New Iranian Seismic Hazard Zoning Map for New Edition of Seismic Code and Its Comparison with Neighbor Countries

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SUMMARY
Seismic hazard zoning map of the new edition of the Iranian code for earthquake resistant design of buildings was revised following a detailed study on seismicity, seismic sources, and strong motion data. The main objective was to update a map for design base acceleration on seismic bed rock for a return period of 475 years. Upon completion of the map, a comparison was made between the updated map with those of the neighbour countries. Overall 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 neighbours. This paper presents the methodology of updating the new Iranian seismic hazard map and its comparison with the neighbour countries. A future collaboration between the countries in the region can aim to develop a unified seismic hazard zoning map for the region and the Middle East countries.

Keywords: Iranian seismic code, Iranian seismic hazard map, Middle East countries seismic hazard maps

1. INTRODUCTION

Iran has a long history of seismicity and has experienced destructive earthquakes since ancient times. As an average, earthquakes take several thousands of lives and cause extensive damage to properties in Iran almost every year. Most damages and casualties occurred mainly in rural areas in the past, but it has also been observed in urban areas in recent decades. Expansion of urbanisation has increased the vulnerability against earthquakes in Iran in recent history. Earthquakes of 1968 Dasht-e Bayaz (Ms 7.2) and its strong aftershock (Ms 6.3) in Ferdows, 1978 Tabas (Ms 7.3), 1990 Manjil (Mw 7.3), and 2003 Bam (Mw 6.6) are just some examples of earthquakes in urban areas in Iran in recent decades.

Iranian seismic code was first introduced following the 1962 Buin-Zahra (Ms 7.2) earthquake and was appeared in the second edition of the World List in 1965. The code has been revised almost every 6 years since its first edition. The last revision took place in 2012.

The Iranian seismic code has a permanent committee who is responsible to update it when necessary. The committee has several sub-committees from which seismic zoning is one of them. This sub-committee consists of different disciplines such as geology (tectonic), seismology, and earthquake engineering. The sub-committee takes advantage of other disciplines such as sociology and economy when needed. It took about two and a half years to complete this last version of the code and its seismic hazard zoning map. This paper presents the outcome of the sub-committee's research and findings which ended to a revised seismic hazard zoning map of Iran.

Except the first edition, all other codes have accompanied a seismic hazard map. All maps have been prepared based on the study on relative seismic hazard zoning taking into consideration of different seismicity of the country's vast area (over 1.6 million square kilometres).

In order to prepare the last version of the map, it was necessary to carry out a comprehensive study on some disciplines, or revise some important aspects such as tectonic of different parts of the country, active fault map, seismic sources, earthquake epicentres, recorded strong motion data, and the case studies performed on seismic hazard analysis for important structures' sites such as dams and power plants.

Details of the above studies are described in the paper and the fact that how they aimed to prepare this last version of the Iranian seismic hazard zoning map. Finally, a comparison is made between the revised map with similar maps of the neighbour countries.

2. A NEW COMPILATION OF FAULT MAP OF IRAN

Geological studies have been carried out for different parts of Iran by different groups since 1950's. During this period, geological maps as well as fault maps have been prepared by many researchers. Among others are Nabavi, Berberian, Noroozi, Nogol, and Hesami. Since the studies have taken place by different groups independently, the prepared maps in some regions do not necessarily match with each other. Although some researchers have published maps for the whole country but they needed revision for complete agreement. Therefore, an updated fault map of Iran was prepared by the efforts of the seismic zoning sub-committee which reflects the valuable works of many researchers in about six decades.

Fault maps that have been compiled for Iran up to now have some differences, lacking, and unequal views. Among others, inequalities, especially on fault length are quite significant. Therefore, in order to have a unified map, the seismic zoning sub-committee decided to compile a revised fault map for Iran. The scale of the map is 1:1,000,000 and is based on the 4-sheet map of the Geological Survey of Iran. In compilation of the map, the following aspects were adapted:

1) Faults with over 20 km in length are mapped.
2) Use only those faults which are published in geological maps with the scale of 1:100,000 to 1:250,000 and avoid inferred and questionable faults.
3) As far as known, the mechanisms of faults are presented.
4) The magnetic basement lineaments were not taken into consideration.

Many maps as well as satellite images were studied and used for compilation of the revised fault map of Iran. Among others and the most important ones were the geological map of Iran (1:1,000,000) by Sahandi and Soheili, and the tectonic map of Iran (1:1,000,000) by Nogol which was the base of the compiled map.

Faults that are appeared in the map were categorized according to their importance to seismogenity based on the following five criteria:

1) Observed earthquakes faults since the beginning of the twentieth century
2) Capable (quaternary and seismogenic) faults
3) Faults on boundaries of mountains and plains
4) Faults which do not have indication of any movement in quaternary
5) Concealed faults

About 700 faults were mapped taking into consideration of above criteria. A special symbol was used for those faults whose mechanisms are known. A unified method was used to adapt a single name for those faults that are appeared with different names in the published maps. Also, all faults without names in other maps are identified by numbers in the revised map.

A table consisting of all faults with their relevant information and also details of all other information not covered here are presented in the seismic zoning sub-committee's report in Farsi (Persian) language.

The updated fault map has created an acceptable correlation among the past studies and existing fault maps. Fig. 1 shows the new fault map which was used as a base map for the sub-committee's studies. This map played an important role in revising the seismic hazard map of Iran.

3. SEISMICITY

The first seismicity map of Iran was prepared by Abdalian (1960) following the 1960 Lar earthquake (Ms 6.5) at the Institute of Geophysics of Tehran University. This map presented the earthquake intensity map of Iran in Modified Mercali Scale. Following the 1962 Buin-Zahra earthquake (Ms 7.2), Ambrasys did more extensive works on Iran's tectonics and seismicity. Also, Moinfar extended the studies at Plan and Budget Organization (PBO) of Iran. Parts of findings of Ambrasys and Moinfar were published by Annali di Geophysica in Italy in 1970's.

Due to shortage of instruments in the past, the difference between the reported earthquakes' locations by different seismological stations was sometimes quite significant. For instance, the 1909 Silakhor earthquake (Ms 7.7) had been reported about 400 km away from its real epicenter!

Following the 1962 Buin-Zahra earthquake, efforts were made to prepare catalogues for both historical and instrumental earthquakes of Iran. Some researchers like M. Banisadr (1970) and M.S. Nabavi (1972) made attempts to prepare earthquake catalogues of Iran. Ambrasys and Melville (1982) published a valuable book entitled "A history of Persian Earthquakes" which has been a major reference for researchers in Iran. A catalogue of earthquakes was published by Moinfar, et. al. in 1994. However, in that catalogue all data reported by different seismological stations (USGS, etc.) were listed without expertise judgments. Since Iran has an old written history, earthquakes belonging to over 2000 years ago were estimated and listed in that catalogue. Also, Berberian (1995) published a book entitled "Natural Hazards and the First Earthquake Catalogue of Iran Prior to 1900".

However, a refined and updated catalogue of the Iranian earthquakes was compiled with the expertise judgements of the seismic zoning sub-committee. Earthquakes up to the end of year 2011 are appeared in this catalogue. This catalogue can act as an acceptable reference for Iranian earthquakes. Fig. 2 shows an updated earthquake epicenter map of Iran. This map played a significant role in revising the seismic hazard zoning map.

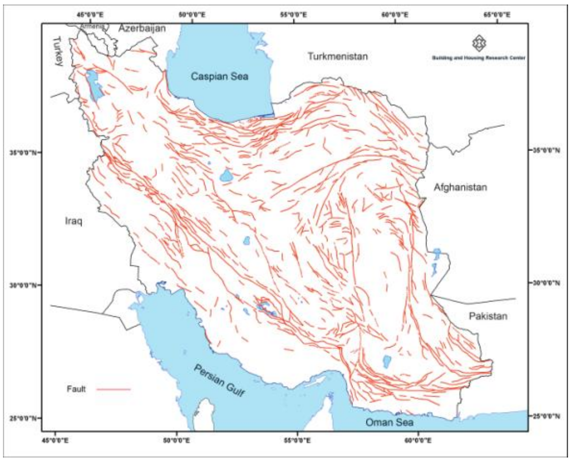


Figure 1. A new fault map of Iran

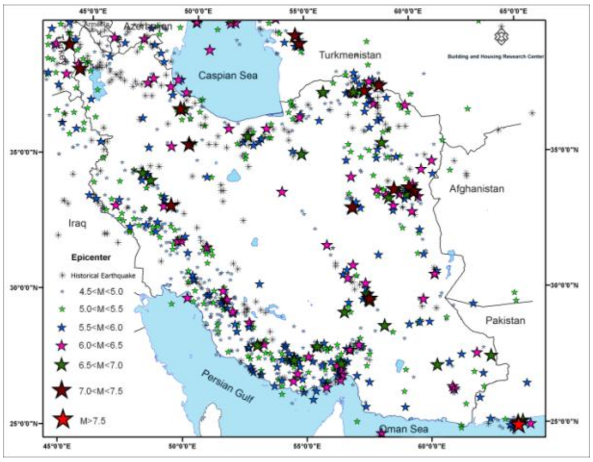


Figure 2. An updated earthquake epicenter map of Iran

4. STRONG MOTION RECORDS

Following the 1972 Ghir-Karzin (Ms 7.2) earthquake an attempt was made to establish a strong motion accelerograph network by Technical Research and Standard Bureau of Plan and Budget Organization of Iran. The network was established with 6 analog instruments in 1974 and had a rapid growth in a way that the number of instruments reached to 330 in just 3 years. With the advancement of technology and introduction of solid state instruments, 1100 digital accelerographs were added to the existing network in 1992-1993. The network now is running with over 1140 instruments. Fig. 3 shows a map of the strong motion accelerograph network of Iran.

In its relatively long history, the network has been able to collect about 8,000 three-component records from different parts of Iran. One of the most significant records of the network belongs to the 1978 Tabas earthquake (Ms 7.3) which was unique in many aspects. The record had peak horizontal ground acceleration of about 0.9g and was recorded only 3 km from the causative fault of the earthquake. This record was considered as one of the most important accelerograms in the world for many years and it is still used in both research and practice. Other than that, recorded motions of the destructive 1990 Manjil (Mw 7.3) and 2003 Bam (Mw 6.6) earthquakes were among the most important records of the network. It should also be noted that the recorded vertical components of the 1994 Zanjiran (Mb 6.1) and the 2003 Bam (Mw 6.6) earthquakes were about 1g. The recorded motions of the network have become a precious databank now.

The strong motion databank has been used in many areas from research to practice. Deriving attenuation relations for the Iranian plateau is just one example of the application of the data. Shoja-Taheri, et. al. (2010) tested the applicability of New Generation of Attenuation (NGA) Models to the strong ground motion data in the Iranian plateau and showed that the NGA models may confidently be applied within the Iranian plateau. More significant application of accelerograms can be achieved through some required refinements with respect to the ground type of the recording stations. It is then that the data can significantly be useful to get real values for base accelerations for the areas where they are recorded. However, the recorded strong motion data, especially those recorded on bedrock, were used as an important factor in revising the seismic zoning map. Fig. 4 shows a map of the recorded accelerations by the Iranian strong motion network.

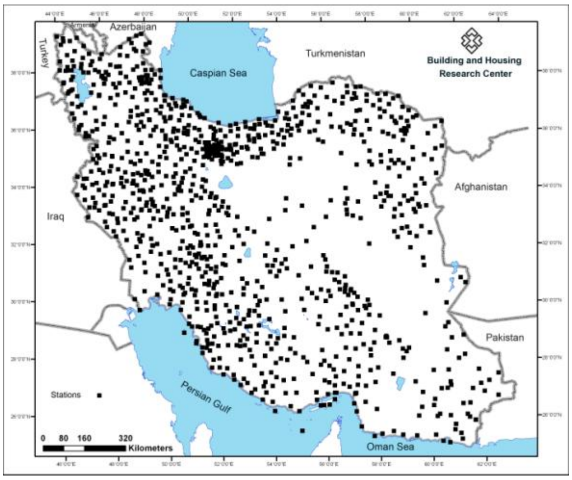


Figure 3. A map of the strong motion accelerograph network of Iran

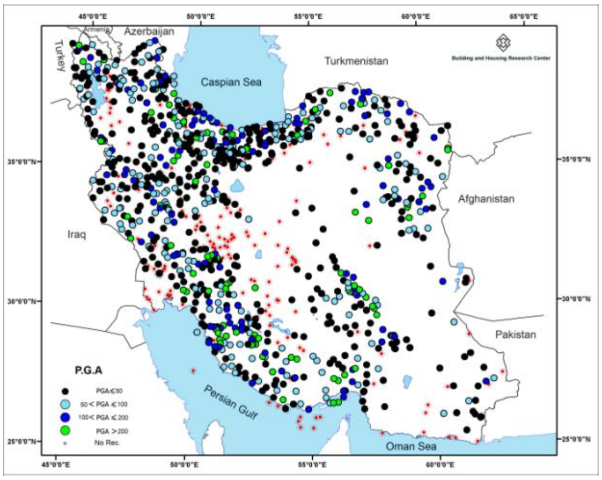


Figure 4. A map of recorded accelerations by the Iranian strong motion network

5. CASE STUDIES

For over 25 years, seismic hazard studies have been carried out for the sites of important structures such as dams, power plants, and unconventional structures in different parts of Iran. In addition, some studies have also been conducted in provincial levels for several provinces of Iran. Although these studies are performed using different methods and different attenuation relations, but collectively, they could be useful for the revision of the seismic hazard zoning map following the refinements and compatibility that were made on them.

Two methods of probabilistic and deterministic seismic hazard analysis are generally performed in order to estimate strong ground motion accelerations for important structures' sites. Briefly, in seismic hazard analysis, the following steps are generally applied as a uniform approach:

1) Carrying out seismotectonic studies to find seismic sources, express their geometry, and estimate their maximum seismogenic potential.
2) Performing studies on the nature of the seismicity in the site area on the basis of the past known earthquake events. Also, applying an updated statistical method to estimate earthquakes' return periods in terms of their magnitudes in the site area.
3) Appropriate accountability of seismicity parameters to probable seismogenic sources in the site area in such a way that satisfies the seismicity nature of these seismogenic sources in the future.
4) Selection of suitable attenuation models of strong ground motion acceleration in the site area to estimate peak ground accelerations in the structures' sites.

It should also be noted that the following two points are considered in seismic hazard analysis:

1) Dam sites locations are considered to be generally on bed rock, and
2) Design base accelerations are generally taken for 475 years return period.

Taking the aforementioned approach has resulted to estimate peak ground accelerations for hundreds of sites throughout the country. Some significant sites were selected to be considered in the revision of the seismic hazard zoning map. Fig. 5 shows the estimated Peak Ground Accelerations (PGA) for the selected sites of important structures in various parts of Iran.

5.1. Attenuation Relations

While considering the case studies reports of the seismic hazard analysis, it was observed that different attenuation relations had been used for different sites in different studies. Therefore, the seismic zoning sub-committee decided to overview the attenuation relations used in different studies. As a result, a collection of available published attenuation relations was prepared. This collection is appeared in the sub-committee's main report.

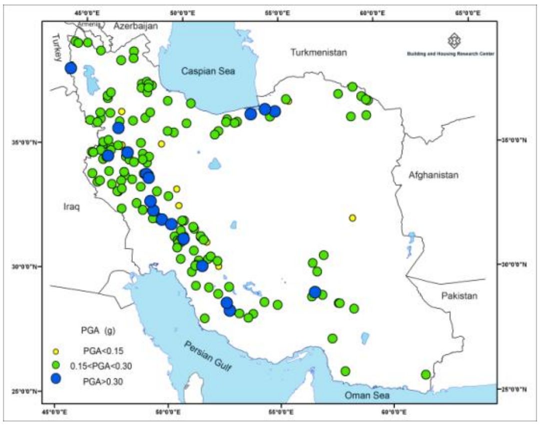


Figure 5. Estimated PGA's for the sites of important structures in Iran

6. SEISMIC HAZARD MAP

An updated seismic hazard zoning map of Iran was obtained through a comprehensive study of the seismic zoning sub-committee. The sub-committee's study was also extended to: Evaluation of seismic hazard studies for some regions, performing case study calculations, observation of strong motion records, and taking into account the seismic sources and seismicity of the country.

The updated seismic zoning map covers Iran's main land and the Iranian islands located in the Persian

Gulf, Oman Sea, and Caspian Sea. The map divides the country into four zones with design base accelerations of 0.35g, 0.30g, 0.25g, and 0.20g. The defined zones are rated as very high, high, moderate, and low hazard, respectively. About 70% of the area in the map corresponds to 0.30g (high hazard) zone. Fig. 6 shows the revised seismic hazard zoning map of Iran which is a part of the Iranian code of practice for earthquake resistant design of buildings (Standard 2800). Besides the map, a table consisting of the names of all cities, towns, and important districts with their relevant seismic hazards is presented in the code. Fig. 7 shows the GIS maps of different layers on the seismic hazard zoning map.

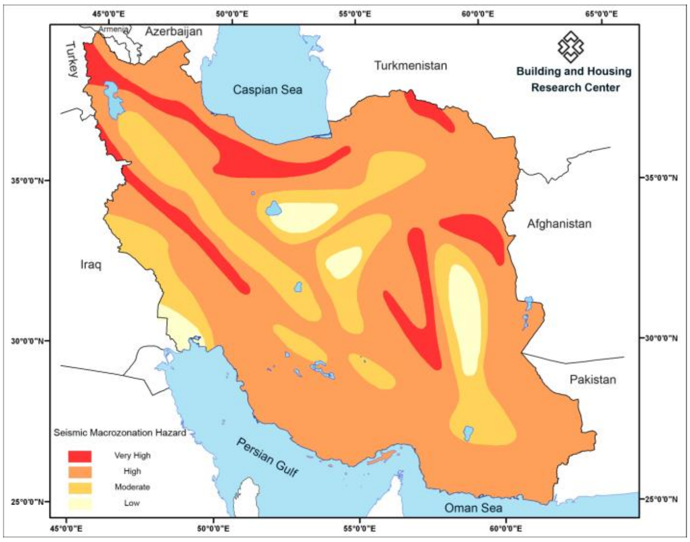
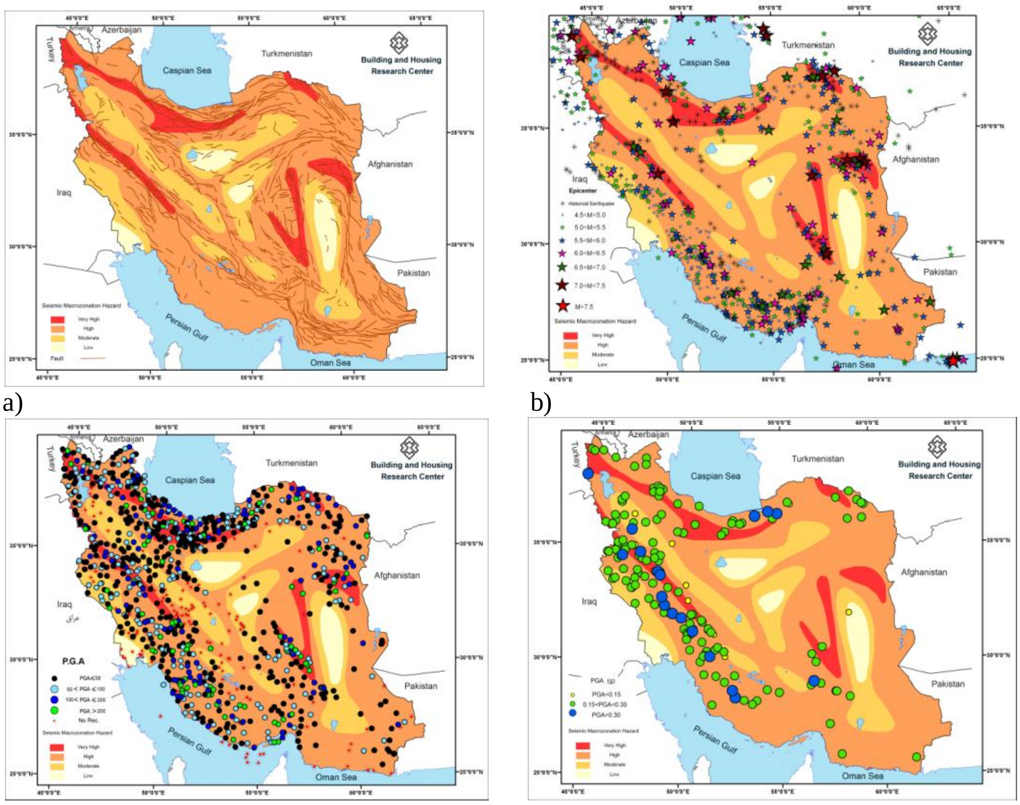


Figure 6. New seismic hazard zoning map of Iran



a) b) c) d)

Figure 7. GIS maps of different layers on seismic hazard zoning map
(a: Fault map, b: Epicentre map, c: Strong motion records, and d: estimated PGA's for case studies)

7. COMPARISON WITH NEIGHBOUR COUNTRIES

Geographically Iran has a relatively significant number of neighbors. In order to make a comparison between the base accelerations of the updated Iranian seismic hazard map with those of the neighbor countries, it was necessary to observe their seismic zoning maps. A search on available documents showed that a few neighbor countries do not have seismic codes. Therefore, in order to make a comparison, a two-step procedure was performed: 1) For those countries that actually have seismic codes, the seismic zoning maps appeared in their codes were used for comparison, and 2) For those which do not have seismic codes, results of some available studies were taken into consideration. To make the comparison feasible, all available seismic zoning maps were located and adjusted with the borders with Iran. Overall comparison shows that there is a relatively good agreement with countries located in the west and northwest of Iran, while there are disagreements with the northeast and eastern neighbors (Fig. 8).

Details and methods used to prepare the seismic hazard zoning maps of the neighbour countries of Iran were not available during the course of this study. Therefore, the scope of the study was to compare the hazard zones of the maps as they are published. Emphasis is made to the hazard zones adjacent to the border lines between Iran and its neighbour countries. All the southern part of Iran is covered by waters of the Persian Gulf and the Oman Sea. Therefore, the seismic hazard maps of the southern Arabic countries located beyond these waters were not considered in this study. The seismic hazard zoning maps of neighbour countries are briefly discussed below starting from Iraq in the west in clockwise direction:

Iraq: Iraq is located in west of Iran and its seismic hazard zoning map has divided the country into 5 zones. Contrary to some other neighbour countries' seismic hazard maps which present PGA's to respective hazard zones, this map provides a range of accelerations for each zone. The defined accelerations are greater than 0.33g, 0.2g-0.33g, 0.1g-0.2g, 0.04g-0.1g, and smaller than 0.04g for the highest to lowest seismic hazard zones, respectively. Four out of five zones of Iraq's seismic hazard map are present in the border with Iran and are the same with the Iranian map whose all four divisions are appeared in the border with Iraq. Extensions of the hazard zones located in the Iran's border have a relatively good agreement with the extensions of the Iran's newly revised seismic hazard map. The whole length of the highest hazard zone in Iraq's map (greater than 0.33g) along the Iran's border corresponds to the 0.35g zone of the Iran's map. Also, most parts of the Iraq's second highest zone (0.2g-0.33g) correspond to the 0.3g zone of the Iranian map. Almost the whole 0.1g-0.2g zone of the Iraqi map corresponds to 0.25g zone of the Iranian map. However, although the length of the 0.04g-0.1g zone of the Iraqi map along the border with Iran is exactly equal to the lowest seismic hazard zone (0.2g) in the Iranian map, but attributed PGA's is lower in the Iraqi map comparing to the Iranian map. Details of all differences can be seen in Fig. 8.

Turkey: Turkey is located in northwest of Iran and its seismic hazard map has 4 zones. PGA's are defined as 0.4g, 0.3g, 0.2g, and 0.1g for the highest to lowest seismic hazard zones, respectively. There are two highest hazard zones (0.4g and 0.3g) in the border with Iran. Similarly, two highest hazard zones of Iran (0.35g and 0.3g) are along the border with Turkey. Significant parts of 0.3g zone from both countries match with each other. Actually, all the length of 0.3g zone of Iran's map in the border with Turkey corresponds to parts of 0.3g zone of Turkish map. Parts of 0.4g zone of the Turkish map correspond to the 0.35g of the Iranian map and also parts of 0.3g zone of Turkey agree with the 0.35g zone of Iran. This close similarity is mainly due to the fact that the great Anatolian fault with east-west trend in Turkey and its continuation, the Master Zagros fault with north-south-southeast trend in Iran are both seismogenic faults with similar high seismicity. Some adjustments in PGA and location of the zones will make both maps similar at the border zones (Fig. 8).

Armenia: Armenia is one of Iran's northern neighbors. Although Armenia's area is relatively small but its 2008 seismic hazard zoning map divides the country into 4 zones. The attributed PGA's are 0.5g, 0.4g, 0.3g, and 0.2g for highest to lowest seismic hazard zones, respectively. The first two highest zones (0.5g and 0.4g) of the Armenian map are relatively high comparing to the same zones of the revised Iranian map (0.35g and 0.3g). However, the hazard zone in the border with Iran corresponds to 0.3g which is the same hazard zone (0.3g) in the revised seismic hazard map of Iran in the border with Armenia. Another word, the zones in both sides of the border have identical seismic hazards (Fig. 8).

Azerbaijan: Azerbaijan is another Iran's northern neighbor. A search in internet did not show any seismic hazard zoning map in Azerbaijan. Therefore, hazard zones presented in a published map by the Global Seismic Hazard Assessment Program (GSHAP) was considered for the comparison purpose in this study. This map divides Azerbaijan into 5 seismic hazard zones. Again, contrary to some other neighbor countries, this map also provides a range of accelerations for each zone. The defined acceleration ranges are greater than 0.33g, 0.24g-0.33g, 0.16g-0.24g, 0.08g-0.16g, and 0.04g-0.08g for the highest to lowest seismic hazard zones, respectively. According to this map, there are two hazard zones (greater than 0.33g and 0.24g-0.33g) in the Azerbaijan's main land in the border with Iran while there is only one zone (0.3g) in the Iran's revised seismic hazard map in the border with Azerbaijan. Also, the defined acceleration range (0.04g-0.08g) to Nakhjevan which is part of Azerbaijan and has border with Iran is very different from the Iranian PGA of 0.3g for the same border (Fig. 8).

Turkmenistan: Turkmenistan is another northern neighbor of Iran in east of Caspian Sea. Like the case for Azerbaijan, no seismic hazard zoning map was found for Turkmenistan in an internet search. Therefore, again the map published by GSHAP was used to compare the seismic hazard maps of that country with the new Iranian map. According to GSHAP map, the seismic hazard zoning map of Turkmenistan divides the country into 4 zones and presents the acceleration ranges of greater than 0.4g, 0.24g-0.4g, 0.08g-0.24g, and 0.02g-0.08g for the highest to lowest seismic hazard zones, respectively. There are three highest hazard zones (greater than 0.4g, 0.24g-0.4g, and 0.08g-0.24g) in the border with Iran out of which the 0.24g-0.4g zone has the longest border. Also, there are two hazard zones (0.35g and 0.3g) in the Iran's revised seismic hazard map in the border with Turkmenistan (Fig. 8).

Afghanistan: Afghanistan is one of Iran's eastern neighbors. Although through a search in internet a preliminary earthquake hazard map of Afghanistan was found in a USGS open-file report by Boyd, et. el. (2007), but for the purpose of a uniform comparison, again the GSHAP map was taken into consideration. According to this map and similar to Turkmenistan, there are 4 seismic hazard zones in Afghanistan which again provides a range of accelerations for each seismic zone. The defined accelerations are greater than 0.4g, 0.24g-0.4g, 0.08g-0.24g, and 0.02g-0.08g for the highest to lowest seismic hazard zones, respectively. The highest seismic hazard zones are located mainly in the eastern part of the country. There are 2 zones with the long border with Iran (the second highest (0.24g-0.4g) and the third highest (0.08g-0.24g)), while according to the revised Iran's map, the second highest hazard zone (0.3g) is throughout the border with Afghanistan (Fig. 8).

Pakistan: Pakistan is another eastern neighbor of Iran. The seismic hazard zoning map of Pakistan divides the country into 5 zones. This map also provides a range of accelerations for each zone. The attributed accelerations are greater than 0.32g, 0.24g-0.32g, 0.16g-0.24g, 0.08g-0.16g, and 0.05g-0.08g for the highest to lowest seismic hazard zones, respectively. The hazard zones in the border with Iran correspond partly to zone 2A (0.08g-0.16g) and partly to zone 2B (0.16g-0.24g) which are considerably different from the hazard zones (0.3g) in the revised seismic hazard map of Iran in the border with Pakistan (Fig. 8).

Actually, the difference between the defined seismic hazards in both sides of the Iran-Pakistan border, especially the border at 2A (0.08g-0.16g) zone in Pakistan is quite significant (0.3g vs. 0.08 to 0.16g) which requires a detailed investigation with respect to the methodologies applied to prepare both maps in both countries. However, since the defined hazard zones in the Iranian map is generally similar to most other neighbor countries, the relatively low acceleration ranges in the seismic hazard map of Pakistan may require a revision. In a revision program two parameters should be taken into consideration: 1) Proposing PGA's instead of range of accelerations for different zones, and 2) Refining the PGA's of the seismic hazard zones to higher figures (upgrading the related PGA's of the zones).

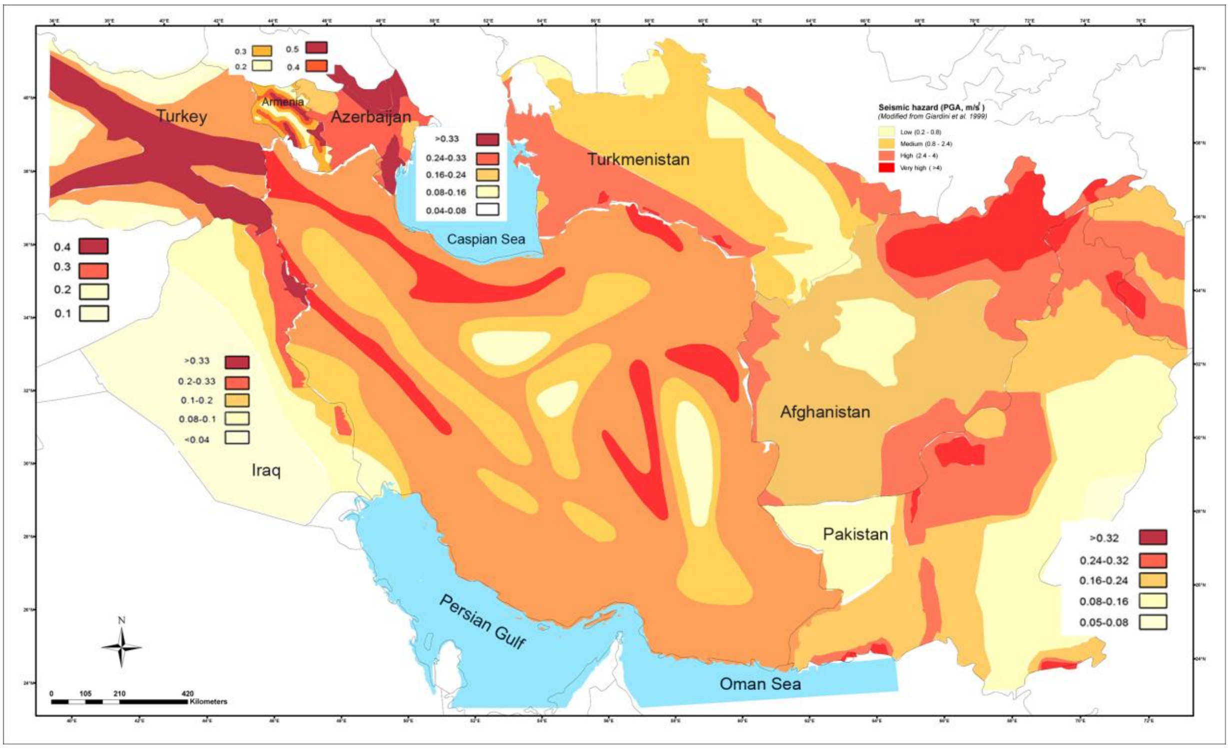


Figure 8. A new seismic hazard zoning map of Iran compared with similar maps of the neighbor countries

In order to overcome to existing differences between the seismic hazard zoning maps, a future collaboration between the countries in the region can lead to develop a unified seismic hazard zoning map in the region and in a greater scale for all the Middle East countries.

8. CONCLUSIONS

This paper presented the methodology and outcome of a comprehensive study carried out to prepare the most recent seismic hazard zoning map for the new edition of the Iranian code of practice for earthquake resistant design of buildings. Other than its own research and study, the sub-committee took advantage of other available studies and data such as site specific studies of important projects (e.g., dams and power plants) and recorded strong motion data, which in turn contributed to a more refined seismic hazard map.

Comparing to the previous version, some changes are appeared in the new seismic zoning map. However, like before, it still consists of four zones with design base accelerations of 0.35g, 0.30g, 0.25g, and 0.20g defined for different zones. The defined zones are rated as very high, high, moderate, and low hazard, respectively.

Comparison of the updated map with those of the neighbor countries 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. Therefore, this finding recommends that a future collaboration between the countries in the region can aim to develop a unified seismic hazard zoning map for the region and the Middle East.

In addition to the map, several other outputs were obtained as by-products of the seismic zoning map. Among others were a unified updated fault map of Iran and a unified updated earthquake catalogue of seismic sources of Iran (earthquake epicenter map of Iran).

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