by Jamileh Vasheghani Farahani¹, Mehdi Zaré² and Artur Cichowicz³

Microseismicity of the Tehran region based on the data recorded in a local monitoring network: 2004-2010

¹ Institute of Geophysics, University of Tehran, Tehran, Iran. E-mail: J_farahani@ut.ac.ir

² International Institute of Earthquake Engineering and Seismology, Tehran, Iran.

³ Council for Geoscience, Pretoria, South Africa

Evaluation of the seismicity of a region depends on records of earthquakes. This article assesses the microseismicity of Tehran region, bounded by the coordinates 34.43°-36.87° N and 49.07°-53.13° E. This was investigated by the Tehran Disaster Mitigation and Management Organization (TDMMO) network from 2004 to 2010. The main purpose of this study was to substantiate the current tectonic activity of the region. We checked whether the observed faults in the region are active or not. Some active trends were found with the strongest activity in the eastern part of the region, especially associated with the North Tehran fault. In addition, records exist of strong historical earthquakes in this zone. These confirm that the area east of Tehran is more active than the west. The magnitude of completeness in the E, NE and SE is $M_c=2$. Major faults criss-crossing Tehran are located in the foot of the Alborz mountain belt. The released seismic energy map of the region demonstrates that the main active zones with high energy values for microearthquakes are in the east of the region.

Introduction

Tehran, the capital city of Iran, had a population of about 13.1 million in 2013 (the population was 8.6 million at night and 4.5 million during the day because people commute to work).

The urban area of this megacity is located near seismically active faults in the north and south. The city is located in the southern foothills of the Alborz mountain belt (Tchalenko et al., 1974). Several active faults have been mapped around Tehran (Fig.1). Historical earthquakes have occurred on the Mosha, Taleghan, Parchin and Garmsar faults but the largest were (most probably) on the Eyvanekey ($M_s \sim 7.6$ during the 4th Cen.BC) and Taleghan ($M_s \sim 7.7$ in the 10th century) faults. The presence of diverse faults in this zone confirms its vulnerability to further destructive earthquakes, therefore it is necessary to study the earthquake record, and particularly microearthquakes, to detect the active faults. The existing maps must be corrected and updated to

define new and concealed faults. This article summarizes the microseismicity of the Tehran region based on the data recorded in a local Network from 2004 to 2010.

Tectonic settings

The Alborz mountain belt formed during Precambrian and Alpine events. It is the result of tectonic movements caused by the northward convergence of Central Iran-Eurasia and NW motion of the southern Caspian basin with respect to Eurasia (Ashtari, 2007). It is an active, NW-SE to EW trending mountain belt, about 100-km wide and 600-km long. Its northern border is the southern coast of the Caspian Sea which is sinking rapidly and is covered by a ~20-km thick layer of sediments. The Alborz mountain belt is bounded by Talesh Mountain in the west and Kopeh Dag Mountain in the east. The total crustal shortening since the early Pliocene is estimated to be 30 km at the longitude of Tehran (Allen et al., 2003). There are several active faults (Fig.1) affecting the Central Alborz (Berberian, 1983; Berberian et al., 1996; Trifonov et al., 1996; Berberian and Yeats, 2001; Allen et al., 2003). GPS measurements show that recent N-S shortening across the Alborz Mountains occurs at 5 ± 2 mm/year and the southern Caspian basin moves NW at 6 ± 2 mm/year. Simultaneously, the left-lateral shear of the overall belt at a rate of 4 ± 2 mm/year is consistent with E-W active strike-slip motion inside the range (Vernant et al., 2004).

The central Alborz and, more particularly the area around Tehran, is a tectonically active region. Earthquakes near Tehran are the main source of seismic hazard that should be taken into consideration in any seismic hazard mitigation plan (Azadi et al., 2010).

Historical and Instrumental Seismicity

Tehran, the capital city of Iran, has about 200 years of history. It is an important city from economical and political points of view. Previous research on its historical and instrumentally detected earthquakes have been carried out by Ambraseys and Melville, 1982; Berberian, 1994; and Berberian and Yeats, 1999, 2001. A "History of Persian Earthquakes (pre-1900)" (Ambraseys and Melville 1982, Fig.2) shows that several historical events have occurred in this region especially around the Mosha, North Tehran, Eyvanekey and Garmsar faults. This area has some of the most important faults including the Mosha, North Tehran, South Ray, Kahrizak, Eyvanekey, Parchin, Pishva and Garmsar faults. It is believed that the Mosha fault (Fig.2)

Figure 1. Active tectonic map of the Tehran region.

has experienced earthquakes greater than 6.5(Ms) in 958 in 1665 and 1830 respectively (Berberian and Yeats, 2001). Historical earthquakes near Tehran in 855, 864 and 1177 were located in the Central Alborz on or near the faults (Figure 2). Some of the largest earthquakes with Ms ~7.6 in the 4th century BC and another large event in 743 (Ms ~7.2) occurred on the Eyvanekey fault

(Ambraseys and Melville, 1982). Ashtari et al (2005) reported that microseismic data gathered along the eastern Mosha fault and some authors proposed that seismic activity is caused by Mosha fault.

North and south crustal shortening has occurred on reverse faults that dipped inwards from the two sides of the mountain belt. The shortening was about 30 km based on a structural cross section at the longitude of Tehran (Allen et al. 2003).

Seismotectonics of the region

Tehran is situated in a southern part of central Alborz mountain, filled with alluvial materials originating from the rising Alborz Range. An abrupt change of about 2750 metres in elevation between the city and the nearest summit of the northern mountain range is a striking topographic feature which is mainly the consequence of vertical movement along the major mountain-bordering reverse fault known as the North Tehran fault (Tchalenko et al., 1974). Extensive longitudinal faulting along the Alborz fold-thrust mountain belt during the Quaternary period was the main tectonic activity in the region. These Quaternary mountain-bordering faults have formed present physiographic features and are the most seismogenic faults in the region (Berberian, 1981). These can be considered as the most likely cause of future earthquakes. Many minor faults are widespread throughout the city and the reactivation of major Quaternary faults may also cause some

Figure 2. Historical seismicity of north-central Iran.

Table 1. Historical (pre-1900) earthquakes of the Tehran region for events having $M \geq 6.5$

Year	Ms	Region	Fault	MMI
300	7.6	Ray-Eyvanekey	Parchin, Ray	X
743	7.2	Caspian Gate	Garmsar	VIII+
855-6	7.1	Ray, Kahrizak	Ray	VIII+
958	7.7	Ray-Taleghan	Mosha, N. Tehran	X
1117	7.2	Ray-Karaj	North-Tehran	VIII+
1665	6.5	Damavand	Mosha	VIII+
1815	?	Damavand	Mosha	V+
1830	7.1	Damavand	Mosha	VIII+

movements along the minor faults. Investigation of these minor faults is part of the microseismic study of the city.

Table 1 summarizes the historical seismicity of Tehran region. In addition to historical earthquakes, a short review of instrumental teleseismic data of 20th century earthquakes in the Tehran region indicates recent activity of a few faults as shown in Table 2. The epicentres of some of the most important historical earthquakes are shown in Figure 2.

Dataset and the Tehran Seismological Network

We analyzed microearthquakes occurred around Tehran using the

Table 2. Some instrumental teleseismic data of Tehran region

Year	M (Ms)	F.D. (km)	Reference
1930	5.2	?	IIS
1930	?	?	NMS
1945	4.7	?	IIS
1945	?	?	NMS
1951	5	?	ISS
1967	?	16	USGS
1969	3.0	29	
1974	4.3	?	
1977	?	16	
1982	5.4	?	
1983	5.4	?	

permanent local seismological network of the Tehran Disaster Mitigation and Management Organization (TDMMO). Records included all events detected in Tehran from 2004 to 2010. The network consisted of 13 seismic stations equipped with CK-1Ī seismometers (Russia) with a natural frequency of 1 Hz. Each station is comprised of a short period, three-component seismometer. Figure 3 shows the arrangement of the Tehran network. Events were located using the model developed by Ashtari et al (2005). Mottaghi et al (2010) has studied the velocity models for Tehran region and recommended the velocity model developed by Ashtari et al (2005).

Figure 3. Location of seismic stations in the Tehran network (TDMMO).

Major faults

The major faults in this region are the Eyvanekey, Kahrizak, Mosha and North Tehran faults (Figure 1). According to historical records of major earthquakes, the Mosha, Eyvanekey and North Tehran Faults are potentially active. In addition, based on recent data for the city of Tehran, two important earthquakes occurred in the south of Tehran (17 October 2009, Mw=4.0, and 20 February 2011, Mw=4.1), near the Eyvanekey Fault. This might be taken as a warning of possible future activity in this area.

Eyvanekey Fault

This fault zone of about 75-80 km length (Zaré 2004) with a compressive mechanism and slip towards the north has mainly a N-NE trend and includes the Parchin and Eyvanekey faults (Berberian et.al. 1985). Overthrusting of older layers on recent alluvial deposits as well as the presence of a crushed zone on the fault indicates a compressive mechanism (Figure1).

Kahrizak Fault

The Kahrizak fault outcrops in the south of Tehran. It is curved with a length of about 40 km. It has the longest continuous fault outcropping in the southern part of Tehran. The eastern outcrop of this fault starts to the west of Karimabad and extends to the east of Mahmoodabad. The general slip of the fault is NNE (Geological Survey of Iran 2003). Azadi et al (2010) used three methods to identify the geometry of this fault at depth. Their results showed that Kahrizak fault (Figure 1) is a high angle normal fault dipping to the south.

Mosha Fault

One of the most important faults in the Central Alborz is the Mosha fault. It is a left-lateral strike-slip fault about 180-km long (Figure 1). It is located close to Tehran city and is an important potential seismic source. Nazari et al 2007 studied the fault within the Tar Lake valley along its eastern part and noted that a historical earthquake had occurred in 1665 (VII, 6.5) allowing them to calculate a preliminary 2.2 ± 0.5 mm/yr minimum left lateral slip rate (Ritz et al., 2004). It is believed that Mosha fault (Figure 2) has experienced events with a magnitude greater than 6.5 (Berberian and Yeats, 2001).

North Tehran fault

The North Tehran Fault is located in the south of the Central Alborz (Figures 4 and 5). It is an important and major active fault in Tehran city and has been the source of several major historical earthquakes. It extends some 110 km and is mainly a reverse fault crossing the northern suburbs of Tehran metropolis (Nazari and et al, 2007). There has been 2.35 m of total reverse displacement along the fault during the last ~ 8000 yrs (0.77 m for the latest event and 1.58 m for the previous event). The average slip rate along the North of Tehran fault is 0.3 ± 0.05 mm/yr (Nazari, 2006; Nazari et al., 2007).

Seismicity of the region

Microearthquake studies are an important part of seismological researches. Results from such studies are usually integrated with other

Figure 4. The North Tehran fault trace in the northern Tehran foothills.

Figure 5. Aerial photo of the North Tehran Fault in the NW of Tehran. Photo taken in 1955.

information and theoretical investigations in order to understand seismogenesis. Microearthquakes have long been studied in Tehran zone (Hedayati et al. 1976; Mohajer-Ashjari and Nowroozi 1981; Kabiri et al. 1982). Anyway, these studies were conducted using few seismographic instruments. Other researches have been conducted on earthquakes recorded in the Iranian Long Period Array (ILPA) at Institute of Geophysics, University of Tehran (IGUT) (Vasheghani-Farahani and Zaré, 2011).

Mohajerashjaei and Nowroozi (1981) suggested that there are six active seismic zones:

- North Alborz trend
- Mosha-Fasham trend
- Kandovan trend
- Eastern Tehran trend
- Varamin-Garmsar trend
- Ipak trend

In order to assess the seismicity of east and northeast of Tehran more precisely, the Earthquake Centre of the Iranian Atomic Energy Organization installed several instruments in these zones for two

Figure 6. Microseismicity map of Tehran, with $M < 4.6$ recorded by the TDMMO Network.

months (Kabiri et al. 1982). The depths of the earthquakes were usually about 9 to 14 km with magnitudes of 1.5–3.0. Two earthquake epicentres were observed in the SE of Tehran zone and subordinate branches of the Mosha fault.

There are several active mines in the south and southeast of Tehran that produce small explosions, especially around Bibi Shahrbanoo Mountains. Quarry blasts in this area are recorded by the permanent local seismological network of the Tehran Disaster Mitigation and Management Organization (TDMMO). We try to remove the effects of microearthquakes explosions from mine and quarry blasts to improve the accuracy of the earthquake catalogue of the Tehran region.

Data on seismic events, earthquakes and blasts in the Tehran region has been classified using a neuro fuzzy ANFIS system that has successfully been trained to recognize seismic events based on seismic parameters (Vasheghani-Farahani et al., 2012).

The present study is based on the surveyed records of microearthquakes in the last decade in Tehran. The distribution of those microearthquakes, as recorded by TDMMO network from 2004 to 2010 is plotted in Figure 6. We have analyzed these records and reviewed the seismicity in the region within latitude of 34.43° and 36.87° N and longitude of 49.07° and 53.13° E. The aim of this study is to characterize the highly active zones/faults for better understanding of the tectonics as well as for planning of future studies in this area.

We established the distribution and rates of occurrence of microearthquakes in the region during the study period. The results show that earthquakes of $M_L = 2$ were more frequent than others (Figure 7). Figures 8a and 8b show time-magnitude diagrams for local earthquakes in the region during 2004-2010 for all of the events and also for those with magnitudes bigger than 3, and 8c shows the

distribution histogram (number of events versus time) for 2004-2010 seismic events recorded by TDMMO. These figures indicate that the microearthquakes that have occurred in this region are mostly of lower magnitude than $M=3$. The correlation of seismicity with surface faults, however, needs a careful examination (Figure 6). Nearly 83 earthquakes of magnitude 3 and more occurred in the region during

Figure 7. The distribution histogram for 2004-2010 - earthquake magnitudes in the Tehran area recorded by the TDMMO network.

Figure 8. Time-magnitude diagram for local earthquakes in the region during 2004-2010- (a) for total data and (b) for $M \geq 3$ (c) the distribution histogram for 2004-2010, seismic events recorded by TDDMO.

the 7-year period covered by this study. Approximately one-sixth of the epicentres with magnitude greater than 3 were located in the study area.

Based on the recorded events during our observation period the epicenters of the earthquakes having magnitude greater than 3 occurred more in the eastern part of the region (comparing to the western part).

In addition, in Figure 9 we can see two important recent earthquakes which occurred in Tehran (2009 and 2011). Their magnitudes were 4 in 17/10/2009 (Vasgheghani-Farahani and Zaré,

2011) and 4.1 in 20/02/2011. We investigated this area and noticed that there is a seismic gap between the epicentral regions of these two earthquakes (Figure 9). We consider that a future major earthquake with magnitude of 7.0 or 7.5 is possible as the worst case scenario in this part of the region.

On 7 April 1937 an earthquake occurred in Daryaye Namak with $M=5.25$. The maximum intensity of the earthquake was estimated around VIII according to EMS98 scale. This earthquake occurred near the northern edge of the Daryaye Namak desert, south of Tehran;

Figure 9. Microseismicity map of Tehran recorded by TDDMO Network. A seismic gap is shown in the sub-figure, between the epicentres of the 2009 and 2011 earthquakes in SE Tehran.

Figure 10. An earthquake of $M=5.25$ in Darayaye Namak and a historical earthquake in 1850.

an almost uninhabited area. However, the shock destroyed water harvesting and supply systems including the qanats of Qale ye No and Hisar Quli, causing the collapse of Abanbars (traditional water reserves built-in houses and districts) and of a few houses. Figure 10 shows the epicenter of this important earthquake (Ettelaat newspaper archive, 1937, and personal communication with A. A. Ambraseys, 2011).

In the south of Tehran, an earthquake occurred in 1850 that was not included in the historical catalogue of Ambraseys and Melville, 1982 and Berberian, 1994. Lady [Mary] Shiel (the wife of the British Ambassador in Tehran in early 1850's) mentioned this earthquake:

"I was resting in my room in which suddenly I felt an earthquake, it was similar to moving of a ship. I was terrified and I got out of the room" (Shiel 1973). Based on her description, the maximum intensity of this earthquake was estimated as VI on the EMS98 scale.

Due to lack of TDMMO data after 2010, we tried to get data from another agency. Figure 11 shows data from Iranian Seismological Center (IRSC) from 2006 to 2013. Green circles show TDMMO data for all magnitudes in the region and brown circles show IRSC data for $M \geq 2$. We observe some trends of activity in this map. A cluster of microearthquakes is found at the intersection of some faults. The strongest activities occurred in the eastern part of the range in Tehran. The intersection of the Mosha and North Tehran faults, especially at Kalan village, shows

clusters of recent microearthquakes. Also, there were no strong earthquakes in the south east of Tehran that might be precursors to a possible major earthquake (based on the capacity of large faults such as Eyvanekey and Parchin faults and evidences of historical and instrumental earthquakes in the Tehran region).

Figure 11. Distribution of the microearthquakes from TDMMO data (2004-2010) and IRSC data for $M \geq 2$ (2006-2013) - green and brown circles respectively. Quarry blasts from TDMMO data, red triangles, and for IRSC data, blue hexagons.

Released seismic energy

Strain energy accumulates by tectonic stresses and is eventually released by an earthquake. A small part of the released energy converts to elastic energy which is then transmitted to different parts of the earth as seismic waves.

The famous formula of Gutenberg and Richter (1956), used for calculating the energy released, has been used in the research:

A numerical equivalent for M from 1 to 8.6, is

$$\log E = 9.1 + 1.75M + \log(9 - M) \quad (1)$$

where M is the magnitude and E is seismic energy in ergs.

There are various methods of showing regional seismic characteristics such as seismicity and seismotectonic. Another useful depiction may be the seismic energy map. The seismic energy map can allow estimations of some parameters such as intensity and maximum magnitude, and may also be a complementary help for seismotectonic interpretations (Ashtari, 2006). In the present study, the catalogue of Tehran region earthquakes during 2004-2010 was analyzed to calculate the energy released in the area and compare values with the seismicity in the area.

Figure 12 shows an energy contour map of the total seismic energy released in the region during the period from 2004 to 2010. The map reveals the seismic zones with high-energy released values where the main activity is concentrated and the numbers in this Figure represent seismic energy. Distribution of the released energy shows the distinct role of the faults in the seismic activity. Most of the activity is concentrated around the main faults especially those in the east of the region with lesser levels in the west.

We have analyzed the catalogue of earthquakes in detail and have identified two dense concentrations of energy release in the area. There are several important faults, particularly inside the area covered by the Tehran network among which are the North Tehran fault and South Ray fault which have an E-W trend. We have focused on securing accurate results for events recorded inside the TDMMO network especially on the North Tehran fault and South Ray fault but partially on the Parchin fault.

Detection threshold of the TDMMO Network

In seismology, the Gutenberg–Richter law expresses the relationship between the magnitude and total number of earthquakes in any given region and the time period of at least that magnitude as:

$$\log N = a - bM \quad \text{or} \quad N = 10^{a-bM} \quad (2)$$

where N is the number of the events in a given magnitude range, M is the minimum magnitude and a and b are constant. The relationship was first proposed by Charles Francis Richter and Beno Gutenberg. The a value is of limited scientific interest because it only indicates the total seismicity rate of the region (Gutenberg and Richter 1954).

This study presents new insights for a better understanding of the seismic activity and assessment of seismic hazard in the Tehran region through from local data and the determined values of the b -value in the Gutenberg–Richter relation.

We know that there is no evidence for significant b value variation with location or major faults (Felzer and Kilb, 2009). In addition, earthquake location catalogues are not an exact representation of true

Figure 12. Energy contour map of the Tehran region during the period from 2004- 2010 (1 erg = 10^{-7} Joule, 1 Joule=1 Newton Metre).

earthquake locations. They contain random errors in, for instance, errors in arrival time picks as well as systematic biases. The most important source of systematic errors in earthquake locations is the inherent dependence of earthquake locations on the assumed seismic velocity structure of the Earth (Husen and Hardebeck, 2010).

Fluctuations in b value have been studied theoretically, in laboratories and in practical investigations in seismotectonics zones such as volcanic areas, continental rifts and mines which present different stress regimes. b value can explain the relative density of large and small events and can be applied in seismic hazard studies, spatio-temporal prediction and earthquake physics (Ashtari, 2009).

When a consistent magnitude scale is applied within a given region, differences in b value can reliably be defined. This allows us to focus on local changes in the b value as a function of space and time and to relate the observed patterns to changing stress conditions or fracture characteristics within the crust (Mignan and Woessner, 2010).

The threshold of completeness is a bulk indicator of the sensitivity of event detection by a seismic network. To find the threshold of completeness (M_c) in this study, events were extracted from Tehran Disaster Mitigation and Management Organization Network (TDDMO) database for 2004-2010.

Assessing the magnitude of completeness for earthquake catalogues is an essential step for any seismicity analysis. The magnitude of completeness (M_c) is defined as the lowest magnitude at which 100% of the events in a space-time volume are detected (Rydelek and Sacks 1989; Woessner and Wiemer 2005). If a seismicity

Figure 13. Cumulative events for 2004-2010 database larger than a given magnitude ($\square$) and maximum best fit ($\blacktriangle$ = number of events for a given magnitude).

dataset strictly follows the Gutenberg-Richter law, M_c can also be defined as the magnitude at which the cumulative Frequency-Magnitude Distribution (FMD) departs from a linear trend (Zuniga and Wyss 1995).

Our catalogue is complete for the time span of the study in the interior of the study area. Based on TDDMO data in a local Network from 2004 to 2010, we obtained $M_{max} = 4.6$ and $M_c = 2.0$.

Figure 14. (a) b -value maps; (b) a -value maps for 2004-2010 from the maximum likelihood method. Dots represent earthquakes. White areas have insufficient data; (c) M_c maps, threshold of completeness of magnitude across the study area; (d) superposition of the b -value map on the fault map of the Tehran region; and (e) M_c variations.

The cumulative number of events larger than a given magnitude has been calculated. The slope has been obtained by using the maximum likelihood method. The results are shown in Figure 13. The cumulative curve deviated significantly from the best-fit line at about ML 2.0, indicating a magnitude threshold. The slope and intercept of the best-fit line are respectively a and b coefficients of the Gutenberg-Richter law (Gutenberg and Richter, 1954). In this study, these were 3.98 and 0.738 respectively. Studying the a and b parameters can be of great help in an area like Tehran which has a large population and diverse social-economical activities and conditions. The value changes were mapped in space using the maximum likelihood method (Figures 14a and 14b) using the earthquake catalogue that is reasonably homogeneous in space, time and magnitude band. All inadequate parts of the catalogue and explosions were removed. In order to find the distribution of the b value map throughout the study area, we divided the region into a grid of 0.1° resolution and calculated the b value of each grid cell.

Some researchers believe that b -value is constant (Frohlich and Davis 1993; Kagan, 1999). A large number of other researchers believe that it varies in time and space (Amelung and King, 1997; Mori and Abercrombie, 1997; Wiemer and Wyss, 1997; Wiemer and Katsumata, 1999; Mignan and Woessner, 2010).

In our study, the b -value was found not to be constant. The value obtained was dominantly 0.738 ± 0.03 . The b -value maps show that b -value is greater in eastern parts than western parts. To the south and north of Tehran, it changes almost in the same way, increasing toward the east.

The method that we used in this study was the Maximum Likelihood (ML) estimation (Aki, 1965).

In order to find the distribution of the M_c values throughout the study area, we divided the region into a grid of 0.1° resolutions and calculated the M_c value of each grid cell with the same method as above.

The results are shown in the M_c map (Figure 14c). For the period of 2004 to 2010, the threshold of completeness between 2 and 2.1 has the largest changes in the region and decreases between 1.9 and 2.0 towards southwest. There are few data for this part of the region. Most of the region has a -value lower than 3.7 indicating a lower rate of seismicity. According to a -value, the east, NE and SE parts of the region have the highest rates of seismicity.

The b -interpretation was carried out for the active zones, as defined by Mohajerashjaei and Nowroozi (1981). North of Mosha-Fasham (Mosha fault), Garmsar and in the east, we observe the higher b -values (Figure 14d). We refer to all ML magnitudes. In our catalogue, we used events with ML smaller than 4.6. The value of the magnitude of completeness (M_c) obtained was 2.0.

M_c calculated by ZMAP (Wiemer, 2001) shows the variations in magnitude (Figure 14e) detected by the TDMMO Network. Therefore, the maximum value of M_c in this Network ($M_c=2.0$) was selected as the completeness level of the dataset.

The Completeness of the Recorded data in Time

To evaluate the quality of the network operation as a whole, we calculated the cumulative number of events which occurred per year (Figure 15). Any significant slowdown in the rate of event detection can be indicative of incompleteness of the recorded data or downtime at the stations. Figure 15 shows that the rate of recording of events remained almost constant before the large local earthquake of

Figure 15. Cumulative frequency of events versus time for 2004-2010 (star denotes events larger than ML 4.2) after declustering.

26 March 2008 (ML=4.6) after declustering. After this earthquake, the rate of event recording was again constant. In addition, there was a small increase in the rate of event recording after 14 August 2009 earthquake (ML = 4.3).

Conclusion

In this paper, we have studied the microearthquakes recorded by TDMMO network in Tehran. The distribution of epicentres and the released energy for the whole network indicate a high potential for seismic activity in the region. The highest level of microseismicity in this area is in the east and the seismicity is confined to some clusters of microearthquakes in the region. The cluster of microearthquakes corresponds with the interconnecting faults of the area. The intersection of the Mosha and North Tehran fault systems (NE of Tehran) shows a major cluster of recent microseismicity (Figure 9). Continuous monitoring of the microseismicity by a permanent microearthquake network may prove a valuable prediction tool for an impending large earthquake in this area.

The Quaternary mountain-bordering faults formed the present physiographic features among the most seismogenic faults in the region (Berberian, 1981) and can be considered as the most likely cause for future earthquakes. Microseismicity of Tehran region shows a similar pattern to seismic activity in this region.

Based on historical seismicity of the region (330BC, 855AD, 1384 A.D) it is possible to assign $M=7-7.5$ to the Ray region. Ambraseys and Melville (1982) proposed $M>7.0$ for the major earthquakes of the region. The fault lengths (Eyvanekey, Kahrizak, Pishva) might be indicative of a possible $M=7.0$ earthquake in the future. The empirical relationship ($M_w = \ln L + 3.66$) has been used to assess the $M_{\max}$ based on the rupture length. Therefore, the $M=7.0$ to 7.5 might be assigned to fault lengths of 80 to 150km in the east-southeast of Tehran. The seismic gap in SE of Tehran is a warning of the probability of occurrence of a major earthquake of 7.0 to 7.5

magnitudes (based on the assessed capability of the major faults such as Parchin and Eyvanekey faults and historical earthquakes) in Tehran city.

The Central Alborz and the area around Tehran is an active tectonic zone. The important seismicity detected using the Tehran Disaster Mitigation and Management Organization (TDMMO) Network from 2004 to 2010 has confirmed some activity in the central Alborz mountain belt. The combined historical records for earthquakes and instrumental seismicity of the region recorded recently shows that the east of Tehran is more active than the west and that the NW and SW, in particular, do not seem to be as seismically active as the areas to the NE and SE of Tehran.

We have calculated b-values for this region using TDMMO data. The highest recorded magnitude was 4.6 and, based on the historical seismicity and the capability of the faults in this region, we may expect that the realistic b-values and $M_{\max}$ should be different and also from recent instrumental earthquakes recorded by TDMMO network. The Network covers the major faults in Tehran well. This study has described the size-frequency distributions of microearthquakes in the suburban areas of Tehran. The dataset represents one of the longest duration and most extensive microseismic catalogues in Tehran city with a permanent local Network.

Based on the historical and microseismic data analysed in this study, we suggest that in future studies, the southeastern region of Tehran should be examined to confirm whether there is a seismic gap or a seismic quiescence.

Acknowledgement

The authors acknowledge their appreciation of the collaboration of the Tehran Disaster Mitigation and Management Organization in providing the seismicity records of the Tehran region which have been used in this study.

References

- Aki, K., 1965, Maximum likelihood estimate of b in the formula $\log N = a - bM$ and its confidence limits: *Bulletin of the Earthquake Research Institute.*, v. 43, pp. 237-239.
- Amelung, F., and King, G., 1997, Earthquake scaling laws for creeping and non-creeping faults, *Geophysical Research Letters.*, v. 24, pp. 507-510.
- Azadi, A., K. Hessami, and Javan-Doloei, G., 2010, Integrated geophysical methods for determining geometry of the Kahrizak Fault, Tehran, Iran. *Natural Hazards*, v. 54(3), pp. 813-825.
- Ambraseys, N. N. and Melville, C. P., 1982, *A History of Persian Earthquakes*, Cambridge Earth Science Series. Cambridge University Press, London.
- Allen, M. B., Ghassemi, M. R., Sharabi, M., and Qoraishi, M., 2003, Accommodation of late Cenozoic oblique shortening in the Alborz range, northern Iran. *Journal of Structural Geology*, v. 25, pp. 659-672.
- Ashtari, M., D. Hatzfeld, and Kamalian, N., 2005, Microseismicity in the region of Tehran. *Tectonophysics*, v. 395, pp. 193-208.
- Ashtari, M., 2007, Time independent seismic hazard analysis in Alborz and surrounding area. *Nat Hazards*, v. 42, pp. 237-252.
- Ashtari, M., 2009, Short period fluctuations of seismicity around Tehran inferred from "a" and "b" values. *Journal of Earth and Space Physics*, v. 35 (1), pp. 45-57 (in Farsi).
- Ashtari, M., 2006, Seismic energy distribution map of Iran. *Geophysical Research Abstracts*, v. 8, 09714. SRef-ID: 1607-7962/gra/EGU06-A-09714, European Geosciences Union 2006.
- Berberian, M., 1981, Active faulting and tectonics of Iran. In: H.K. Gupta and F. M. Delany (Eds.), *Zagros-Hindukush-Himalaya geodynamic evaluation*, American Geophysical Union, Geodynamic Series, v. 3, pp. 33-69.
- Berberian, M., 1983, The southern Caspian: a compressional depression floored by a trapped, modified oceanic crust. *Canadian Journal of Earth Sciences*. v. 20, pp. 163- 183.
- Berberian, M., 1994, *Natural Hazards and the First Earthquake Catalogue of Iran*, v.1, Historical Hazards in Iran Prior to 1900. IIEES, Tehran.
- Berberian, M., Ghoraishi, M., Shoja-Taheri, J., and Talebian, M., 1996, Seismotectonic and earthquake-fault hazard investigations in the Semna region. *Geological Survey of Iran*, Publication no. 63.
- Berberian, M., and Yeats, R.S., 1999, Patterns of historical earthquake rupture in the Iranian plateau. *Bulletin of the Seismological Society of America*. v. 89, pp.120- 139.
- Berberian, M., M. and Yeats, R. S., 2001, Contribution of archaeological data to studies of earthquake history in the Iranian plateau, *Journal of Structural Geology*, v. 23, pp. 563-584.
- Frohlich, C., and Davis, S. D., 1993, Teleseismic b values: Or, much Ado about 1.0, *Journal of Geophysical Research*, v. 98, pp. 631-644.
- Felzer, K., and Kilb, D., 2009, A Case Study of Two $M \sim 5$ Mainshocks in Anza, California: Is the footprint of an aftershock sequence larger than we think, *Bulletin of the Seismological Society of America.*, v. 99, pp. 2721-2735.
- Geological Survey of Iran, 2003, *Final Report of Alborz Basic Seismic Faults*. Geological Survey of Iran, Rep. No. 328.
- Gutenberg, B., and Richter, C. F., 1954, *Seismicity of the Earth* (Princeton Univ. Press). 1st ed., 273 pages; 2d ed. 310 p.
- Gutenberg, B., and Richter, C. F., 1956, *Earthquake Magnitude, Intensity, Energy, And Acceleration* (Second Paper). *Bulletin of the Seismological Society of America*, v. 46 (2), pp. 105 - 145.
- Hedayati, A., J. L. Brander, and Berberian, M., 1976, Microearthquake survey Tehran region, Iran. *Bulletin of the Seismological Society of America*, v. 66 (5), pp. 1713-25.
- Husen, S., and Hardebeck J. L., 2010, Earthquake location accuracy, Community Online Resource for Statistical Seismicity Analysis, doi: 10.5078/corssa-55815573.
- Kabiri, A., A. Mohajer-Ashjai, E. A. Zohurian-Izadpanah, and Ghamsari, M. H., 1982, Gathering and Mechanism for local earthquakes in Tehran area. June-August 1980. *Journal of the Earth and Space Physics*, v. 13-14, No. 1-2.
- Kagan, K., 1999, The universality of the frequency moment relationship, *Pure and Applied Geophysics*, v. 155, pp. 537-547.
- Mignan, A., and Woessner, J., 2010, Completeness magnitude in earthquake catalogs, Community Online Resource for Statistical Seismicity Analysis, doi: 10.5078/corssa-00180805.
- Mori, J., and Abercrombie, R., 1997, Depth dependence of earthquake frequency magnitude distributions in California: Implications for the rupture initiation, *Journal of Geophysical Research.*, v. 102, pp. 15081-15090.
- Mohajer-Ashjai, A., and Nowroozi, E. A., 1981, Seismicity and active tectonic trends in Tehran area. *Iranian Petroleum Institute Bulletin*, v. 77, pp. 1-14.
- Mottaghi, A. A., Rezapour, M., and Yaminifard, F., 2010, Double-Difference Relocation of Earthquake Hypocenters along the Southern Flank of the Central Alborz, Iran. *Bulletin of the Seismological Society of America*, v. 100 (5A). pp. 2014-2023.
- Nazari, H., 2006, *Analyse de la tectonique recente et active dans l'Alborz Central et la region de Teheran: Approche morphotectonique et paleoseismologique*, PhD thesis, Montpellier II, Montpellier.
- Nazari, H, Ritz, J.F., Salamati, R., Solaymani, S., Balescu, S., Michélot, J.L., Ghassemi, A., Talebian, M., Lamothe, M. and Massault, M., 2007, Paleoseismological analysis in Central Alborz, Iran. the Anniversary earthquake conference commemorating the 1957 Gobi-Altay earthquake (July - August 2007- Ulaanbaatar-Mongolia). 1-6.
- Rydelek, P. A and Sacks I. S., 1989, Testing the completeness of earthquake catalogs and the hypothesis of self-similarity, *Nature*, v. 337, pp. 251-253.

- Sheil, M., 1973. Glimpses of life and manners in Persia. London: John Murray, Albemarle Street, 1856. Arno Press.
- Tchalenko, J.S., Braud, B., J. and Berberian, M., 1974a, Discovery of three earthquake faults in Iran. *Nature*, v. 248, pp. 661-663.
- Trifonov, V.G., Hessami, K.T., and Jamali, F., 1996, West-Trending Oblique Sinitral-Reverse Fault system in Northern Iran. IIEES Special Publication, v. 75. Tehran, Iran.
- Vasheghani-Farahani J, and Zaré, M., 2011, The southeastern Tehran earthquake of 17 October 2009 ($M_w = 4.0$). *Seismological Research Letters*, v. 82 (3), pp. 404-412.
- Vasheghani-Farahani, J. M. Zaré, and Lucas, C., 2012, Adaptive neuro-fuzzy inference systems for semi-automatic discrimination between seismic events: A study in Tehran region, *Journal of Seismology*, v.16 (2), pp. 291-303.
- Vernant, Ph., Nilforoushan, F., Chery, J., Bayer, R., Djamour, Y., Masson, F., Nankali, H., Ritz, J. F., Sedighi, M., and Tavakoli, F., 2004, Deciphering oblique shortening of Central Alborz in Iran using geodetic data, *Earth and Planetary Science Letters*, v. 233, pp. 177-185.
- Woessner, J., and Wiemer, S., 2005, Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty, *Bulletin of the Seismological Society of America*, v. 95 (2), pp. 684-698.
- Wiemer, S., and Wyss, M., 1997, Mapping the frequency magnitude distribution in asperities: An improved technique to calculate recurrence times? *Journal of Geophysical Research*, v. 102, pp. 15115-15128.
- Wiemer, S., and Katsumata, K., 1999, Spatial variability of seismicity parameters in aftershock zones, *Journal of Geophysical Research*, v. 104, pp. 13135-13151.
- Wiemer, S., 2001, A software package to analyze seismicity: ZMAP. *Seismological Research Letters*, v. 72, pp. 373-382.
- Warpinski, N., 2009, Microseismic Monitoring: Inside and Out, *Journal of Petroleum Technology*, v. 61 (11), pp. 80-85.
- Yaminifard, F., Siahkali-Moradi, A., Hosseini and M., Norouzi, R., 2009, Seismicity study of grade Tehran and suburban region using recorded data in seismicity Network of Tehran. *Earth science (Olum Zamin) Journal*, in Persian, No. 73, pp. 133-138.
- Zuniga, F. R., and Wyss, M., 1995, Inadvertent changes in magnitude reported in earthquake catalogs: Their evaluation through b-value estimates, *Bulletin of the Seismological Society of America*, v. 85, pp. 1858-1866.
- Zaré, M., 2004, Seismic hazard analysis for Tehran metropolitan Area, Research Report, International Institute of Earthquake Engineering and Seismology, Tehran, Iran (in Persian).
- Zaré, M., 2005, An Introduction to Applied Seismology. Tehran: International Institute of Earthquake Engineering and Seismology (in Persian).

Jamileh Vasheghani Farahani is PhD of geophysics/engineering seismology in Institute of Geophysics, University of Tehran. Her research is focused on strong ground motion and engineering/explosion seismology. Her interest is discrimination between seismic events using nonlinear pattern recognition techniques and spectral methods. Moreover, she is interested in the ray path by estimating the geometrical coefficient and the frequency-dependent quality factor and non-parametric approach to a ground motion prediction problem for Blast and Earthquake data. She is working on modern observational seismology.

Mehdi Zare is Associate Professor of engineering seismology in the Seismology Research Center of (international Institute of Earthquake Engineering and Seismology; IIEES, Tehran, Iran. He is now the head of Engineering Seismology Department, and the member of the editorial board of *Journal of Soil Dynamics and Earthquake Engineering and Seismology* and *Earthquake Engineering*. His main fields of interest are Strong Motion and Engineering Seismology, Seismic Hazard Analysis and Earthquake Prediction.

Artur Cichowicz is a seismologist with 30 year experience in South African mining seismology, specialising in the area of seismic source mechanism, source spectral parameters, complexity of the seismic source, attenuation of seismic waves, relative location, determination of the P and S wave first arrival and automatic processing.