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Investigation of the Zagros recurrence earthquakes using the network theory

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Abstract

Human beings have encountered numerous natural disasters over time, andthe phenomenon of earthquake is one of the most destructive of them.In recent years, the complex behavior of earthquakes in terms of time and space has been investigated using complex networks, which has enabled us to know the global characteristics of this phenomenon. Studies on the earthquakes using the network method are based on how the network is constructed. In this paper, by constructing the network, the spatio-temporal recurrence of earthquakes which occurred in the Zagros region and were recorded at all broadband and short-period stations of the Iranian Seismological Center (ISC, http://irsc.ut.ac.ir) are subject to statistical review. The results showed that in the Zagros area the spatial recurrenceis about 0.020 km, and the time recurrencefor all magnitudethresholds issimilar topower relationship ($1/T^{\alpha}$) with$\alpha = -0.9$.

Keywords: Complex network, earthquake, spatio-temporal recurrence

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1Introduction

Being unpredictable in nature, earthquake is one of the most harmful natural disastersand its occurrence without warning causes thousands of deaths and catastrophic economic damage in such areas. The Iranian Plateau is considered as one of the seismically active regions of the world because of its special position on the Alpine-Himalayan orogenic belt. Due to the convergence of the Arabian and Eurasian plates, Iran has suffered a lot of human and economic losses in the distant past as well as in recent years caused by earthquakes. Therefore, studyingthe different aspects of earthquakes in seismically active areas such as Iran will help to better understand this complex phenomenon.

In recent years, complex network theory has been used as a powerful tool to describe complex phenomena (Costa et al. 2011).Earthquake is a temporally and spatially complex phenomenon that occurs suddenly because of the displacement of faults in the Earth's lithosphere (Stein and Wysession, 2003).

Considering all the factors that result in the movement of faults and putting them in a set of mathematical equations that can describe the earthquake phenomenon is a difficult task and also faces with uncertainty due to the lack of access to the focal depth.

Statistically study is one of the ways to analyze earthquakes. Since the number of earthquakes is large and there are complex correlations between earthquakes in terms of space, time and intensity, earthquakes can be considered as complex systems.

Two well-known classical laws, Gutenberg-Richter law (Gutenberg and Richter, 1941) and Omori law (Omori, 1984) confirm the complexity of earthquakes.Complex networks are defined as tools to study complex systems such as earthquakes.Based on the complex network theory, it is not necessary to know the details of the fault system, but only by knowing the magnitude, time and epicenter of earthquake,different aspects of this phenomenon can be studied.In this method,the epicenters of earthquakes are system components shown by nodes and the interactions between them are represented as edges between nodes. Due to the lack of dependency of system components on fault parameters extracted from kinematic and dynamic analysis of earthquakes, the method is much simpler and far from heavy calculations. It solves complex mathematical equations, and only using the earthquakescatalog, various aspects of earthquakes can be studied.For example, examining the parameter of the recurrence interval of earthquakes helps to understand this complex phenomenon. Analysis of the recurrence interval of large earthquakes is closely related to the dynamic of seismic faults and is a key parameter for assessing seismic risk in a fault zone (McCalpin, 2009; Yeats et al., 1997).

In this study, using the networking and statistically methods, the temporal and spatial return periods of earthquakes occurred in the Zagros region are investigated.These earthquakes were recorded in the stations of seismic networks affiliated to the Institute of Geophysics, University of Tehran.

2 Sesismotectonic of the Zagros

One of the youngest and most seismically active continental collision zones onthe Earth is the Zagros fold and thrust belt, which is a part of the Alpine–Himalayan mountain belt (Snyder and Barazangi, 1986). It is about 1500 km long with a width of 200 to 400 km from the Taurus Mountains in southeastern Turkey to the Minab fault in the east of Hormuz Island in southern Iran (Berberian, 1995; Alavi, 1994).

The formation of the Zagros Fold and Thrust Belt (ZFTB) (Koyi, 1988) began after the closure of the Neotethys Ocean and the collision of Arabian and Central Iranianplates in the Main Zagros Thrust (MZT).The MZT fault marks the northern boundary of seismicity in the Zagros.This fault is in fact a suture zone between the Arabian and Central Iranian colliding plates, which continues with the direction of northwest-southeast from west of Iran to the north of Bandar Abbas, then its trend is changing to west-east.

North-northeast convergence of Arabian plate to Eurasian plate is divided into thrust and strike-slip faults in the Zagros Mountains (Maggi and Priestley, 2005; Talebian and Jackson, 2002).The highest part of the Zagros Mountains is in the form of a narrow width (10 to 65 km) which is sometimes called the High Zagros Fault (HZF).The northeastern boundary of this sub-zone is close to the MZT and

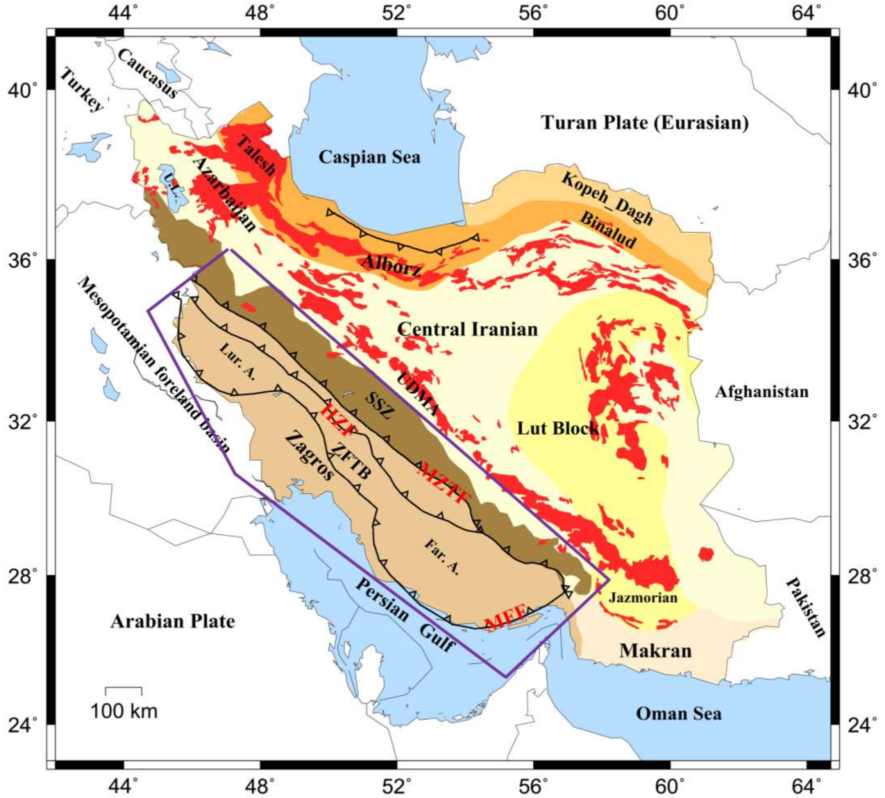

Figure 1. Location of the study area (Zagros) and its main faults (purple box). Red spots indicate intrusive rocks in the area. The file of faults is from JimeezNez-Munt et al. (2012).

the south-western boundary is close to an important thrust, i.e., HZF(Figure 1).

Zagros is the most seismic region in Iran and most of the Zagros earthquakes occur at a depth of 8-12 km.One of the most important earthquakes in the region is the 1957 earthquake with a magnitude of 6.7 on the scale of surface waves in the Kermanshah region.The other important earthquake is the earthquake of May 17,1999 with a magnitude of 6.2 on a global scale in the Kahmareh region of Fars province.

3 Methodology of earthquake network

Being one of the largest branches of mathematics, network theory was first proposed in 1736 with the publication of an article by Leonard Euler (Euler, 1736). It is closely related to algebra and matrix theory.In mathematical terms, a network is a set of interconnected points and lines.In fact, a network is a mathematical model for a discrete set whose members are interconnected in some way. Network members are defined as a set of nodes and the interaction between members is defined by a set of edges. In a society, the members of a set can be human beings and the friendship between them can be the edges. For a molecular set, atoms can be considered as members of the set and the chemical bondsbetween them are defined as the edges (Babelian, 2007)

Recent advances in mathematics, especially in its applications, have led to the dramatic expansion of network theory, so that network theory is now a very useful tool for research in various fields such as coding theory, statistical operations research, electrical networks, computer science, chemistry, biology, social sciences, design of electrical circuits, geometric modification of streets to solve traffic problems, urban planning,and civil engineering. In some networks, such as the network of earthquakes, due to various unknown parameters, it is more complex to understand the behaviors of complex networks methods derived from statistical mechanics;therefore, defining statistical quantities such as degree distribution function and cluster coefficient is useful to provide information about the general state of the network (Boccaletti et al., 2006).

To examine these quantities, an appropriate network must be set up. To build any network (e.g. earthquake network in this study), firstly, the nodes and edges that are the main parameters of each network must be defined.There are two main approaches for constructing an earthquake network. In the first approach, the geographical area under study is divided into boxes of the same size. If earthquakes occur in these boxes, they will act as nodes. Consecutive seismic events are connected by edges in terms of time. This network model is related to the model presented by Abe and Suzuki (2004a,b; 2005; 2006; 2007; 2009) and Abe et al. (2011). Theyshowed that the network of earthquakes is scaleless and has the structure of a small world.Also, the effect of box size on the characteristics of Iran seismic networks will be studied and network characteristics such as degree distribution function, cluster coefficient and characteristic length will be defined. Moreover, seismic active points in Iran will be obtained (Daroonehand Lotfi, 2014).

In the second approach, seismic events are considered as nodes and two nodes are connected when they are interconnected by the relationships that are true for an earthquake event.Telesca and Lovallo (2012) used phenomenal algorithms to make connections between earthquakes. This algorithm was proposed as a tool for time series analysis (Lacasa et al., 2008).

Baiesi and Paczuski (2004) presented a quantitative relationship between earthquakes.This relationship includes the quantities of time interval and spatial distance between two earthquakes, as well as the magnitude of the first earthquake.

To construct the earthquake network in this study, the recursive seismic method of Davidsen et al. (2006) is used. This method uses the concept of waiting time to return the occurrence of earthquakes in space and time. By considering that Earthquake$A$occurs in time before Earthquake$B$,Earthquake B is a return from Earthquake A provided that no other earthquakes occur spatially closer to Earthquake B after Earthquake A.In fact, $\overline{AB}$should be the lowest value in terms of distance, in the time interval$(t_A - t_B)$ which isthe time between event Aandevent B.Each return is denoted by the interval $L = \overline{AB}$and the time interval $(t_A - t_B)$.In other words, the space window is the center of the first event, and each return to this event is at the closest spatial distance to the other events.

The distribution of L intervals between return events for different thresholds of magnitude m is calculated using the centrifugal coordinates of the earthquake catalog (Baiesi-andPaczuski, 2004):

$$L_{ij} = R_0 Arccos\,[sin(\theta_i)\,sin(\theta_j) + cos(\theta_i)\,cos(\theta_j)\,co\,s(\varphi_i - \varphi_j) \quad (1)$$

where$i$ and j represent the first and second earthquakes, respectively. θ and $\varphi$are the longitude and latitude of the epicenter of the earthquake, respectively.$R_0$is the radius of the earth.

Earthquake networks are constructed in such a way that seismic events represent nodes.To create an edge between nodes in the earthquake catalog, we define the temporal and spatial return of earthquakes. Each return from the next event to the previous event is represented by an edge between a pair of nodes in the temporal and spatial series of earthquakes.Separate events have different input and output edges that indicate their relationship to other events, and thus nodes have different degrees.The output edges of each node determine the structure of the returns in its neighbors.In other words, the output edges of each node are the input edges of its neighbors.

4 Data

In this study, we used earthquakes that occurred in the Zagros region in the period time of January 1, 2006 to January 1, 2016 with 77245 earthquakes recorded in the permanent stations of the national seismic network of the Institute of Geophysics, University of Tehran (http://irsc.ut.ac.ir). Figure2 showsthe frequency of the earthquake magnitudes which are mostly less than 3 on the Nuttli scale(M_N).

To determine the magnitude threshold (m_c) for data processing, magnitude versus year-was plotted (Figure 3). The value of the large threshold for starting the process is $m_c = 2$

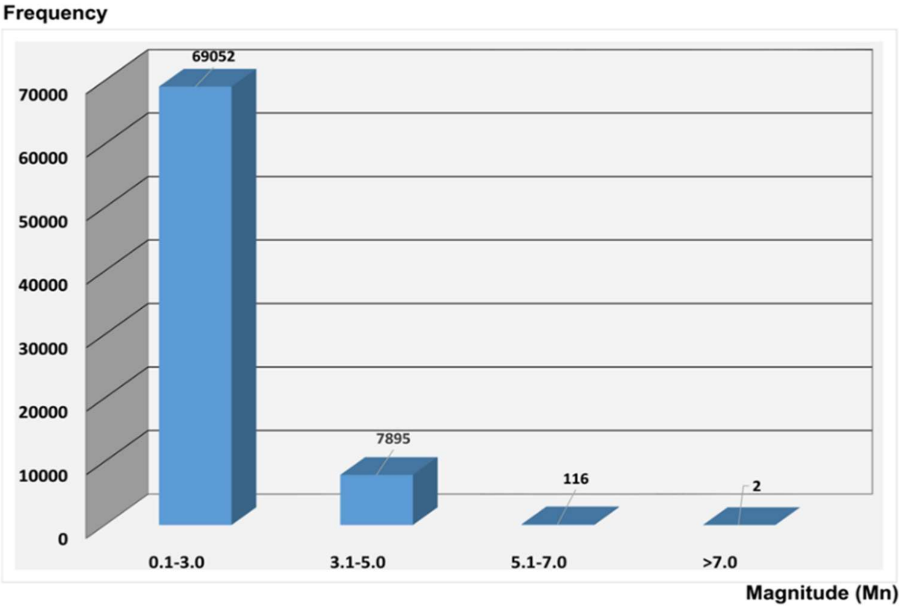

Figure 2. Data distribution in terms of M_N.

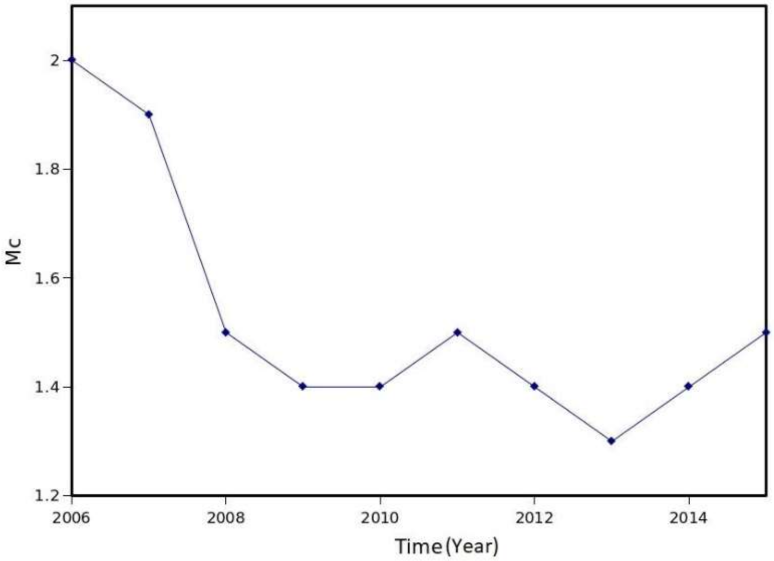

Figure 3. Analysis of m_c by year for the data catalog used in this research from 2006 to 2016.

5 Discussion

To describe seismicity, we examined earthquakes in the Zagros region in Iran with algorithm of Davidsenet al.(2005).In this way, the seismic network was first constructed by considering seismic events as nodes and defining the spatial and temporal return relationship as the edge between nodes.For this purpose, the distribution of *L* distances between return events for different thresholds of magnitude m was calculated using the centrifugal coordinates of the catalog of earthquakes and the relation of Baiesi and Paczuski (2004).

The shortest distances specified are shown schematically in Figure 4.The black nodes are the center of earthquakes and the shortest distance (*L*, in meters) between adjacent earthquakesis represented by colored arrows.

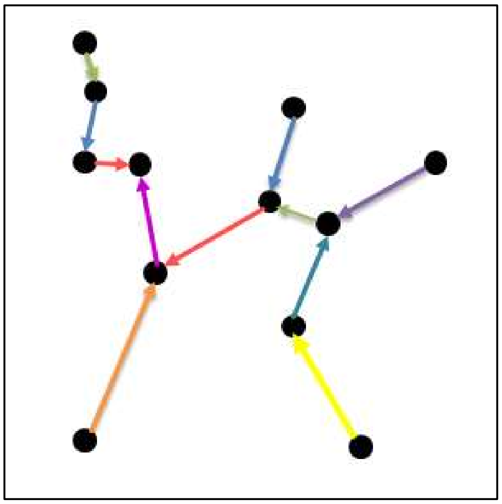

Figure 4. Schematic diagram of a spatial return between earthquakes. The solid black dots are the center of earthquakes and the colored arrows are the shortest distances between adjacent earthquakes.

Using Baiesi and Paczuski (2004) equation, the shortest distance between adjacent earthquakes was calculated.Firstly, we consider a given magnitude, for example, earthquakes with a magnitude greater than 2, and we get all the spatial distances that have recurrent earthquakes and are calculated with the relation L_{ij}. The P function is a function of the distribution of distances that specifies how many data have a distance L in the data. Because distances are real numbers, and it is certainly rare to find several earthquakes that haveexactly the same distance, we consider the same spatial intervals and, for example, specify how many data there are in the distance between 10 and 11.

In Figure 5, the distribution of distances L between recurring events ($P_m(L)$) is plotted for earthquakes in the Zagros region for different magnitudes $m_c \geq 2$.In the graph L^*, for any magnitude m, the distance is the place where the distance distribution function reaches its maximum value on the graph.

As shown in Figure 5, the value of the distance L^*(m) increases by magnitude m where the distribution function reaches its maximum value at the peak. Moreover, for large values of L, the distribution functions show a descending behavior with a slope of 1.65 to the point where there is no more data and the points of the graph are exhausted.

As the magnitude of the earthquake increases, the value of L^* shifts to the right(Figure 6).It seems that by performing a series of mathematical operations on the graphs, all of these graphs show the same behavior. Then,the appropriate scale must be selected. For this purpose, different equations with different coefficients were investigated.For earthquakes in the Zagros region with a value of 0.5 m, the behavior of the graphs with different magnitudes was the same as Figure 5.

The experimental relationship of the F function, which is a function of the scaling factor, can be calculated for the Zagros region (Figure 6) by extrapolation as Eq.(2):

$$P_m \text{ (L)} \sim \text{L}^{-1.65} \text{ F(l / } 10^{0.5m} \text{)} \qquad (2)$$

According to Figure 6, it can be seen that for the F function at low values, there is a power relationship with the power of 2.9 and an almost constant behavior at high values.The transfer point between these two states, which is shown by the dashed line on the figure, was obtained by extrapolation, L_0=0.020 km.The experimental relation $L^* \approx 0.020 \times 10^{0 \cdot 5m}$,is established for this diagram.

In the study of Wells and Coppersmith (1994), the value of L^* is expressed as the length of the L_R rupture, and in their study they obtained the value of $L_R \approx 0 \cdot 018 \times 10^{0 \cdot 46m}$for the California region. Kagan (2000) obtained the relation $L_R \approx 0 \cdot 02 \times 10^{0 \cdot 5m}$ for the California region.

The results of the present study for the values obtained in the Zagros region are in good agreement with the values suggested by Wells and Coppersmith (1994).

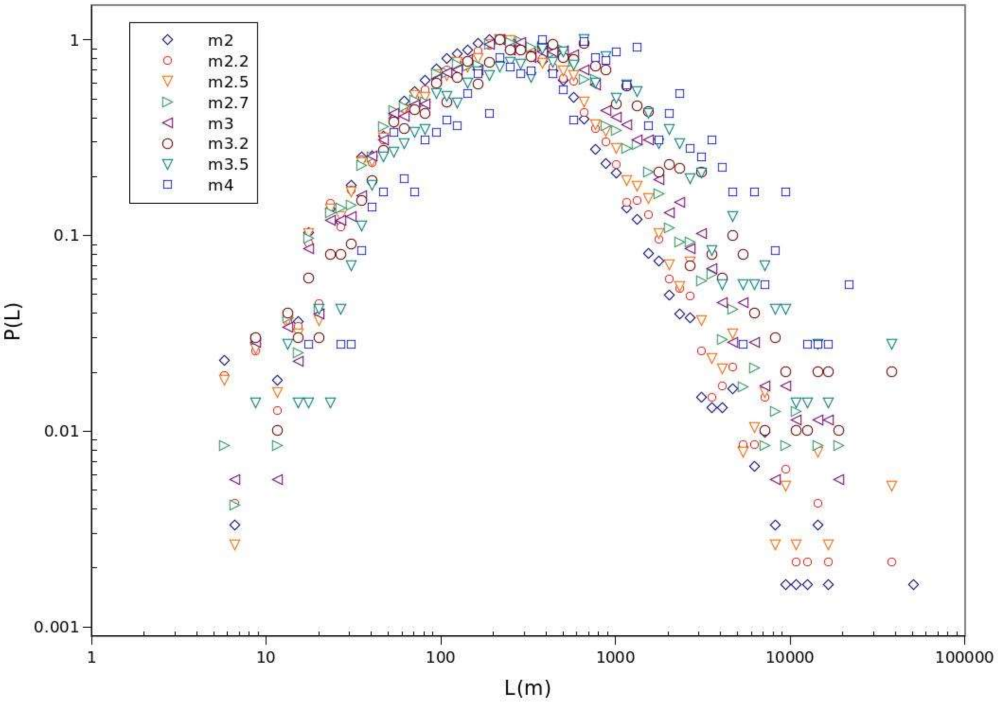

Figure 5. Graph of the distribution function of L distances between return events for different thresholds of magnitude. Where the distribution function reaches its maximum value, L*(m) increases.

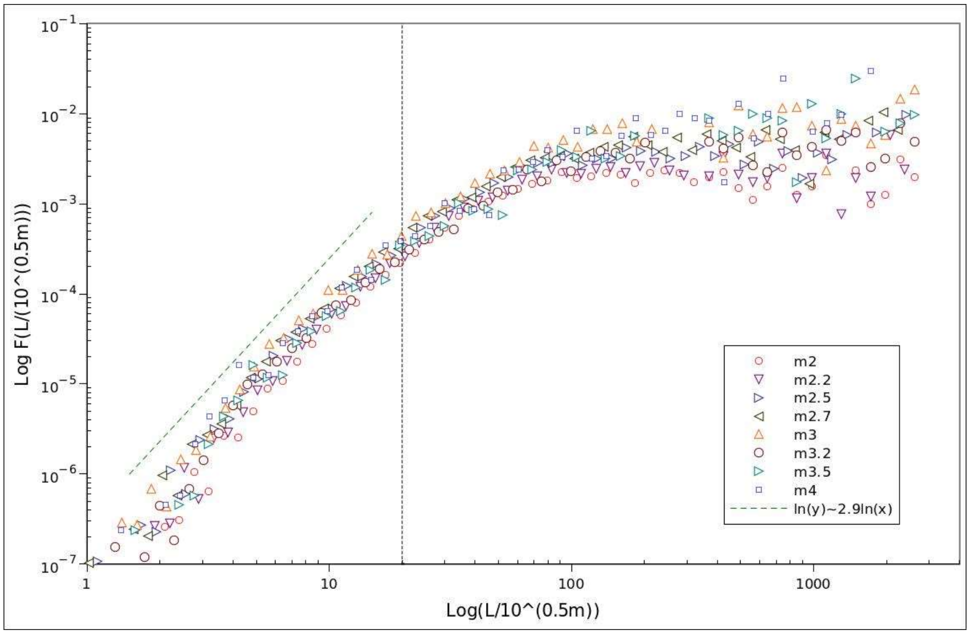

Figure 6. Rescale diagram of distances in terms of their distribution based on the relationship $P_m(l) \sim l^{-1.65} F(l/10^{0.5m})$in the Zagros region. The vertical line shows the value of L_0 in the scaling rule for the characteristic distance equal to 0.020 km. The diagonal line shows the power relationship in small values with a slope of 2.9.

In addition to calculating the spatial return of recurrent events, the temporal return of earthquakes in the Zagros region was also studied.To calculate this quantity, two earthquakes *A* and *B* are considered.In terms of time, Earthquake *A* occurred before Earthquake *B*.Earthquake *B* is considered as a time return from Earthquake *A* if it is the closest time distance from Earthquake *A*. The time return for earthquakes in the Zagros region in

Iran is calculated and the graph changes of the distribution function of return events over time can be seen in Figure 7.

As shown in Figure 7, for all magnitude thresholds, there is a similar power behavior $(1/\mathrm{T}^{\alpha})$ with a value of $\alpha = -0.9$. For long periods of time, this behavior does not follow the power law because the number of long timeintervals between earthquakes is small.Even in small amounts of time, this relationship is not established, which can be due to an error in determining the times used in the catalog. For the California region, Davidsenet al.(2005) showed a graph of the distribution function of recurring events over time with similar power behavior with a slope of –0.95.

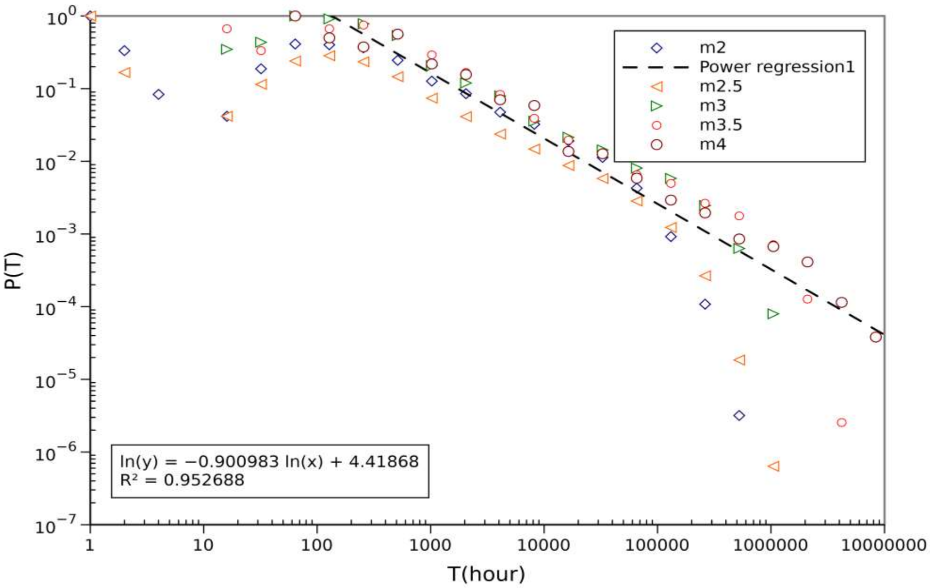

Figure 7. Graph changes in the distribution function of recurring events over time for the Zagros region of Iran in exchange for thresholds of different magnitudes. The dashed line shows the power relationship with the slope of 0.9.

6 Conclusion

In this study, using the network model of earthquake phenomenon, the temporal and spatial return period of earthquakes by method of Davidsenet al.(2005) were studied in the Zagros region.The results showed that in the Zagros region, the spatial return period of earthquakes is about 0.020 km. Moreover, the time return period for all magnitude thresholds greater than 2 ($m_c \geq 2$) has the same power behavior $(1/T^{\alpha})$ with value of $\alpha = -0.9$.

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