Visibility Graph Analysis of the 2005-2015 Earthquake Sequence in Northern Iran

Abstract

The seismicity of northern Iran between 2005 and 2015 is investigated by means of visibility graph (VG) method. According to the seismicity, in this study the northern Iran is divided into three tectonic seismic regions including Azerbaijan, Alborz, and Kopeh Dagh. The aftershocks and foreshocks are removed from the catalog and the magnitude time series are generated for each tectonic seismic zone. Using declustered catalog, we studied the VG properties of the magnitude time series. The results show a relationship between the $k - M$ slope and the $b - value$ of the Gutenberg-Richter law. Topological properties (i.e. $< T_c >$, $k - M$ slope) of network and dynamic properties of magnitude time series (i.e. $b - value$) significantly decrease before large earthquakes. Cumulating the results of this study into two similar previous studies, improves the linear correlation coefficient factor and empower the idea of universal relationship between $b - value$ and $k - M$ slope. The behavior of the VG's properties are similar to previous studies and could be considered an alternative method to analyze the earthquake sequence.

Key words: Visibility Graph, Earthquake Magnitude, North Iran, b-value

1. Introduction

Lacasa et al. [1] presented a simple and fast computational method; known as visibility algorithm, to convert the time series into the graphs. Basically the visibility graph presents the connection between nodes in the network. In each time series two characteristics are attributed to each incidents, including the time and the value of the incident. Two events are connected to each other, or visible to each other, if there is not any other event to interrupt their linear connection. In mathematical form, event i and event j are visible to each other if the following equation fulfills:

$$\frac{y_i - y_k}{t_k - t_i} > \frac{y_i - y_j}{t_j - t_i} \tag{1}$$

where, y is the value of the event and t is the time of the event. k is the index of any event between event i and event j.

The visibility graph that is generated from the time series holds the following conditions, 1) each event is visible to the events at the right and left side (if there is any) of the event (Connectivity), 2) The algorithm is developed without defining a direction for the links (Undirected), 3) Rescaling or translation of the time series are not changing the resulted visibility graph (Invariant under affine transformations of the series data)[1].

The analysis of seismicity sequence through visibility graph for various tectonic seismic regions, revealed an alternative approach to study the magnitude time series. Telesca and Lovallo [2] studied the seismic sequence of Italy between 2005 and 2010 through using the visibility graph method. Using different threshold magnitude, and observing the collapsing effect of all the distribution degrees, they argued that in analyzing the magnitude time series, VG seems to depend only on the values of the magnitude and independent of the threshold magnitude. In other study, Telesca et al. [3] studied the Seismicity of the Mexican subduction zone through visibility graph approach. They extracted the characteristics of the visibility graph for five different tectonic seismic regions. According to their study visibility graph could identify one of the regions that has a different seismicity characteristics, which is because of different tectonic processes that governs the area. The relationship between Gutenberg-Richter parameters and $k-M$ slope (The slope of regression line of Magnitude of each event (M) and its connectivity degree k) is investigated in their study. In a similar study Telesca et al. [4], studied the seismicity of 2002-2011 Pannonian seismicity using the visibility graph. They classified seismic catalog into shallow and deep earthquakes and extract the visibility graph characteristics for each class. According to their study there is close relationship between Gutenberg-Richter $b-value$ and $k-M$ slope of the visibility graph. High linear correlation coefficient of $b-value$ and $k-M$ slope suggests the universal character of the relationship between these parameters [4]. Telesca et al. [5] , used the $< T_C >$, as the parameter window mean interval connectivity time , that indicates the mean linkage time between earthquakes, to study the 2003-2012 earthquake sequences in the Kachchh region of western India. They found that the $< T_C >$ changes through time, indicating that the topological properties of the earthquake network are not stationary; also $< T_C >$ significantly decrees before the largest shock of the catalog. Analyzing Gutenberg-Richter values of magnitude time series of an earthquake sequence revealed more opportunities to study the magnitude time series using the features of networks.

In this study we used visibility graph analysis to study the earthquake sequence of northern Iran. We divided northern Iran into three tectonic seismic regions including Azerbaijan, Alborz, and Kopeh Dagh. Recently, northern Iran has been studied in detail from different seismological points of view. Nemati [6] studied the most recent 200 years' seismicity in northern Iran. The frequency of shocks vary widely from one main shock per 6 years (0.17 event/ year) for the Azerbaijan region to 13 earthquakes per 4 years for the Kopeh-Dagh (3.25 event/year) region.

Northern Iran has an elaborate seismic history. Having considerable number of earthquake and also being in different seismic tectonic zone, northern Iran is a good platform to analysis the visibility graph method's capabilities for studying the magnitude time series. In this study we present the relationship between $K-M$ slope and the $b-value$ in three different tectonic seismic region. We also investigate the variation of $< T_C >$ value through time.

2. Tectonic seismic zones and seismicity parameters

Iran is situated over Himalayan-Alpide seismic belt, which has frequently experienced strong shaking induced by earthquakes. These earthquakes are categorized in various tectonic seismic zones. Based on seismicity parameters different tectonic seismic devisions have been defined for Iran. Some studies defined more detailed division [7, 8], and some of them defined one simplified province [9, 10, 11]. Mirzaei et al. [12] divided Iran into five tectonic regions, including Azerbaijan-Alborz, Kopeh-Dagh, Zagros, Central-East Iran, and Makran. Considering Mirzaei et al. [12] devision, Karimiparidari et al. [13] divided the Azerbaijan-Alborz tectonic seismic region into two regions, which are Azerbaijan and Alborz Mountain Range (hereinafter, Alborz). Azerbaijan, Alborz and Kopeh-Dagh tectonic seismic regions encompass most of northern Iran. Fig. 1 shows the study region and tectonic seismic regions.

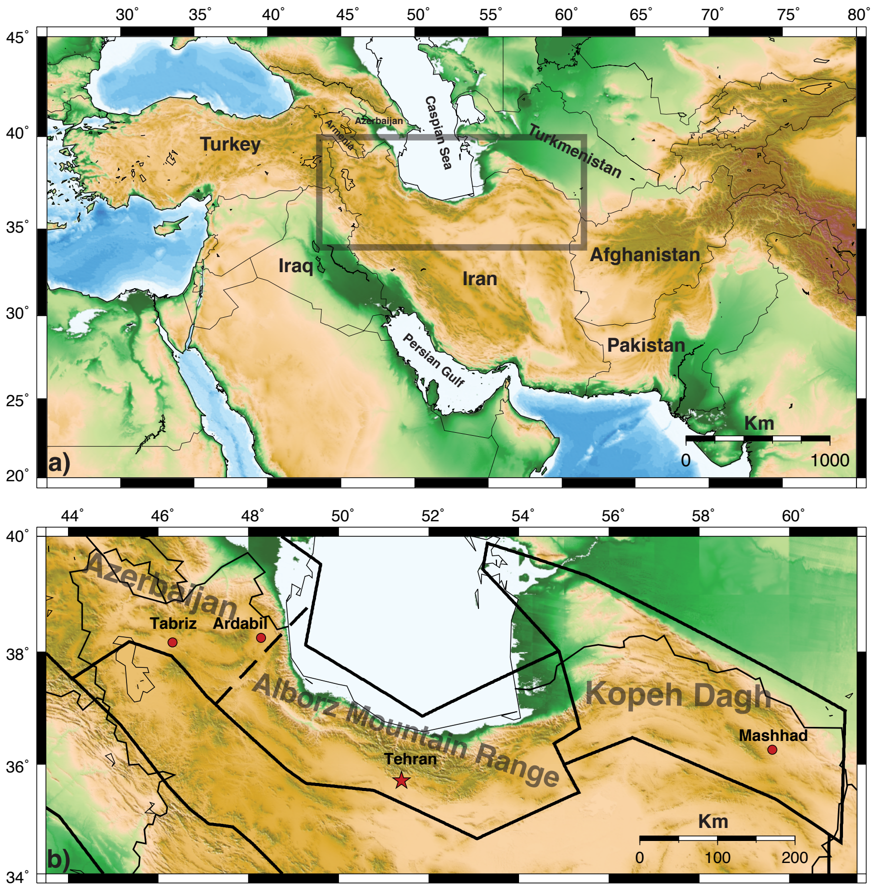

Figure 1: a) Map of Iran and surrounding countries. The study area is presented in gray box. b) The study area containing seismotectonic provinces after Mirzaei et al. [12], and location of big cities. Dashed line is the subdivision that is proposed by Karimiparidari et al. [13]

Alborz tectonic seismic region has active reverse faults, which are parallel to the northwest-trending structural gain of the Alborz Mountains belt. Here a series of historical earthquakes occurred within a time period of more than 1100 years. At least three damaging earthquakes in 958 (western segments), 1655 (eastern segments), and 1830 (central segments), ruptured adjacent segments of the Mosha fault, located in northern Tehran. The North Tehran Thrust (NTT) adds more complexity due to the presence of south-dipping reverse faults, which are in part blind, such as the Davudieh, Shian, and Bagh-E Feyz. The northwest continuation of the Alborz Mountains, known as the Rocks of the Talesh Mountains, have been thrust northeastward and eastward over rocks of the south Caspian depression. An earthquake with Ms 6.0 in 1978 led to a focal mechanism consistent with a low-angle thrust [14].

There were three earthquakes from 1721-86 that ruptured the North Tabriz Fault system from southeast to northwest, as part of Azerbaijna tectonic seismic zone. The Tabriz region is in the Araxes structural block of northwestern Iran, southwest of the continuation of the western Alborz Mountains towards the Caucasus. The North Tabriz Fault (NTF) is a complex northwest-trending structure, which contains evidence observed on aerial photographs, and vertical displacement with the north side up, of right-lateral strike-slip displacement [14].

The NTF system and nearby reverse faults ruptured from southeast to northwest in three earthquakes over 65 years: the Shebli earthquake with magnitude 7.3 in 1721 on the southeastern NTF with a surface rupture more than 35 km long, reported by Jones [15] the Tabriz earthquake with magnitude 7.4 in 1780 on the northwestern NTF, with a surface rupture more than 42 km long and vertical separation of 2 to 4 m; and the Marand-Mishu earthquake with magnitude of 6.3 in 1786 on the Mishu reverse fault and the Sufian segment of the NTF. Another earthquake with magnitude 5.5 struck the Tasuj reverse fault farther west in 1807 and an earthquake of M 6.7 took place along the South Bozqush reverse fault farther southeast in 1879. Prior to the 1721-86 earthquake sequence, Tabriz was shaken by earthquakes in 858 (M 6.0), 1042 (M 7.3), 1273 (M 6.5), and 1304 (M 6.7)[14]. Most recently, earthquakes with Mw 6.1 in 1997 and Mw 6.4 in 2012 occurred in Ardabil and Tabriz, respectively.

The main Kopeh-Dagh fault system has experienced some historic earthquakes. Ashgabat, the capital city of Turkmenistan, was destroyed by an earthquake of Ms 7.2 in 1948 and destroyed more than 30 villages in Iran. This was the strongest earthquake to strike this region since at least 1455. The main Kopeh-Dagh fault consists of several partly overlapping segments parallel to the overall $NW - SE$ structure with step-overs. The regions of overlap are characterized by shorter south-dipping thrust faults striking about E - W [16]. Trifonov [17] reported active displacement along the main Kopeh-Dagh fault for more than 500 km. Massive destruction of the capital city of Mithradatkert is attributed to the 10 BC event Ms 7.1, roughly 30 kilometers from the border of Iran (Nesa mound) [16]. The Neyshabur sequence of four earthquakes between 1209 and 1405 respected the segment boundary between the Neyshabur and Binalud reverse fault system [14]. Historical records show that in 1209, the district of Neyshabur from Neyshabur city in the west to Daneh village in the east was totally destroyed [14].

2.1. Magnitude Conversion

The catalog of recorded earthquake from 2005-2015 which is downloaded from IIEES is reported the earthquake based on different magnitude scale (reference). We converted the M_L, M_S, and mb magnitudes through conversion relationships which is defined in Zare et al. [18]. There also some of data which is recorded in M_D (Duration magnitude). These data are reported by International Seismological Centre (ISC). Deniz and Yucemen [19] developed a set of empirical equations to convert earthquake magnitudes in mb, M_D, M_L and M_S scales to the M_W scales using orthogonal regression procedure. They used data of earthquake that occurred in Turkey from different data centers including ISC. In this study we use the conversion equation of Deniz and Yucemen [19] to convert the M_D to M_W. Although they defined the equation based on $4.5 \leqslant M_W$, we extrapolate the equation for lower magnitude. We believe having those earthquakes, even with small error in magnitude is important for estimating an accurate Gutenberge-Richter values.

2.2. Declustering

It is generally assumed that the seismicity of each tectonic seismic source follows a Poissonian occurrence process. Therefore, in order to accomplish this, we declustered the earthquake catalog. In compiling the catalog of events, foreshocks and aftershocks were removed using a declustering methodology Gardner and Knopoff [20]. Fig. 2 shows the epicenter of declustered instrumental earthquakes.

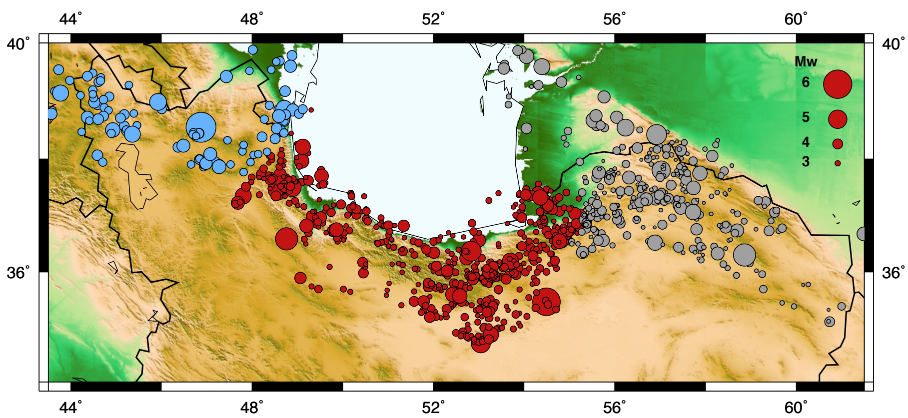

Figure 2: Declustered instrumental seismicity map (2005 - 2015) of Northern Iran.

2.3. Catalog Completeness

Completeness of catalog is an important factor in studying the earthquake sequence. In this study we used the Maximum curvature method (MAXC) [21]. According to MAXC method, a complete catalog should follow the Gutenberg-Richter power law distribution of magnitude. The steps for picking the completeness magnitude for each catalog include, 1) Calculating the $a-$ and $b-$ value based on the minimum magnitude, 2) generate synthetic events based on the achieved value that the cumulative number of events obey the power law distribution, 3) Calculate the goodness of fit for predicted and observed cumulative numbers for each magnitude bin. Higher [21]. We increase the minimum magnitude and repeat the process. For each tectonic seismic region, we pick the magnitude corresponding to the highest goodness of fit. Wiemer and Wyss [21] assumed the threshold of goodness of fit as 90% in order to completeness of the catalog, however, not all frequency-magnitude distributions reach the 90% mark. Fig. 3 , shows the goodness of fit value for three tectonic seismic regions.

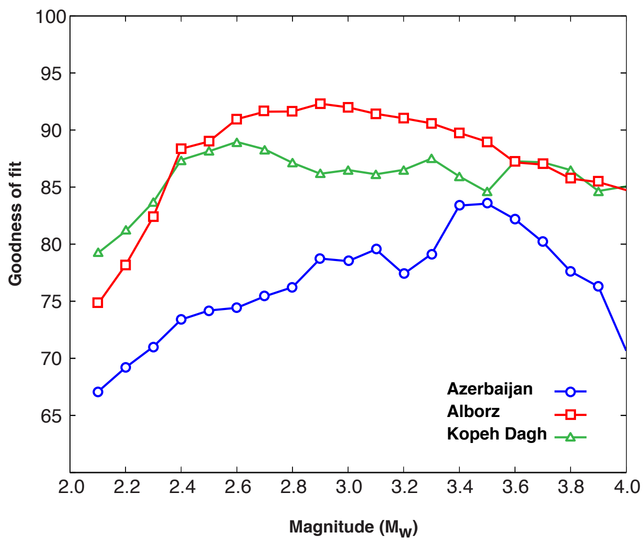

Figure 3: Goodness of fit value of MAXC method for three tectonic seismic regions for seismicity of 2005-2015 (a) Azerbaijan b)Alborz c) Kopeh Dagh)

In this study we assumed the minimum magnitude for complete recording, M_C, are 2.9, 3.5, and 2.6 for Alborz, Azerbaijan, and Kopeh Dagh, respectively. Fig. 4 shows the magnitude time series of the declustered data for three regions. Earthquake with magnitude bigger than completeness magnitude are represented.

3. Results

We generated the visibility graph characteristics for three tectonic seismic regions in northern Iran for the period from 2005 to 2015. Number of earthquake in each catalog after declustering and the seismicity parameters are presented in Table. 1.

Table 1: Seismic parameters and K-M slope values for north Iran tectonic seismic zones.

Region	Number of Earthquake	Mc	b-value	K-M slope
Azerbaijan	93	3.5	1.0190	9.2004
Alborz	488	2.9	0.8532	9.2821
Kopek Dagh	282	2.6	0.5799	6.5818

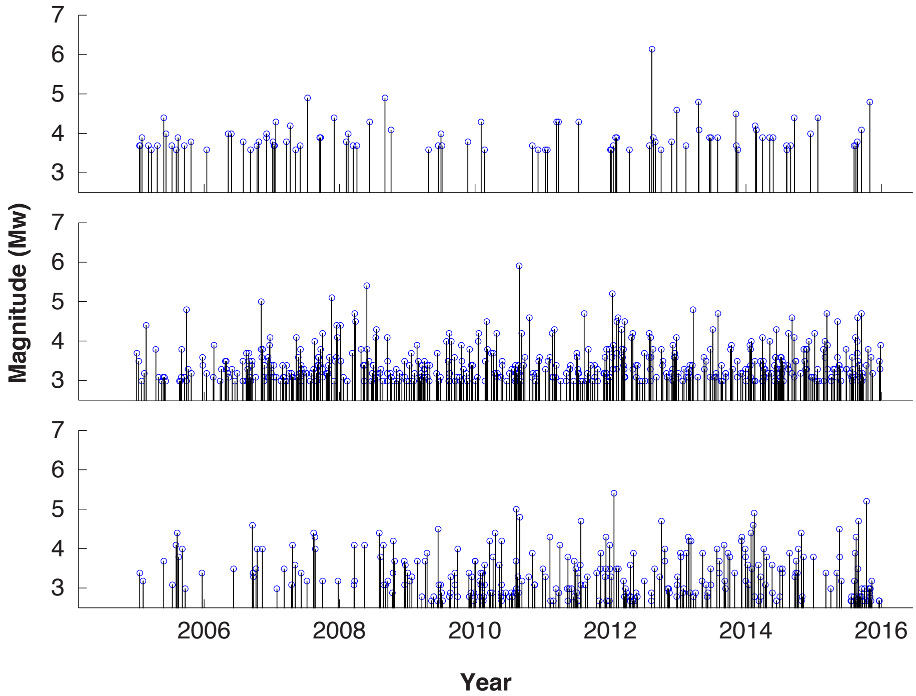

Figure 4: Variation of moment magnitude of earthquake in 2005-2015 for north Iran. (a) Azerbaijan b)Alborz c) Kopeh Dagh)

Fig. 5 shows the $k - M$ relationship for the study regions. In general with increasing magnitude the connectivity degree increases which results in increasing the slope of the $k - M$ relationship. We compared the $k-M$ slope with the $b-value$ of the Gutenberg-Richter law in the whole catalog and also in the sliding window in time. The $b-value$ is generated through the maximum likelihood estimation [22].

$$b = \frac{log_{10}(e)}{\overline{M} - M_{min}} \tag{2}$$

where $\overline{M}$ is the average magnitude and M_{min} is the minimum magnitude in the sample, which in this case is the completeness magnitude for each tectonic seismic zone. Number of sequences and threshold magnitude are considerably different for all tectonic seismic zones. Telesca et al. [3] studied the effect of number of earthquake in catalog on the $k - M$ slop. Comparing the result of Guerrero region with reduced random sequence, Telesca et al. [3] found that the number of sequence doesn't affect the $k - M$ slope. According to Telesca and Lovallo [2], the threshold magnitude has a minor effect in the VG parameters. In order to analyze the sensitivity of the catalogs to the number of events and the threshold magnitude we randomly picked 200 sequence from the catalogs with various sequence size. The minimum size of random windows are 150 events (note that the number of events in each catalog, before removing the events with magnitude less than completeness magnitude, are 271, 1262, and 399 for Azerbaijan, Alborz, and Kopek Dagh regions, respectively) and the maximum size is the whole catalog. For each randomly picked

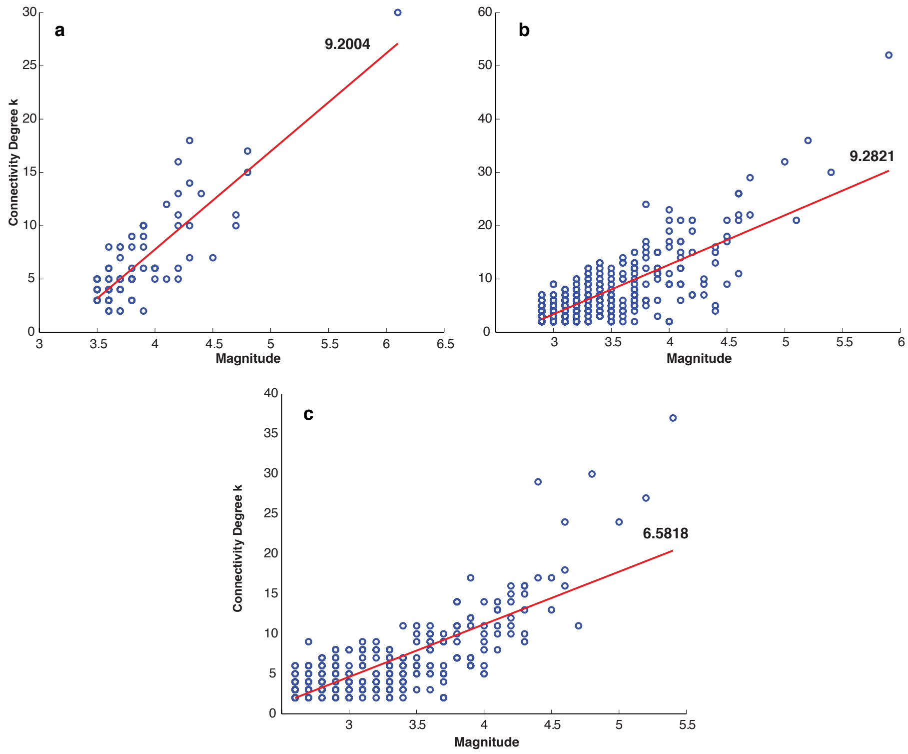

Figure 5: K-M relationship for north Iran seismicity. a) Azerbaijan b) Alborz c)Kopeh Dagh

magnitude time series we estimated the Mc and calculated the $k-M$ and $b-value$. Fig. 6 shows the relationship between $k-M$ slope and $b-value$ of the randomly selected data and statistical parameters for variables. Although changing number of events and the threshold magnitude are slightly change the results, they are fairly well clustered for each tectonic seismic region.

figures/pdf/Figure066.pdf

Figure 6: Relationship between $K-M$ and $b-value$ of three Iranian tectonic seismic zones (this study) and two other studies of Mexican zones [3], and Pannonia zones [4]. The dashed red line shows the regression line for data of Mexican zones and Pannonia zones [4], and the solid blue line shows the regression line for data of all regions (Mexican, Pannonian and North Iran)

The $k-M$ slope shows the maximum coefficient of variation. We may argue that the $k-M$ slope is much dependent to the window size and threshold magnitude than $a-$ and $b-value$, which suggest the idea that $k-M$ slop can better represent the dynamic characteristics of the magnitude-time series.

Fig. 7 shows the relationship between the $k-M$ slope for three tectonic seismic zones in Iran and two other studies of Mexican zones [3], and Pannonia zones [4]. Adding the results of this study into two previous similar studies' results, improves the regression factor (increase from R=0.95 to R=0.958) and empower the idea of universal character of the relationship between the $b-value$ and the $k-M$ slope as Telesca et al. [4] concluded.

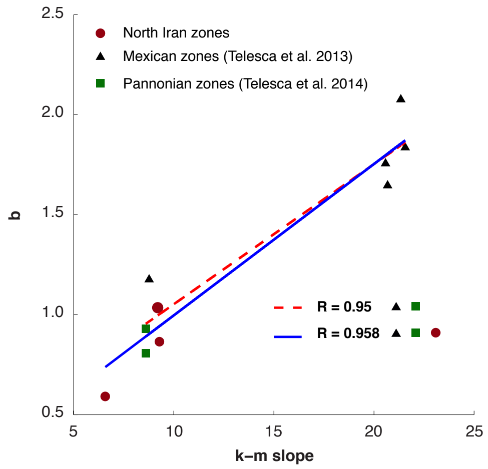

Figure 7: Relationship between $K - M$ and $b - value$ of three Iranian tectonic seismic zones (this study) and two other studies of Mexican zones [3], and Pannonia zones [4]. The dashed red line shows the regression line for data of Mexican zones and Pannonia zones [4], and the solid blue line shows the regression line for data of all regions (Mexican, Pannonian and North Iran)

The relationship between $b - value$ and $K - M$ slope for Azerbaijan and Alborz region, suggested the idea of similar tectonic activity in these zones, in contrast with the $b - value$. In other words, may $K - M$ slope is more robust and less sensitive than $b - value$. Adding the value of this study into two previous similar studies results improves the regression factor (increase from R=0.95 to R=0.958) and empower the idea of universal character of the relationship between the $b - value$ and the $k - M$ slope as Telesca et al. [4] pointed out.
Fig.8 shows the variation of the $k - M$ slope and $b - value$ with time. Having lower number of event, we used 40 events as a window length. We analyzed the sensitivity of the results to the window size. Even though there is a very good similarity between the $K - M$ slope and $b - value$ in Alborz tectonic seismic region, there is no as good as fit for Azerbaijan Tectonic seismic region. The results indicate the fact that, $K - M$ slope may provide extra information about the seismic sequence of the region than the $b - value$.

The value of the K-M is increasing with increasing the magnitude. Fig yy shows the time vacation of the $K - M$ plot and $b - value$ for all tectonic seismic regions.

In general, In all regions the $b - value$ and $K - M$ slope considerably drops before big earthquakes. Dropping the $b - value$ before large earthquakes have been studied in many different region [e.g. 23, 24, 25, 26]

Earthquake is a time dependent phenomenon, so studying the dynamic properties of the earthquake sequence is important to get different time dependent parameters.

Telesca et al. [5] observed the decreasing of the $< Tc >$ before large earthquake of Western India earthquake sequence. Fig. 8 shows the time variation of $< Tc >$ in the study area. The decreasing of the $< Tc >$ for large earthquakes have been shown in the figure. Telesca et al. [5]

demonstrated that the decrement of $< Tc >$ before large earthquake are independent of window size and the threshold magnitude.

The fluctuation of magnitude time series' topology properties (e.g. the $k-M$ slope and $< Tc >$) could be affected by the window size. Sharp changes in the VG parameters happens through small windows. Using higher number of samples in the window will reduce the temporal effects of small or moderate earthquakes and highlight the effects of big earthquakes, even though the behavior of the parameters in time and also before big earthquake are similar [5]. In general, more number of samples in a window smooth the results.

In this study with increasing window size we can see the same behavior as small window. Undoubtedly, larger window size will reduce the effect of

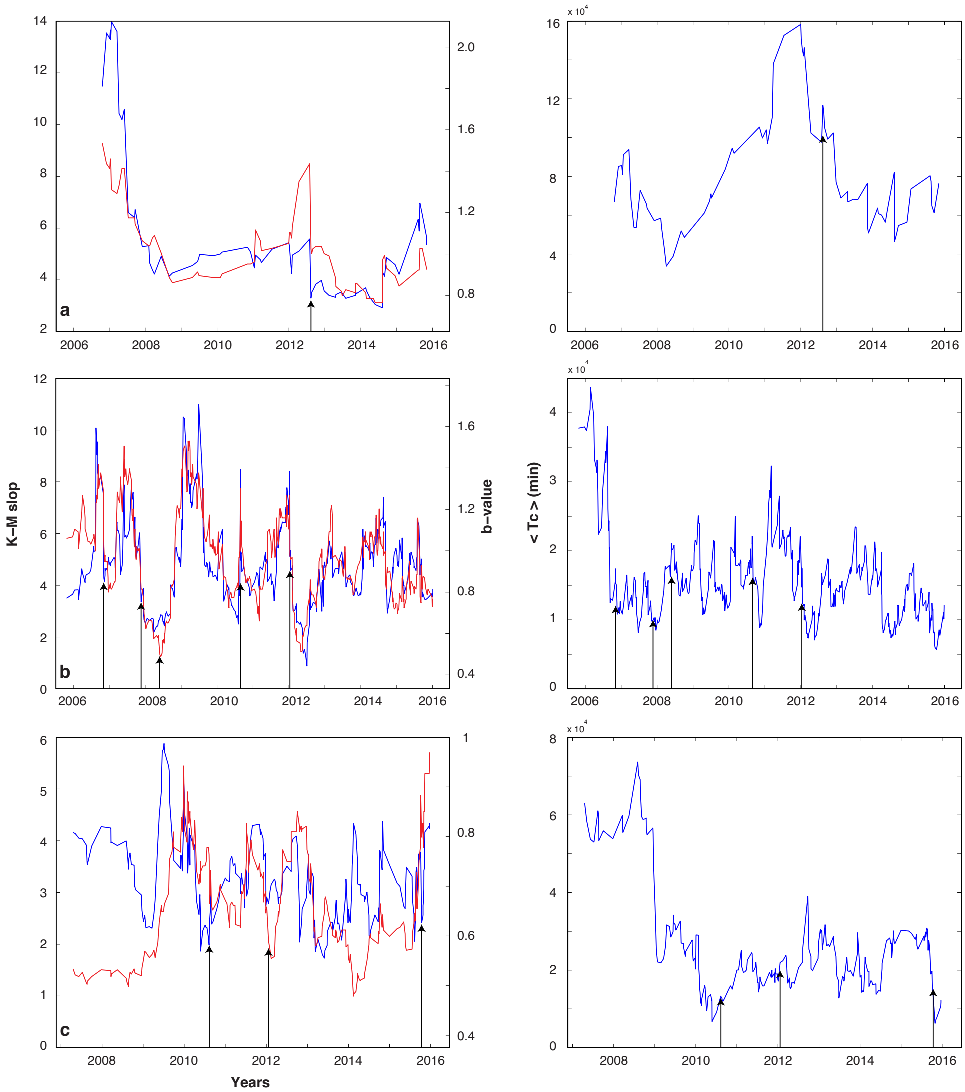

Figure 8: Relationship between $K-M$ and $b-value$ of three Iranian tectonic seismic zones (this study) and two other studies of Mexican zones [3], and Pannonia zones [4]. The dashed red line shows the regression line for data of Mexican zones and Pannonia zones [4], and the solid blue line shows the regression line for data of all regions (Mexican, Pannonian and North Iran)

References

[1] L. Lacasa, B. Luque, F. Ballesteros, J. Luque, J. C. Nuno, From time series to complex networks: The visibility graph, Proceedings of the National Academy of Sciences 105 (13) (2008) 4972–4975.

[2] L. Telesca, M. Lovallo, Analysis of seismic sequences by using the method of visibility graph, EPL (Europhysics Letters) 97 (5) (2012) 50002.

[3] L. Telesca, M. Lovallo, A. Ramirez-Rojas, L. Flores-Marquez, Investigating the time dynamics of seismicity by using the visibility graph approach: Application to seismicity of Mexican subduction zone, Physica A: Statistical Mechanics and its Applications 392 (24) (2013) 6571–6577.

[4] L. Telesca, M. Lovallo, L. Toth, Visibility graph analysis of 2002–2011 Pannonian seismicity, Physica A: Statistical Mechanics and its Applications 416 (2014) 219–224.

[5] L. Telesca, M. Lovallo, S. Aggarwal, P. Khan, B. Rastogi, Visibility Graph Analysis of the 2003–2012 Earthquake Sequence in the Kachchh Region of Western India, Pure and Applied Geophysics 173 (1) (2016) 125–132.

[6] M. Nemati, Intermediate-term variations in 200 years seismicity of South of Iran, Geomatics, Natural Hazards and Risk (ahead-of-print) (2015) 1–16.

[7] A. A. Nowroozi, Seismotectonic provinces of Iran, Bulletin of the Seismological Society of America 66 (4) (1976) 1249–1276.

[8] B. Tavakoli, M. Ghafory-Ashtiany, Seismic hazard assessment of Iran, Annals of Geophysics 42 (6).

[9] J. Stocklin, Structural history and tectonics of Iran: a review, AAPG Bulletin 52 (7) (1968) 1229–1258.

[10] M. Takin, Iranian geology and continental drift in the Middle East, Nature 235 (1972) 147–150.

[11] M. Berberian, S. Arshadi, On the evidence of the youngest activity of the North Tabriz Fault and the seismicity of Tabriz city, Geol. Surv. Iran Rep 39 (1976) 397–418.

[12] N. Mirzaei, G. Mengtan, C. Yuntai, Seismic source regionalization for seismic zoning of Iran: major seismotectonic provinces, Journal of Earthquake Prediction Research 7 (1998) 465–495.

[13] S. Karimiparidari, M. Zaré, H. Memarian, A. Kijko, Iranian earthquakes, a uniform catalog with moment magnitudes, Journal of seismology 17 (3) (2013) 897–911.

[14] M. Berberian, R. S. Yeats, Patterns of historical earthquake rupture in the Iranian Plateau, Bulletin of the Seismological Society of America 89 (1) (1999) 120–139.

[15] H. Jones, An Account of the Transactions of His Majesty's Mission to the Court of Persia: In the Years 1807-11, vol. 1, James Bohn, 1834.

[16] M. Berberian, R. S. Yeats, Contribution of archaeological data to studies of earthquake history in the Iranian Plateau, Journal of Structural Geology 23 (2) (2001) 563–584.

[17] V. G. Trifonov, Late Quaternary tectonic movements of Western and Central Asia, Geological society of America bulletin 89 (7) (1978) 1059–1072.

[18] M. Zare, H. Amini, P. Yazdi, K. Sesetyan, M. B. Demircioglu, D. Kalafat, M. Erdik, D. Giardini, M. A. Khan, N. Tsereteli, Recent developments of the Middle East catalog, Journal of Seismology 18 (4) (2014) 749–772.

[19] A. Deniz, M. S. Yucemen, Magnitude conversion problem for the Turkish earthquake data, Natural hazards 55 (2) (2010) 333–352.

[20] J. Gardner, L. Knopoff, Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian, Bull. Seismol. Soc. Am 64 (5) (1974) 1363–1367.

[21] S. Wiemer, M. Wyss, Minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the Western United States, and Japan, Bulletin of the Seismological Society of America 90 (4) (2000) 859–869.

[22] K. Aki, 17. Maximum likelihood estimate of b in the formula logN= a-bM and its confidence limits .

[23] M. Wyss, D. Schorlemmer, S. Wiemer, Mapping asperities by minima of local recurrence time: San Jacinto-Elsinore fault zones, Journal of Geophysical Research: Solid Earth 105 (B4) (2000) 7829–7844.

[24] M. Wyss, R. Stefansson, Nucleation points of recent mainshocks in southern Iceland, mapped by b-values, Bulletin of the Seismological Society of America 96 (2) (2006) 599–608.

[25] D. Schorlemmer, S. Wiemer, M. Wyss, Variations in earthquake-size distribution across different stress regimes, Nature 437 (7058) (2005) 539–542.

[26] C.-H. Chan, Y.-M. Wu, T.-L. Tseng, T.-L. Lin, C.-C. Chen, Spatial and temporal evolution of b-values before large earthquakes in Taiwan, Tectonophysics 532 (2012) 215–222.