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Seismic hazard assessment of Iran by Ising cellular automation modeling

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Abstract

It is essential to use statistical models and theoretical analysis of the data for preparing comprehensive geological and seismic hazard mapping. A cellular automaton consists of an array of cells, each one of which has a finite number of possible states, together with a rule for updating all cells simultaneously based only on the states of neighboring cells. In the present paper, Ising cellular automation modeling has been used for establishing temporal relations between the energy releases of the seismic events that occurred in neighboring parts of the crust. The catalogue is divided into time intervals, and the region is divided into cells which are declared active or inactive by means of a threshold energy release criterion. Thus, a pattern of active and inactive cells which evolves over time is determined. The best model is chosen by maximizing the mutual information between the past and the future states. Finally, a Probabilistic Seismic Hazard Map is given for the different energy releases considered. The method has been applied to the wide range of Iran's geological and geophysical data and Iran catalogue from ISC and USGS from 1960 to 2009, (ISC and USGS).

Keywords: Seismic Hazard, Ising model, seismotectonics map

1. Introduction

Among natural disasters, earthquakes cause more damage in less time so that they are often associated with the social, economic and the political shocks. Although the earthquake events are short, their occurrences are due to long-term internal processes within the Earth (Pour Kermani and Asadi, 1995). Preparing the surface and subsurface maps is one of the vital Earth Sciences purposes for showing tectonics structures and Assessing the evolution trend of the geological events in any area. Less geological data is used in drawing of common existed maps so that the analysis of these maps is not useful for understanding the geological developments.

Iran is a region of high seismicity and tectonics activities. Several destructive earthquakes have occurred in various parts of Iran in the past few decades. Studies of seismicity of Iran were investigated by many Earth Scientists such as Nowroozi (1971, 1976), Berberian (1976, 1979), Shoji-Taheri and Naizi (1981), Nabavi (1977). Although works on seismic risk of Iran are rather limited, it has attracted the interest of seismologists for a long time.

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2. Methodology

The observed scaling laws associated with earthquakes, and their large-scale correlations, have led several researchers to the conclusion that these events can be regarded as a type of generalized phase transition, similar to the nucleation and critical phenomena that are observed in thermal and magnetic systems (Rundle et al., 2003). As a result, many investigators have explored the possibility of using formalisms from statistical physics to model the spatial, temporal and magnitude distributions (Wyess et al., 1999). The relationship between stress and strain according to released energy during time, in this method has been investigated. The target is earthquake directly, so that it is more suitable compared with other methods which are indirect and static.

Today, the volume of data has increased with the progress of science and invention of new devices, therefore, the old method of mapping has been substituted by using statistical models and theoretical analysis of data (Rundle, 1988; Jimenez et al., 2005). So using statistical criteria (Bazargan lari, 2006), the optimal pattern was selected and a new seismic hazard map was drawn.

The Ising model and Cellular automata models (Jimenez et al., 2006; Nakanishi, 1991) were used for determining the Seismic hazard and earthquake-prone regions. By this procedure and calculations based on the magnitude intensity and energy of earthquakes in Iran using ISC and USGS from 1960 to 2009 (International Seismological Centre, 2011; U.S. Geological Survey, 2012), new results of hazard assessment were obtained based on the structures in different regions of Iran.

Since the faults causing earthquakes in the region have a complex topology and the fractures caused by increasing forces due to plate tectonic movements are complex and non-visible, one can predict and divide the possibility of earthquake using spatial-temporal models related to time, location and magnitude of sudden earthquakes and the region from the view of high and low seismic hazard, respectively. Eventually, this led to understanding the dynamics that cause earthquakes. Among these models we can name an Ising Cellular Automata model which is a technique for development and reconstruction of these models.

The CA supply useful models for many investigations in natural sciences; in particular, they represent a natural way of studying the evolution of large physical systems (Nakanishi, 1990). They are simple mathematical idealizations of natural systems, and consist of a lattice of discrete identical sites, each site taking on a finite set of integer values; values which evolve in discrete time steps according to rules that specify the value of each site in terms of the values of neighboring sites. A configuration of a cellular automaton is an assignment of a state to every cell of the automaton; the update rule of a cellular automaton forms a function from configuration to configuration with the requirement that the updated value of any cell depends only on some finite neighborhood of the cell, and that the function is invariant under translations of the input array.

Not only with this model can a strong relationship in the earthquake-prone be discovered, regions but also the application of this model in seismic hazard assessment and earthquake prediction can be achieved with middle range.

The Ising model, named after the physicist Ernst Ising, is a mathematical model of ferromagnetism in statistical mechanics. The model consists of discrete variables that represent magnetic dipole moments of atomic spins that can be in one of two states (+1 or −1). The spins are arranged in a graph, usually a lattice, allowing each spin to interact with its neighbors. The model allows the identification of phase transitions as a simplified model of reality. The two-dimensional square-lattice Ising model is one of the simplest statistical models to show a phase transition (Baxter and Rodney, 1982).

Ising model was used to study the properties of ferromagnetic materials in 1920 by Wilhelm Lenz, who gave it as a problem to his student Ernst Ising (Niss, 2005). The one-dimensional Ising model has no phase transition and was solved by Ising (1925) himself in his 1924 thesis (Binder, 2001). Larson Sager (1944) used this model to demonstrate two-dimensional phase-transfer conditions in absence of external magnetic field. This model was also used for prediction and analysis of earthquakes in Greece from 1901 to 1999 (Krieger, 1996). Finally, Jimenez and Posadas (2006) developed this model with Cellular Automata method (Jimenez et al., 2006). In fact, Ising model offers a spatial-temporal model using Information Theory and Cellular Automata for occurred earthquakes.

In general, the Ising model consists of an array of cells, the state of each of which represents a spin, either up or down. The energy of the system is measured by a function that depends on the number of neighboring pairs of cells that have the same spin as each other; therefore, if a cell has equal numbers of neighbors in the two states, it may flip its own state without changing the total energy. However, such a flip is energy-conserving only if no two adjacent cells flip at the same time (Toffoli and Margolus, 1987a).

Cellular automaton models of this system divide the square lattice into two alternating subsets, and perform updates on one of the two subsets at a time. In each update, every cell that can flip does so. This defines a reversible cellular automaton which can be used to investigate the Ising model (Toffoli and Margolus, 1987b).

A formal definition of CA is as follows (Jimenez et al., 2005): a d-dimensional Cellular Automata (or d-CA) is a 4-update (Zd , S, n), where Zd is a regular lattice (the elements of Zd are called cells, or c), S is a finite set, the elements of which are the states of c; n is a finite ordered subset (with m elements) of Zd , called the neighborhood of c, and (Sm+1!S) is the local transition function or local rule of c. In the construction of a CA to simulate a specific problem, many choices have to be made. Firstly, the available set of states for each cell (the S set); for simplicity, only two states are usually chosen, active or inactive.

CA creates a fixed spatial relationship between occurred seismic events by spatial-temporal intervals of cells in adjacent parts of the crust which display active or inactive cells by the amount of Critical energy released from any events. Interaction between cells to adjacent cells is shown in two-dimensional and three-dimensional models whereby the best model selects the maximum correlation coefficient between past and future.

Seismic catalogs are divided to intervals of the length of t (NT), the division of the cell (nd) and dimension (d), so if the network is the square d it is equal 2 and if it is Québec d is 3. CA is used in the case d =2. Finally, an active or inactive state is considered in the function of amount of energy released in each time interval. If this energy is greater than or equal to the threshold energy, it is defined as the active cell, otherwise it is inactive.

The upward and downward rotation of each cell is considered +1 and -1 in Ising model, respectively. The interaction between the nearest cell with neighboring cell is shown -j if the rotation was parallel and+ j if the rotation was non-parallel.

$$S_i\sum S_iS_j - B\sum E = -j \quad (1)$$

If $S_i = \pm 1$, J is constant equation and B is the external magnetic field. It is important to state that the Ising model is used only to investigate the Possibility of Earthquake occurrence in this study. This model has a separate formula based on its application in a variety of branches.

Sequence pattern can be modeled in terms of Cellular Automata. The state of neighboring cells is determined by calculated energy level (E_q). A state (active or not active in the view of seismic activity) is considered for each cell in each time stage after spatial-temporal division.

In this study, the energy of all of earthquakes was calculated by formula 2 (the Estimate of seismic energy equation in terms of Erg) and then the amount of required strain was determined by formula 3 (the determination of strain equation, E_i is the energy of the event and $N(t)$is the number of earthquakes in time) in a period of 49 years the range of which was based on the hour.

$$\log E = 11.8 + 1.5\, M_b \quad (2)$$

$$\sum(t) = \sum_{i=1}^{N(t)} E_i(t)^{\frac{1}{2}} \quad (3)$$

The sum released energy of earthquakes (formula 4) was calculated based on mb category. In this study, 4 groups are defined for this category (Table1):

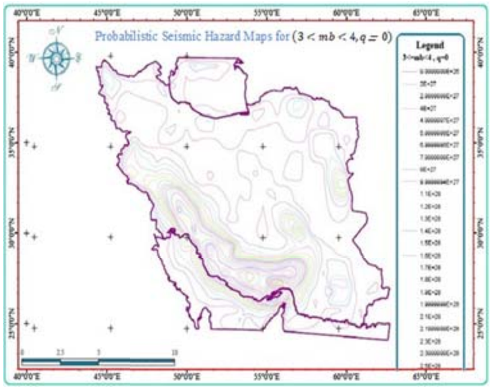
Table 1. Four groups are defined for this study

Group number	Properties
1	The sum of energy for earthquakes with magnitude $3 < mb < 4$
2	The sum of energy for earthquakes with magnitude $4 < mb < 5$
3	The sum of energy for earthquakes with magnitude $5 \leq mb < 6$
4	The sum of energy for earthquakes with magnitude $mb \geq 6$

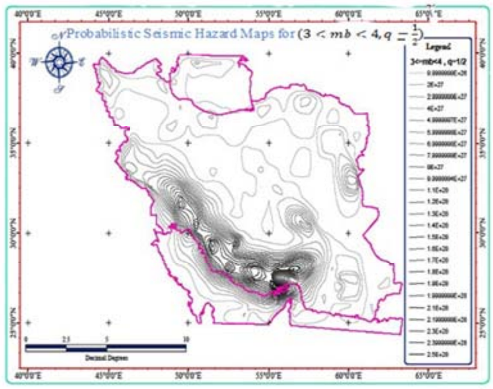
For each of these groups 866 data are recorded.

$$\sum q(N(t)) = \sum_{n=1}^{N(t)} \sum_n^q N(t) \quad (4)$$

$\sum n$ is released energy of nth earthquake and n(t) is the number of occurrence of earthquakes in t time. Energy is calculated by equation between magnitude and energy and q=1 is the sum of energy. Finally, Iran maps are drawn based on earthquakes energy for 4 groups. (Fig. 1-4). Then, each region is divided which is active or inactive in the view of seismic intensity according to the drawn maps and faults in the vicinity of Iran's seismic regions.



a.



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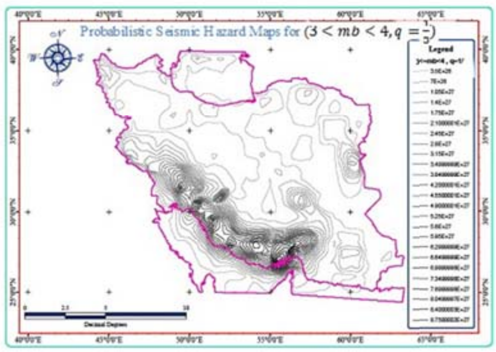
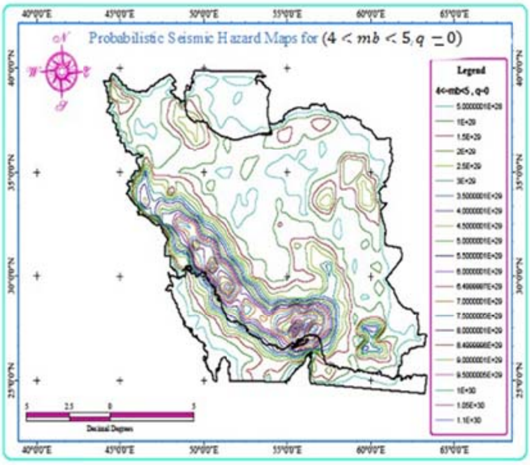
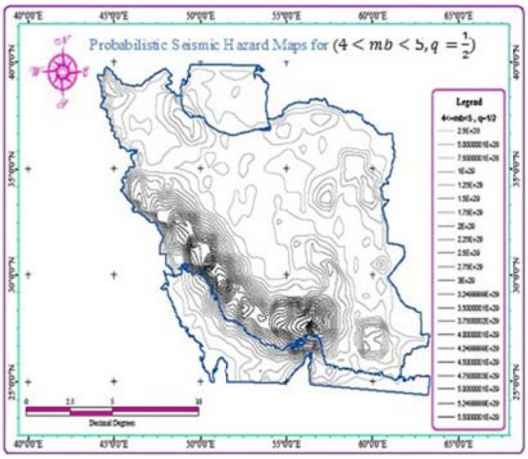


c.

Fig. 1. Probabilistic Seismic Hazard Maps for the different energy releases analyzed a. $(3 < mb < 4, q = 0)$, b. $(3 < mb < 4, q = \frac{1}{2})$, c. $(3 < mb < 4, q = \frac{1}{3})$. The color lines represent the probability of surpassing the corresponding energy threshold for the period of time.



a.



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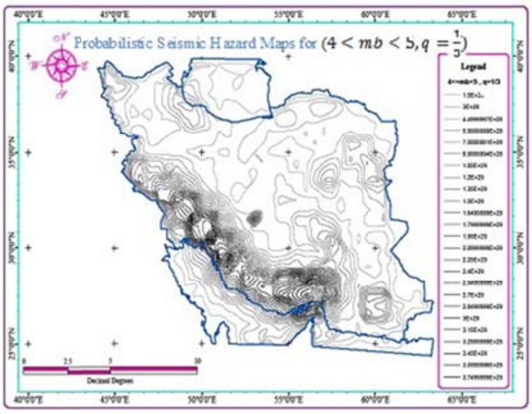
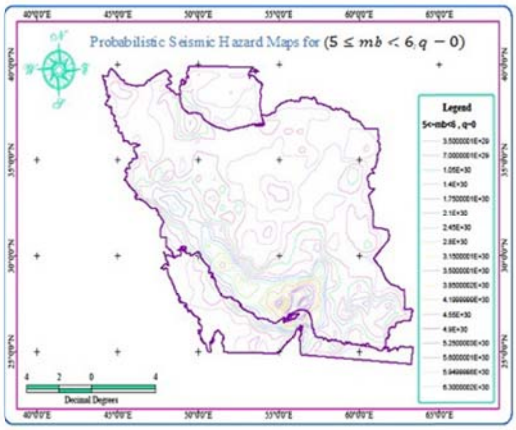


c.

Fig. 2. Probabilistic Seismic Hazard Maps for the different energy releases analyzed a. $(4 < mb < 5, q = 0)$, b. $(4 < mb < 5, q = \frac{1}{2})$, c. $(4 < mb < 5, q = \frac{1}{3})$. The color lines represent the probability of surpassing the corresponding energy threshold for the period of time.



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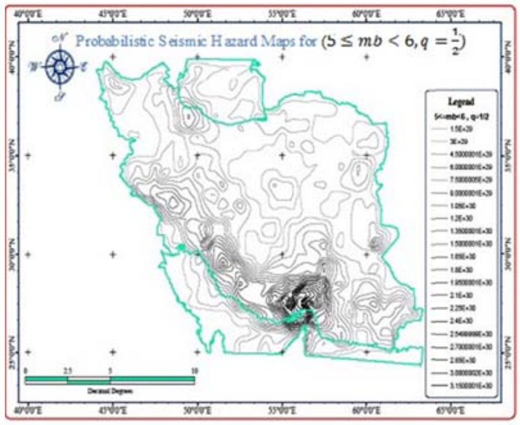
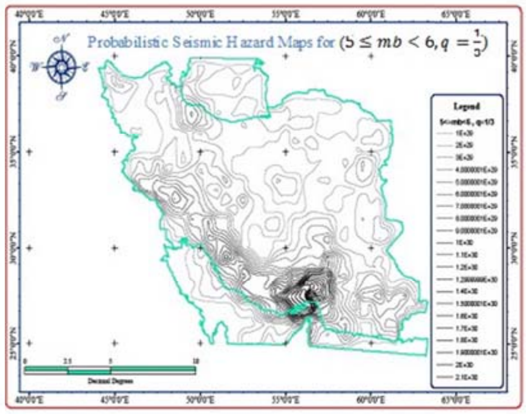
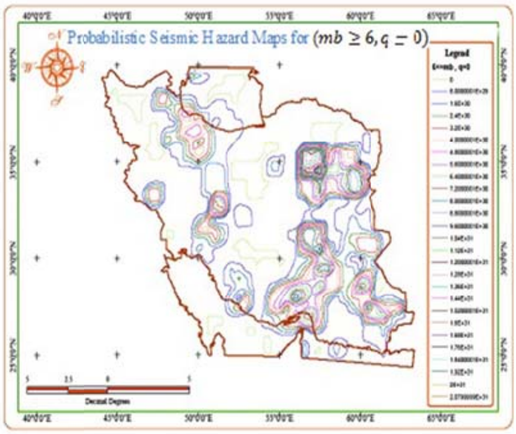


b.



c.

Fig. 3. Probabilistic Seismic Hazard Maps for the different energy releases analyzed a. $(5 \leq mb < 6, q = 0)$,b. $(5 \leq mb < 6, q = \frac{1}{2})$,c. $(5 \leq mb < 6, q = \frac{1}{3})$. The color lines represent the probability of surpassing the corresponding energy threshold for the period of time.



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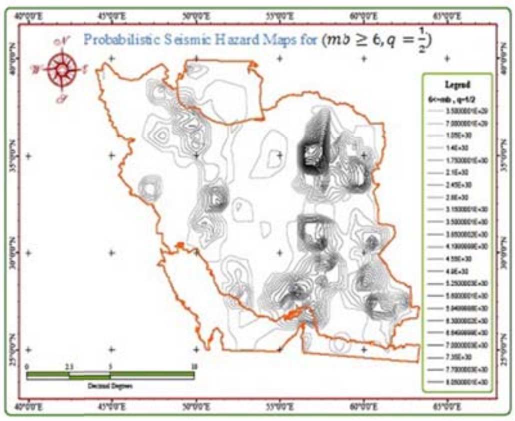

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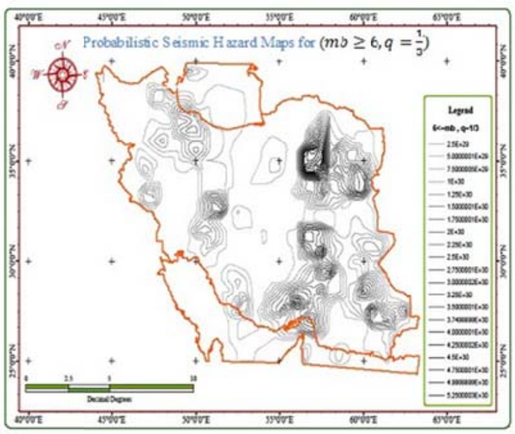

c.

Fig. 4. Probabilistic Seismic Hazard Maps for the different energy releases analyzed a. $(mb \geq 6, q = 0)$, b. $(mb \geq 6, q = \frac{1}{2})$, c. $(mb \geq 6, q = \frac{1}{3})$. The color lines represent the probability of surpassing the corresponding energy threshold for the period of time.

3. Discussion and Conclusions

The results of zonation by Ising model are:
a. for the earthquakes of magnitude 4 to 5:
The earthquake zoning map of Iran divides Iran into 3 seismic zones (Zone 1, 2a, 2b and 3) for this magnitude.
1. Seismic zone 1: This is a seismically active zone in which earthquakes magnitude are increased but the number of them decreases with low intensity in it rather than other parts of Iran.
2. Seismic zone 2a: This region has a moderate level of seismicity with high intensity. Many occurred earthquakes have low to moderate magnitude with short recurrence intervals. This zone consists of a part of the Zagros Simply Folded Belt and High Zagros, in the view of geology. Zagros Thrust System is surrounds it in the north. Kermanshah and Ilam are capable cites for the earthquake of magnitude 4 to 5.
3. Seismic zone 2b: This region has a moderate level of seismicity with moderate intensity. It consists of the Makran structural zone limited to the Bashagard fault from the south, the Nehbandan fault from the east and the Nayband from the west. Part of Zahedan city is located in this zone. Frequency of the earthquakes in low to moderate magnitude is low there. The probability of occurrence of 4-5 magnitude earthquakes is very low in this zone.
4. Seismic zone 3: This region is a seismically inactive zone which includes a major part of the structures zones such as Alborz, Kopeh Dagh and central Iran. These locations are representative of low hazard area in Iran. The attribute of 4-5 magnitude earthquakes is uniform here.

b. For the earthquakes of magnitude 5 to 6:
The earthquake zoning map of Iran divides Iran into 1 seismic zones (Zone 1, 2a, 2c and 3) for this magnitude.
1. Seismic zone 1: This is a seismically active zone in which the magnitude of earthquakes increased rather than other regions of Iran and the number of low magnitude earthquakes decreased. This region is located between the Nayband fault in the east and Zagros Thrust System in the north. Bandar Abbas and Minab cities are located here. This zone is a representative of the high hazards zone and the probability of occurrence of earthquakes with abundant 5-6 magnitude.
2. Seismic zone 2a: This region has a moderate level of seismicity with high intensity. The main part of the Simply Folded Belt and the High Zagros which is limited by Zagros Thrust System to the north is located here. The Qatar-Kazerun Fault is also located in this zone.
3. Seismic zone 2c: This region has a moderate level of seismicity with low intensity. This zone is located in the eastern part of Iran and includs the main part of the Makran structural zone. This includes the Bashagard, Nehbandan active fault and Zahedan, Kerman cities. The high magnitude

earthquakes are reported in this zone and several low to middle magnitude earthquakes.

4. Seismic zone 3: This region is a seismically inactive zone which belongs to less hazardous zones of Iran. The probability of occurrence of 5-6 magnitude earthquakes is very low in this region. In general, a uniform trend is shown here for 5-6 magnitude earthquakes.

c. For the earthquakes of magnitude 6 to >6:

The earthquake zoning map of Iran divides Iran into 1 seismic zones (Zone 1a, ab, 2a, 2b, 2c and 3) for this magnitude.

1. Seismic zone 1a: This is a seismically active zone with high intensity. This region covers the Kopeh Dagh structural zone which includes the Ferdous, Birjand, Malas and Nayband cities. This region is limited to the Miami fault forward in the north and Nehbandan fault forward to the east. There are also other active faults such as the Daroneh, Posht-e-Badam and Nayband in it. This area is very active in the view of seismicity and belongs to most hazardous zones of Iran. The probability of occurrence of high up to 7 magnitude earthquakes.

2. Seismic zone 1b: This is a seismically active zone with moderate intensity. This region belongs to the north of Iran which consists of Tehran, Rasht, Qazvin and Zanjan city. The Astra and Tabriz faults are located in this region. This region belongs to hazardous zones of Iran such as zone1a with the probability of abundant 7 magnitude earthquakes but in comparison to the zone1a, the intensity is low.

3. Seismic zone 2a: This region has a moderate level of seismicity with high intensity. Yazd, Ardakan and Nain cities are located in this region. There are many faults in it such as the Great Kavir Fault in the west and east-west and the Nain fault in the south-east. The probability of the high severity earthquakes is low in this zone.

4. Seismic zone 2b: This region has a moderate level of seismicity and moderate intensity. The Nayband and Bashagard faults exist here in the western and southern parts, respectively. High magnitude earthquakes have occurred whereas there is the probability of the high intensity earthquakes this zone.

5. Seismic zone 2c: This region has a moderate level of seismicity with low intensity. This zone is bordered by the Nehbandan fault in the east, Dehshir Baft fault in the west and Oman line in the south. It is mid active in the view of seismicity and the probability of the occurrence of high intensity earthquakes is low in this zone.

6. Seismic zone 3: This region is a seismically inactive zone in which the probability of the occurrence of earthquakes with magnitude 6 and occurrence of magnitude >6 is very low.

Finally, it is recognized that Zagros is divided to four active seismic zones which includes:

1. Seismic zone 1: This is a seismically active zone which is surrounded by the Oman Line from the east, the Qatar-Kazerun from the west and Zagros Thrust System from the north, has high quantitative seismic compared to other regions. It includes Lar, Bandar-e-Abbas, Jahrom and Neyriz cities. According to Ising model, this region is an active and hazardous zone because of the earthquakes with magnitude 3 to 4.

2. Seismic zone 2a: This region has a moderate level of seismicity with high intensity. Many earthquakes have occurred in it with low to middle quantitative. It is bordered by the active Zagros fault in the north and Kazerun fault in the west. Cities such as Kazerun and Shiraz are located in it. Ising model showed this is a mid-active zone.

3. Seismic zone 2b: This region has a moderate level of seismicity with moderate intensity. This zone consists of Ahvaz, Behbahan, Yasouj and Khorramshahr is limited to Kazerun fault in the east and zagros fault in the north. Of course, this zone is an active seismic zone in Ising model.

4. Seismic zone 3: This region is a seismically inactive zone which consists of total areas of central Iran, Alborz and KopehDagh is located in seismically inactive or very low seismic zones in Ising model. It has abundant earthquakes with magnitude 3-4. In general, this region has a uniform trend in the view of seismicity.

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