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PERSIA, A NOVEL TIME-DEPENDENT SEISMIC HAZARD MODEL FOR IRAN, PRELIMINARY RESULTS FOR THE GREATER TEHRAN AND SURROUNDING AREAS

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ABSTRACT

Iran is one of the most seismically active continental regions in the world and an accurate assessment of earthquake hazard has a significant effect on decreasing earthquake losses and making plans for urban development. In this regard, using novel and alternative approaches in hazard assessment will greatly improve our knowledge and many questions about spatial-temporal distribution of earthquakes could be answered. Probabilities of Earthquake Ruptures in Iran (PERSIA), is a framework to evaluate mid and long-term time-dependent seismic hazard through a comprehensive study of the likelihood of large Iranian earthquakes. This study presents preliminary results of time-dependent approach for seismic hazard in Tehran and surrounding areas. Using available historical and paleoseismological data or empirical relation, the recurrence time and maximum magnitude of characteristic earthquakes for the major faults have been explored. Using the Brownian passage time (BPT) distribution, equivalent fictitious seismicity rate for major faults was calculated. Finally, Tehran time-dependent seismic hazard maps have been presented for the first time, through a logic-tree of seven ground motion prediction equations, which include ground motion epistemic uncertainty.

Time-dependent models; Brownian passage time distribution; Background Smoothed seismicity; Earthquake return period; Slip rate

1. INTRODUCTION

Tehran province is a very important large urban area, with high population density, incompatible design and construction, and inappropriate planning which has leading cause for its vulnerability to natural disasters, especially earthquakes. Tehran is the largest city in Iran and a large population (near fifteen million people) are living in the capital and surrounding urban areas. Tehran area had large historical earthquakes caused severe damage to ancient Rey city, which is a part of Tehran megacity at present (see, e.g., Berberian and Yeats, 1999). This activity demonstrates the presence of numerous and large active faults. Tehran metropolitan area is home to the one of the most vulnerable urban populations on Earth. Therefore, it is of paramount importance to conduct detailed hazard and risk assessment studies in this region. The traditional time-independent probabilistic seismic hazard analysis only presents average hazard through a time period. However, the actual hazard of a region should be time-dependent. Poisson time-independent models, widely used in engineering seismic hazard analysis, are adequate for small earthquakes, but owing to their memoryless property, they may not be appropriate for large earthquakes occurring on the specific faults. Non-Poissonian models, renewal time-dependent models, are more appropriate for characteristic earthquakes.

Probabilities of Earthquake Ruptures in Iran (PERSIA, https://www.researchgate.net/project/Probabilities-of-Earthquake-Ruptures-in-Iran-PERSIA), is a framework to evaluate mid and long-term time-dependent seismic hazard through a comprehensive study of the likelihood of large Iranian earthquakes. The project is funded by the International Institute

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of Earthquake Engineering and Seismology and is on-going. There are more than 10 collaborators from IIEES and School of Civil Engineering of Tehran and Shiraz Universities. Different aspects of engineering seismology and earthquake engineering; such as compilation and processing of a modern Iranian strong-motion database; development of new GMPEs for different Intensity Measures (IMs), evaluation of different GMPEs against local data; development of regional spatial correlation models for seismic hazard analysis of distributed systems; evaluation of geodetic and geological fault slip-rates ; fault interaction effects and clustering characteristics of earthquakes and investigation of time-dependent behavior of fault ruptures in Iran are included in the project. Some results published in peer-reviewed journals. Here, preliminary results of seismic hazard values in terms of Peak Ground Accelerations (PGAs) are presented for the Greater Tehran region.

2. SEISMICITY AND ACTIVE FAULTS OF THE REGION

The delineation of seismic source plays an important role in the evaluation of seismic hazard. Seismic source characterization is dealt with three fundamental elements: (1) the identification, location, and geometry of significant sources of earthquakes; (2) the maximum size of the earthquakes associated with these sources; and (3) the rate at which they occur. Therefore, it is of special importance to identify the seismogenic sources of the region. Existence of several active faults, e.g., the North Tehran, Mosha, Taleghan, Ipak, Firuzkuh, Evanekey, Garmsar faults, is the main causes of seismicity of this region. Seismicity parameters are calculated on the basis of historical and instrumental earthquakes for a time period, from fourth century BC to the present time.

Historical earthquakes used in this study consist of the pre-1900 earthquakes gathered from different published sources available in the literature (Ambraseys 1978; Berberian et al. 1993; Berberian and Yeats 2001; Ambraseys and Melville 1982). According to historic sources, the oldest earthquake in Tehran region happened in 312–280 BC by the rupture of North Tehran fault (Ritz et al. 2012). During the 743 to 1177 AD, five main earthquakes have affected Tehran region. The source of earthquake in 743 was somewhere at the east of the ancient city of Rey (in south of Tehran), maybe the Garmsar fault (Berberian and Yeats 2001). The earthquake of 958 ruptured the Taleqan fault (Nazari et al. 2007). In 1119, the North Qazvin fault ruptured and shook the city of Qazvin at the west of today’s Tehran (Berberian and Yeats 1999). Ritz et al. (2012) believes that the NTF caused the 1177 earthquake of Rey. After 1177 AD until present, this area has experienced two main earthquakes in 1665 and 1830 because of the rupture of east and central segments of the Mosha fault, respectively (Berberian and Yeats 1999). However, during the twentieth century, the region of Tehran has not experienced any strong seismic activity. Figure 1 illustrates the major historical earthquakes in the study area with active faults.

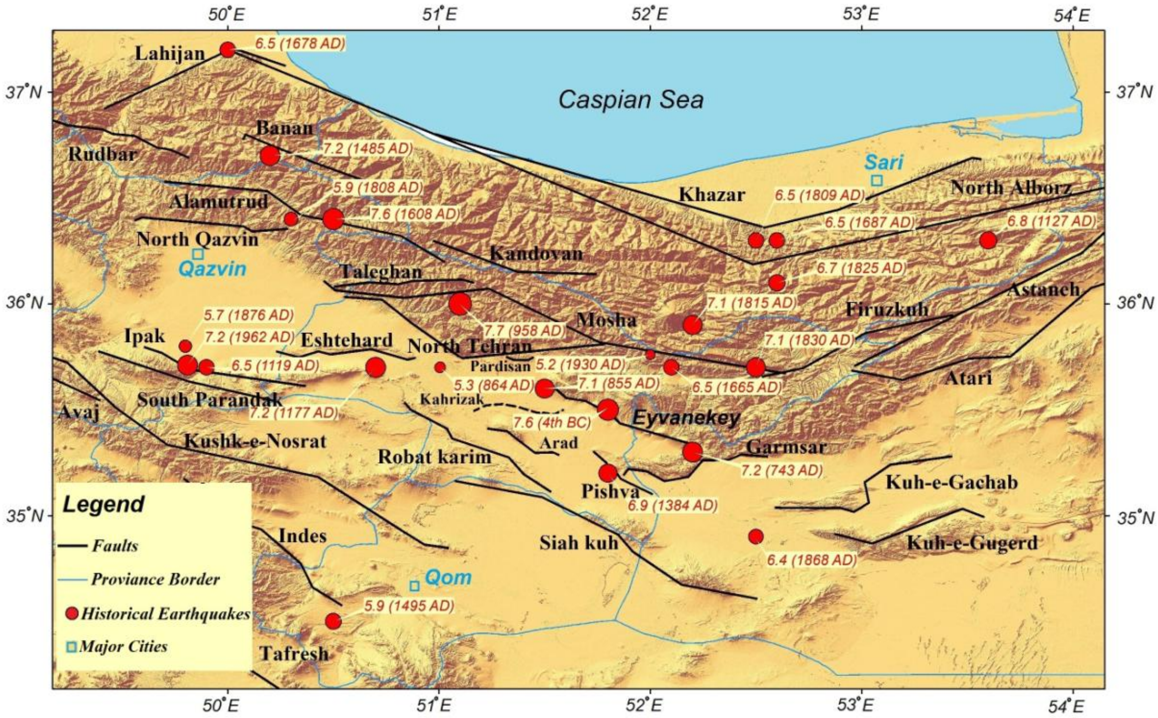

Figure 1. Map showing the active faults (black lines) considered in this study and a geographical distribution of historical earthquakes (red circles)

The earthquake catalog with a radius of 150 km around Tehran has been used to calculate seismicity parameters. Earthquake catalog helps us to obtain comprehensive information about ground shaking happened in Tehran and its vicinity. A rectangular area with 49.86-53.03 E longitudes and 34.30-36.85 N latitudes around the center of Tehran is used to choose all earthquakes with Mw greater than 4 located inside the rectangular. Earthquakes with magnitudes between 4 and 6.5 are not assigned to any fault or fault segment. These are considered as sources which are spread over a large area. The smoothed historic seismicity approach suggested by Frankel (1995) is implemented to smooth the distributed seismicity.

All Major historical earthquakes associated with the nearest possible faults in the study area (see table 1) are taken into account. To estimate recurrence interval and last historical event for a number of individual faults, paleoseismological, historical, and archeoseismological data have been gathered where available. For the other faults, the recurrence intervals have been estimated based on the recently derived slip rates. Khodaverdian et al. (2015) studied on long-term fault slip rates in the Iranian, plateau. Their kinematic deformation model is fitted to the newest data set of Iran including updated fault traces, geological slip rates, geodetic velocities, principal stress directions, and velocity boundary conditions. For those faults without paleoseismological or archeoseismological studies, earthquake recurrence interval of each fault can be evaluated by dividing average of characteristic displacement to its slip rate value (Akinci et al. 2010). By applying the Wells and Coppersmith (1994) relationship, average of characteristic displacement can be evaluated from maximum moment magnitude.

Table 1. Major historical earthquakes associated with the nearest possible faults

Date	Magnitude (Ms)	Lat.	Long.	Nearest Faults
4th BC (a)	7.6	35.5	51.8	Eyvanekey, Garmsar, Pishva
743 (a)	7.2	35.3	52.2	Garmsar, Eyvanekey
855 (a)	7.1	35.6	51.5	Eyvanekey, Pishva, N-Tehran
864 (a)	5.3	35.7	51	Eshtehard, Robat karim, N-Tehran
958 (a)	7.7	36	51.1	Mosha, Taleghan
1119 (a&b)	6.5	35.7	49.9	N-Qazvin, Alamutrud,
1127 (a)	6.8	36.3	53.6	N-Alborz, Astaneh
1177 (a&c)	7.2	35.7	50.7	N-Tehran,Eshtehard, Ipak
1384 (d)	?	Rey and Varamin		Pishva, Garmsar, Evanekey
1485 (d)	7.2	36.7	50.2	Banan, Alamutrud, N-Alborz
1495 (d)	5.9	34.5	50.5	Indes, Tafresh, Kushknosrat
1608 (a)	7.6	36.4	50.5	Alamutrud, N-Qazvin, Taleghan
1665 (a)	6.5	35.7	52.1	Mosha
1678 (d)	6.5	37.2	50	Khazar, N-Alborz
1687 (d)	6.5	36.3	52.6	Lahijan, N-Alborz
1808 (d)	5.9	36.4	50.3	N-Qazvin, Alamutrud
1809 (d)	6.5	36.3	52.5	Khazar, N-Alborz
1815 (b)	7.1	35.9	52.2	Mosha, N-Alborz
1825 (d)	6.7	36.1	52.6	N-Alborz, Firuzkuh
1830 (a)	7.1	35.7	52.5	Mosha, Firuzkuh
1868 (d)	6.4	34.9	52.5	Siah kuh, kuhe gachab, kuhe gugerd
1876 (d)	5.7	35.8	49.8	Ipak, S-Parandak
1930 (d)	5.2	35.76	52	Mosha, N-Tehran
1962 (a)	7.2	35.71	49.81	Ipak, S-Parandak

(a) [Ambraseys, 1978]
(b) [Berberian et al., 1993]
(c) [Ritz et al., 2012]
(d) [Ambraseys and Melville, 1982]

3. METHOD

Seismic hazard in the region has been assessed by combining the contributions from (I) earthquakes with magnitudes between 4 and 6.5 that are not assigned to any fault or fault segment and referred to as "background seismic activity" (Frankel, 1995) and (II) earthquakes with magnitudes equal to or greater than 6.5 that may emanate from faults or fault segments. The final seismic hazard maps in the region are obtained by combining the contributions of background seismic activity and characteristic earthquakes emanating from faults. For the contribution of background seismic activity to seismic hazard, the small earthquakes are not assigned to any fault source. The spatially smoothed seismicity model assumes that future earthquakes will occur in the vicinity of past earthquakes.

Previous studies in Iran usually have assumed seismically homogeneous area sources with uniformly distributed seismicity parameters. Here, for small to moderate events (i.e. those with Mw between 4 and 6.5), a time-independent model based on the spatially smoothed seismicity rate of earthquakes (Frankel, 1995) has been used. Initially, the area under study was divided into 192 square cells with a spacing of 0.2×0.2 degree. The number of earthquakes out of the total of 161 earthquakes in the catalog that have taken place at a given cell is counted and smoothed. The cumulative number of earthquakes (n_i) are spatially smoothed by multiplying them by a Gaussian function having a correlation distance (c). For each cell, the spatially smoothed values ($\tilde{n}_i$) are calculated by using a Gaussian function (Frankel, 1995).

$$\tilde{n}_i = \frac{\sum_j n_j \exp(-\Delta_{ij}^2 / c^2)}{\sum_j \exp(-\Delta_{ij}^2 / c^2)} \tag{1}$$

Δ_{ij} is the distance between the i_{th} and j_{th} cells and c is the correlation distance and the radius of smoothing is equal to 3c. In this equation j represents the number of grids around the i_{th} grid within the smoothed radius of 3c.

Zafarani et al. (2015) evaluated the completeness of earthquake records in the different zones of the plateau. The estimated values indicated that spatial variations in quality of seismic catalog and its completeness magnitude are decreasing with time. Therefore for this problem we used an appropriate method for incomplete catalogs called “mean method” (Milne and Davenport, 1969). In this method we calculate the corrected b-value in the region. We assign a b-value of 0.94 based on the analysis of the de-clustered catalogs as well as using mean method for incomplete catalogs. The frequency-magnitude distribution for background earthquakes follows Gutenberg-Richter distribution. The b-value is evaluated 0.94 for all of the seismic cells whereas different amounts are calculated for a-value differentiating from one cell to another. Using the resulting seismic parameter at each grid sources, seismic hazard maps corresponding to background seismicity can be constructed. As mentioned above, each square cell contributes to hazard as an area source. There are a and b values for each cell, Therefore necessary parameters to calculate hazard in classical formulation are available. Using Poissonian model and classical formulation for PSHA, the seismic hazard for background seismicity has been calculated.

The time-predictable characteristic earthquake model was adopted to evaluate the seismic hazard for the major active faults. Earthquake recurrence intervals for characteristic events from the active faults were analyzed and modeled by the probability distribution function. The recurrence time of characteristic earthquakes for the major faults have been explored. Using time-dependent model, we calculate the probability of occurrence of earthquakes with Mw > 6.5 for individual fault sources. Based on historical earthquakes and paleoseismological data in the region, if available, or empirical relation between fault length and magnitude we explored maximum magnitude for individual faults. The probability of occurrence of the next large earthquake during a specified time interval can be calculated by using BPT distribution (see following paragraphs).

Khodaverdian et al. (2015) recently have researched on Long term Fault slip rates, distributed deformation rates and forecast of seismicity in the Iranian plateau. They have calculated the long-term crustal flow of the Iranian Plateau using a kinematic finite element model. They find the best kinematic model which has acceptable compatibility with geological slip rates, geodetic velocities, and interpolated stress directions. We have used the result of this effort on studying slip rate and other sources in our work.

Here we combine geological data (fault length, slip rate, and paleoseismological data) with historical seismicity data to explore the recurrence times of characteristic earthquakes for the 31 major faults. Some seismogenic sources have very low slip rates and recurrence times are longer than the completeness interval of the historical information. In some fault segments, due to lack of paleoseismological investigations, we assume that last characteristic earthquake occurred before 2000 years ago and a mean return period of 2000 years for those faults that does not have historical and paleoseimological data is considered. In other words there is evidence implies that these faults are active but there is no record in historical documents. Therefore we use a pessimistic assumption that explains these faults passed a period of 2000 years equal to their earthquake cycle. Faults with length beyond 150 km (i.e. the Mosha, North Tehran and khazar) have been divided to two east and west segments.

Using the characteristic earthquake model, we calculate the probability of occurrence of earthquakes with Mw > 6.5 for each fault sources. Large earthquake recurrence on a single fault is thought to be

cyclic, as a result the probability of the next earthquake depends on the time since the last one (Frankel et al., 2002; Hebden and Stein, 2009). A time-dependent model in which some probability distribution describe the time between characteristic earthquakes is used to calculate conditional probability of a large earthquake for each fault in the next 50 years. The probability is small shortly after the last one and then increases with time. For times less than about 2/3 of the assumed mean recurrence interval since the previous earthquake, time-dependent models predict lower probabilities. Eventually, if a large earthquake has not occurred by this time, the time-dependent models predict higher probabilities.
In the literature, various models are recommended for the probability density function of inter-event times such as The Gaussian, Lognormal, Gamma and Weibull (Hagiwara et al., 1974; Hogg and Craig, 1978; Lindh, 1983; Sykes and Nishenko, 1984; WGCEP, 1995; Jackson and Kagan, 1998). Most recently the Brownian Passage Time (BPT) model has been proposed to describe the probability distribution of inter-event times (Matthews et al., 2002). The BPT distribution is defined by two parameters, the mean time or period between earthquakes (μ), and the aperiodicity of the mean time (α). The aperiodicity known as the coefficient of variation, accounts for the periodicity in the recurrence times for an earthquake; a coefficient of variation of 1 represents irregular Poissonian behavior and a coefficient of variation of 0 indicates periodic behavior (Matthews et al., 2002). In this study, BPT model is used as the probability distribution of inter-event times. The probability density for the BPT model is given by equation 2:

$$f(t) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}}\, e^{\frac{-(t-\mu)^2}{2\alpha^2\mu t}} \tag{2}$$

The hazard function increases with decreasing values of α and becomes Poissonlike with increasing values that approach 1.
Information including seismographic and paleoearthquake data are not sufficient to really determine recurrence of large earthquakes and its aperiodicity. Anyway, to explore appropriate value of α by using the correction proposed by (Zöller et al., 2008) using three values of 0.25, 0.5 and 0.75 are mentioned for a sensitivity study.
Conditional probability specifies the likelihood that a given earthquake will happen within a specified time. This likelihood is based on the information about past earthquake occurrences in the given region and the basic assumption that future seismic activity will follow the pattern of past activity. The conditional probability of an earthquake recurring on a fault at some time t_e after the last event in the interval t_e to $t_e + \Delta T$, conditioned on the fact that it has not occurred prior to t_e, is given by:

$$P_{cond}(t_e \le t \le t_e + \Delta T) = \frac{\int_{t_e}^{t_e+\Delta T} f(t)dt}{\int_{t_e}^{\infty} f(t)dt} \tag{3}$$

This probability is said to be conditional because it changes as function of the time elapsed since the last earthquake. The probabilities of occurrence for the next event were assessed using Brownian passage time statistical distributions. For the BPT model, the 50 year conditional probabilities for each fault are calculated. The 50yr conditional probabilities are converted to effective Poissonian annual probabilities by the use of following expression:

$$\mathrm{R_{eff}} = \frac{-\ln(1-\mathrm{P_{cond}})}{\mathrm{T}} \tag{4}$$

R_{eff} is named equivalent fictitious seismicity rate and is equal to the annual probability of a Poisson

Process. For each fault, equivalent annual mean rates (R_{eff}) have been calculated based on the assumptions described above.
In this study, seismic hazard maps obtained by using characteristic model, time-dependent annual activity rates and classic formulation for these faults. We have chosen the most appropriate ground motion prediction equations (GMPE) based on their applicability in the region described in the next section. Four local (Ghasemi et al. 2009 and Soghrat et al. 2012, Kale et al. 2015, Zafarani et al. 2017), one regional attenuation models (Akkar and Bommer 2010) and two NGA models have been selected (Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008). Using equivalent time-dependent annual mean rates, selected GMPEs and classical formulation of hazard analysis seismic hazard maps are calculated.
Final seismic hazard maps in the region are obtained by combining the contributions of background seismic activity and characteristic earthquakes emanating from faults. In case of characteristic earthquakes there were different scenarios in return period and time of last event for some faults. In order to capture other epistemic uncertainties (e.g. uncertain slip rates and uncertain paleoseismological dating and, hence, uncertain recurrence times), a logic-tree has been setup. The technique of "logic trees" has been widely used to incorporate scientific uncertainty in a PSHA. The fact that there are significant scientific uncertainties in earthquake source characterization and ground motion estimation means that there is not a unique result for the relationship between ground motion level and probability of exceedance. In fact, there is usually a significant range of possible ground motion levels for a given probability of exceedance.
By applying Seven GMPEs and two values for earthquake recurrence interval for the North Tehran, Taleghan and Mosha Fault the logic tree is completed for the Hazard calculation. As a result, we have 56 independent calculations (2×2×2×7) which have to be combined to achieve the final result (see Figure 2). The final seismic hazard maps for PGA, are shown in Figure 3.

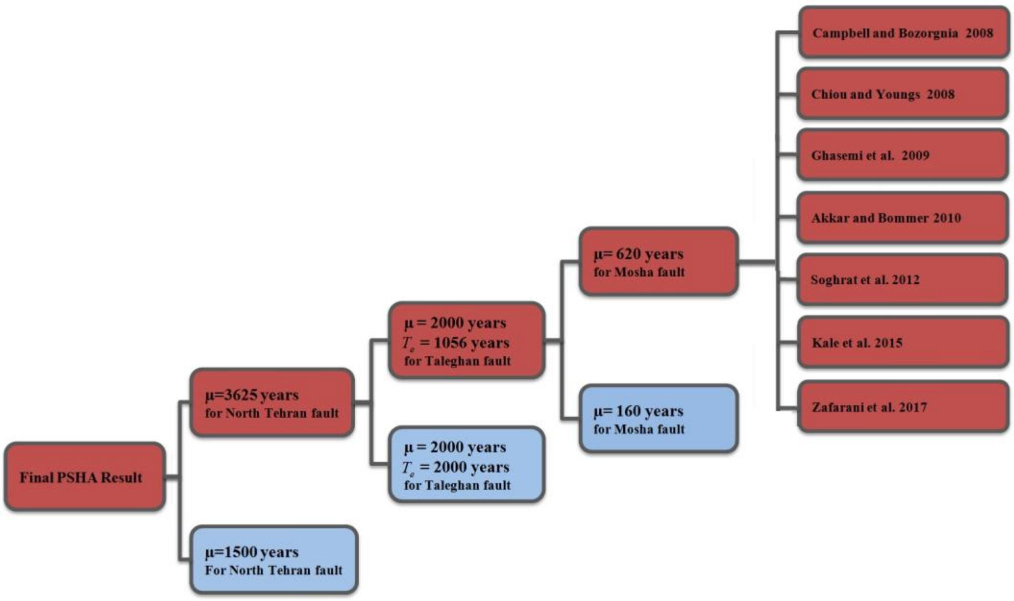

Figure 2. The logic tree used for time-dependent seismic hazard model and appropriate GMPEs that used only for PGA calculations (Jalalalhosseini et al. 2017).

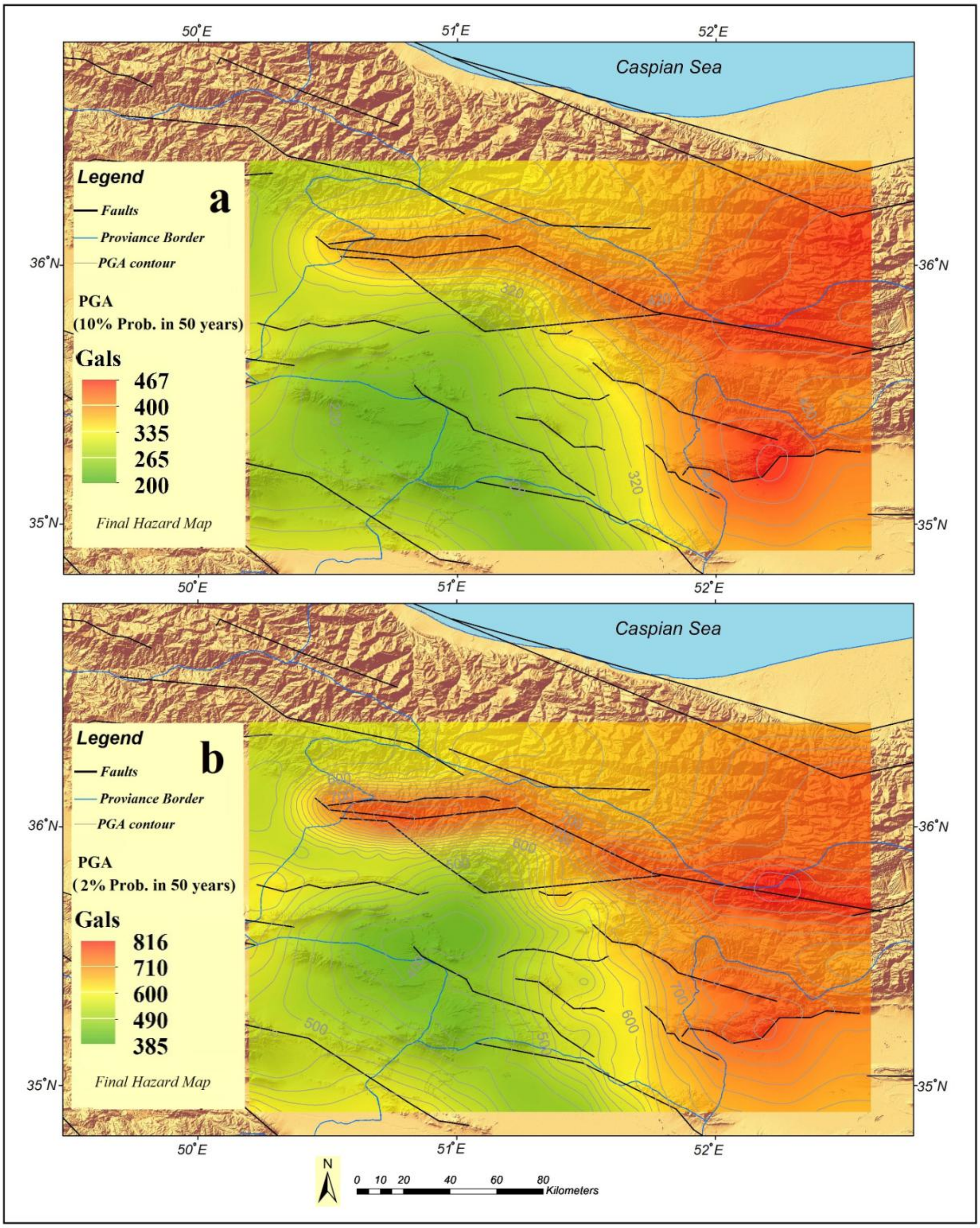

Figure 3. Final seismic hazard maps for PGA (in gal) obtained by combining background seismic activity and time-dependent characteristic earthquakes emanate from faults corresponding to a return period of (a) 475 and (b) 2475 year

4. DISCUSSION AND CONCLUSIONS

The resulting seismic hazard map (in return period of 475 and 2475 years) are presented in terms of PGA in Figure 3. In these maps, the eastern parts of the region represent a larger value of PGA than western parts. This is due to the large number of small earthquake with magnitude 4 to 6.5 in eastern parts near the Garmsar, Eyvanekey, and Mosha faults. Moreover, it is obvious that there are some hidden and unknown faults in Iran that have not shown any distinguished event yet. For example, two hidden faults caused serious damages during two recent earthquakes of Baladeh (M6.2, 2004) and the Ahar– Varzaghan (M6.5, 2012). Therefore, the earthquakes with low to moderate magnitudes distribute randomly across the area, and it would be better to cluster into background sources. A smoothing radius of 120 km is selected for background seismicity smoothing. Obtained results represent larger values near the cells which include a large number of earthquakes, and those cells which are empty or include less number of earthquakes show lower seismicity rate. The maximum PGA for a return period of 475 and 2475 years obtained around 380 and 670 cm/s2 respectively in south-east of the region around the Garmsar and Mosha fault.

By combining the background seismic sources with the individual faults, we can consider all earthquakes of the area. This method can improve our judgment about the seismicity of the region concerned to return long period earthquakes and can omit the inefficiency due to the incompleteness of the earthquake catalog. PSHA calculations have been performed for two levels of probability of exceedance, i.e., 10 and 2% probabilities of exceedance in 50 years. Here, the ground motions are determined for soft rock conditions, and final hazard maps created for PGA, SA, and PGV with a 10 and 2% probability of exceedance for a time period of 50 years. Time-dependent method shows that by increasing in time elapsed since last earthquake, the probability of earthquake increases. The result maps indicate that hazard increases around the large faults that can produce characteristic earthquakes. For faults which have elapsed a long time since the last event, probability of earthquake augment and it brings about hazard. The time-dependent maps differ from the time-independent maps near a fault sources. Therefore, our result maps (Figure 3) illustrate that hazard increases in the vicinity of faults which are late in their cycles. It has been a long time since there was any earthquake in these faults; therefore, the 50-year BPT model conditional probabilities for these faults are high.

The generated PGA hazard maps indicate an increase in PGA toward the northern part of the map, where the Alamutrud, Taleghan, Mosha, and North Tehran faults are located. It means that for this region, time-dependent behavior of seismic sources has an important contribution to the seismic hazard maps. Therefore, the new maps introduce significant improvements over the previous time-independent maps of the region. In the studied area, numerous seismological, geological, and paleoseismological data are available together with good records of instrumental earthquakes for recent century. We note that in many situations, no information other than a priori estimates of certain parameters is available. For example, for those faults which do not have historical and paleoseimological data, we assume that last characteristic earthquake occurred before 2000 years ago. Uncertainties in background seismicity such as the minimum magnitude, b value parameters, and edge effect for cells located near the corner and edge of the studied area should be considered in a separate study. Several attenuation functions including NGA were selected in order to consider the type of rupture mechanism and site effect.

Accounting for uncertainties, the logic tree was implemented. Hazard maps should be updated regularly, as new information on earthquake recurrence and maximum magnitude becomes available from new researches. Research on such important hazard topics as recurrence time, maximum magnitude, long-term slip rate, rupture histories of historical earthquakes, magnitude–frequency distributions for individual faults, and the effects of shallow and deep site conditions on attenuation relation will improve the seismic hazard maps in the future. We study the influence of the aperiodicity and the elapsed time on the hazard estimation for North Tehran fault. Knowing the fault and the statistic of the earthquake recurrence times (i.e., the elapsed time and the BPT distribution), the impact on hazard ranges about 10 for 10% in 50 years; we are currently studying on uncertainties and its influence on seismic hazard that can improve the seismic hazard maps in the future. We determined the maximum value of PGA around 470 cm/s^2 and 800 cm/s2 for return periods of 475 years and 2475-years, respectively. For most parts of the study area, located well away from the time-dependent sources, the ground motions are similar for both time-dependent and time-independent methods. The northern and eastern parts of the region which are located near north Tehran, Taleghan, Mosha, Eyvanekey, and Garmsar fault zones generally have elevated hazard relative to the time-independent maps.

This is because it has been quite a long time since the last earthquake, and all of these faults are, most likely, in the latter half of their seismic cycles. The southern and western parts of the region which are near Rudbar, Ipak, and Avaj falt have time-dependent hazard that is lower than the in time-dependent hazard due to the relatively short period since the 1990 Manjil-Rudbar earthquake, 1962 Buyin Zahra earthquake, and 2002 Avaj earthquake, which places these faults in the first half of their seismic cycles.

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