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Earthquake Hazard Zonation and Seismotectonics of the Bandar Abbas Area, Zagros, Iran

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Abstract

The study area (Bandar Abbas area) is located in the Zagros fold-thrust belt as part of the Alpine-Himalayan orogenic belt as seismically active belt. This area is located between the Makran accretionary prism and Oman Mountains from east and the Zagros collision belt from west as transition zone. The Zagros fold-thrust belt from the viewpoint of seismicity, is very active and Iran's major earthquake-prone area. The study area has main active faults and some high magnitude earthquakes occurred in current century. Because the Bandar Abbas area has high seismic activity, the main goal of this research is prepared to earthquake hazard zonation and identify hazardous seismic zones, based on Decision Support System method for define active seismotectonic in this area. The seismotectonic study has been done in 30 - 100 km radius, for Bandar Abbas area. In this research, we used Decision Support System method by in corporate and combine essential data such as seismic data from 1900-2015, Digital Elevation Model of the study area (DEM), surface geology, seismicity parameters, soil classification and location main faults. In this research the Decision Support System (DSS) base on GIS database is used for calculate seismicity parameters. Based on the relative risk of earthquake zonation map, the Bandar Abbas area is located from the north to the East and from the South to the East, in area with high seismic risk (with Orange color). Some small regions with very high relative seismic risk have been limited to these areas with high risk. Also from north to west and from south to west "the study area" is located mainly in the area with earthquake relative risk of in areas with moderate and low relative risk of earthquakes. In the far southwestern region of the study, the small area is located in an area with high and very high seismic relative risk and this case may be due to the activity of the Mountain Front Fault (MFF) and Zagros Fore deep Fault (ZFF). Finally, the study area has been affected by active faults and it causes high vulnerability of the study area in the face of a possible occurrence of earthquakes. Based on of Seismotectonic investigations, there are existed minor faults of the Zagros fault from East to West and in the middle part. This case has been caused some parts in the study area with low and

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moderate seismic risk to be considered in the face of possible earthquakes and seismic damages, as an area with high seismic risk.

Keywords

Zagros, Bandar Abbas, Earthquake Hazard, Zonation, Active Faults

1. Introduction

Iran is one of the most seismically active countries worlds and this area is located in the Alpine-Himalayan orogenic belt (**Figure 1**). The study area (Bandar Abbas area) is located in the Zagros fold-thrust belt as part of the Alpine-Himalayan orogenic belt as seismically active belt. The Alpine-Himalayan orogenic belt or Alpide belt have been created by closure of the Tethys Ocean and process of collision between the northward-moving African, Arabian and Indian plates with the Eurasian plate from Mesozoic-Cenozoic to recent. In addition, the Zagros fold-thrust belt as part of the Alpine-Himalayan orogenic belt as seismically active belt consequence of the Arabian-Iranian convergence [1]. In Iran country, especially in the Zagros fold-thrust belt, the earthquake events with high magnitude above 6 Richter can be caused disaster. These cases have been happened as catastrophes because of the earthquake focal depth usually located in sedimentary cover with 10 km thickness of the Zagros belt. The study area is located in southeastern of the Zagros fold-thrust belt (Bandar Abbas area, Hormozgan province) (**Figure 1**). The Bandar Abbas area as syntaxis constitutes and it is one of the main structural features within the Alpine-Himalayan orogen [2]. This area is located between the Makran accretionary prism and Oman Mountains from east and the Zagros collision belt from west as transition zone [2].

The earthquake events are eternal events on the earth planet and this event is active in the interior body of the

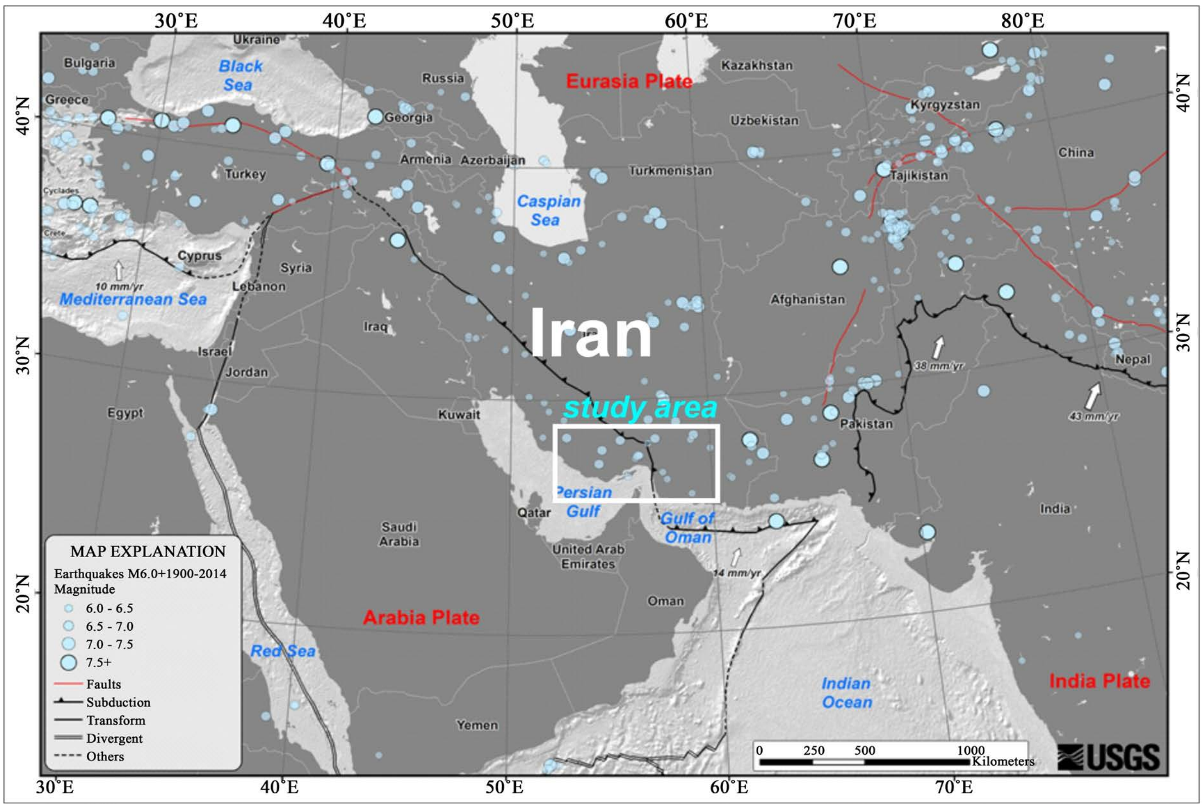

Figure 1. Map of the study area in the middle east context. In this map, the earthquake events have been shown with magnitude more than 6 richter from 1900 to 2014 (USGS).

earth. This event usually happens in the high activity seismic areas. Sometimes, the earthquake event happens in urban or industrial area sometimes occurs in area without any inhabitants such as desert. When earthquakes have occurred in urban or industrial areas, this event is nominated disaster.

The high magnitude earthquakes events in several decades in Iran country have killed many people. This natural event should be investigated by active tectonic, seismotectonic and seismology studies. The seismicity report for an area with high seismicity history has important, especially for rehabilitation of the main constructions such as dams, powerhouses and other essential constructions in urban or industrial areas.

Seismic hazard analysis has been required an assessment of earthquake hazard parameters and the future earthquake potential in a region. Kijko and Selevoll (1992) [3] has been evaluated for each seismotectonic province of Iran, earthquake hazard parameters such as maximum expected magnitude, M_{max}, seismic rate and other related parameters. In addition, geologists and seismologist with using this method, can be defined the high and very high hazardous zones that related to main active faults in any study area. Indisputable, the seismic hazardous regions have been controlled by activity of the main faults in high-risk regions. The study area has main active faults and some high magnitude earthquakes occurred in current century. Until now, many researchers have research on seismicity of Iran, Zagros and the study area (Bandar Abbas), but there have not been investigation based Decision Support System (DSS method) to deal with possible risks in the study area and so, this research has presented for the first time.

Various researchers have been done researches based on the earthquake hazard zonation. Some of these researchers have used DSS method (e.g. [3]-[7]). The Decision Support System method (DSS) is an effective and powerful method for managing earthquake risk and preparing map of the earthquake hazard zonation for urban or industrial region is GIS based Decision Support System (DSS). The system's output is very practical for prepared earthquake hazard zonation, forecasts of damage and human impacts, which will result from future earthquakes [7]. The earthquakes epicenter and active faults in the study area have been shown in the **Figure 2**. Be-

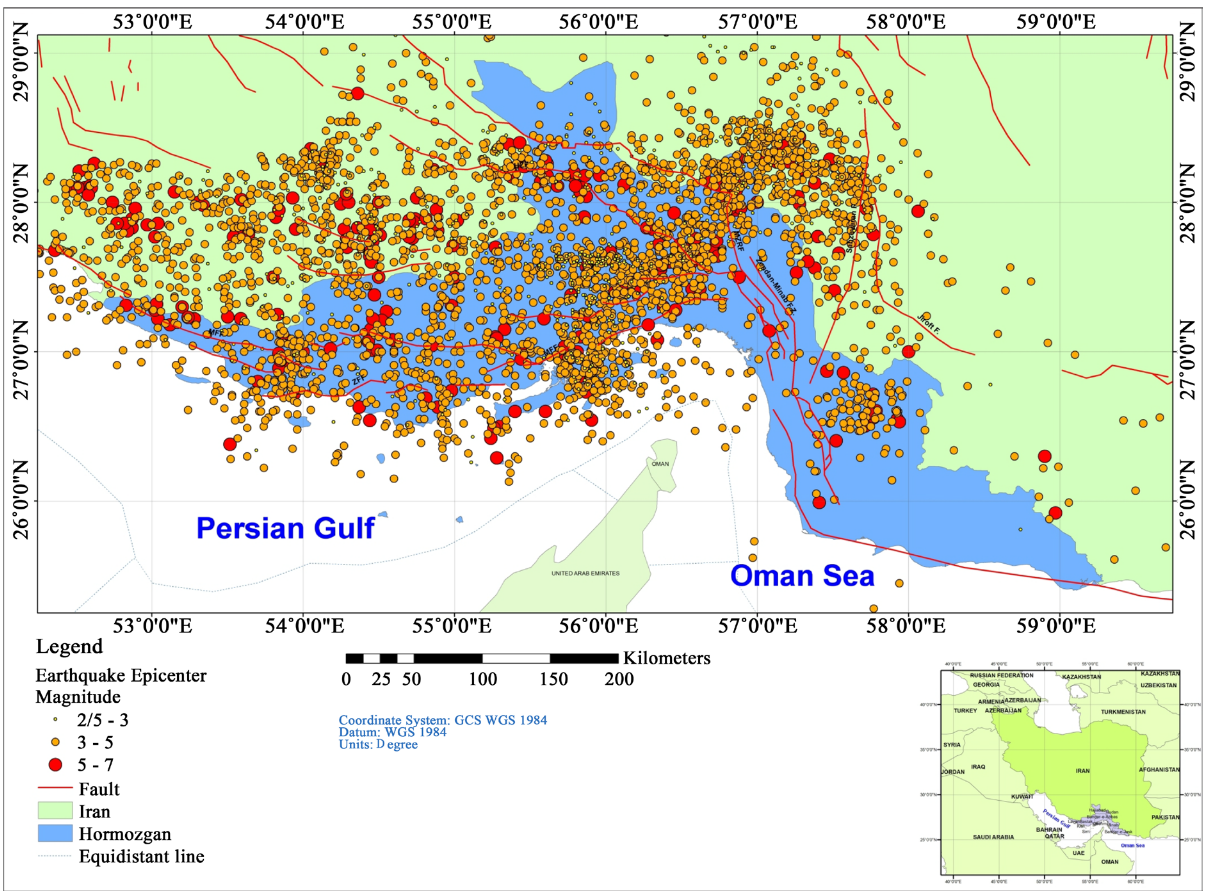

Figure 2. Map of the earthquakes epicenter and active faults in the study area and its surroundings.

cause of the Bandar Abbas area, has high seismic activity[8]-[10], the main goal of this research is prepare to earthquake hazard zonation and identify hazardous seismic zones, based on Decision Support System method for define active seismotectonic in this area.

2. Material and Methods

Today, the seismic hazard zonation has been applied in many countries to prevent losses incurred from earthquakes in seismically active areas.

In addition, mapping of seismic hazards is called seismic zonation at local scales to incorporate the local site response [11]-[21]. In each seismotectonic and earthquake hazard zonation, the seismicity study has two main part seismotectonic investigation and earthquake hazard analysis the radius study around the main construction or main area have been defined with focused on geological maps scales (1:100,000 or 1:250,000 scale) and other require data. The seismotectonic study has been done in 30 - 100 km radius, for Bandar Abbas area. In this research, we used Decision Support System method by in corporate and combine essential data such as seismic data from 1900-2015, Digital Elevation Model of the study area (DEM), surface geology, seismicity parameters, soil classification and location main faults. In this research the Decision Support System (DSS) base on GIS database is used for calculate seismicity parameters.

Based on [22] the total stratigraphic thickness has been estimated different parts of the Zagros fold-thrust belt, for example in the central SFB about 12 km and in the far southeast about 10 km. The sedimentary cover has plays a major role in this Belt and in its deformation and entitle more explanation. The simplified stratigraphic column shows in **Figure 3** for southeast of the Zagros. The Proterozoic Hormuz Salt formation has important role in formation of salt plugs and diapirs across the central and southeastern SFB. This sequence of the Zagros fold-thrust belt corresponds to the mobile Hormuz evaporites. Many large Hormoz Salt Diapirs, some still active, reach the surface in the Zagros Active Folded Belt. In the Zagros belt and study area, the Paleozoic and lower Mesozoic strata have been composed of conglomerates, dolomites, massive limestones that totally nominated the "Competent Group". Upper Cretaceous to middle Miocene rocks encompasses a more mixed sequence of

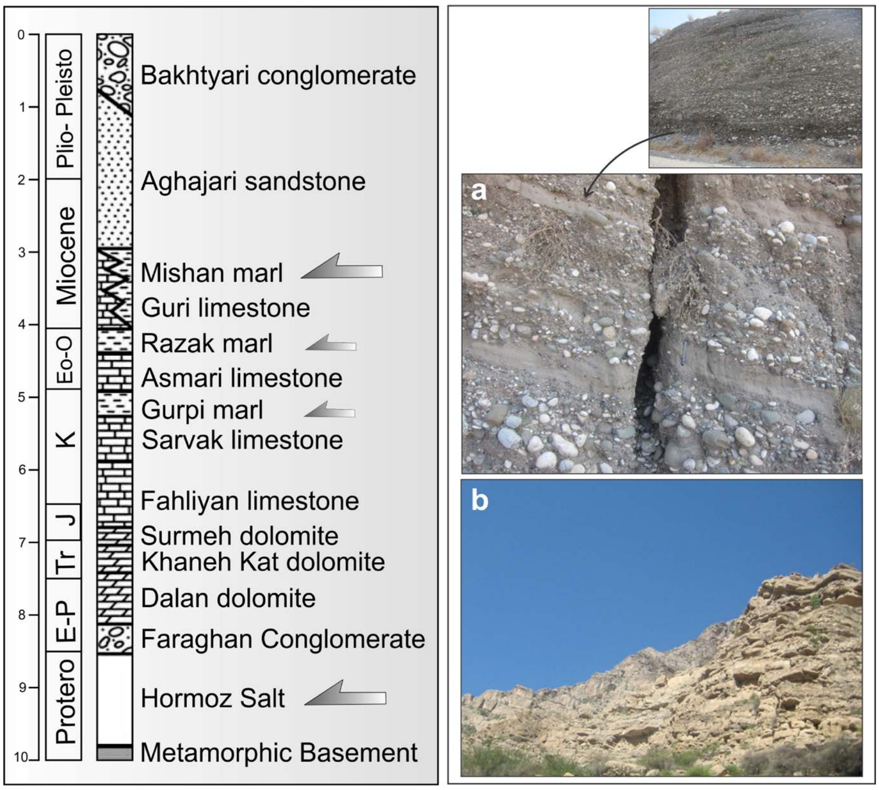

Figure 3. The simply stratigraphic column of the Bandar Abbas area (Nissen *et al*., 2010), images: (a) The conglomerate facies of the Bakhtiari formation in the study area, (b) The outcrop of the Aghajari formation in the kuh-e Zendan area.

mechanically weak marls and evaporites (e.g. Gurpi, Razak and Mishan formations) intermingled with competent limestones (for example Asmari and Guri formations). In the study area from Miocene to Recent, strata composed of course, clastic sediments. This strata has been indicated the onset of regional continental shortening and uplift in the Zagros fold-thrust belt. In this belt, shallow earthquakes have been occurred within the sedimentary cover from 10 - 15 kilometer depth. This case can show deformation of the sediments and/or movements of the salt layers and their diapirism have been happened in these parts [10].

2.1. Seismotectonic Setting and Faults

The Zagros fold-thrust belt from the viewpoint of seismicity, is very active and Iran's major earthquake-prone area. In Iran country, more than 50% of earthquakes have been occurred in the Zagros belt and global networks have recorded these earthquakes. Most earthquakes in the Zagros have been occurred with small to medium magnitude in the sedimentary cover. The epicenter of the earthquake across the Zagros Folded Belt is distributed, but the macroseismic areas of larger earthquakes have been located along the special landforms. Large earthquakes of the Zagros have been occurred, mainly on various parts of the Zagros such as main active faults.

Earthquakes in the Zagros fold-thrust belt have been occurred in Focal depth about 4 to 18 mainly in the High Zagros Simple Folded (SFB). This event show that faulting earthquakes have been occurred in the sedimentary cover and above the Zagros basement. The largest earthquake has been happened in the Bandar Abbas area is dated back to 21 March 1977 Khurgu with 7 MS magnitude in north of the study area. It killed 152 people, injured 556 and caused destruction over an area of 550 km. Some of the earthquakes in the Zagros belt have been happened in the Sub-sedimentary cover and the Khurgu earthquake was another "Sub-sedimentary Zagros-type earthquake". This event can considered as one of the evidence of the Zagros Active Folded Belt and show that the tectonic deformation along with surface faulting at the top of the sedimentary cover of this belt. The density of the earthquake events map in the study area has been shown in the **Figure 4**.

The study area is located in the Bandar-E Abbas seismotectonic province and in southeastern part of over

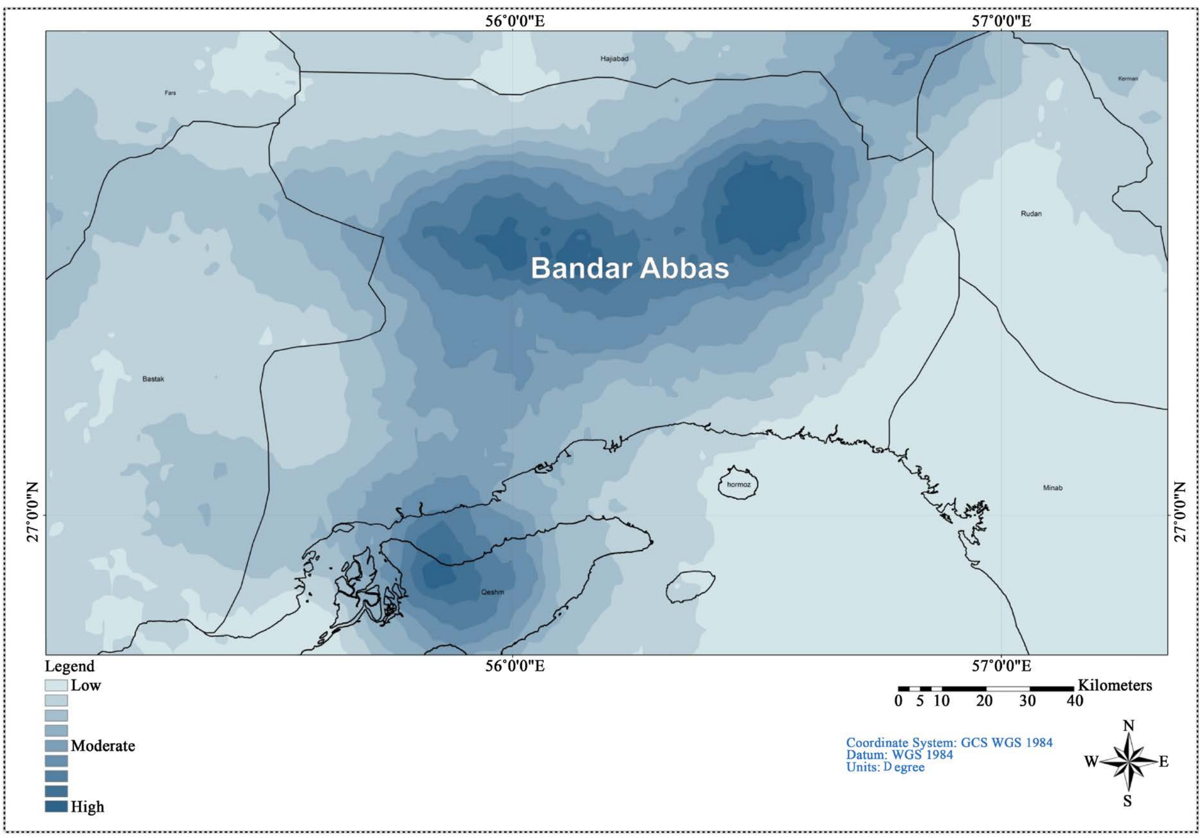

Figure 4. Density of the earthquake events map based on the earthquake epicenters in the study area.

thrust of the Zagros simple folded belt. This area has NE-SW structural trend and earthquakes focal mechanism of the Bandar Abbas area have been shown reverse and thrust faulting mechanism such as Khurgu (Ms = 7, 1977). Main destructive earthquakes in the Bandar Abbas and adjacent area have been shown in **Table 1**. Based on the seismicity characteristics, the Bandar Abbas province has been highlighted with strike of the earthquake epicenters with low frequency, short repeat time and 10 - 20 Km focal depth. The intensity of earthquakes is high in the middle detachment layers (ductile rocks in sedimentary covers) of the study area. The most vigorous seismic hazards have been happened in the Bandar Abbas province. Some of these events have been affected on the large cities such as Bandar Abbas, Qeshm, Bandar-e Lengeh and Hajiabad. These events have been created tsunami in southern margins, rapid uplift in northern margins and inhabitants in some lowlands and coastal areas.

Iran is one of the most seismically active countries in the world and this area is located in the Alpine-Himalayan orogenic belt. The study area (Bandar Abbas area, Hormozgan province) is located in the Zagros fold-thrust belt as part of the Alpine-Himalayan orogenic belt as seismically active belt. In the Bandar Abbas area, the Zagros Mountain Front Fault and other secondary related faults joint with together in Khurgu area. Most of the main active faults in the Bandar Abbas area have been jointed to the "Minab-Zendan" fault in the East of this region (**Figure 5**). In addition, these faults are located in the eastern border of the Zagros belt. The active faults in the study area have been caused severe seismicity in the Hormozgan province (**Table 1**). The location of the active faults of the Bandar Abbas area and the epicenter of the main earthquakes are shown in **Figures 4-6**.

The first active main fault in the study area is the Minab-Zendan fault (MZF). This fault is located in eastern part of the Minab city with northern-southern trend (Active faults in the study area, see **Figure 5**). The Minab fault is a dextral strike slip fault between two plates of Arabia and Iran continental-continental as boundary in this area based on Iran geology history, the Minab fault has important role and the sedimentary facies insides of this fault have different characteristics. This fault is a structural boundary with fundamental changes in sedimentation history, paleo-geography and seismicity with NW-SE trend is located in the northern part of the study area (north of the Bandar Abbas).

The second active main fault in the study area is the Main Zagros Reverse fault. The Zagros fold-thrust belt have been bounded on the northeast by both the Main Zagros Reverse fault (MZRF) and Main Recent fault (MRF).

The main reverse fault Zagros (MZRF): along the NW-SE side (N130E) of the Marivan (western boundary of the Iran and Iraq) over 1350 kilometers to the north of Bandar Abbas to extend. Zagros main fault is characteristic of the continental margin of the Central Iran border conflict (in the northeast) and the continental margin of Afro-Arab (fold belt-thrust belt).

Other active main faults such as the High Zagros Fault (HZF), Mountain Front Fault (MFF), Zagros Foredeep Fault (ZFF), Jiroft fault (JF) and Sabzevaran fault (SF) have been affected on the study area and may be have been happened severe earthquake events in the study area. The epicenter of earthquakes has shown in **Figure 5**, from 1900 to 2105 year in the study area. These epicenters have been related to the location of the main active

Table 1. Main previous destructive earthquakes in the bandar Abbas and adjacent area, based on [10].

	Event Location	year	Description
1	Qeshm Island earthquake	1981-1 (?)	A destructive earthquake
2	Strait of Hormoz	1482-1483	A damaging shock at Hormoz and Oman
3	Hengam and Kish Islands earthquakes	1703-4 (?) and 1883-4 (?)	Two destructive earthquakes on these islands
4	Qeshm Island earthquake	1884 May 19-20	Destructive earthquake in the central Part of Qeshm island
5	Qeshm Island earthquake	1897 January 11	Destructive earthquake in Qeshm city (northeast of the island)
6	Qeshm Island earthquake	1902 July 9, (?)	Damaging earthquake at Qeshm, Bandar Abbas and Genu
7	Bandar Abbas earthquake	1905 April 25	Damaging earthquake at Bandar Abbas, Qeshm and Hengam
8	Bandar Abbas earthquake	1907 July 4	An earthquake felt at Bandar Abbas
9	Nakhl-e-Nakhoda earthquake	1949 April 24	An earthquake of magnitude **6 - 6.5** which destroyed Nakhl-e-Nakhoda and damaged Bandar Abbas
10	Sarkhun earthquake	1975 March 7	A magnitude **5.8 - 6.1** earthquake damaged Sarkhun
11	Genu earthquake	1977 January 5	Damaged Genu (north Bandar Abbas)

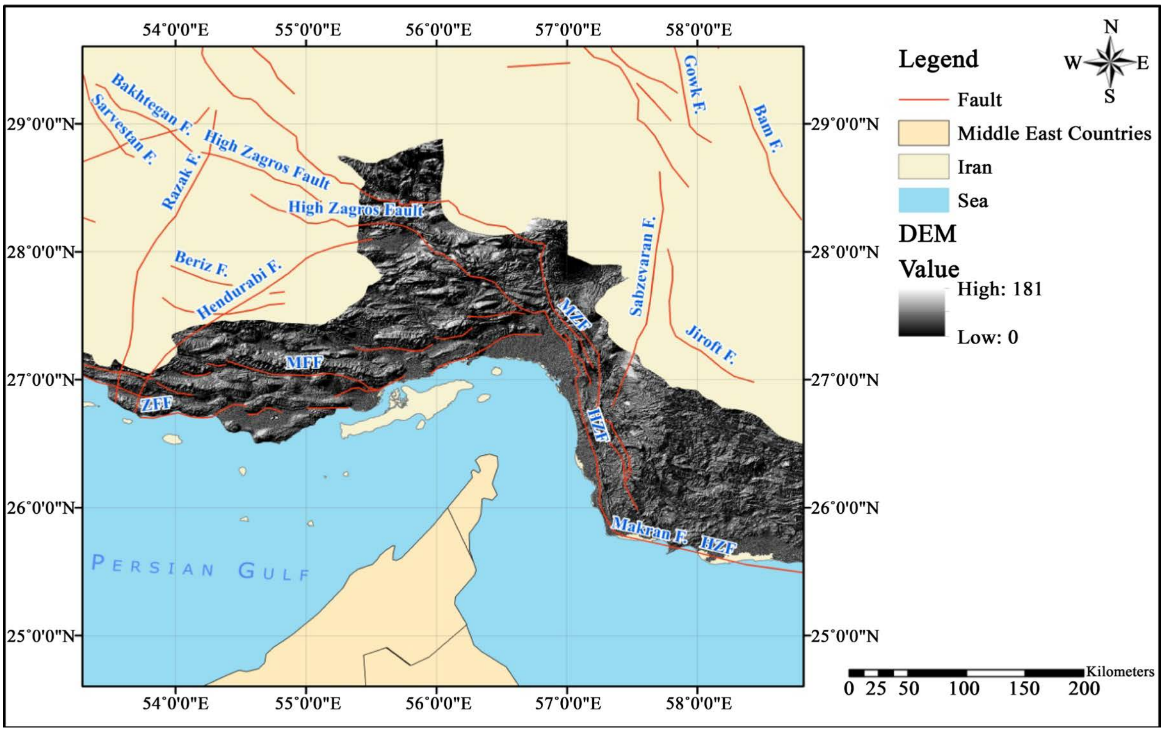

Figure 5. Active fault in the study area (Bandar Abbas, Hormozgan province).

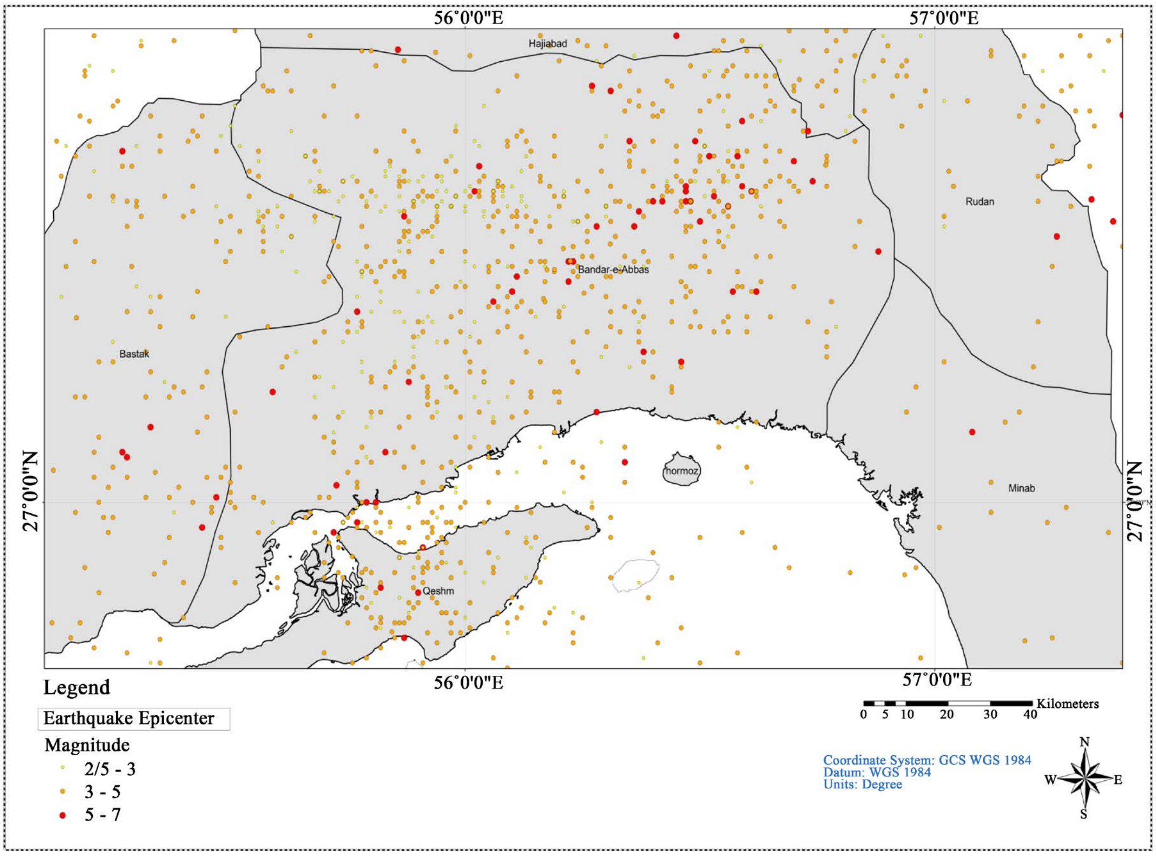

Figure 6. The epicenter of earthquakes (from 1900 to 2105 year in the study area).

faults in the study area specially belongs to the Minab-Zendan fault (MZF), High Zagros Fault (HZF) and secondary order faults that related with Minab-Zendan fault (MZF).

2.2. Earthquake Hazard Zonation

The Decision Support System method for Earthquake Hazard Zonation, is a powerful GIS-base method that developed to assist geologists and geophysicist as defining earthquake hazardous zone and managing earthquake risk for an urban area [7]. The hazard map preparation is a very common use of GIS in risk assessment in natural catastrophe such as earthquake risk and other natural disasters. In developed system for identify potential hazardous seismic zones of special locations or areas; the GIS database has significant value. For applying Decision Support System method and preparing map of earthquake hazard zonation, a GIS based DSS for earthquake hazard assessment has been developed by some researchers. In this research, we used Decision Support System method by in corporate and combine essential data such as seismic data from 1900-2015, Digital Elevation Model of the study area (DEM), surface geology, seismicity parameters, soil classification and location main faults.

In this study, the Decision Support System (DSS) base on GIS database has been used for prepared earthquake hazard zonation maps for define active seismotectonic area. Some seismicity parameters such as acceleration and intensity of earthquake have been estimated for nearest active faults in the study area. In addition, for prepared DSS tree, except define seismicity parameters (e.g. **Table 2**), lithology has been classified in the study area. One of the main part in our GIS database is distribution of earthquakes, epicenter and focal depth of earthquakes occurred in 1900-2015 period time. Other parameters have been considered such as alluvial sediments, quality of alluvial, slope, elevation, concentrate of populations and locations of main constructions specially.

After preparing DSS tree base on GIS database, each of the prepared layers have been connected to each other by Decision tree. In this stage, all of the mentioned parameters have been considered based on GIS methods, seismicity and tectonic analysis. Also, after preparing DSS tree base on GIS database, the final score is given to

Table 2. Some of the earthquake events in the study area with 100 km study radius base on seismotectonic investigation.

Year	Latitude	Longitude	Depth	Magnitude	Location
2000	27.56	56.84	41	4.2	Hormozgan, North-West of Dehbarez
2000	27.51	56.83	0	4	Hormozgan, West of Dehbarez
2002	27.64	56.69	15	4.8	Hormozgan, North-West of Dehbarez
2002	27.49	56.62	33	4.4	Hormozgan, North-East of Bandar-e Abbas
2002	27.64	56.74	12	5.3	Hormozgan, North-West of Dehbarez
2002	27.61	56.62	33	3.8	Hormozgan, North-East of Bandar-e Abbas
2002	27.6	56.67	33	4.1	Hormozgan, North-West of Dehbarez
2002	27.62	56.71	15	4.6	Hormozgan, North-West of Dehbarez
2005	27.34	56.77	31	3.1	Hormozgan, North-West of Minab
2005	27.62	56.62	14	3.8	Hormozgan, North-East of Bandar-e Abbas
2006	27.74	56.81	16	3	Hormozgan, North-West of Dehbarez
2006	27.59	56.63	14	3	Hormozgan, North-East of Bandar-e Abbas
2006	27.78	56.7	14	3.8	Hormozgan, North-West of Dehbarez
2006	27.46	56.58	14	3.9	Hormozgan, North-East of Bandar-e Abbas
2007	27.44	56.63	13	3.7	Hormozgan, North-East of Bandar-e Abbas
2008	27.37	56.65	17	3.3	Hormozgan, North-East of Bandar-e Abbas
2008	27.66	57.03	15	3.5	Hormozgan, North-West of Dehbarez
2009	27.55	57.02	14	3	Hormozgan, North-West of Dehbarez
2009	27.57	57.02	32	3.1	Hormozgan, North-West of Dehbarez
2010	27.35	56.79	14	2.9	Hormozgan, North-West of Minab
2010	27.77	56.82	14	2.9	Hormozgan, North-West of Dehbarez

each branch of DSS tree.

At finally, Decision within the system has been done and the quality value of each parameter have been logged and combined in GIS system. According to this method, each created polygons have been determined the final value. In this research, the nearest active faults, seismic data, then lithology and other parameters in order have different value. At last, the earthquake hazard zonation map has been prepared base on GIS database and DSS method for seismotectonic and seismic risk analysis (**Figure 7**).

Based on the earthquake hazard zonation map has been prepared in the Bandar Abbas area, the main part of the area is located in an area with high seismic relative risk from North to east and from south to east. The northeast-east of the study area and a small area in the central part of the Bandar Abbas area are located in zones with very high seismic relative risk in red (**Figure 7**). Also, this map show that the Bandar Abbas area is located from the north to the East and from the South to the East, in area with high seismic risk (with Orange color). Some small regions with very high relative seismic risk (red color) have been limited to these areas with high risk (Orange color) (**Figure 7**). In addition, from north to west and from south to west of the study area are located mainly in the area with relative risk of earthquake in areas with moderate and low relative risk of earthquakes. In the far southwestern region of the study, the small area is located in an area with high and very high seismic relative risk and this case may be due to the activity of the Mountain Front Fault (MFF) and Zagros Foredeep Fault (ZFF).

In the Bandar Abbas area, most of the main active faults in this area have been jointed to the "Minab-Zendan" fault in the East of this region. These faults are located in the eastern border of the Zagros belt. The active faults in the study area have been caused severe seismicity in the Hormozgan province**.** The active faults with minor faults have been caused the study area as an area with high seismicity. It seems that activity of the main faults in the study area, seismicity history and location of the main active faults such as Minab-Zendan fault, Mountain Front Fault (MFF) and Zagros Foredeep Fault (ZFF) and other faults have been caused high activity based on

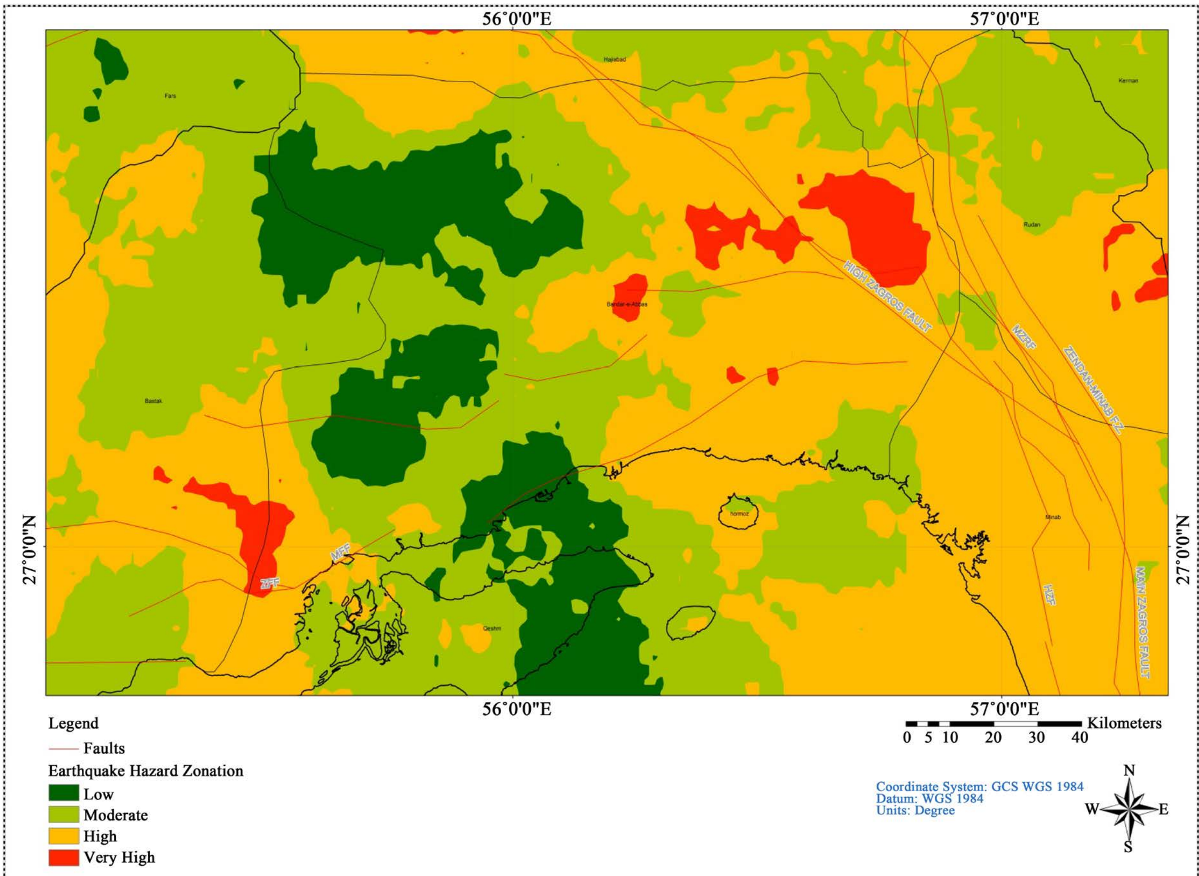

Figure 7. Earthquake hazard zonation map of the Bandar Abbas area.

seismicity and seismotectonic. At finally, the study area has high vulnerability in the face of a possible occurrence of earthquakes.

3. Results and Discussion

Neotectonic regime of the study area is due to the Neogene collision between the Arabian and Iranian plates. The Zagros sedimentary rocks shows the syn-rifting facies of passive margin from the late Proterozoic to early Permian (Hormuz to Zakeen formations), post-rifting facies of passive margin from early Permian to the late Cretaceous (Faraghan to Gurpi formations) and foreland facies of syn-orogeny from the late Cretaceous to recent (Pabdeh to Bakhtyari formations) [23]-[26].

The Hormuz Salt formation with Infra-Cambrian to Cambrian age had been deposited on northeastern part of Arabian plate. The name of the Hormuz salt with up to 1000 meters thickness was taken from the Iranian Hormuz Island, in the Persian Gulf. The sedimentary succession in the study area has got about 10 km thickness.

Based on previous work on the salt and mud diapirism [27]-[40] and neotectonic regime in Iran [41]-[44], Zagros in south Iran is the most active zone [45]-[67]. Then, North Iran [68]-[106] and Central Iran [107]-[121] have been situated in the next orders. Based on [122], the study area is located in Bandar-e Abbas province. This province is hit by moderate to high earthquakes with low frequency, short repeat time and 10 - 20 Km focal depth. The intensity of earthquakes is in middle levels in which there are ductile rocks in sedimentary covers. The most severe seismic hazards in Bandar-e Abbas province, containing large cities such as Bandar-e Abbas, Gheshm, Bandar-e Lengeh and Hajiabad, are rapid uplifting in northern margins, settlements in some lowlands and coastal areas and Tsunami in southern margins.

But based on this research, the study area has got different relative seismic risks in the larger scale that they can be classified in four levels. The areas with very high, high, moderate and low relative seismic risks have been shown by red, Orange, green and dark green colors, in respectively. The areas with very high and high relative seismic risk are closed to the Mountain Front Fault and Zagros Foredeep Fault that they have been known as active longitudinal faults.

4. Conclusions

Based on the relative risk of earthquake zonation map, the Bandar Abbas area is located from the north to the East and from the South to the East, in area with high seismic risk (with Orange color). Some small regions with very high relative seismic risk (red color) have been limited to these areas with high risk (Orange color) Figure. Also from North to West and from South to West “the study area” is located mainly in the area with earthquake relative risk of in areas with moderate and low relative risk of earthquakes. In the far southwestern region of the study, the small area is located in an area with high and very high seismic relative risk and this case may be due to the activity of the Mountain Front Fault (MFF) and Zagros Foredeep Fault (ZFF).

Finally, the study area has been affected by active faults and it causes high vulnerability of the study area in the face of a possible occurrence of earthquakes. Based on of seismotectonic investigations, there are existed minor faults of the Zagros fault from east to west and in the middle part. This case has caused some parts in the study area with low and moderate seismic risk to be considered in the face of possible earthquakes and seismic damages, as an area with high seismic risk.

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