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Seismic Hazard Zoning in Iran: A State-of-the-Art on the Studies during Four Decades

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ABSTRACT

This is a state-of-the-art paper on the seismic hazard zoning studies performed in Iran since the mid-1970s to 2015. Reliable seismic hazard studies depend on having a robust earthquake catalog, good knowledge of tectonic conditions and relevant attenuation models applied for the hazard calculations. The better input for hazard analysis results in the more reliable parameters and seismic hazard assessments. The first generations of seismic hazard zoning maps in Iran were developed based on the deterministic approaches for calculation of maximum intensities (e.g. [1] and [2]). In 1982, Bozorgnia and Mohajer-Ashjai [3] published the first comprehensive probabilistic hazard assessment for major cities of Iran. The first PGA zoning map for the greater Tehran region was also published by Berberian et al. [4]. The next generations of seismic hazard zoning studies were carried out for dam sites, which were under construction during the 1980s and 1990s in Iran. A seismic hazard zoning map of Iran for the "design earthquake" (so called 475 years of return period), was published in 1999 as an attachment to the Iranian seismic code for buildings (Standard No. 2800). In the recent years, a number of detailed hazard zoning maps for the greater cities and specific industrial sites have also been presented. The defined spectral attenuation equations for Iran (e.g. [5-17]) can be used for producing spectral zoning maps. These maps can be developed using region specific ground-motion prediction equations by considering various ground-motion parameters that involve spectral acceleration, displacement and peak ground-motion values. Therefore, there are still ongoing attempts to develop the probabilistic seismic zoning maps for Iran. In this paper, the seismic hazard zoning maps of Iran developed in the last 40 years are investigated. It is tried to depict the development history of the seismic hazard zoning studies for Iran, which have been started since the mid-1970s. Briefly, the trend of such studies was started by the application of deterministic approaches for estimation of intensity and then was continued using probabilistic approaches. Future studies on the seismic hazard zoning in Iran seems to cover new approaches such as the realistic acceleration and the neo-deterministic approaches, time-dependent mapping, intelligent updating of hazard maps as well as the development of site-specific hazard analysis based on the development of more detailed data.

Keywords:
Deterministic approach; Probabilistic approach; Seismic hazard; Iran; Seismotectonic provinces

1. Introduction

From the seismotectonic point of view, the Iranian Plateau is exposed to high seismic activity and is greatly influenced by the continental convergence and active crustal shortening between the Arabian and the Indian plates to the northeast and northward with respect to the Eurasian plate. The geodetic, seismic and tectonic studies in Iran confirm the existence of a complex active tectonic framework with high deformation rates, a part of which expresses in terms of earthquakes. Based on the GPS measurements, most of the shortening is accommodated by the Makran subduction zone (19.5±2 mm/yr) and less by the Kopet-Dag (6.5±2 mm/yr) [18].

According to the regional tectonic regime of the Iranian plateau, the focal mechanism solutions of the most earthquakes are compressional, strike-slip or a combination of these two mechanisms. This region experiences different earthquake magnitudes each year, some of them may reach M_w 8 (e.g. 27 November 1945 M_w 8.1 Makran earthquake). Several earthquakes with magnitude over 7.0 and some destructive events have occurred in Iran during the last century such as the 1909 Silakhor (M_w 7.3), 1930 Salmas (M_w 7.1), 1962 Bou'in-Zahra (M_w 7.1), 1968 Dasht-e-Bayaz (M_w 7.4), 1978 Tabas (M_w 7.4), 1990 Manjil (M_w 7.4),1997 Ghaen (M_w 7.3), 2003 Bam (M_w 6.6), 2012 Varzeghan (M_w 6.4) and 2013 Savaran (M_w 7.8) earthquakes.

Earthquake hazard analysis is an efficient tool to reach earthquake resistant design of civil structures, especially for seismically active regions like Iran. It is essential to have the fullest possible understanding of earthquake hazard by preparing detailed seismic zoning maps in terms of intensity, peak ground motion parameters, spectral accelerations, etc. It should be noted that reliable seismic hazard studies depend on the completeness level and accuracy of available data and analysis method such as a robust earthquake catalog, good knowledge about tectonic frameworks, rates of active deformations, and relevant attenuation models. The better input for hazard models results in the more reliable parameters and fewer uncertainties. Taking into account the seismotectonic framework and high seismicity with destructive earthquakes as well as the large population density settled in the earthquake-prone areas of Iran, it is necessary to revise and update the seismic hazard and risk models for this region along with developments of databases and methodologies.

Since the mid-1970s, several seismic hazard zoning maps have been established for Iran. Simultaneously, seismicity catalogs as well as tectonic and seismotectonic maps have been developed as the input data for hazard assessments. The main maps of the seismotectonic, seismic sources and tectono-sedimentary for the whole Iran have been prepared by [19-45]. In addition, various studies have been conducted to provide seismic catalogs for Iran among which the most important works have been carried out by [46-65]. Continuous improvement in providing earthquake catalogs and defining seismotectonic provinces has led to evolution of the hazard analysis.

In this study, it is first tried to depict the development history of the most important seismic hazard zoning maps of Iran started from 1977 and continues to the last updated versions of such maps until 2015. Then, the seismic hazard zoning maps of Iran are compared and it is explained that why these maps are different and which one is probably a better representation of the earthquake hazard in Iran. After the occurrences of some earthquakes (such as the 1978 M_w 7.4 Tabas earthquake, 1990 M_w 7.3 Manjil earthquake and 2003 M_w 6.5 Bam earthquake), several questions have been raised about the reliability of the seismic hazard zoning maps as well as the comparison between the recorded ground motions and the previously assessed ground motions. This work reviews some factors by which the hazard zoning maps may fail to predict the correct hazard levels. It is also explained that to what extent the discrepancies are acceptable.

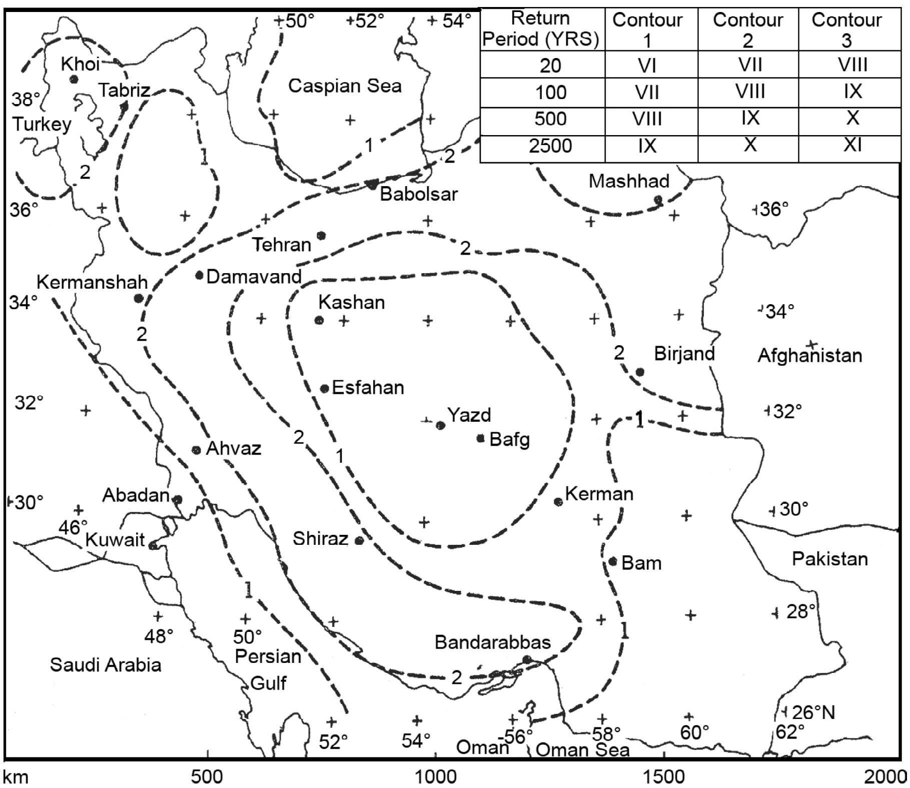
2. Development History of the Seismic Hazard Zoning Studies in Iran

Since the mid-1970s by 2015, dozens of seismic hazard zoning studies have been carried out for the whole Iran, using different data, parameters and methods. In this section, some of the most referred earthquake hazard zoning studies of Iran are explained.

In 1977, Neghabat and Liu [1] prepared an earthquake microzonation analysis of Iran. They initially divided the geologic area of Iran into four overlapped seismic regions including the Zagros folded belt, the Rezaiye-Esfandagheh orogenic belt, the central and southeast Persia and the Alborz ranges in order to analyze them independently. Each of these regions was divided into several sub-regions to be considered as earthquake source areas (a total of 48 source areas). The earthquake database of their analysis comprised of the instrumental main shocks with Richter magnitude greater than or equal to 4.0, recorded during 1900-1970. Then, the probability of the maximum earthquake intensity for each independent zone was determined based on the seismic hazard method developed by Cornell [66] as well as using the different relationships such as the

Gutenberg-Richter reoccurrence relationship, arrival rates, and an intensity attenuation function. Finally, by synthesizing the results of the four mentioned geologic regions, a general isoseismic contour map was presented for the entire country in terms of the Modified Mercalli intensity corresponding to the return periods of 20, 100, 500 and 2500 years (Figure 1). Neghabat and Liu [1] concluded that the highest intensity levels occur in the northeastern section of Iran near the city of Mashhad, and this result is expected according to the relatively shallow focal depth of earthquakes, i.e. 15 kilometers in this region. The second highest intensity level belongs to the Persian Gulf, the northwest corner of Iran near Turkey and areas surrounding Mashhad. And the lowest hazard belongs to three places i.e. the northwest between Tehran and Tabriz; the central Iran including Kashan, Isfahan, Yazd and Bafq; and the southeastern part of the country between Bam and Pakistan.

In the same year, Berberian and Mohajer-Ashjai [2] prepared another seismic hazard map of Iran based on a deterministic estimate of the maximum intensity. They applied the following steps successively. (i): Preparation of an isoseismal map of Iran based on gathering and plotting 52 individual isoseismal maps from the well-documented instrumental earthquakes (1900-1977) on one map [67]; (ii): Preparation of a historical seismicity map (pre-1900) with approximate estimated Richter magnitude equal to or greater than 6.0 [68] and preparation of the historical (4th century B.C. to 1900 A.D) intensity zone map of Iran [69]; (iii): Preparation of the 20th century seismicity map with earthquake magnitudes ranged from 3.0 to 7.4 on the Richter scale and focal depths of 10 km to 150 km [70] as well as preparation of the intensity zone map of Iran (1900-1977) with eight zones from III to X [71]; (iv): Preparation of a new intensity zone map of Iran covering the whole time span of the 4th century B.C. to 1977 A.D. based on the maps prepared in the previous steps [72]; (v): At the 5th step, Quaternary and recent earthquake faults and a fault hazard zone map of Iran were prepared in order to consider the effect of young and major faults on the intensity distribution in Iran. On the fault hazard zone map, the probable intensity distribution, due to the fault movement, was ranked in three categories: Zone 1 including the intensities of VIII, IX, and X on the Modified Mercalli Intensity scale (MMI) drawn



Return Period (YRS)	Contour 1	Contour 2	Contour 3
20	VI	VII	VIII
100	VII	VIII	IX
500	VIII	IX	X
2500	IX	X	XI

Figure 1. Earthquake intensity contour map of Iran in terms of maximum probable intensity for the 20-year, 100-year, 500-year and 2,500-year return periods [1].

approximately 15 km around the major long Quaternary faults; Zone 2 with the intensity of VII (32 km on each side of the major Quaternary faults); and finally Zone 3 with the intensity of VI (50 km on each side of the major Quaternary faults); (vi): Finally, by compiling the data of the all maps discussed in the five steps above, the preliminary seismic hazard map of Iran was prepared (Figure 2) in which the country was divided into four zones on the MMI intensity scale including the zone 1: VIII, IX, X; zone 2: VII; zone 3: VI and zone 4: V.

One year later, Mohajer-Ashjai and Nowroozi [73] made two intensity zoning maps, including an observed/calculated intensity map and a probable intensity map using thirteen available isoseismal maps of the Iranian major earthquakes, reports of historical damages, distribution of moderate and large earthquakes and post Quaternary faults and volcanoes. For the first zoning map, the data of the observed intensity distribution in Iran were prepared. In addition, wherever information on the distribution of intensities was not available, the maximum intensity was calculated based on the observed instrumental magnitude using the equation $I=1.7M-2.8$ defined by Mohajer-Ashjai and Nowroozi [73]. Then, the observed/calculated intensity zoning map of Iran was depicted with five zones covering intensities from III and lower to IX and higher (Figure 3-a). The second zoning map was produced with regard to the probable intensities based on the assumption of the capability of post-Quaternary faults for generating destructive earthquakes and damages. According to the data of the Southwest Asian earthquakes, Mohajer-Ashjai and Nowroozi [73] developed an equation in the form: $M=5.4+\log L$, in which M is the surface-wave magnitude and L is the earthquake rupture length (=50% of total fault length) in kilometers. Then, the intensity was calculated based on the equation $I=1.7M-2.8$. At that time, due to the lack of an appropriate intensity attenuation law for each area, Mohajer-Ashjai and Nowroozi [73] assumed that distances up to 20 km from the strike of a major recent fault in each direction, would have the same intensity level for

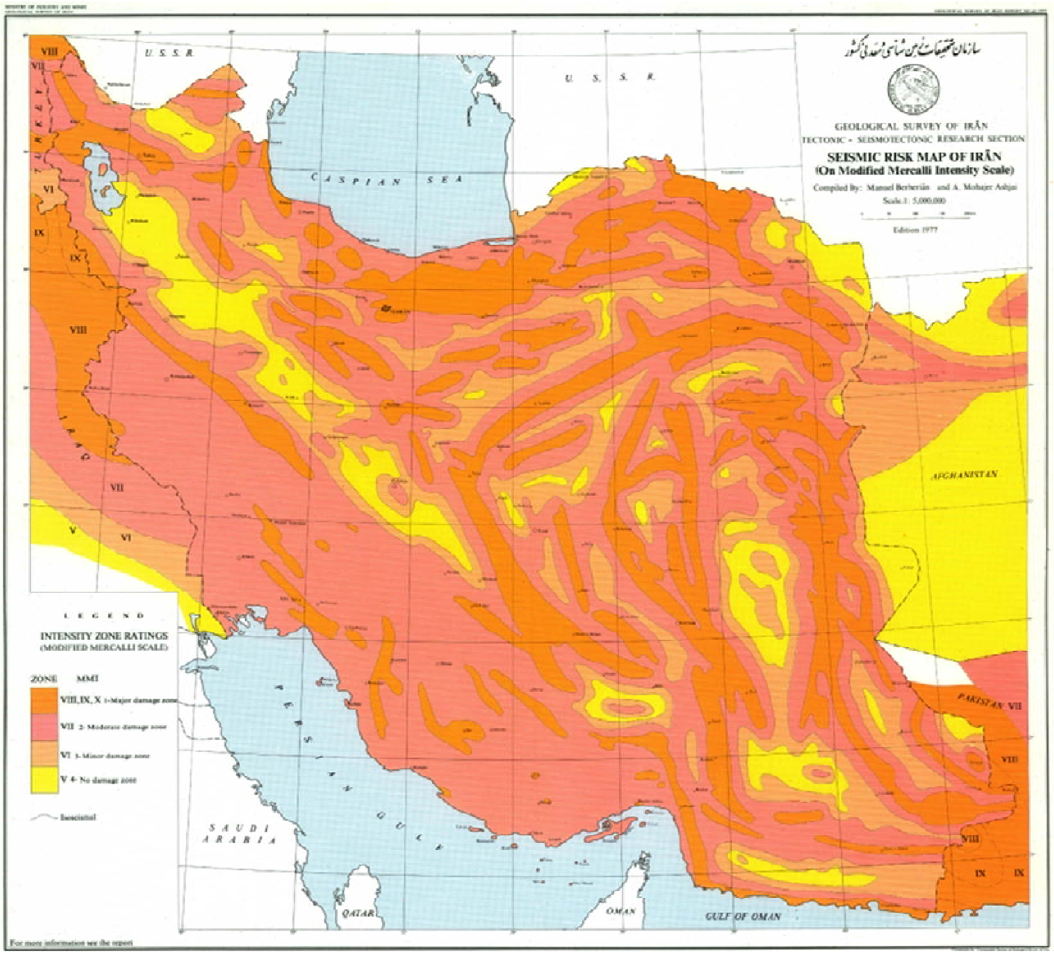
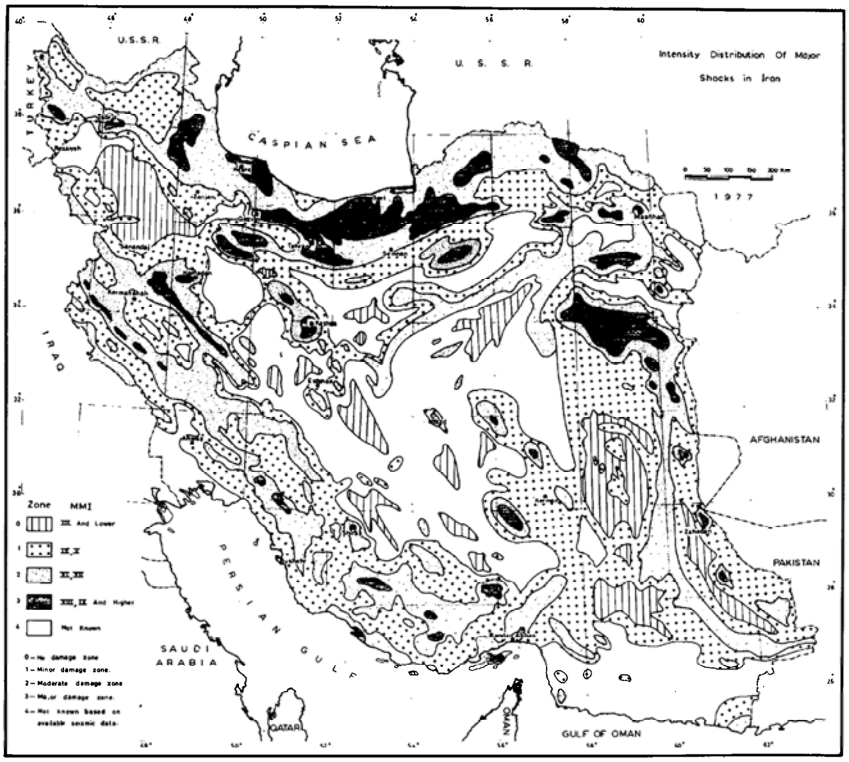
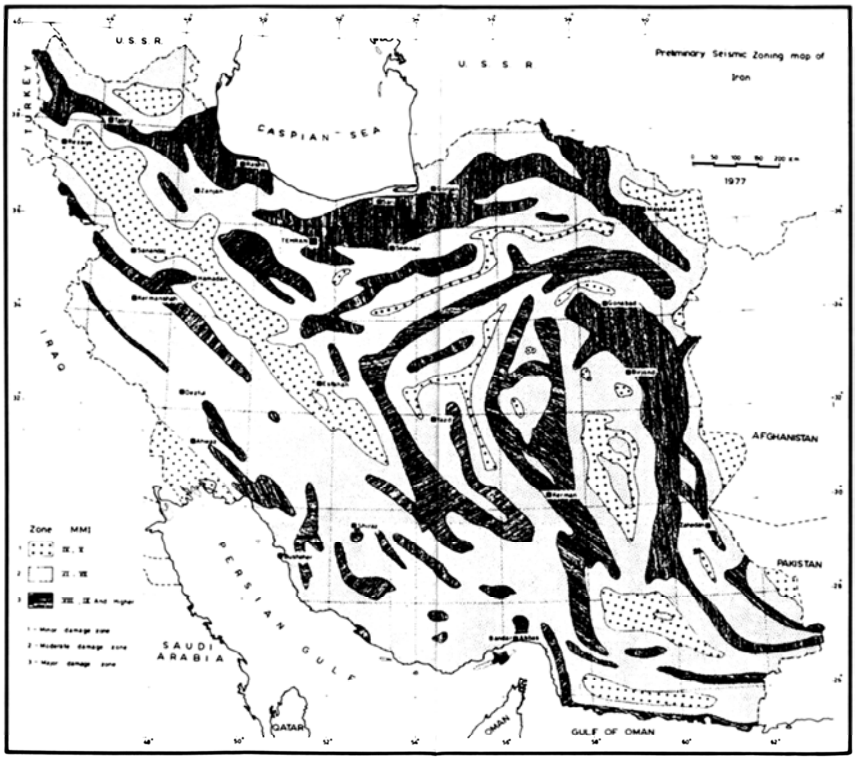


Figure 2. Earthquake intensity zoning map of Iran in terms of maximum deterministic intensity on the MMI scale [2].

the high damage zone. Similarly, the area bounded between 20 and 35 km from a recent fault trace would have a lower intensity range, corresponding to moderate damage zone. Beyond that, it falls within the low damage zone. With respect to the observed intensity map and the intensities obtained by the above procedure, the probable intensity map of Iran was depicted that divided the country into three zones covering probable intensities from IV to IX and higher (Figure 3-b). The authors concluded



(a)



(b)

Figure 3. (a) Observed and calculated intensity distribution of the Iranian earthquakes and (b) probable intensity zoning map of Iran [73].

that Esfahan and Abadan are in the low damage zone; Yazd, Ahwaz, Bushehr and Kermanshah are in the moderate damage zone; and the remaining large Iranian cities including Tehran are in the high damage zone.

Berberian [28] found that the seismic hazard map of Iran prepared by Berberian and Mohajer-Ashjai [2] was incomplete because prior to the 16 September 1978 M_w 7.4 Tabas earthquake, its causative fault was unknown and the region was not considered as a high seismic hazard zone. Thus, Berberian [28] attempted to revise this map and prepared a new version of seismic hazard map of Iran (Figure 4) using all the available reliable and updated data e.g. the new detailed fault map and an up-to-date active fault map of the country, as well as using the results of several field investigations. In this new map, Iran is divided into three zones of minor (VI-VII), moderate (VII-VIII) and major (VIII-X; zones of the Quaternary faults and the areas associated with the past destructive earthquakes) damage zones. The intensities shown on this map are not the maximum possible intensity, but only probable.

Until 1982, most of the seismic hazard studies were concentrated on the estimation of earthquake intensity. Since then, by progress in data collection and statistical methods, the probabilistic seismic hazard analysis (PSHA) has been employed to calculate the probable ground motion parameters especially peak ground acceleration (PGA) and spectral acceleration (SA). The PSHA approach considers all the possible earthquake occurrences and ground motions to calculate a combined probability of exceedance that incorporates the relative frequencies of occurrence of different earthquakes and ground-motion characteristics [74].

The first probabilistic hazard analysis in terms of horizontal PGA versus different annual hazards was carried out for 26 major cities of Iran by Bozorgnia and Mohajer-Ashjai [3]. For this purpose, they used a catalog of 2346 recorded instrumental events

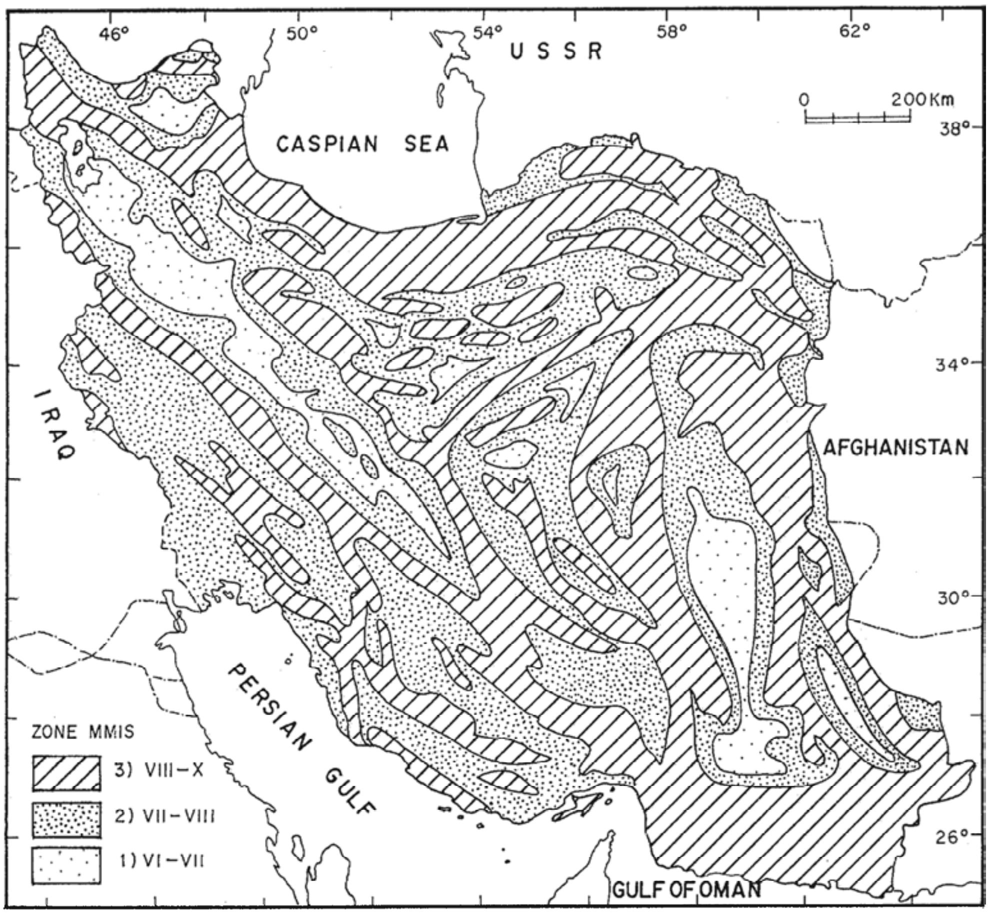
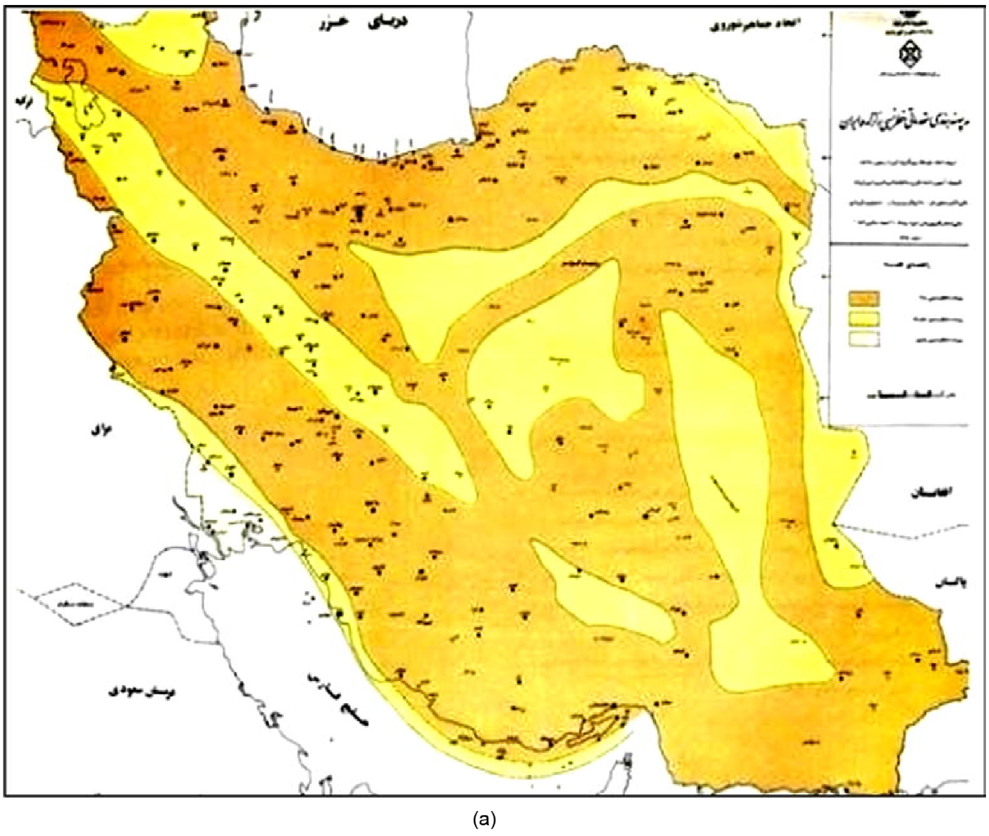


Figure 4. Seismic hazard map of Iran in terms of probable intensities [28]. On this map, zone 3 (maximum intensities) covers the regions of the Quaternary faults and the areas associated with the past destructive earthquakes. The intensities shown are not the maximum possible intensity, but only probable.

during 1900-1981 in Iran. They also modeled a total number of 324 seismic sources out of which 304 sources were fault segments and 20 were area sources. They finally presented the estimated PGA for the 26 major cities of Iran for various return periods of 20, 50, 100, 150, 200, 500, 1000 and 10,000 years.

Nowroozi and Ahmadi [75] also conducted a probabilistic hazard study for Iran using a seismotectonic model with 22 zones. They initially calculated the seismicity parameters (a-value, b-value, α, β and γ of log-linear and log-quadratic magnitude-frequency relationships) and calculated the return periods of several earthquake magnitudes for each of the 22 seismotectonic zones. They estimated the probable intensities, seismic hazard and ground acceleration for a set of return periods and epicentral distances. Nowroozi and Ahmadi [75] concluded that areas between southwest of the Zagros thrust and northeast of the Arabian landmass have the most earthquakes with the magnitude of about 6 in less than a decade, while the northern and northeastern areas of the country are capable of producing a magnitude 7.5 earthquake about each century. According to their study, the seismic hazard is lowest for Esfahan-Sirjan, Arabian Platform, Persian Gulf, Kavir in the central Iran and Arvand-Shatt-al-Arab seismotectonic provinces and the highest seismic hazard is for Alborz, Kopet-Dag, Ferdows and Fars seismotectonic provinces. The expected peak ground acceleration is highest, for a time exposure of 30 years, for Fars, Ferdows, and Tabas provinces, and least for Esfahan-Sirjan. For a time exposure of 200 years, the expected peak ground acceleration is highest for Alborz, Kopet-Dag and Ferdows provinces.

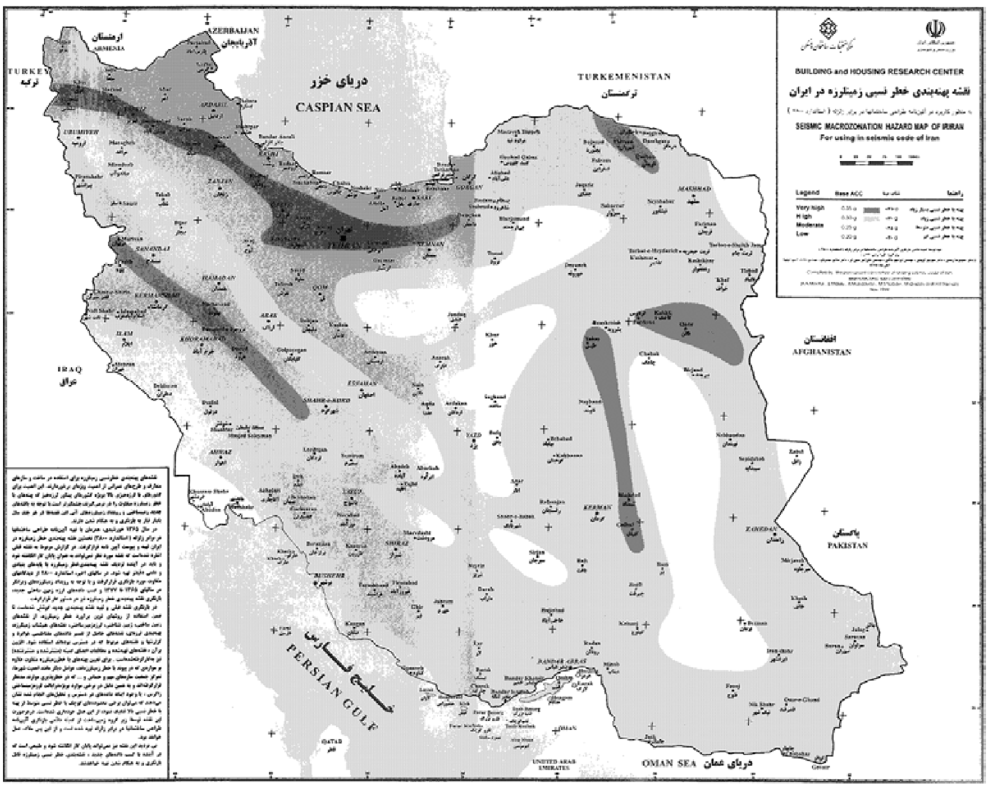
One of the most important seismic hazard zoning maps of Iran has been made as an attachment to the Iranian code of practice for seismic resistant design of buildings (also known as the Standard No. 2800). Until now, four editions of the Iranian seismic code for buildings have been published and revised in 1987 [76], 1999 [77], 2005 [78] and 2012 [79], respectively (Figures 5-a, b, c, d). The Iranian seismic code has a permanent scientific committee who is responsible for producing the seismic hazard zoning map and updating it when necessary. The details about the procedure of producing these maps



(a)

Figure 5. Seismic hazard zoning map of Iran as an attachment to the Iranian code of practice for seismic resistant design of buildings (Standard No. 2800) published in: 1987 [76] (a), 1999 [77] (b), 2005 [78] (c) and 2012 [79] (d).

are not published in the Code and are not publicly available, but Moinfar et al. [80] have described some details about the last version map [79]. To make the seismic hazard zoning map of Iran in the 4^{th} edition of the Iranian seismic code, a comprehensive study was carry out on the tectonic framework of Iran, active faults, seismic sources, earthquake epicenters, recorded strong motion data, as well as the case studies performed on seismic hazard for important structures' sites such as dams and power



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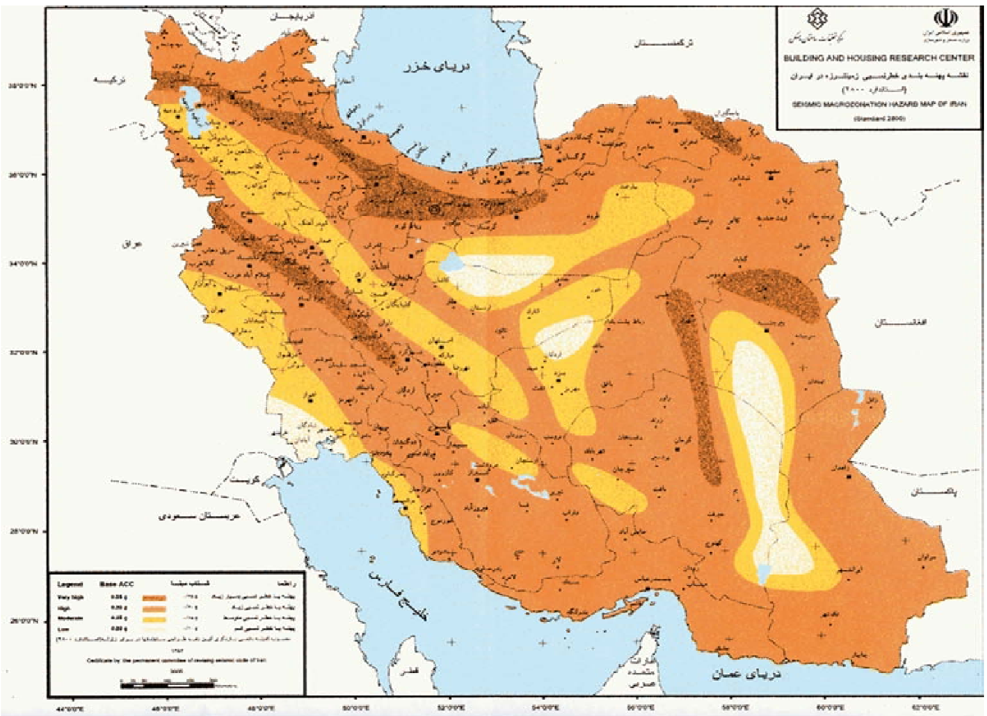

(c)

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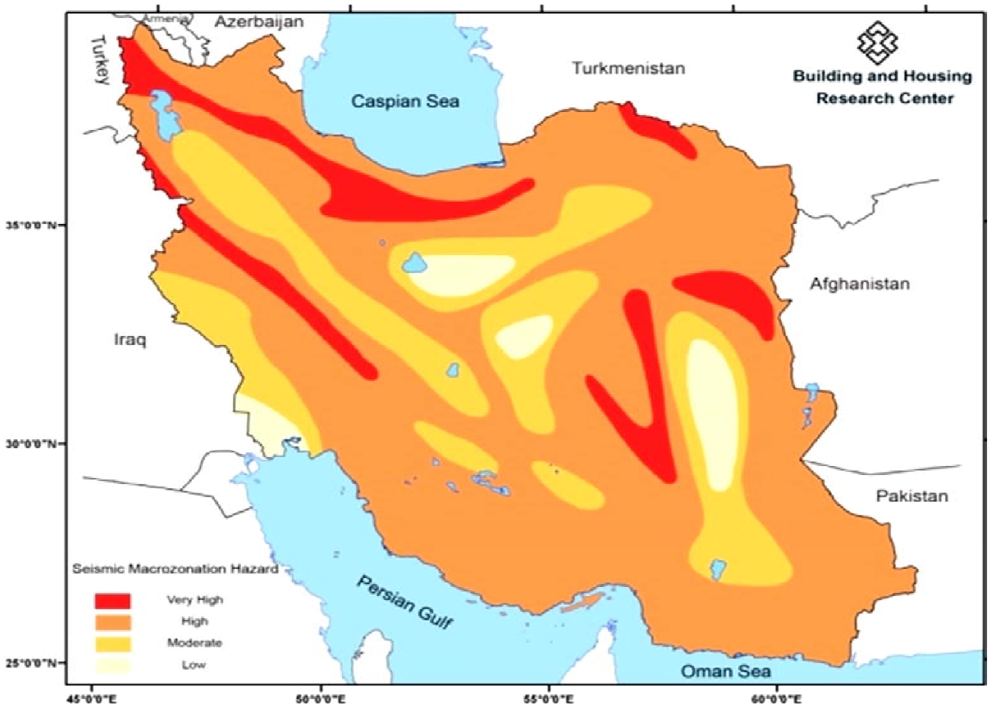


(d)

Figure 5. Continue

plants. Some important factors such as considering the socio-economic importance of different sites and the possibility of unknown Quaternary faults were also taken into account. In addition, a new unified fault map was compiled in the scale of 1:1,000,000 in which 700 faults with the length of over 20 km were mapped. Moreover, an updated seismicity catalog of the Iranian earthquakes including the historic and instrumental (up to 2011) events with magnitude equal to and greater than 4.5 was compiled based on the available data and the expert judgments of the seismic zoning sub-committee. Therefore, on the basis of combination of these updated data, a new seismic hazard zoning map of Iran was depicted which divides the country into four zones with design base accelerations of 0.35 g (very high hazard), 0.30 g (high hazard), 0.25 g (moderate hazard), and 0.20 g (low hazard) (Figure 5-d). Moinfar et al. [80] also tried to make a comparison between the base accelerations of this updated hazard map with those of the neighbor countries. Their comparison shows that there is a relatively good agreement with countries located in the west and northwest of Iran, while there are some disagreements with the northeast and eastern neighbors (Figure 6). It should be noted that the seismic hazard zoning map in the Iranian seismic code is useful for the design of conventional structures, but for important sites such as towers, tall building, dams and power plants, it is necessary to carry out site-specific studies with respect to the geotechnical features, site responses and seismological surveys. This would lead to obtain more precise design factors for future earthquakes.

Tavakoli and Ghafory-Ashtiany [38] developed two seismic hazard maps of Iran, one in the form of iso-acceleration contour lines (Figure 7-a) and the other in the form of seismic zoning (Figure 7-b). They used PSHA method and conducted their study in the four stages: (i) compilation of the historical and instrumental earthquake databases, (ii) consideration of seismotectonic provinces of Iran, (iii) calculation of seismicity parameters including maximum expected magnitude (M_{max}), activity rate (λ) and the b-value of the Gutenberg-Richter relation, (iv) selection of a proper attenuation relation. Then, on the basis of these stages, the computer program SEISRISK III was used to calculate the PGA values. Accordingly, the two mentioned maps (contour lines and zoning) were originally presented on 1:5000000 scale. These maps indicated that the minimum and maximum accelerations ranged from 15% to 48% g. The highest PGA corresponds to the North Tabriz, North

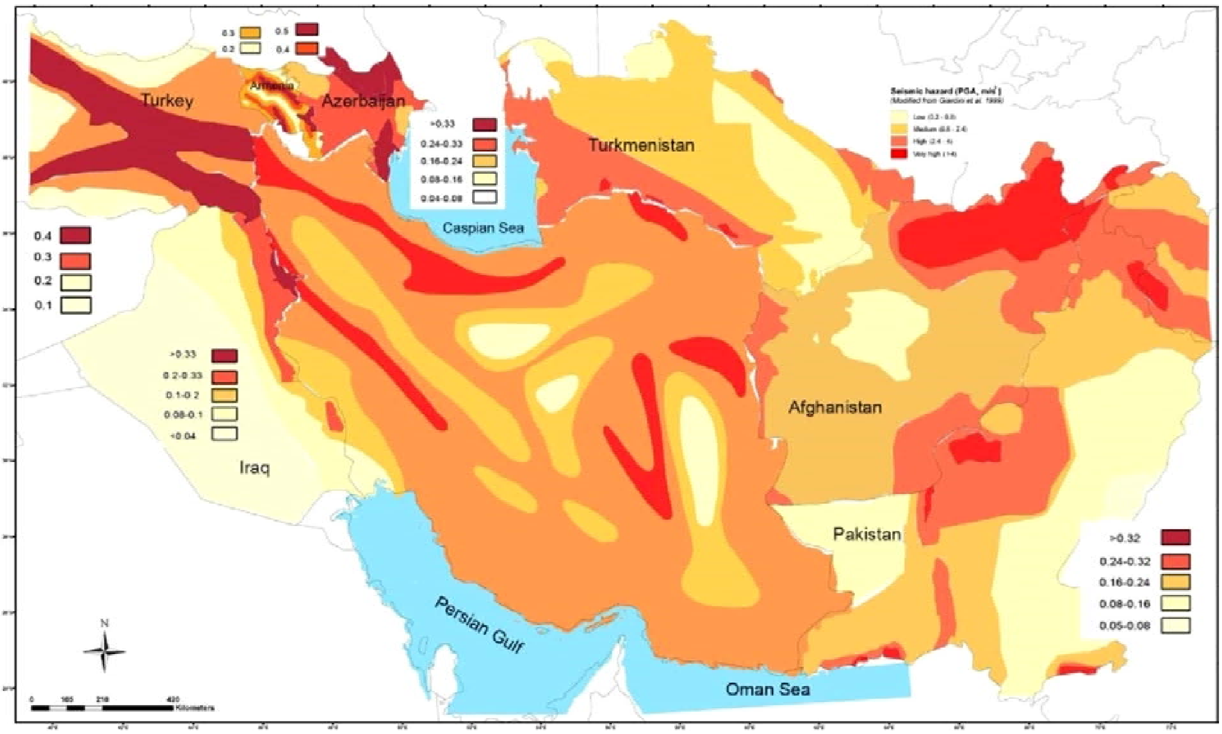
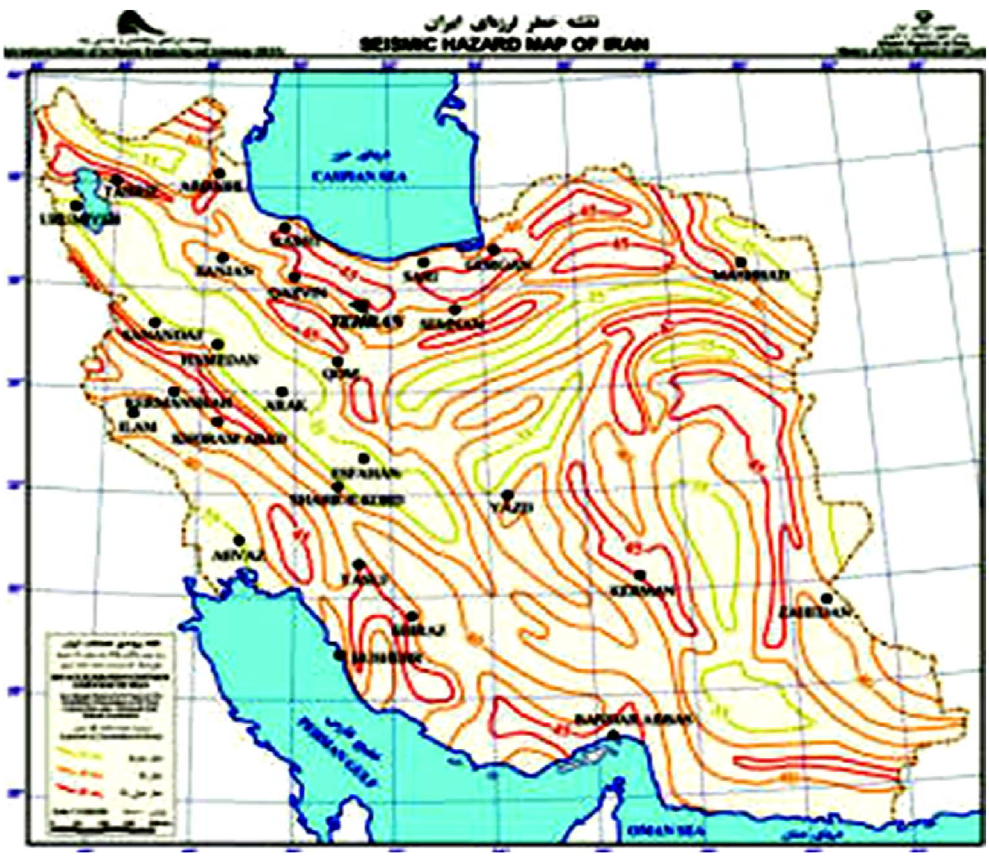
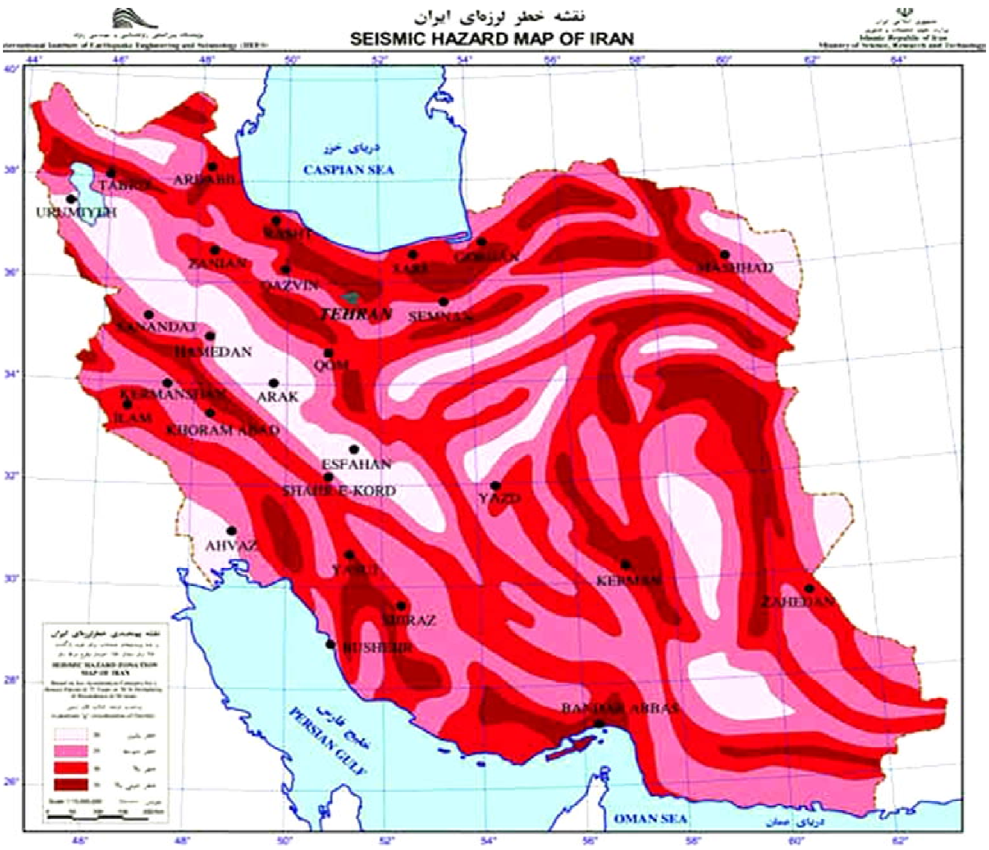


Figure 6. Comparison between the base accelerations of the Iranian seismic hazard map (4th edition of the Iranian seismic code) with those of the neighbor countries. This comparison shows that there is a relatively good agreement with countries located in the west and northwest of Iran, while there are some disagreements with the northeast and eastern neighbors [80].



(a)

Figure 7. (a) Iso-acceleration contour lines (PGA) for return period of 75 and 475 years, (b) seismic hazard zoning of Iran with four hazard zones [38].



(b)

Figure 7. Continue

Tehran and Dasht-e-Bayaz fault zones, while the lowest PGA were predicted for a narrow NW-SE band from Urmia to Esfahan and in the Central Lut zone. These maps were also published in the Global Seismic Hazard Assessment Program (GSHAP) [81-82] and are now available on the IIEES website (www.iiees.ac.ir).

In 2000, Moinfar et al. [83] prepared a new seismic hazard map for the implementation in the national physical planning of Iran. They used seismotectonic and seismological data to prepare a seismic source model consisting of the line sources (faults) and area sources. They also determined the seismicity parameters (β, annual rate and threshold magnitude) for the nine seismotectonic zones (Azarbaijan, Alborz, Central Iran, Kopet-Dag, Binalud, Western Zagros, Eastern Zagros, Lut and Makran) and also applied an attenuation model [84] in their seismic zonation study. By selection of a grid of 0.5°NÍ0.5°E, Moinfar et al. [83] calculated the PGA with return periods of 500, 1000 and 2000 years for sites located throughout the study region. Zoning maps were prepared in 1:1,000,000 scale. The range in computed acceleration values throughout the area is 0.14 to 0.64g for a 500-year return period; 0.19 to 0.72g for a 1000-year return period; and 0.24 to 0.80 g for a 2000-year return period. As shown in Figure (8), six zones were defined in the map of the region. The defined zones were rated as very high hazard (along the great North Tabriz

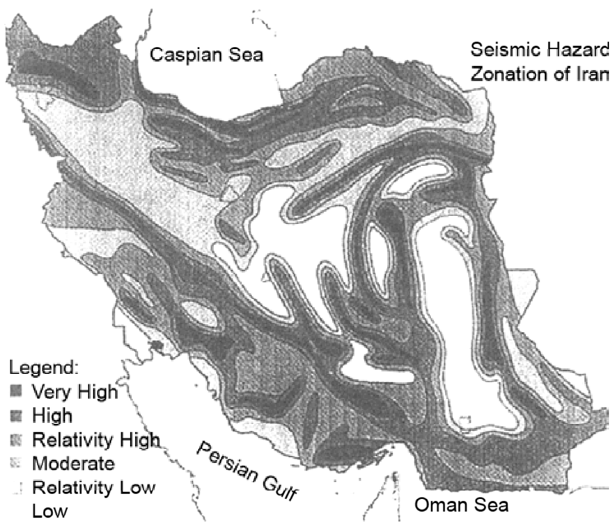


Figure 8. Seismic zoning map of Iran in terms of PGA [83].

fault and the main Zagros thrust fault), high hazard, relatively high hazard, moderate hazard, relatively low hazard, and low hazard.

In 2007, Mantyniemi et al. [85] used a new method called "parametric-historic" method [86-87] to map PGA, peak ground velocity (PGV) and peak ground displacement (PGD) in Iran. This method does not require any definition of seismic sources and/or seismotectonic zones and permits the use of both incompletely reported historical and complete instrumental earthquake catalogs as input data, considering the inherent magnitude errors and uncertainties of earthquake locations. Mantyniemi et al. [85] used 3345 earthquake main shocks in the time span of 734-2002 compiled by Zaré [59]. They also employed the Iranian attenuation relationships given by Zaré et al. [88]. By application of the parametric-historic approach, which combines features of both the deductive and historic approaches to the probabilistic seismic hazard assessment (PSHA), the final seismic hazard zoning map of Iran was prepared (Figure 9). This map specifies a 10% probability of exceedance of the given horizontal PGA values for an exposure time of 50 years, corresponding to a return period of 475 years. It should be noted that the new map does not show strong elongation of contours as previous works that were based on assumptions of seismotectonic units. In the new map of this study, the resulting PGA values are lower than those of previous works which can be due to a different methodology used.

With regard to earthquake risk mitigation programs and retrofitting of structures, infrastructures and lifelines, a new detailed seismic hazard analysis project was proposed by the President Deputy for Strategic Planning and Control of Iran. The main purpose of this project is to present a seismic hazard zoning map of Iran according to the DSHA and PSHA approaches as well as to study the national strong motion attenuation relations and to introduce a design spectra for the whole country. This project has been divided into seven phases to reach the mentioned purpose. The seven phases include the phase 1 (the Greater Tehran), phase 2 (Alborz ranges), phase 3 (northwestern Iran), phase 4 (eastern Iran), phase 5 (central Iran), phase 6 (South

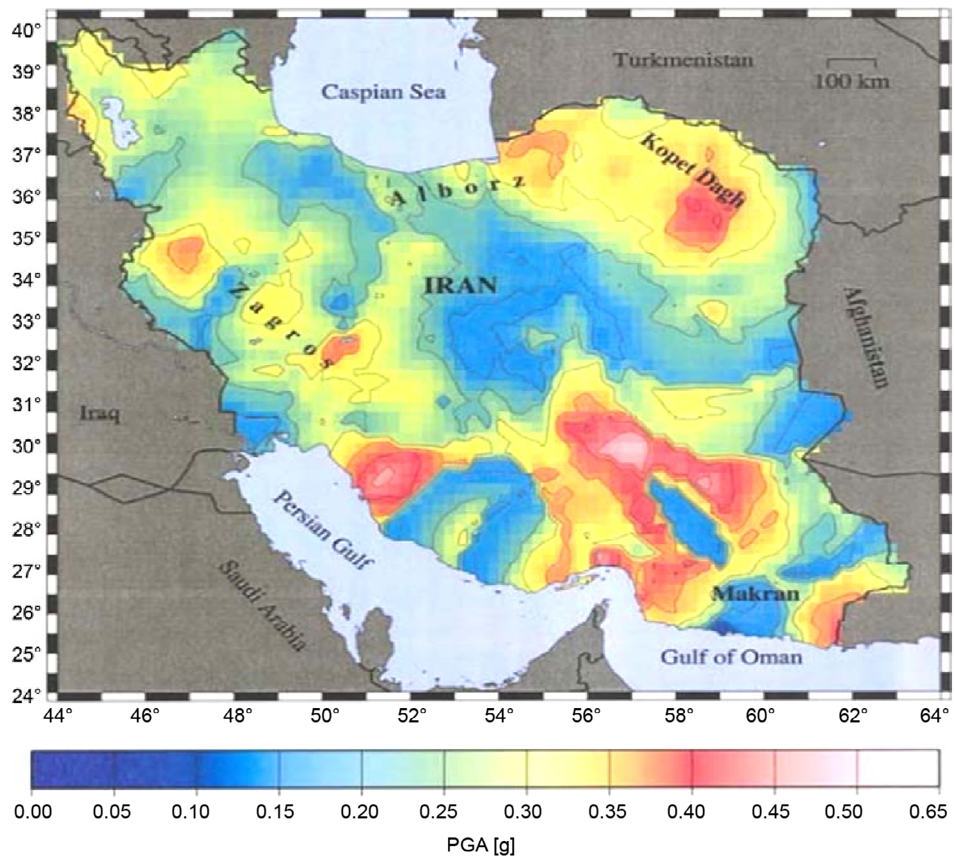
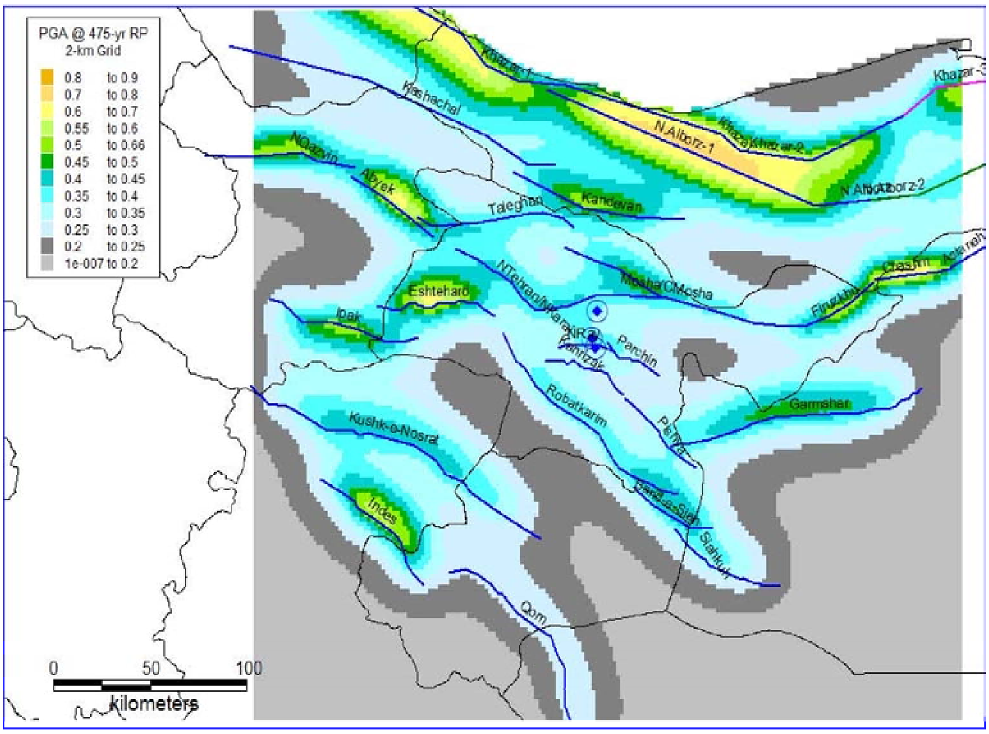


Figure 9. Seismic hazard zoning map of Iran in terms of PGA for the return period of 475 years based on the "parametric-historic" approach [85]..

Zagros) and phase 7 (combination of the results of the phases 1 to 6). Thus, the results of these areas will be further combined to derive a unique map for the country. Until now, the study on the first three phases (the Greater Tehran, Khorasan and Azarbaijan) have been completed. The first phase of the program (the Greater Tehran) has been published under the consideration of the Faculty of Engineering, University of Tehran [89]. At the first step of the seismic hazard analysis for the Greater Tehran region, the characteristic of the tectonic framework of the study area including the major faults and tectono-sedimentary basins were investigated. At the second step, the seismicity of the region including the historic earthquake catalog (pre-1900), the early instrumental catalog (1900-1963) and the modern instrumental catalog (1964-2007) was prepared and the completeness and accuracy of the data was determined. Then, the regional seismotectonic model including fault and area sources and their associated parameters like characteristic magnitude, maximum magnitude, slip rates, fault displacements, etc. were determined and seven proper attenuation relations were selected. Finally, the seismic hazard analysis was performed based on the PSHA approach. The seismic hazard zoning maps in terms of PGA and spectral accelerations (*Sa*) for the periods of 0.2, 1 and 3 seconds were prepared for the 75, 475, 1000 and 2475-year return periods. The maps assume a uniform site condition with average shear wave velocity of the top 30 meters, Vs30, to be equal to 150, 255, 525, 760 and 1070 m/s. The PGA hazard maps for the study region are shown in Figures (10- a, b, c). In addition, uniform seismic response spectra and simplified uniform spectra for 475-year and 2475-year return periods have also been presented in this work.

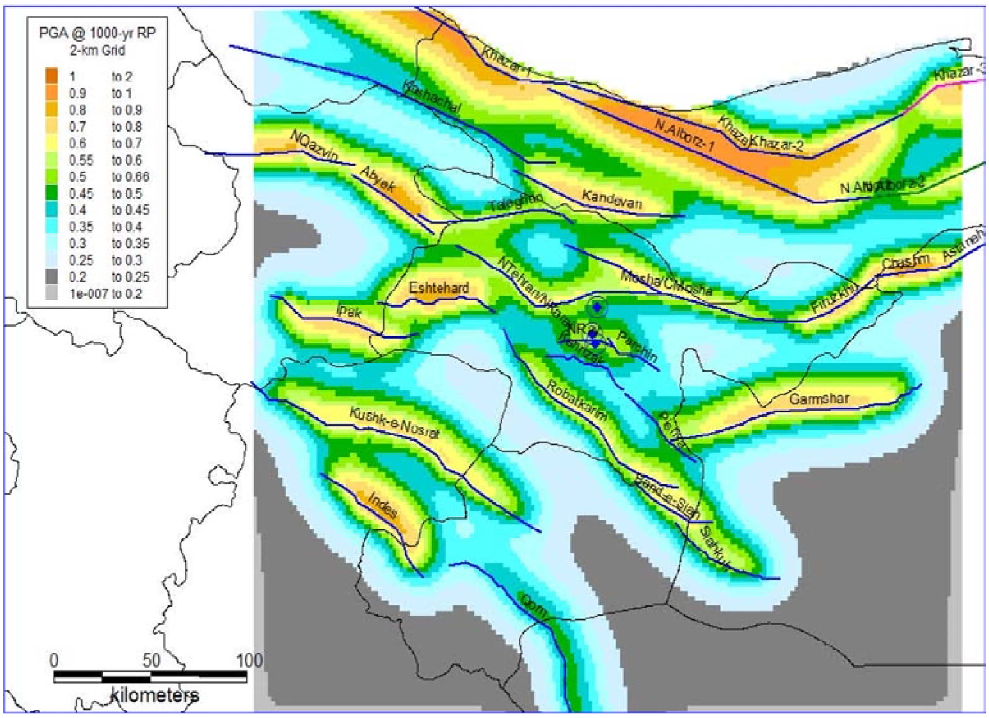
In order to develop an effective system for financial recovery and compensation through insurance and financial incentives as well as to reduce the risk of future developments of urban and rural area and increasing the safety level, Ghafory-Ashtiany and Naser-Asadi conducted a comprehensive study on earthquake premium index for buildings in Iran in 2011 [90]. As a part of their study, Ghafory-Ashtiany and Naser-Asadi provided earthquake hazard maps in terms of PGA with 475-year return period for different points of Iran as well as for all the counties of Iran (Figures 11- a, b).

Zaré [91] introduced a new seismic hazard map of Iran based on new seismic sources and seismotectonic zoning map of Iran, which includes

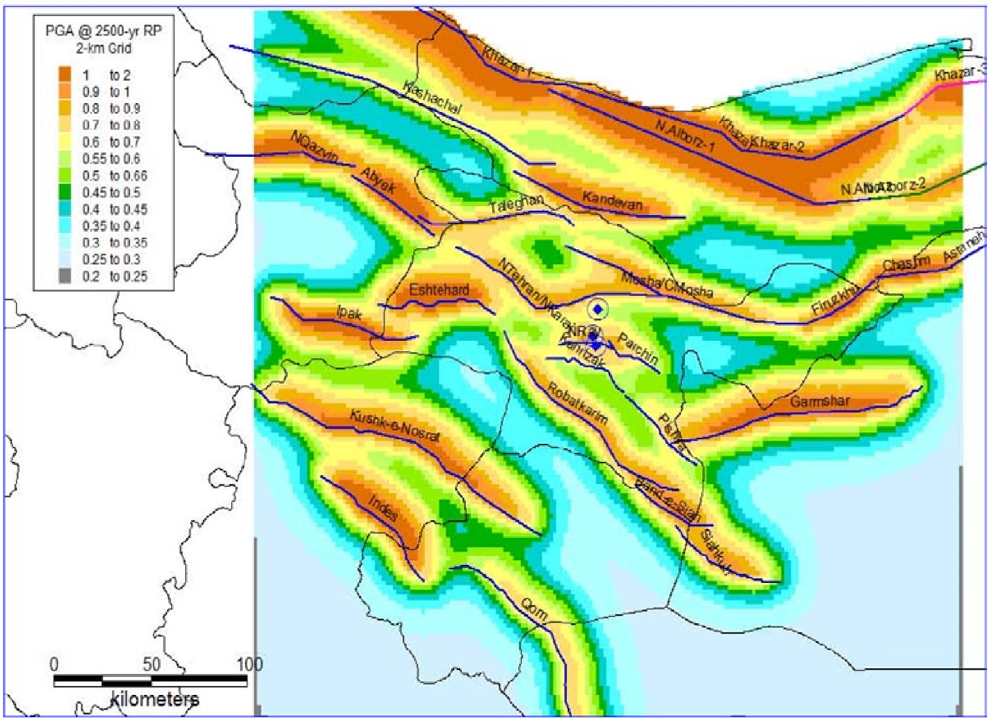


(a)

Figure 10. PGA maps for the greater Tehran region with 475-year return period: (a) 1000-year return period, (b) 2475-year return period, (c) [89].



(b)

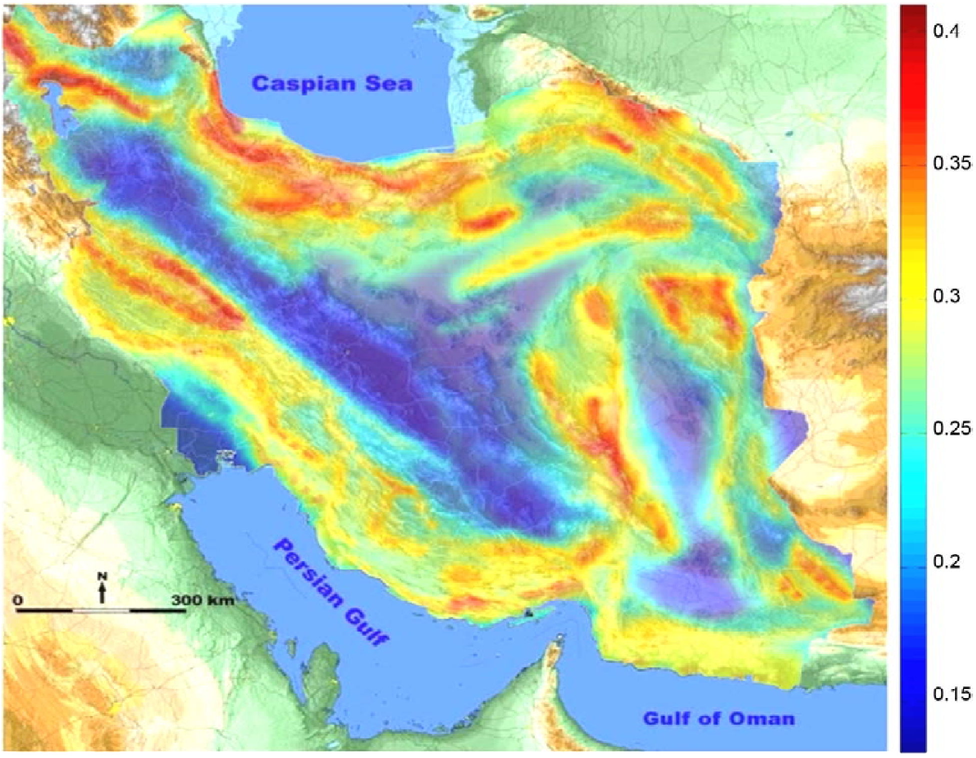


(c)

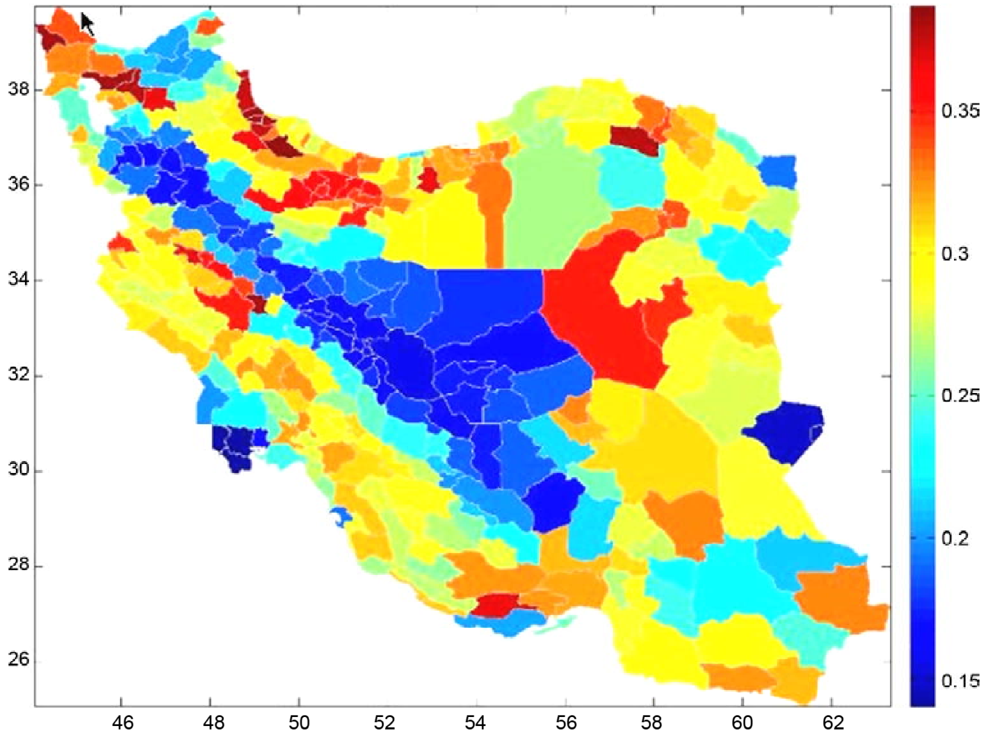
Figure 10. Continue

29 zones with different seismotectonic characteristics [44]. The determination of the borders of each zone was performed using the up-to-date geophysical and geodetic measurements such as seismicity catalog, active fault maps, magnetic intensity map, and topography data. The seismicity catalog used in this study contained both historical (734 BC-1900 AD) and updated instrumental data. It should be noted that magnitude and epicentral errors may be significant especially for the oldest observations. The magnitude uncertainties were assumed to be in the interval of ±0.25 magnitude units and epicentral errors ±30km. Although the errors associated with historical data may easily be much larger, these values were

chosen, because only about 5.5% of the data stems from the time prior to the mid-1960s. After the removal of dependent events using the method described by Gardner and Knopoff [92], the completeness of all seismotectonic zones were determined and the seismicity parameters were also evaluated. The magnitude completeness for most zones was around Mw4.0 except in Makran



(a)



(b)

Figure 11. Earthquake hazard map in terms of PGA for 475-year return period prepared for earthquake premium index evaluation for buildings in Iran [90] for: (a) different points of Iran, (b) counties of Iran.

coast that is M_w 4.5. This study employed the attenuation relationship given by Zaré et al. [88], which was the first based solely on accelerograms recorded inside the territory of Iran. Then, a new map was prepared according to new seismic source data and parametric method and the seismic hazard zoning map was provided with PGA values for a return period of 475 years in Iran (Figure 12). The hazard levels in Alborz and Azerbaijan based on

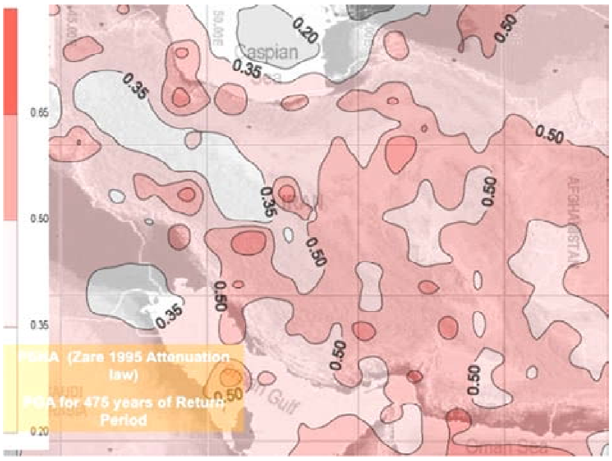
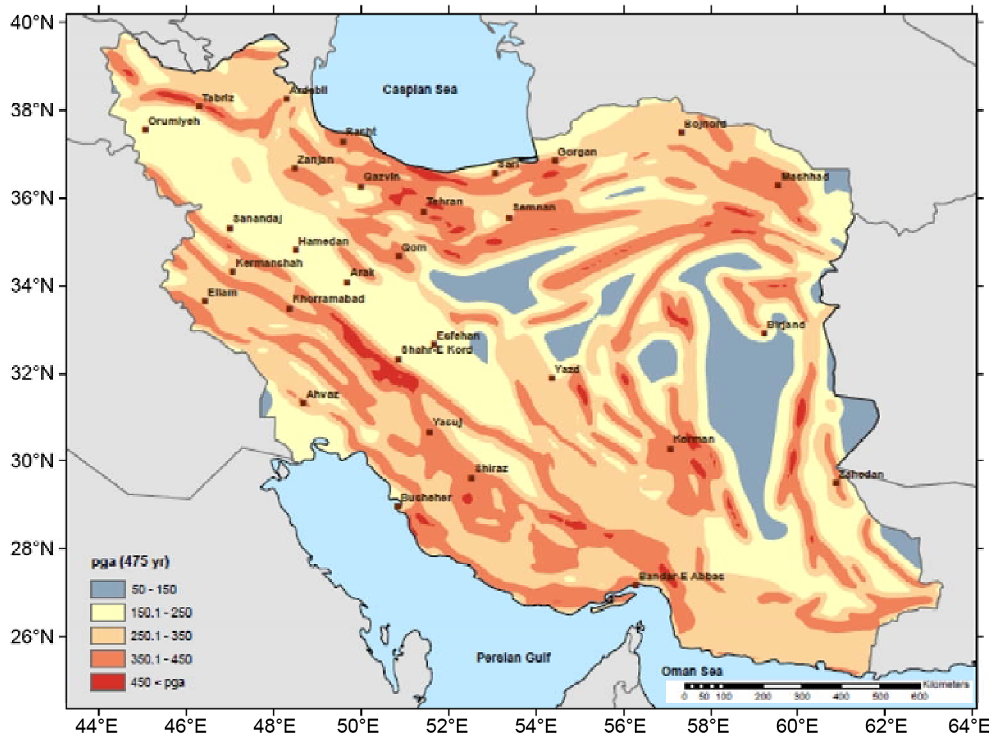


Figure 12. Seismic hazard zoning for Iran, using new seismic source data and parametric method and assessing PGA for 475 years of return period [91].

existing seismicity data might still seem to be a challenge to be discussed in the future; there is lack of recent seismicity; meanwhile, there are reported historical earthquakes. The new data showed that the revision in seismic hazard zoning maps in local and regional (nation-wide) scale is necessary.

Hamzehloo et al. [93] also developed new seismic hazard maps for Iran based on probabilistic earthquake hazard analysis. For the seismicity catalog, the IIEES database and the reports from Ambraseys and Melville [53] were used considering the moment magnitude (M_w) scale. In this respect, the authors estimated the seismicity parameters and the return period for different earthquake magnitudes using the Kijko [94] method that makes it possible to combine the information of the historical part of earthquake catalog with those of the instrumental part. On the basis of geological and seismological studies, Hamzehloo et al. [93] found 25 source zones in which seismicity parameters were estimated after omitting foreshocks and aftershocks from the catalog. In addition, they applied four attenuation relationships ([9], [95-97]) in their analysis. Figures (13- a, b, c, d) show the calculated PGA and spectral acceleration for the period of 0.2 sec maps for return

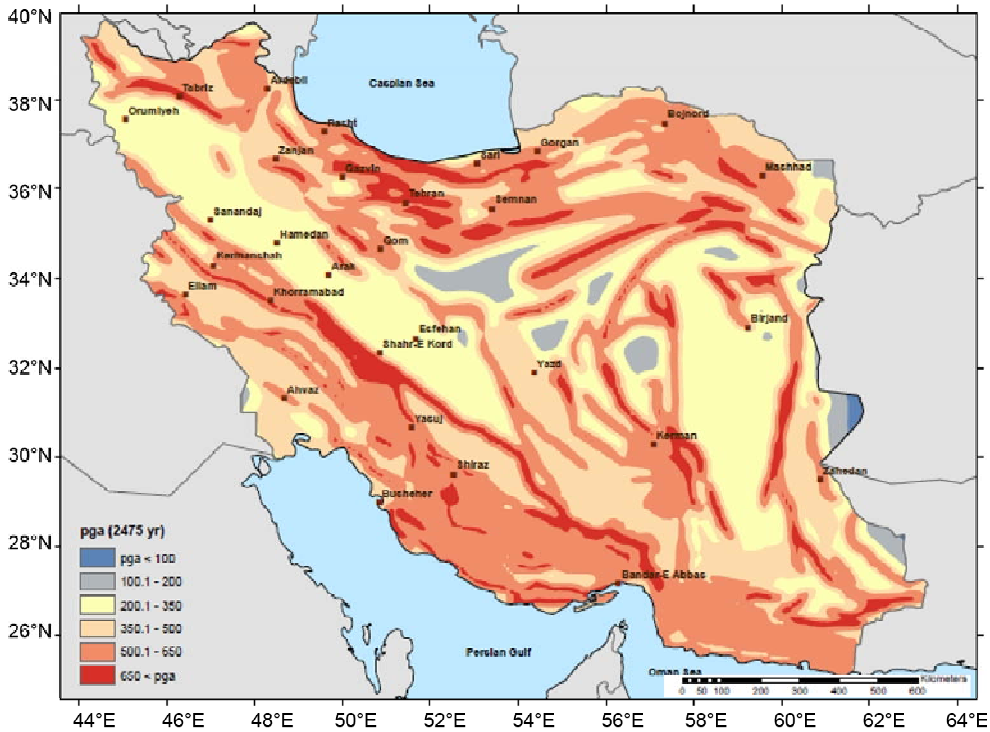


(a)

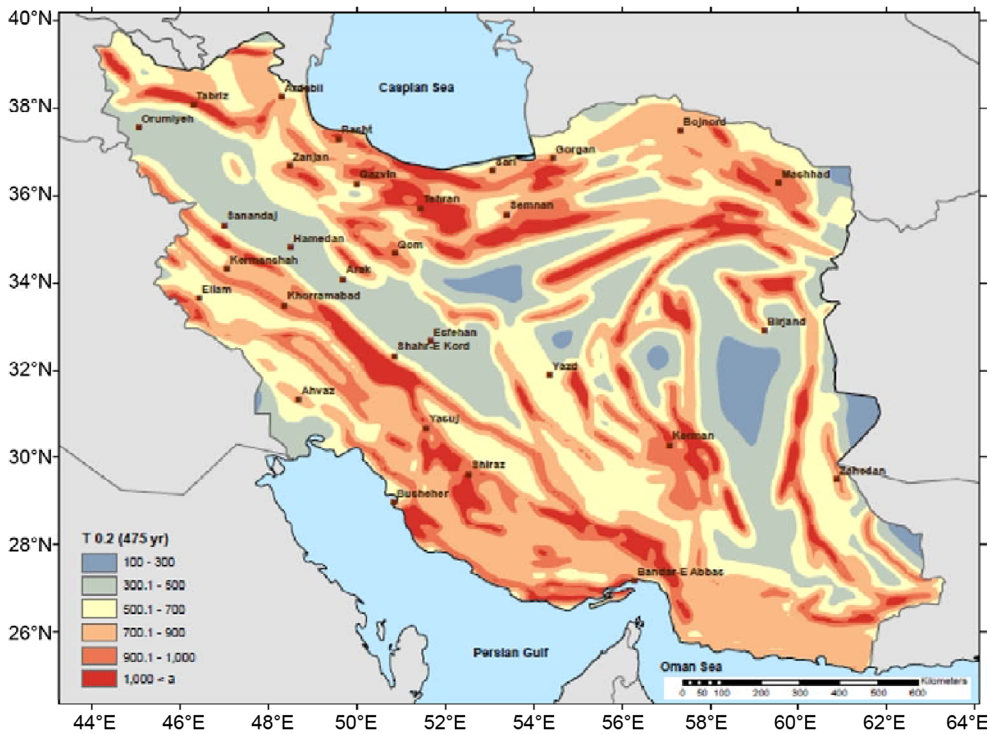
Figure 13. Seismic hazard zoning map of Iran consisting of a PGA map for 475-year return period: (a) a PGA map for 2475-year return period, (b) a spectral acceleration map for 475-year return period and the period of 0.2 sec, (c) a spectral acceleration map for 2475-year return period and the period of 0.2 sec, (d) [93].

periods of 475 and 2475 years. They also presented the disaggregation and uniform hazard plots showing the contribution of hazard for major cities in Iran.

Yazdani and Kowsari [98], for the first time, used the time-independent Bayesian probability method for seismic hazard analysis in Iran. The historical and instrumental earthquake data with surface magnitude 5.0 ≤ Ms were used in the prior estimation including 140 historical and 495 instrumental events (after the removal of the aftershock and foreshock). Prior estimation of the mean rate of earthquake occurrence seismic parameters was obtained in each

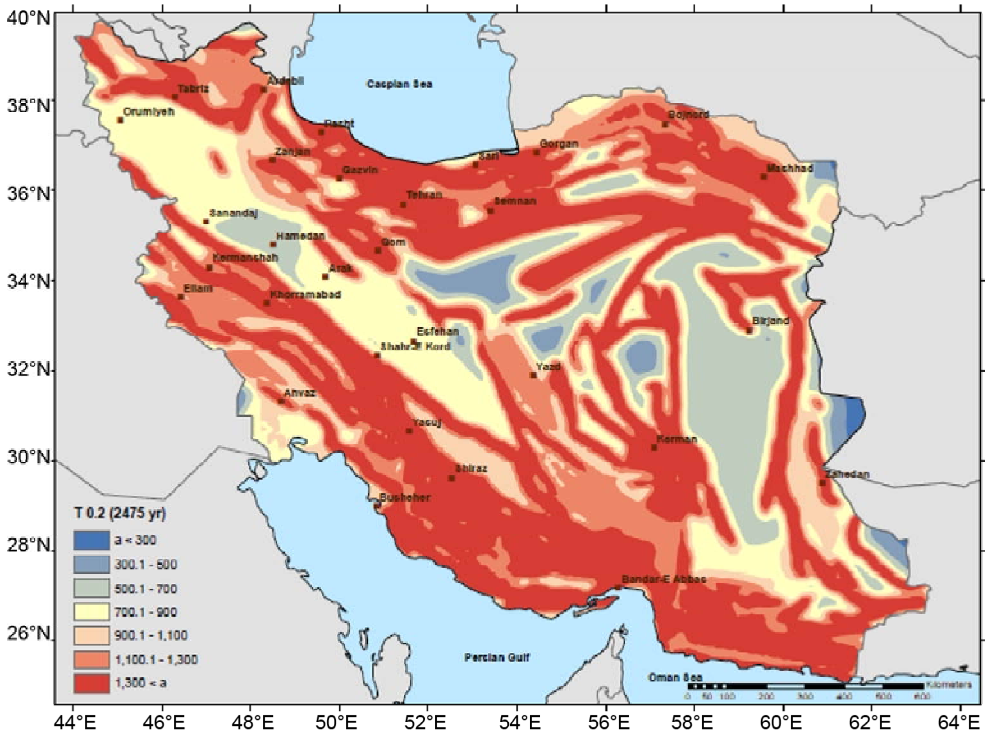


(b)



(c)

Figure 13. Continue



(d)

Figure 13. Continue

area using Kijko and Sellevoll method ([99-100]) in order to consider uncertainty by maximum likelihood estimation in the magnitude of recorded earthquakes and in the incomplete earthquake catalog. Then, the Bayesian approach was applied to calculate the probability that a certain cut-off magnitude would be exceeded at certain time intervals in different regions of Iran. They focused on 53 earthquakes with magnitudes above 6.5 from an instrumental catalog covering the time period of 1900-2011. The final seismic zoning maps were prepared using Bayesian approach for over 50 years and 100 years (Figure 14). The results for the cut off magnitude of 6.5 indicated that the highest probability of seismic hazard exists in the Alborz, Kopet-Dag, Bandar-Abbas, Kerman, and Zagros regions. Seismic hazard was assessed to be lowest for the Esfahan-Sirjan region, the Arabian Platform, the Persian Gulf, and Kavir in Central Iran.

In 2014, a comprehensive earthquake seismic hazard analysis was performed under the framework of EMME (Earthquake Model of the Middle East Region) project [101]. The EMME Project is a regional project under the umbrella of GEM (Global Earthquake Model) project. This project was started with the contribution of different scientific institutions including IIEES from Iran, Bogaziçi University, Middle East Technical University and Sakarya University from Turkey, University of Peshawar from Pakistan, Yarmouk University from Jordan, American University of Beirut from Lebanon, Ivane Javakhishvili Tbilisi State University from Georgia, National Academy of Sciences from Armenia, National Academy of Sciences from Azerbaijan, and ETHZ from Switzerland. In this project, a huge data containing earthquake historical and instrumental catalogs, seismogenic sources, seismotectonic zonings, strong motion catalogs, ground motion prediction equations, and model building were used in order to compute seismic hazard in the Middle East region. The PSHA approach and the existing source models were revised or modified by the incorporation of newly acquired data e.g. the EMME seismicity catalog [63] and seismogenic sources [102]. In 2014, a part of the GEM project was finished and new seismic hazard maps were released for a return period of 475 years for the Middle-East region (Figure 15). For more information, see http://www.emme-gem.org.

In 2014, Mousavi-Bafrouei et al. [103] published new PGA and SA hazard maps for Iran using modified probabilistic seismic hazard assessment.

As the input data, they used a unified declustered earthquakes catalog containing both historical and instrumental events from the 3rd millennium BC until late 2012 as well as an area source model that contains 238 potential seismic sources within five major seismotectonic provinces. They also determined the seismicity parameters and the background seismicity for each seismotectonic province. Then,

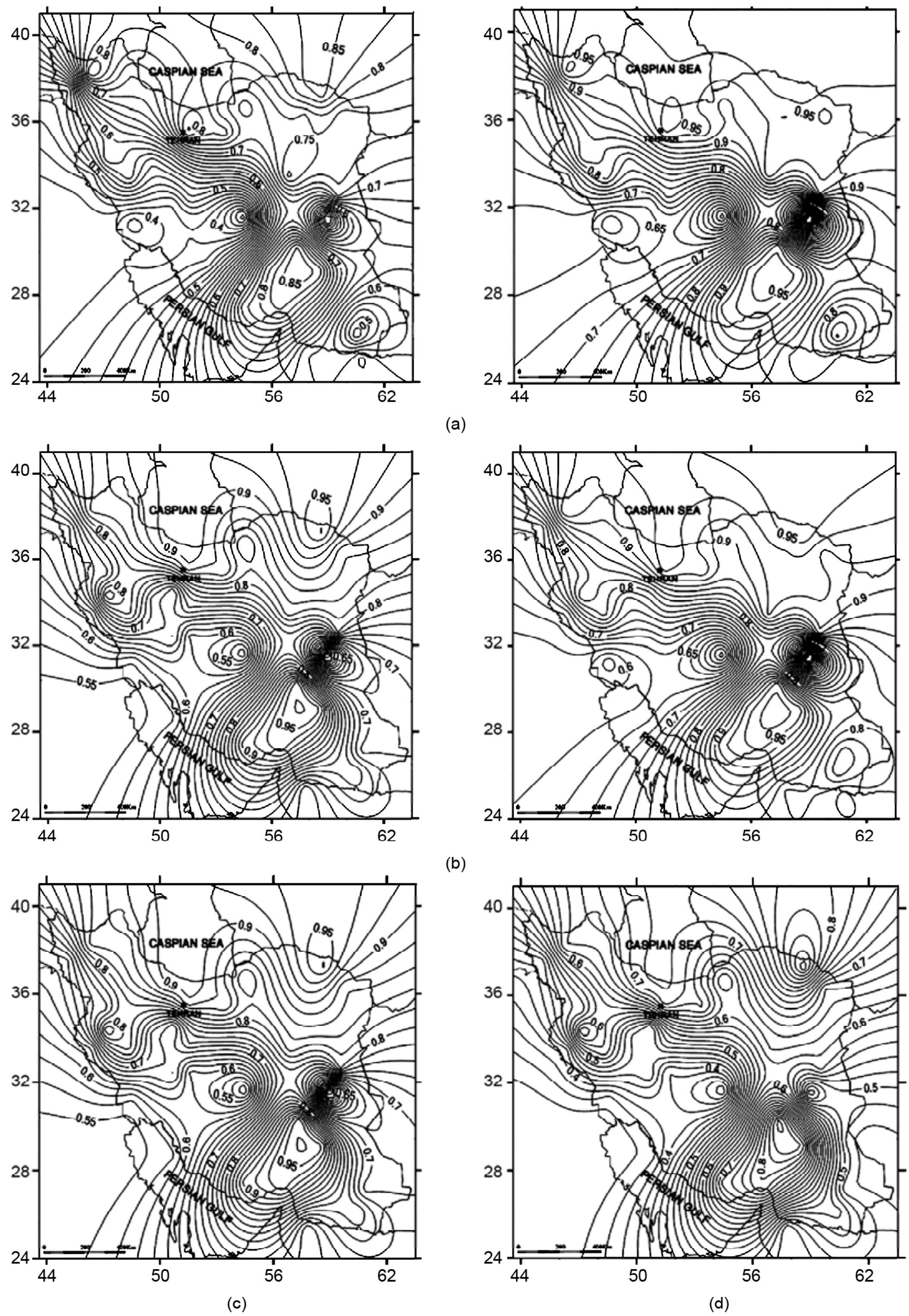


Figure 14. Left: Seismic zoning map of Iran (probability of exceeding minimum magnitude bounds) using the Bayesian approach over 50 years: (a) The coefficient of variation of 0.1 for prior information; (b) the coefficient of variation of 0.25 for prior information; and (c) the coefficient of variation of 0.5 for prior information. Right: Seismic zoning map (probability of exceedance) of Iran using the Bayesian approach for 100 years: (a) The coefficient of variation of 0.1 for prior information; (b) the coefficient of variation of 0.25 for prior information; and (c) the coefficient of variation of 0.5 for prior information [98].

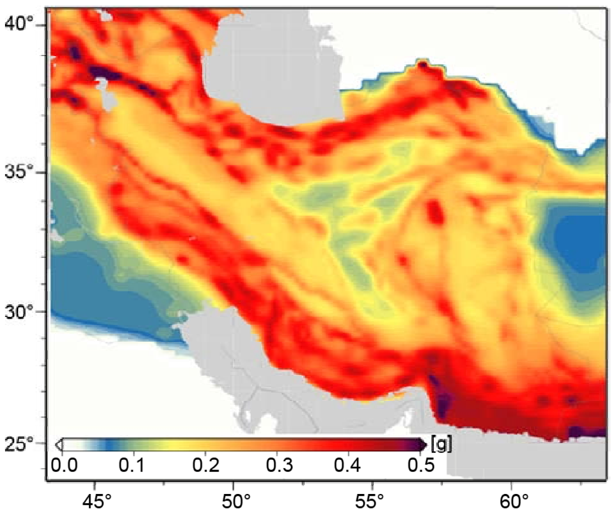


Figure 15. Seismic hazard map for the 475-year return period prepared in the framework of the EMME project [101].

seismic hazard assessment of Iran for a grid of over 40,000 points with 10 km interval was carried out using OpenQuake software as well as by application of three different ground motion prediction equations [104-106] and two models of seismicity for potential seismic sources in a logic tree. Finally, Mousavi-Bafrouei et al. [103] calculated the PGA and SA for 5% damping ratio at 0.2 and 2 seconds corresponding to 10% and 63% probability of exceedance within 50 years (475-year and 50-year mean return periods, respectively) (Figure 16). They found the maximum and minimum PGA for 475-years return period to be 0.63g in North-East of Lorestan and 0.1g in central Iran, respectively. They also compared their results with the last version of the seismic hazard map in Standard No. 2800 [79] and showed significant

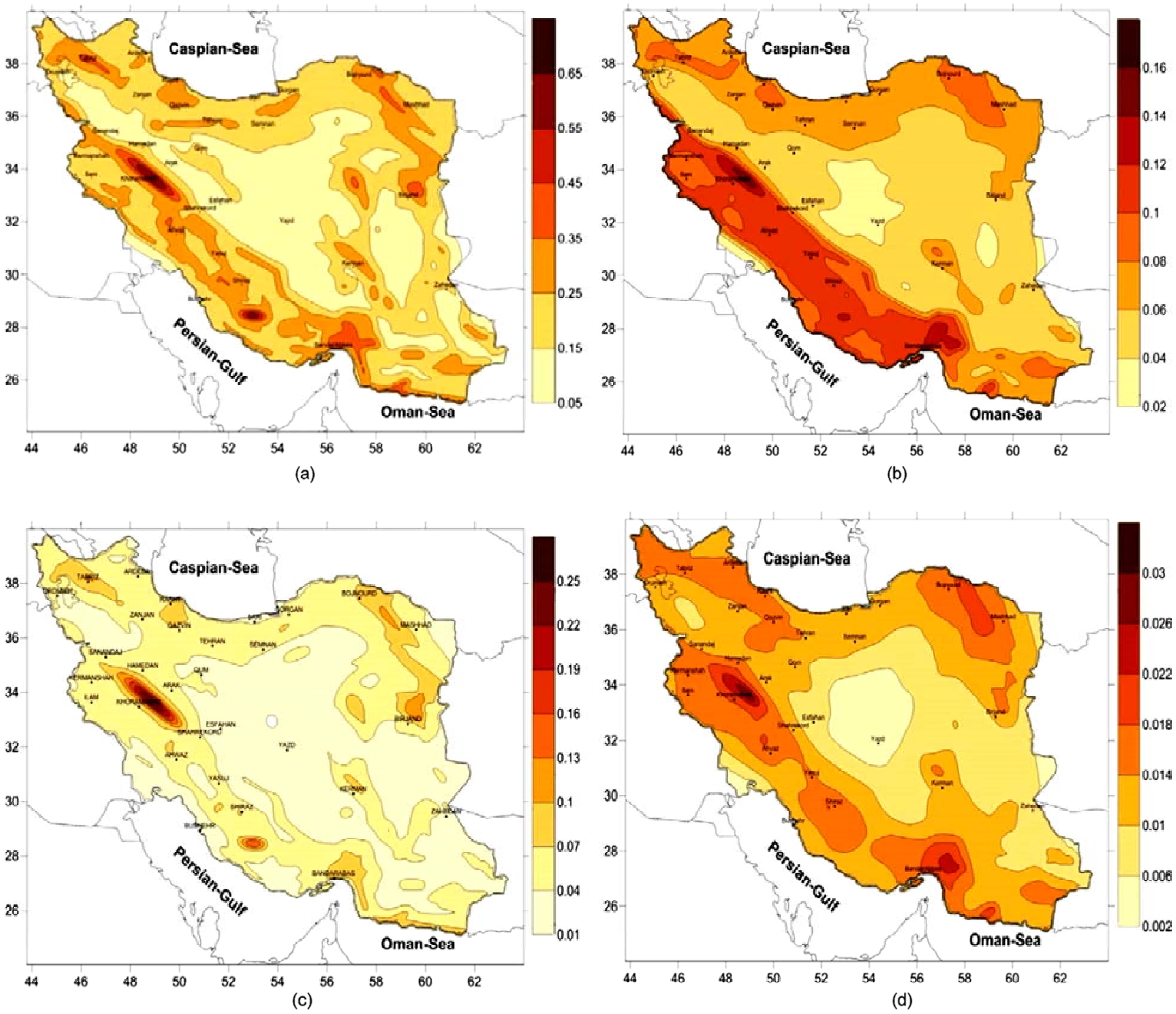


Figure 16. Seismic hazard zoning map on bedrock level. (a) PGA for 475-year return period, (b) PGA for 50-year return period, (c) spectral acceleration for 2-second period and 475-year return period, (d) spectral acceleration for 2-second period and 50-year return period, (e) spectral acceleration for 0.2-second period and 475-year return period, (f) spectral acceleration for 0.2-second period and 50-year return period [103].

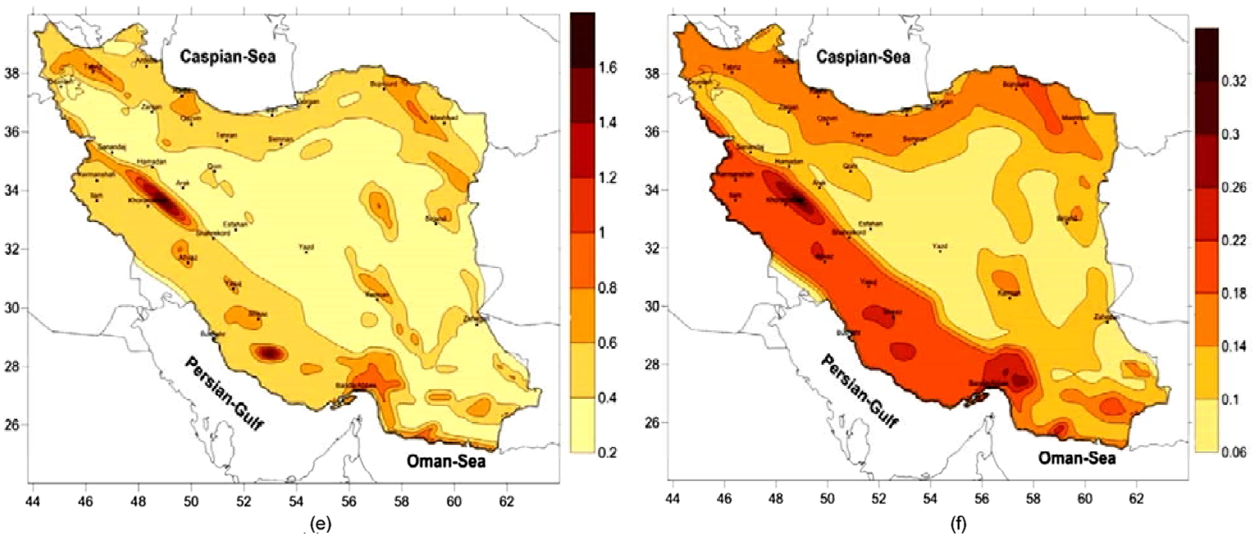


Figure 16. Continue

differences, so that seismic hazard levels estimated in this study for the southern Iran, Sistan-Baluchestan, Hormozgan and Fars provinces, indicated significantly higher values.

The most recent seismic hazard map of Iran has been developed by Karimiparidari [107] using the most recent comprehensive data and PSHA approach. In this regard, a homogeneous earthquake catalog of Iran developed by Karimiparidari et al. [61] was used, which includes the Iranian events in terms of the uniform moment magnitude (M_w) with the range of M_w 3.5-7.9 from the 3rd millennium BC to April 2010. This covers a wide time span of earthquake history and contains uniform scaled magnitudes. Karimiparidari also developed new seismic source models and seismotectonic zoning map of Iran [44] in her study. The seismotectonic models were developed based on the latest data of active tectonic, topography, magnetic intensity and seismicity catalog. These new maps divide the area of Iran into 27 seismotectonic zones and demonstrate two models for linear and regional seismic sources. Modification and computation of the local coefficients of the space-time windows in the well-known window algorithm developed by Gardner and Knopoff [92] was also performed in the research by Karimiparidari [107]. The updated temporal and spatial windows were applied to the seismic catalog in different seismotectonic zones of Iran. After declustering, the seismic catalogs were found to follow a Poisson distribution in all the studied zones based on the results of the statistical Kolmogorov-Smirnov test. The same test on times between successive declustered events showed that the inter-event times of all catalogs follow an exponential distribution. Following the removal of foreshocks and aftershocks, the magnitude of completeness of each seismotectonic zone was established for the entire time span of the catalog. Karimiparidari [107] also compared available strong motion attenuation relations in order to select proper models and weighted them using a logic tree. In this respect, six attenuation models ([9], [104], [108-111]), which had the best coincidence to the Iranian data were used to conduct the PSHA. Then, a grid network with 0.2Í0.2 square kilometers cells in the area of study was taken into account and seismic hazard zoning map of Iran with 475-year return period was prepared using CRISIS2007 software and Kriging interpolate method (Figure 17). Karimiparidari [107] also compared her results with some previous works. She showed that the calculated seismicity parameters in her study agree to some extent with the results of the study by Tavakoli and Ghafory-Ashtiany [38], while considering the application of two different seismotectonic zoning models and two different threshold magnitudes in these studies, it is not easy to compare seismicity parameters, accurately. In addition, results of her study were compared to other studies such as Iranian research center of urban planning and architecture [112], Tavakoli and Ghafory-Ashtiany [38], 3^{rd} edition of Standard No. 2800 [78] and Hamzehloo et al. [93] for some important and earthquake-prone cities of Iran. Karimiparidari [107]

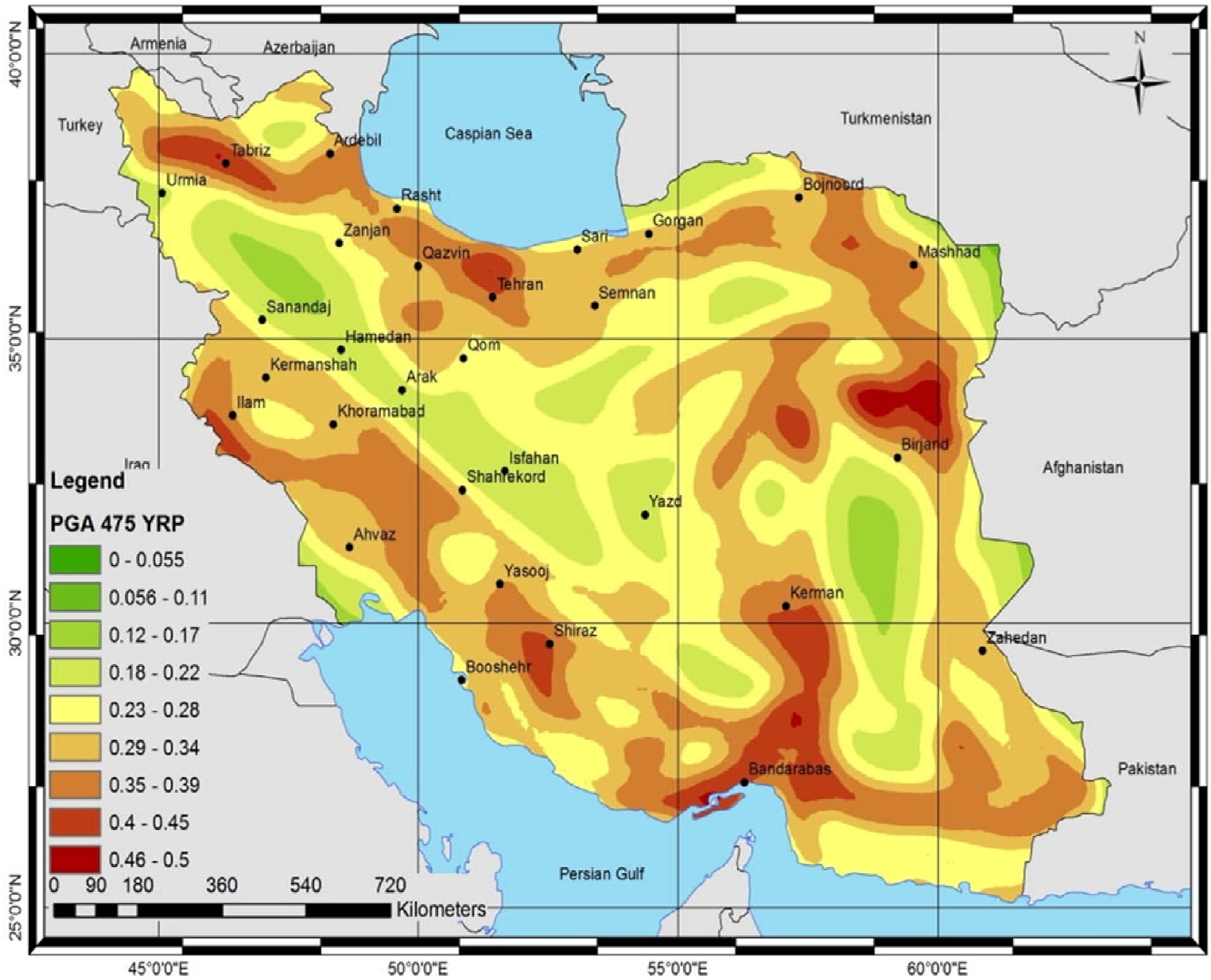


Figure 17. The latest seismic hazard zoning map of Iran in terms of PGA for 475-year return period [107].

found the maximum acceleration to be about 0.5 g, while it was calculated 0.5 g, 0.45 g, 0.35 g, 0.46 g in the studies by Iranian research center of urban planning and architecture [112], Tavakoli and Ghafory-Ashtiany [38], 3rd edition of Standard No. 2800 [78] and Hamzehloo et al., [93] respectively. In the all seismic hazard maps, the city of Tabriz shows the highest acceleration. In this study, the PGA of Tehran was calculated 0.36-0.4 g for 475-year return period, which is more than the acceleration calculated by Iranian research center of urban planning and architecture [112] and 3rd edition of Standard No. 2800 [78], while it is less than the acceleration calculated by Tavakoli and Ghafory-Ashtiany [38] and it is close to the acceleration calculated by Hamzehloo et al. [93].

3. Discussion

In the previous section, the most important seismic hazard zoning maps of Iran were reviewed briefly. One may ask that why we have so many seismic hazard maps? And which one is a better reflect of the hazard levels in Iran?

In response to the first question, it should be noted that the seismic hazard maps of a particular region should be revised frequently along with producing new data as earthquakes occur and adding more information about the seismicity and seismotectonic conditions of the region as it becomes available. On the other words, the development of seismic hazard maps strongly relies on the development in other areas such as the completeness of datasets, methodologies, accuracy of the input data and our level of knowledge about the seismic source parameters (e.g. fault geometry and mechanics, return periods of large and destructive earthquakes, paleoseismological data, archaeological information, etc.). Indeed, one of the reasons for having so many seismic hazard maps is the development of seismological data and active tectonics in Iran that leads to different seismic zoning maps.

In response to the second question, it should be mentioned that, in fact, with respect to the different data, methodology, and strategies used for each seismic hazard map of Iran, all the maps are valuable in their kind, and these maps propose various types of ground motion or intensity information to their users. However, in general, the recent versions of the maps would offer more accurate information, since they have been produced based on the latest achievements about seismicity data, seismotectonic conditions, and methodology especially by consideration of uncertainties in different stages of the hazard analysis. In Table (1), a general comparison is shown between the different databases and methodologies used as well as the output hazard parameters for different seismic hazard studies of Iran during the last four decades. According to the table, by moving over the time from the first study by Neghabat and Liu [1] toward the last study by Karimiparidari [107] and checking the items, the progress is clear in updating the seismic catalogs and employing different input data e.g. earthquake catalogs, active fault maps, seismotectonic models, seismicity parameters, attenuation models and uncertainty treatments. Considering this issue, it seems that the recent works by Karimiparidari [107] and the EMME project [101] are currently more proper studies than others.

In addition, there are still continuous challenges associated with seismic hazard maps both in the world and in Iran. Scientific model's predictions should be continuously validated by observations. Recently, some destructive earthquakes such as the 2011 Tohoku (M_w = 9.1), 2008 Wenchuan (M_w = 7.9) and 2010 Haiti (M_w = 7.0) have occurred in the areas that were predicted to be relatively safe by the existing hazard maps. This indicates that in some cases, earthquake hazard maps may clearly fail to predict the actual strong motions. Stein et al. [113] mentioned a number of factors by which errors can emerge in seismic hazard maps. These factors are bad physics, bad assumptions, bad data and bad luck.

After some destructive earthquakes in Iran (such as the 1978 Tabas (M_w = 7.4), 1990 Manjil (M_w = 7.4) and 2003 Bam (M_w = 6.5) earthquakes), there are some discussions on the reliability of the seismic hazard zoning maps and a comparison between the recorded and the previously assessed ground motions. For example, an unexpected situation was observed during the September 16, 1978, M_w 7.4 Tabas earthquake in which about 15,000 people were killed. A big challenge related to this earthquake was that, before the earthquake, we did not recognize the causative fault which could generate such a great catastrophic event. According to Berberian [114], the earthquake ruptured the unmapped and unknown Tabas thrust fault at the western Neogene foothills of the Shotori Mountains.

The errors in prediction draws attention to the questionable efficiency of the existing seismic hazard maps and emphasize on the necessity to revise such maps continuously based on updated data and improved methods. Although there are fairly good recorded historical and instrumental data in Iran and there are also good studies on some critical active faults of the Iranian Plateau (e.g. studies on, GPS, seismicity rates and paleoseismic of North-Tehran [115], North Tabriz and Mosha faults), more investigation such as paleoseismic investigations and evaluation of seismic capability of all major active faults as well as identification of blind faults are still a matter of concern.

Although in case of lack of complete knowledge about different hazard parameters (e.g. long return periods of earthquakes, unknown characteristic of seismic sources, etc.) different levels of error are unavoidable, it should be considered that many of the seismic hazard maps have been prepared only for ordinary buildings not for special structures (tall buildings, power plants, dams, etc.). These maps have been prepared only for a special return period on the bedrock and are not site-specific maps, and they also do not consider special conditions like site effects, near-field effects (e.g. forward and backward directivity, fling step, pulse-like motions). Therefore, the difference between the predicted hazard levels with actual hazard levels emphasizes on the necessity of revision and evaluation of the efficiency of the previous hazard maps in order to determine that to what extent these maps are acceptable and to what extent they may contain large errors. In should be also noted that, in seismic hazard assessments, it is a common practice to consider the 'ground shaking' that includes the calculation of strong motion at the bedrock level or at the ground surface based on site effects, while

Table 1. Databases, methodology and output parameters used in different earthquake hazard zoning studies of Iran. Note that for the column 5 to 9, if the input data for the analysis were available, there is ✓, otherwise there is ×.

No	Study	Year	Earthquake Catalog	Active Fault Map	Seismotectonic Model	Seismicity Parameters	Attenuation Model	Uncertainty Calculation	Method	Hazard Parameter
1	Neghabat and Liu [1]	1977	1900-1970; $4.0 \le M_R$	×	✓	✓	✓	×	Maximum Probable Intensity	I_{20} - I_{100} - I_{500} - I_{2500}
2	Berberian and Mohajer-Ashjai [2]	1977	400 BC-1900; $6.0 \le M_R$ 1900-1977; $3.0 \le M_R$	✓	✓	×	×	×	Maximum Deterministic Intensity	I_{Max}
3	Mohajer-Ashjai and Nowroozi [73]	1978	1900-1977; $5.3 \le M$	✓	✓	×	×	×	Observed/Calculated and Probable Intensities	I_{obs} , I_{prob}
4	Berberian [28]	1981	400 BC-1900; $6.0 \le M$ 1900-1980; $3.0 \le M$	✓	✓	×	×	×	Probable Intensity	I_{prob}
5	Bozorgnia and Mohajer-Ashjai [3]	1982	1900-1981	✓	✓	✓	✓	×	PSHA	PGA_{20} - PGA_{50}, PGA_{100} - PGA_{150}, PGA_{200} - PGA_{500}, PGA_{1000} - $PGA_{10,000}$
6	Nowroozi and Ahmadi [75]	1986	1900-1976	×	✓	✓	✓	×	Probabilistic	Mean Return Periods for Several Magnitudes, I_{prob}, PGA
7	Tavakoli and Ghafory-Ashtiany [38]	1999	Pre1900 1900-1997	✓	✓	✓	✓	×	PSHA	PGA_{75} - PGA_{475}
8	Moinfar et al. [83]	2000	-	✓	✓	✓	✓	×	PSHA	PGA_{500} - PGA_{1000} - PGA_{2000}
9	Mäntyniemi et al. [85]	2007	734 BC-1900; $4.0 \le M$ 1900-2002; $4.0 \le M$	×	×	✓	✓	✓	Parametric-Historic	PGA_{475}
10	Gholipour et al. [89]	2008	850-1900; $5.5 \le M$ 1900-2007; $3.5 \le M$	✓	✓	✓	✓	✓	PSHA	PGA_{75} - PGA_{475}, PGA_{1000} - PGA_{2475}, SA_{75} - SA_{475} - SA_{1000}- SA_{2475}
11	Iranian Seismic Code for Buildings (4th Edition) [79]	2012	400 BC-2011; $4.5 \le M$	✓	✓	✓	✓	×	PSHA	PGA_{475}
12	Zaré [91]	2012	734 BC-1900; $4.0 \le M$ 1900-2012; $4.0 \le M$	×	✓	✓	✓	✓	Parametric	PGA_{475}
13	Hamzehloo et al. [93]	2012	Pre-1900 1900-2012	×	✓	✓	✓	×	PSHA	PGA_{475} - PGA_{2475} SA_{475} - SA_{2475}
14	Yazdani and Kowsari [98]	2013	700 BC-1900; $5.0 \le M_s$ 1900-2011; $5.0 \le M_s$	×	✓	✓	×	✓	Bayesian Probability Estimation	Probability of Exceeding a Magnitude of 6.5 over 50 and 100 Years
15	EMME project [101]	2014	1250 BC-2006; $4.0 \le M_w$	✓	✓	✓	✓	✓	PSHA	PGA_{475}
16	Mousavi-Bafrouei et al. [103]	2014	3rd Millennium BC-2012; $4.0 \le M_w$	×	✓	✓	✓	✓	PSHA	PGA_{50} - PGA_{475} - SA_{50} - SA_{475}
17	Karimiparidari [107]	2014	3rd Millennium BC-2010; $3.5 \le M_w$	✓	✓	✓	✓	✓	PSHA	PGA_{475}

M_R= magnitude on the Richter scale; I_{Max}= maximum intensity; I_{obs}= observed intensity; I_{prob}= probable intensity;

PGA_i= peak ground acceleration with i-year return period; SA_i= spectral acceleration with i-year return period.

the 'ground deformation' in terms of secondary earthquake-induced phenomena (e.g., landslides, subsidence, liquefaction, etc.) can also be included as an important factor in the future seismic hazard analysis.

4. Conclusions

In this study, the development history of the most important seismic hazard zoning maps of Iran from 1977 until 2015 was reviewed. During the first years of the last four decades, the seismic hazard zoning studies mostly focused on deterministic earthquake intensity approaches. On the basis of the development of strong motion data, attenuation relations and probabilistic methods, the deterministic intensity method was replaced by the probabilistic acceleration approaches. Most of the recent seismic hazard analysis in Iran were conducted based on PSHA method, meanwhile, some other mathematical/statistical algorithms were also rarely used.

Although the deterministic and probabilistic PGA methods are efficient, some other modern seismic hazard analysis approaches are currently proposed such as spectral analysis, neo-deterministic and realistic acceleration approaches. Further studies should focus on the new approaches and the development of spectral zoning maps. Focus should be also made on the M_{max} assessment and historical data. There are currently some published spectral acceleration hazard maps (e.g. [93] and [103]) and a comprehensive study is under preparation by IIEES. The future trend in earthquake hazard mapping seems to cover the intensity assessment, realistic acceleration and the neo-deterministic approaches, time-dependent mapping, intelligent updating of maps as well as the development of site specific hazard analysis for Iran based on the more detailed and integrated databases and calculations.

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