recorded earthquakes which are not related to important rupture length. For larger earthquakes (Mw ≥5.5), the smoothing process takes into account the geometry of seismotectonic features and fault rupture. To do so, we use a non-symmetric Normal distribution with higher dispersing along the fault rupture versus dispersing across rupture lines, as an example correlation distance of 25 km along and 10 km across fault line are used to smooth earthquake frequencies. In practice smoothing processes can be performed for several magnitude intervals in several raster layers representing frequency of events with a given magnitude interval. Figure 4 shows smoothed frequency maps for different magnitude interval for Iran. An attempt has been made to assign a cell-based faulting orientation to generalize rupture geometry in Iran and to allow all the previous earthquakes to take faulting characteristics from a synthetic orientation fault map which is shown in figure 3. In this study we used the developed fault database for Iran and topography map in order to draw line segments, showing orientation of potential fault ruptures for Iran territory. We used fault plane solutions for almost all events with magnitude Mw≥5.5 for post-1977 earthquakes to estimate fault mechanisms as well as faulting orientation, especially in region without any surface rupture. We assigned uniform symmetric buffer zones with different sizes to all line segments of fault orientation map to consider uncertainties.

Moreover in this study, records of past earthquakes in the region are used to determine the distribution of seismic moment released by historical earthquakes in time and space. We can estimate an average slip rate on faults by assessing cumulative seismic moment along that fault. In this study, we use smoothed cumulative seismic moment maps in order to define the seismotectonic models boundaries in an accurate way. We used a Normal distribution across fault ruptures and a uniform distribution along fault ruptures to model the seismic moment generated by each event in the catalogue. Figure 5 illustrates smoothed cumulative seismic moment released over the last 1100 years.

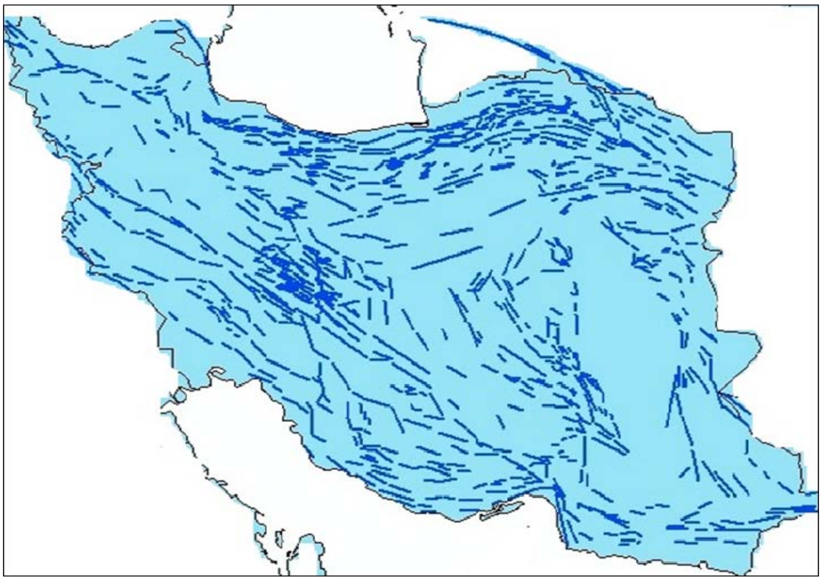

Figure 3. Iran faults orientation map

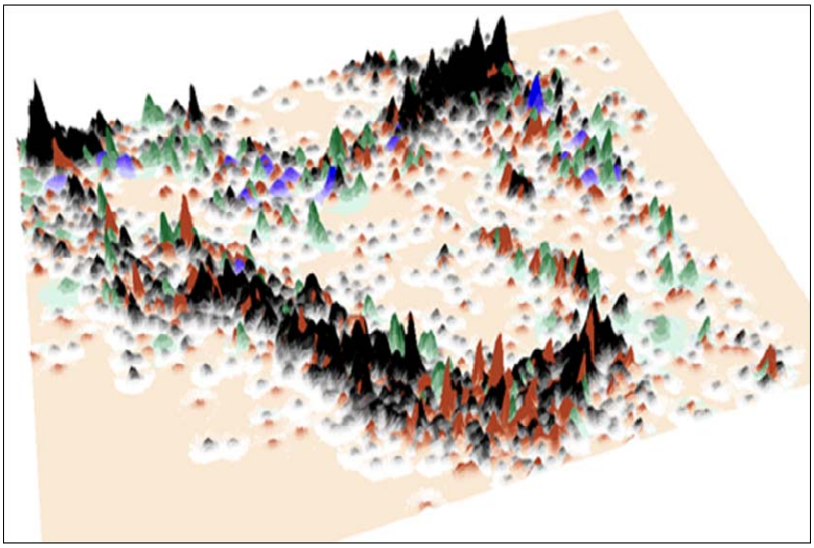

Figure 4. Smoothed frequency of events for magnitude interval (4-8 Mw)

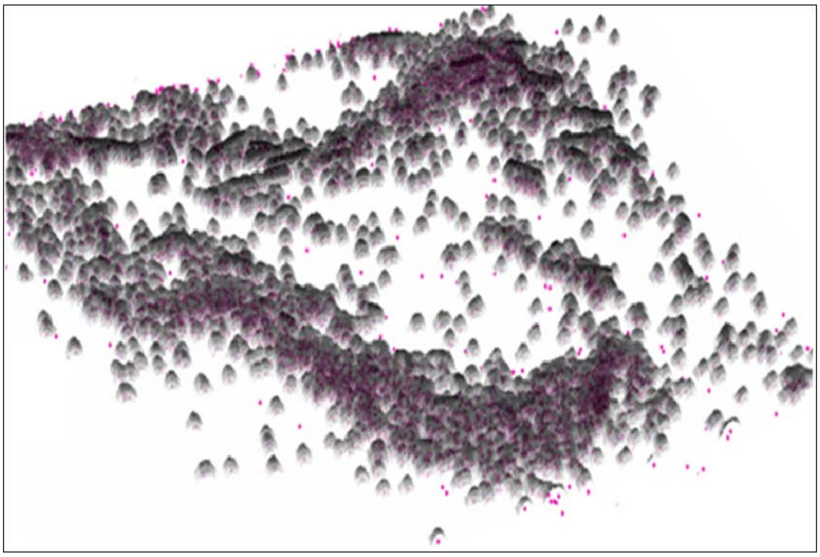

Figure 5. Smoothed cumulative seismic moment released over the last 11 centuries (900-2011).

SEISMOGENIC SOURCE MODELLING

One of the first steps in any seismic hazard study is the definition of seismogenic sources. For regions with unknown fault locations or seismically active by various pattern of small to large faults, earthquake sources are modeled by area source zones that are usually defined based on a combination of historical seismicity and specifications of tectonic features. In this study we presented two seismic source models for Iranian territory using the cell-based approach proposed by Zolfaghari (2009). These two sets of Iran seismic source models are based on the topographic and tectonic maps and presented faults map as well as seismicity maps. In addition to the epicentral maps usually used to define source zones, other maps representing spatial and temporal distribution of seismicity such as smoothed earthquake frequency and cumulative seismic moment maps are used here also. According to the cell-based source model approach, these maps are implemented in raster-based layers; better representing observed seismotectonic variation in a region. The cell-based maps layers represent seismogenic information on 0.05 decimal degree cells (or approximately 5km in the equatorial areas).

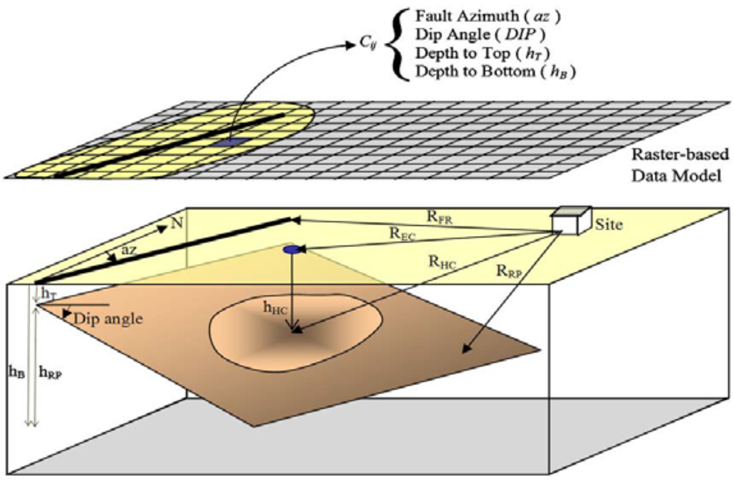

Figure 6. 3D representation of a fault rupture plane using raster data model (cell-based data system Zolfaghari 2009)

To delineate boundaries of the first set of seismic source areas, priority is given to the topographic maps, tectonic features and fault map. Figure 7 shows first set of seismic source model dividing Iran into 31 seismotectonic provinces. To delineate boundaries of the second set of seismic source areas, priority is given to the epicentral maps, smoothed earthquake frequency and cumulative seismic moment maps. Figure 8 shows second set of seismic source model dividing Iran into 25 seismotectonic provinces.

SEISMIC PARAMETERS

The method of Hanks and Cornell (1994) assumes that the occurrence of earthquakes in the region approaches a Poisson process, with a constant rate of earthquakes in time and space. A completeness analysis of earthquake catalogue was done using the Stepp (1972) methodology which provides estimate of the mean time period for different ranges of magnitude in various time windows with Poisson distribution and the constant mean rate of occurrence for each seismic zone. The seismicity parameters such as a-value, b-value and maximum magnitude are determined for each seismotectonic source using frequency-magnitude relationships, seismic moment released by past occurrence of earthquakes and expert judgment.

Maximum magnitude for each seismic zone is determined considering maximum potential earthquake for each zone and maximum historical earthquake. Maximum probable magnitude for each seismic zone is also checked against cumulative seismic moment released by historical earthquake as the maximum potential earthquake for each seismic zone. Exponential and combined characteristic-exponential relationships were used to model the frequency-magnitude distributions. Each of these relationships has been chosen by aid of expert judgment. In the following figures (figure 7, 8) determined b-values is shown schematically for different zones of first and second sets of seismic sources.

CONCLUSIONS

In this study a new database is developed for active faults in Iran using all publically available seismotectonic, geological sources as well as topographic and other available maps. A complete digital fault database is generated which contains geometric characteristics as well as other information representing fault activity, such as strike and dip angles, fault length, fault mechanism, horizontal and vertical slip rates. The database also contains information on historical earthquakes field observations and photographic images, satellite images, tectonic geo-referenced images and published articles for all known faults within Iranian territory. The other achievement of this study is providing two sets of seismotectonic models for Iran. The geological and tectonic maps of Iran, spatial distribution of earthquakes frequency, earthquake ruptures and distribution of cumulative seismic moment have been prepared as tools to determine the boundaries of seismotectonic models. In this study attempts are made to incorporated spatial uncertainties associated with location of earthquakes using spatial smoothing process. To model the temporal and spatial distribution of earthquakes frequency and cumulative seismic moment, faults orientation map is developed and used here. Completeness of earthquake catalogue has been studied for each seismic source. The seismicity parameters such as a-value, b-value and maximum magnitude are determined for each seismotectonic sources in the two source model.

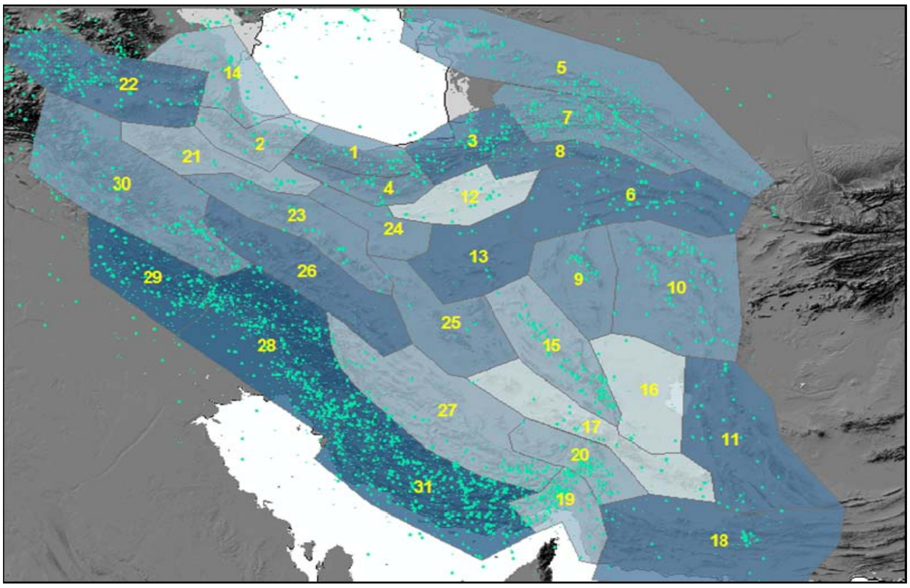

Figure 7. Schematic view of b-values for the first type seismic source model

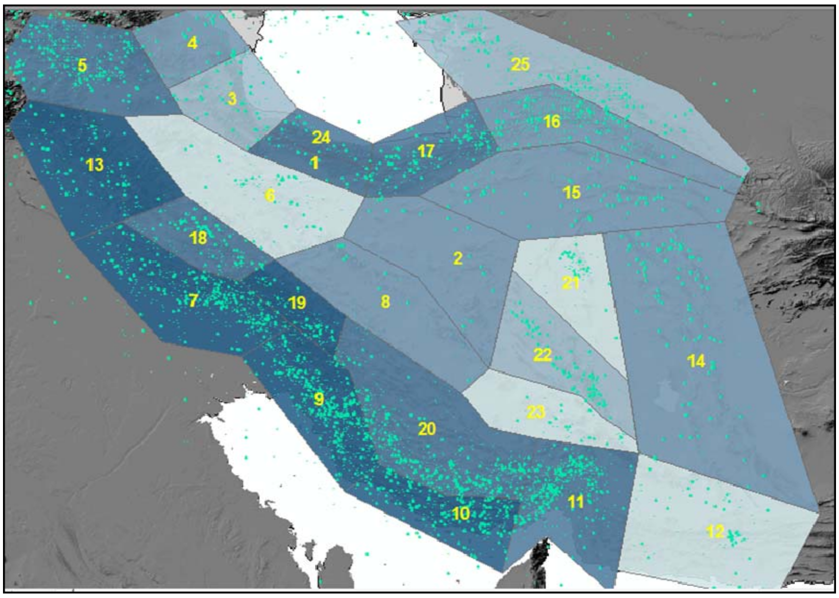

Figure 8. Schematic view of b-values for the second type seismic source model

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