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Probabilistic Seismic Hazard Assessment of Babol, Iran

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Abstract: This paper presents a probabilistic seismic hazard assessment of Babol, one of big cities in north of Iran. Many destructive earthquakes happened in Iran in the last centuries. It comes from historical references that at least many times; Babol has been destroyed by catastrophic earthquakes. In this paper, the peak horizontal ground acceleration over the bedrock (PGA) is calculated by a probabilistic seismic hazard assessment (PSHA). For this reason, at first, a collected catalogue, containing both historical and instrumental events that occurred in a radius of 200 km of Babol city and covering the period from 874 to 2004 have been gathered. Then, seismic sources are modeled and recurrence relationship is established. After elimination of the aftershocks and foreshocks, the main earthquakes were taken into consideration to calculate the seismic parameters (SP) by Kijko method. The calculations were performed using the logic tree method and four weighted attenuation relationships Ghodrati, 0.35, Khademi, 0.25, Ambraseys and Simpson, 0.2 and Sarma and Srbulov, 0.2. Seismic hazard assessment is then carried out for 8 horizontal by 7 vertical lines grid points using SEISRISK III. Finally, two seismic hazard maps of the studied area based on Peak Horizontal Ground Acceleration (PGA) over bedrock for 2 and 10% probability of exceedance in one life cycles of 50 year are presented. These calculations have been performed by the Poisson distribution of two hazard levels. The results showed that the PGA ranges from 0.32 to 0.33 g for a return period of 475 years and from 0.507 to 0.527 g for a return period of 2475 years. Since population is very dense in Babol and vulnerability of buildings is high, the risk of future earthquakes will be very significant.

Key words: Historical earthquakes % Probabilistic seismic % Hazard assessment % Uniform hazard spectra

INTRODUCTION

Iran is one of the most seismic countries of the world which is situated over the Himalayan-Aliped seismic belt and many disasters have been occurred in it due to the occurrence of earthquakes, causing large economic and many human lives losses. Figure 1 shows the recent seismicity of Iran and demonstrate in this country a destructive earthquake occurs every several years that some of these catastrophic earthquakes show in Table 1, with the casualty rate. In addition, in recent years, the Bam earthquake (December, 2003) was happened and about 40000 people were died in this event. This statistic demonstrates lack of our knowledge about the earthquakes and the necessity more studies in this country.

Babol is one of the big cities of Mazandaran province in north of Iran. This city is situated near to four main faults, e.g. Alborz, Gorgan, Khazar and Babol faults and many other small faults which are along in the south of Caspian (Khazar) sea. Occurrence of several earthquakes in recent years proves that these faults have been activated and all indicate the high seismicity of this region and they have caused the probability of occurrence of severe earthquakes to be very high.

This city has fundamental installations and attractive places for tourists and its many other potentialities for development can make it one of the significant region of the country. Any strong earthquake may then make considerable damages in there. So, the importance of such studies is apparent.

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Table 1: Recent destructive earthquakes in Iran [1]

No.	Year	location	Damage	Magnitude
1	1909	Silakhor	8000 dead, 64 villages destroyed	7.4
2	1930	Salmas	2514 dead, 60 villages destroyed	7.4
3	1953	Torud	183 dead, 200 villages destroyed	6.4
4	1960	Lar	400 dead, 75% of Lar destroyed	6.7
5	1962	Buyin Zahra	10 000 dead, destructive damage	7.2
6	1968	Dasht-e-Bayaz	10 500 dead, 61 villages destroyed	7.4
7	1972	Qir	4000 dead, a lot of damage	6.9
8	1977	Khorgu	128 dead, very economical damage	7.0
9	1978	Tabas	19 600 dead, 16 villages destroyed	7.7
10	1979	Qayen	130 dead, 150 villages destroyed	7.1
11	1990	Rudbar-Manjil	35000 dead, some cities and villages destroyed	7.2
12	1997	Birjand	over 1500 dead	7.3

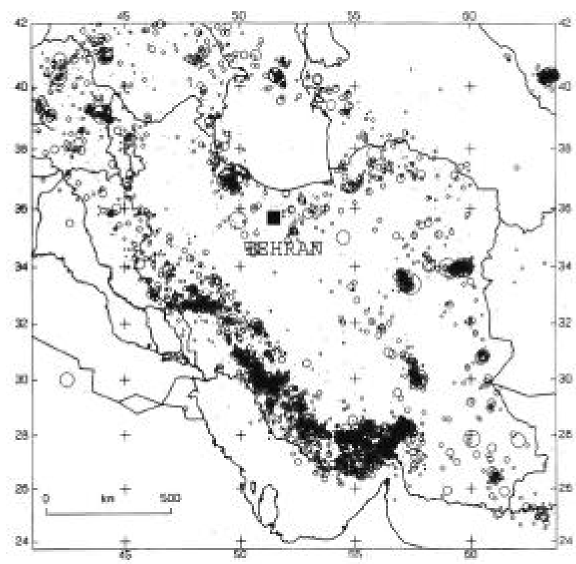

Fig. 1: Recent seismicity map of Iran [1]

Figure 2 represents the active faults of this region. The existence of active faults of Behshahr, Gorgan, Babol, Khazar and the fault of Alborz edge in the vicinity and occurrence of severe earthquake in past decades showed that the region has high seismicity and severe earthquakes are the most probable in the future.

Seismotectonic Structure of Babol: Active faults and volcanic high surface elevations along Himalayan-Alpied earthquake belt characterize the Iranian plateau. According to the earthquake data of Iran, most activities are concentrated along the Zagros fold thrust belt in comparison to the central and eastern parts of Iran (Fig. 1). Thus several regions are vulnerable to destructive earthquakes. The seismotectonic conditions of the Babol region are under the influence of the condition of the

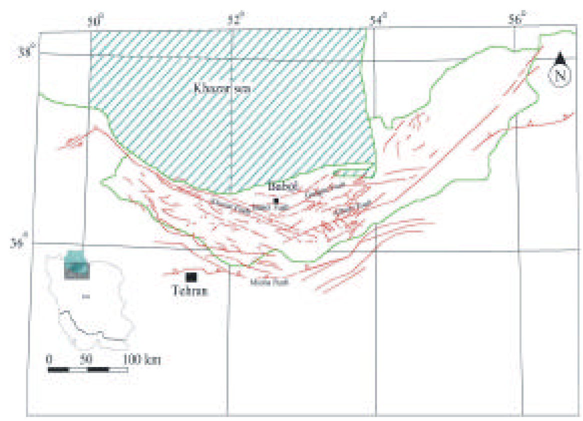

Fig. 2: Map of the region faults [2]

Iranian tectonic plate in the Middle East. Several studies have been done on the seismotectonic structure of Iran in the past. Stocklin [3], Takin [4] and Berberian [2] have suggested simplified divisions consisting of nine, four and four regions, respectively. A more elaborated division, consisting of twenty-three seismotectonic provinces was suggested by Nowroozi [5]. Tavakoli [1] proposed a new model of seismotectonic provinces using a modified and updated catalogue of large and catastrophic Iranian earthquakes. He has divided Iran into 20 seismotectonic provinces (Fig. 3).

As the ground motion along the faces of a fault usually accompanies with earthquakes, consideration of active faults is important for the seismotectonic studies. The most significant and primary faults in the vicinity of Babol include: Behshahr fault, Gorgan fault, Babol fault, Khazar fault and Alborz fault. List of these faults together with their specifications is shown in Table 2. The locations of these faults can also be seen in Figure 2 within Babol region.

Table 2: Maximum magnitudes of the region active faults

No.	Fault Active	Type of Faulting	Length (km)	M_{1max}	M_{2max}	M_{3max}
1	Behshahr fault	Strike-slipe	105	7.1	7.5	7.3
2	Gorgan fault	Strike-slipe	50	6.7	7.1	6.9
3	Babol fault	Strike-slipe	50	6.7	7.1	6.9
4	Khazar fault	Thrust	130	7.2	7.6	7.4
5	Alborz fault	Thrust	130	7.2	7.6	7.4

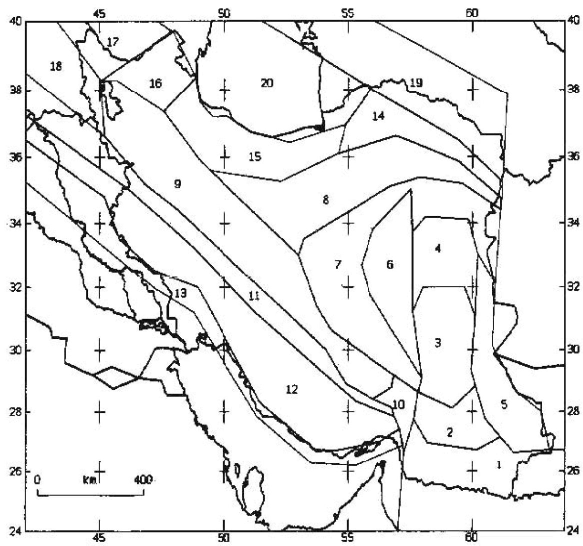

Fig. 3: Seismotectonic provinces of Iran [1]

Estimation of Maximum Expected Magnitude: Several methods are used to assess seismic potential of faults which can be divided into two categories. In the first category the length of surface rupture and maximum displacement are the most common parameters of evidences and some other parameters like fault rupture or seismic moment are used also. Initial evidences are used to estimate the magnitude of earthquakes in this category. In other category, secondary evidences like liquefaction and landslides are used to assess the magnitude of earthquakes. In this research, the maximum earthquake magnitude has been estimated by the length of surface rupture based on Nowroozi [6] relationship (Eq. [1]).

$$M_{max} = 1.259 + 1.244 \log (L) \qquad (1)$$

Where M_{max} is the maximum surface wave magnitude and L is rupture length in meter.

Two models of faulting are used to calculate the maximum magnitude. In the first model 50% of fault length is ruptured during earthquake and in the second one the rupture is 50% to 100% of fault length. Final results will then be extracted using the logic tree mentioned in Figure 4. In Table 2, M_{1max}, M_{2max} and M_{3max} are the maximum magnitudes for the active faults of the studied region calculated by the first model of faulting, second model of faulting and on the basis of the logic tree, respectively.

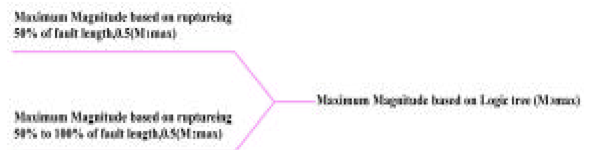

Fig. 4: Applied logic tree in calculation of the maximum magnitude

Seismicity of Babol: The earthquakes occurred in Babol can be classified in three categories:

- The historical earthquakes (the earthquakes occurred before 1900), which unfortunately the information of the historical earthquakes of Babol city is too incomplete
- The inaccurate instrumentally recorded earthquakes (the earthquakes have been recorded since 1900 till 1964 by seismographs).
- The accurate instrumentally recorded earthquakes (the earthquakes occurred after 1964)

Earthquakes are considered to be the most catastrophic natural events due to their disastrous social and economical outcomes and destructive effects. Therefore, these events have been considered by historians, authors, travelers, political and social leaders and journalists. Also such events were reflected in many historical notes. Iran, due its ancient civilization, has a clear and known seismic history. First historical earthquake recorded in the north of Iran is the one that occurred in the 874 and it destroyed the ancient city of Gorgan as well as current Babol.

Since our knowledge of past earthquakes is based on historical notes, itineraries, scientists' diaries, magazines and newspapers, its validity is related to the authenticity of the source of information. The magnitudes of the historical earthquakes are estimated based on damage, extent of the region in which the earthquake was felt or some other factors which can be compared with the seismic data obtained from the recent earthquakes. Researchers like Berberian [2], Ambraseys and Melville [7] have performed some investigations in this regard and have reported seismic data. From all reports, the list of Iranian historical earthquakes, reported by Ambraseys and Melville [7], was more homogenous compared to other seismic lists. Since Babol used to be a small village on the Plateau of Alborz Mountain ranges, the nearest big city to the old Babol is considered in the studies on the historical earthquakes of the new great Babol. In general, 8 earthquakes with magnitudes greater than $M_S = 5.3$ were reported over the time before 1900, the maximum of which occurred in 1127 with magnitude of $M_S = 6.9$.

Seismicity Parameters of Babol: The seismic evaluation is based on data on the earthquakes occurred in the concerned region and using probabilistic methods. The earthquake catalogue in a radius of 200 km has been gathered and processed, assuming that the earthquakes follow a Poisson distribution. The seismic parameters, recurrence intervals and the probability of the occurrence of earthquakes were calculated using the Kijko method [8].

Earthquake Catalogue: For this research, a list of earthquakes was gathered and selected in a preliminary manner for a radius of 200 km around Babol (Appendix). Due to the incompleteness of data regarding the depth and magnitude of earthquakes, application of probabilistic methods and the use of other references were necessary. Several studies were done by Ambraseys and Melville [7] providing a review of Iran’s historical earthquakes (before 1900) and by Ambraseys and Bommer [9] collecting historical and instrumentally recorded earthquakes. Furthermore, there are other catalogues available for this region which these mainly include the International Seismological Center (ISC) and the National Earthquake Information Center (NEIC). In order to prepare the final collective catalogue, the foreshocks, aftershocks and the incorrect reported events were eliminated from the data and finally, these filtered data were evaluated in Poisson distribution. The elimination of foreshocks and aftershocks were performed by the variable windowing method in time and space domains [10].

The cleaned and updated catalogue contains earthquake magnitudes given in several scales. The magnitude scales included in this catalogue are Richter local magnitude scale (M_L), surface-wave magnitude scale (M_S) and body-wave magnitude scale (m_b).

Earthquake Magnitude: Earthquake magnitude is one of the important parameters to analyze and predict the strong ground motion. In fact the strength of an earthquake is assessed by magnitude scales. This parameter is estimated from the peak wave amplitude which is recorded by seismograms. Different types of magnitudes are defined considering type and period of waves and also distance from epicenter. In seismic hazard analysis usually one kind of magnitude is used, the surface-wave magnitude, M_S. In some special cases, the body-wave magnitude, m_b, can also be used. The most appropriate statistical method to compensate for the incompleteness of data is the least squares method in finding the best fitted line from the data in which both magnitudes (e.g. M_S and, m_b) are reported. Since a few earthquakes with both magnitudes, M_S and m_b, were reported, the fitted line of this data could not be used. Therefore the equation presented by the Iranian Committee of Large Dams, IRCOLD [11], was employed, [Eq. (2)] and the magnitude of m_b is converted into M_S.

$$M_S=1.2m_b-1.29 \qquad (2)$$

Elimination of the Foreshocks and Aftershocks: In seismic hazard analysis of a region it is assumed that the occurrence time and location of an upcoming earthquake is independent from the last earthquake and earthquakes occur successively in space and time along faults. For this purpose, the foreshocks and aftershocks should be eliminated from the data base.

The most common method to eliminate aftershocks and foreshocks is to consider the time and location windows for their occurrences. Therefore in order to separate aftershocks and foreshocks from principal earthquakes and eliminate them from Catalogue, following conditions are followed:

- Their magnitudes must be less than the magnitude of the principal earthquake (M).
- Time differences between these earthquakes and the principal earthquake should not be more than T_M.
- The distance between epicenters of these earthquakes from the principal earthquake must be less than S_M.

Where, S_M and T_M are experimental parameters. In this research, Gardner and Knopoff method [10] is used to

Table 3: Time and location windows for elimination of foreshocks and aftershocks by Gardner and Knopoff method [10]

Magnitude (M_S)	Distance (km)	Time (day)
4.0	30	42
4.5	35	83
5.0	40	155
5.5	47	290
6.0	54	510
6.5	61	790
7.0	70	915
7.5	81	960
8.0	94	985

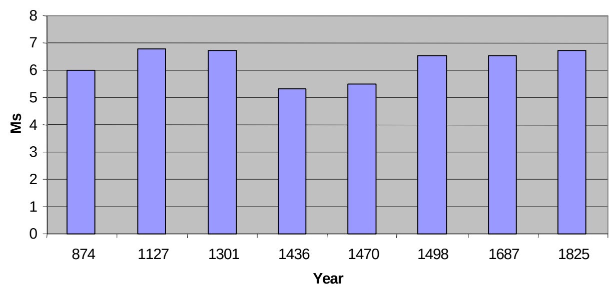

Fig. 5: Time distribution of peak magnitude of the historical earthquakes in a 200 km radius of Babol city

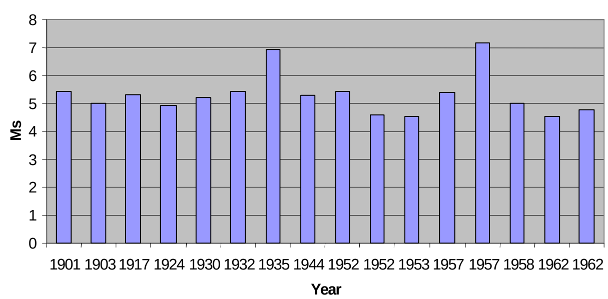

Fig. 6: Time distribution of peak magnitude of inaccurate instrumental earthquakes (1900-1964) in a 200 km radius of Babol city

eliminate aftershocks and foreshocks. Table 3 shows time and location windows for elimination of foreshocks and aftershocks by Gardner and Knopoff method [10].

Time Distribution of Peak Earthquake Magnitudes: In order to probabilistic seismic hazard study the earthquake catalogue in a 200 km region encircling Babol has been gathered and processed to eliminate aftershocks and foreshocks. Figure 5 represents the time distribution of peak earthquake Magnitudes of historical earthquakes and Figures 6 and 7 represent the distribution for inaccurate and accurate instrumental earthquakes occurred in a 200 km radius of Babol city, respectively.

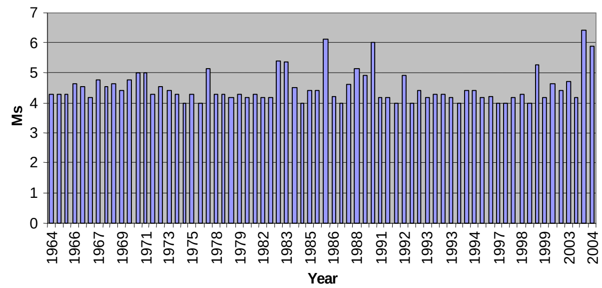

Fig. 7: Time distribution of peak magnitude of accurate instrumental earthquakes (1964-2009) in a 200 km radius of Babol city

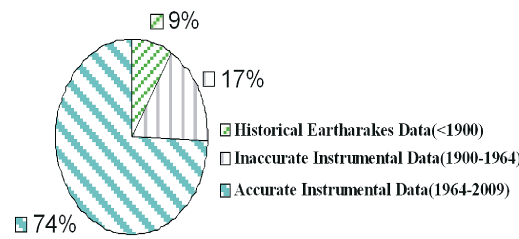

Fig. 8: Percentage of historical and instrumental earthquakes collected for this study

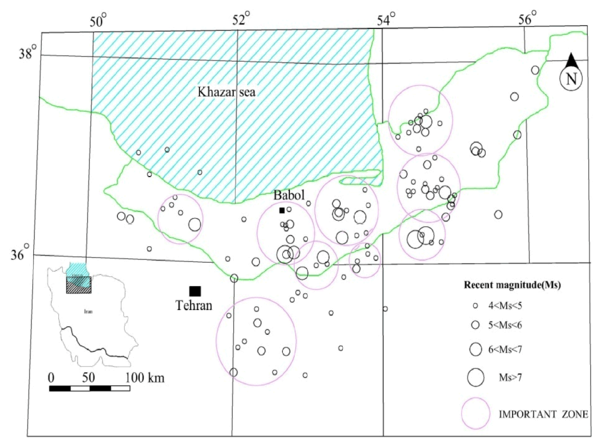

Fig. 9: Distribution of peak magnitude of historical and instrumental earthquakes in a 200 km radius of Babol city

The highest recorded magnitude of instrumental earthquakes in the studied region is 7.18 in the form of surface wave (Ms) that happened in 1957.

Finally, 8 historical earthquakes (with Ms = 5.3), 16 inaccurate instrumental earthquakes (with Ms = 4.6) and 70 accurate instrumental earthquakes (with Ms = 4), totally 94 earthquakes, were collected over the time span of studied catalogue which the percentage and distribution of them show in Figures 8 and 9, respectively.

Selection of the Assessment Method of Earthquake Hazard Parameters: Seismic hazard analysis requires an assessment of earthquake hazard parameters and the potential of future earthquakes in a region. These parameters describe a statistical model of any region as a numerical quantity. In order to assess these quantities, the seismic specifications of past earthquakes in a region should be studied and their effects on the site should be calculated.

Different methods are used in assessment of seismic hazard parameters. The calculations for the evaluation of seismic parameters were done based on the occurrence of earthquakes and the relationship between their magnitudes and frequencies. Several methods have been presented for coefficients that specify the seismic parameters. Of course all of them are based on the preliminary relationship of Gutenberg–Richter [12]. The recurrence relationship is the relation between the cumulative frequency of earthquake occurrence and its magnitude. Gutenberg and Richter [12] presented this logarithmic relationship for seismic hazard analysis (Eq. (3)).

$$\text{Log } N = a - b \times M \tag{3}$$

Where N is the number of earthquakes having magnitudes greater than M, M is the earthquake magnitude, a and b are constants and they depend on the source area. The value of a indicates the number of earthquakes above magnitude zero and depends on the number of events, size of the source region and the number of years. b specifies the relative number of small magnitude earthquakes to large magnitude earthquakes. Seismicity parameters such as the maximum expected magnitude, M_{max}, activity rate, λ and the b value of the Gutenberg–Richter relation were evaluated for Babol.

Assessment of Seismic Hazard Parameters with Kijko [8]: In this study, in order to consider the high effects of seismic hazard parameters on the determination of earthquake hazard, the new method of Kijko [8] was used based on the double extreme distribution function of Gutenberg–Richter and the probabilistic method of maximum likelihood estimation. The assumptions considered in the Kijko [8] method are as follows:

- The occurrence of earthquakes is assumed independent from time and space domains to conform to the Poisson distribution.
- Uniform seismicity properties were assumed in the radius of 200 km around Babol.

Since earthquake magnitudes have always been reported with some uncertainties in Iran; the maximum likelihood estimation for defining the seismicity parameters has good applicability in Iranian earthquake data. Therefore, applied maximum likelihood method defined in [8] allowed combination of historical and instrumental data. In this research, seismic gaps and uncertainties of earthquake magnitudes were considered in the analysis. These considerations were necessary for regions like Iran where few earthquake databases are available. Due to the lack of sufficient seismic data and the low precision in the available data, it is not possible to relate the occurrence of the earthquakes to their causative sources. As a result, it is not possible to calculate the seismic parameters for each source. Therefore, in this work, the seismic parameters were obtained for Babol city in a radius of 200 km.

Kijko [8] computer program is based on the use of extreme distribution function for the historical events with low precision and large magnitudes, the double truncated Gutenberg–Richter distribution function for the instrumentally recorded earthquakes and the application of maximum likelihood estimation probabilistic method. Based on the defined method, three types of earthquakes were considered in this paper:

- Historical earthquakes (before 1900) with magnitudes uncertainty from 0.3 to 0.5
- Instrumentally recorded earthquakes from 1900 to 1964 (the time of world seismography network installation) with uncertainty of 0.2 and the threshold magnitude of 4.5.
- Instrumentally recorded earthquakes from 1964 to 2000 with uncertainty of 0.1 and the threshold magnitude of 4.

In order to study the rate of seismicity and the effects of historical and instrumental data on seismic parameters in this region in the past, the Kijko [8] method was used in three cases (Table 4). In case 1, only the twentieth century earthquakes were used to evaluate seismic parameters. In case 2, only the historical earthquakes were used and in case 3, a combination of the historical earthquakes (with extreme value distribution function) and the twentieth century earthquakes (double extreme distribution function) were applied. The obtained values of λ ($b \times \ln 10$) and β for each case are shown in Table 4.

Table 4: Seismicity parameters in different cases for Babol

Catalogue	Parameter	Value	Data Contribution to the Parameters (%)		
			1900 <	1964 - 1900	1964<
Historical Earthquakes Data	Beta	1.88	100	---	---
	Lambda (Ms=4)	0.21	100	---	---
Instrumental Data	Beta	2.19	---	45	45.3
	Lambda (Ms=4)	0.38	---	15.8	84.2
Historical and Instrumental Data	Beta	2.19	51.5	23.1	25.4
	Lambda (Ms=4)	1.6	14.9	15.8	69.3

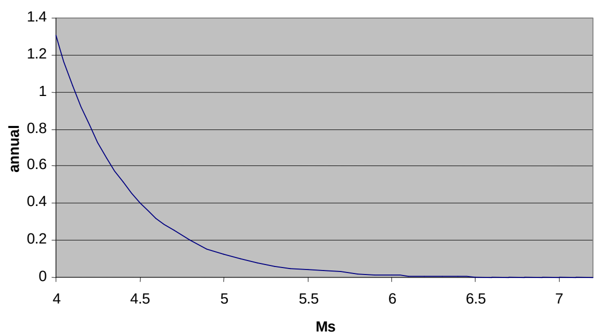

Fig. 10: Annual rates estimated by Kijko [8] method for Babol

Note that the calculated M_{max} value using this method is 7.3 ± 0.2 for Babol.

With respect to the aforementioned remarks, the benefits of the Kijko [8] method for combining the historical and the instrumental data are more apparent and it can also be guessed how much error will be introduced into the calculations in the case of negligence of each of the time spans or their incorrect combination. In Figure 10, the annual rate of occurrence, 8, for earthquakes with magnitude greater than 4 is presented for Babol.

In order to calculate the PGA and the important parameter required is the annual rate; the computer program SEISRISK III [13] was used. Also, the use of the historical earthquakes (for extending time span of the catalogue and increasing the obtained authenticity) and the instrumental earthquakes (for their exactness and completeness) will improve the validity of the results. Therefore, in this paper, the primary emphasis was on the simultaneous application of all earthquakes (case 3) and all the calculations were based on the seismic parameters (8, $) obtained from case 3 (Fig. 10).

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Seismicity Parameters Calculated by Tavakoli[1] for Iran: Since the assumption of uniform seismicity properties in Kijko method is somewhat uncertain, in order to improve the uncertainty, the seismicity study of Tavakoli [1] was also used in this research through the logic tree method. Tavakoli [1] has divided Iran into 20 seismotectonic provinces, as shown in Figure 3 and earthquake hazard parameters have been calculated for each seismotectonic province. In this study, the maximum likelihood method [14] was applied and suggested values for seismicity parameters for Babol (province No. 20) are shown in Table 5. Also, this method almost compensates the assumption of seismic homogeneity in the radius of 200 km around Babol.

Seismic Hazard Assessment: Since seismic hazard is the expected occurrence of a future adverse earthquake that has implications of future uncertainty, therefore, the theory of probability is used to predict it [Shah *et al.*, 1976]. The probabilistic approach, used in this study, takes into consideration the uncertainties in the level of earthquake magnitude, its hypocentral location, its recurrence relationship and its attenuation relationship [15].

The following steps are used for seismic hazard assessment [16-19]:

- Modeling of seismic sources
- Evaluation of recurrence relationship (i.e. frequency-magnitude relation)
- Evaluation of attenuation relationships for peak ground acceleration
- Estimation of activity rate for probable earthquakes
- Evaluation of basic parameters such as maximum magnitude

Table 5: Seismicity parameters for seismotectonic province of Babol [1]

Province No.	Span of Time	Beta	M_{max}	Lambda (M_S = 4)
20	1929-1995	2.32 ± 0.16	7.5 ± 0.9	0.33

Table 6: Specifications of selected attenuation relationships

Attenuation Relationship	Year	Area	Nr	Ne	M_{min}	M_{max}	M_{scale}	W.C.
Ghodrati	2007	Iran	305	89	4.5	8.7	Ms, mb	0.35
Khademi	2002	Iran	160	28	3.4	7.4	Ms, mb	0.25
Ambraseys and Simpson	1996	Europe and Mid. East	422	157	4.0	7.9	Ms	0.20
Sarma and Srbulov	1996	World and Mid. East	350	114	3.9	7.7	Ms	0.2

N_r = Number of horizontal records

N_e = Number of earthquakes

W.C. = Weighted Coefficient

M_{scale} = Magnitude scale

- Evaluation of local site effects such as soil types, geotechnical characteristics of sediments, topographic effects, etc.

Steps 1 through 5 represent the seismic hazard assessment for an ideal "bedrock" condition while the inclusion of step 6 represents the seismic hazard assessment for a specific site. In this study the seismic hazard assessment is done assuming ideal bedrock conditions.

Selection of the Proper Attenuation Relationship: Attenuation relationships are one of the most important elements in the seismic hazard analysis which represent the relationship between peak ground acceleration, the distance from the surface epicenter of the earthquake and the magnitude. Selection of the most proper model among the various attenuation models of the strong ground motion is done based on following criteria:

- The relationship can be applicable for the studied region.
- The distance of the site or sites from the seismic sources must be in the determined maximum and minimum range of the relationship.
- The earthquake magnitude scale of the region is as the same as the magnitude scale in the relationship.
- The maximum and minimum values of earthquake magnitudes in the region are the same as the magnitudes from relationship.
- The focal depth of earthquakes of the region must be in the range of the attenuation relationship.
- The soil type of the studied region and the attenuation relationship must be the same.

In this study, after assessing different attenuation relationships according to mentioned conditions, four attenuation relationships Ghodrati Amiri *et al*. [20], Khademi [21], Ambraseys and Simpson [22] and Sarma and Srbulov [23] with the weighted coefficient 0.35, 0.25, 0.20 and 0.20, respectively, were employed using the logic tree method. Specifications of these attenuation relationships are collected in Table 6. Since Ghodrati Amiri *et al*. [20] and Khademi [21] relationships are merely for Iran, therefore they are thought over to be more accurate for the calculation of the strong ground motion in Iran and consequently higher weighted coefficients are given to them. The highest weighted coefficient is given to Ghodrati Amiri *et al*. [20] because it is recent. The reason for using the other attenuation relationships is that Iran's data does not have the required accuracy. On the other hand, attenuation relationships like Ambraseys *et al*. [22] and Sarma and Srbulov [23] are global and data from other countries of the world or Europe have also been used in them and the precision of data used in these relationships is very high.

Logic Tree Method: Since Iran's data is limited and consequently input parameters to Probabilistic Seismic Hazard Analysis (PHSA) such as fault dimensions, recurrence rates, maximum magnitudes, attenuation relationships, etc. often has to be estimated from these limited data or determined by subjective judgment, therefore the logic tree is a popular tool used to compensate for the uncertainty in PSHA. Logic tree reflects uncertainty by allowing the analysis of each assigned parameter within the range of values, along with an assessment of the probabilities; thus each of these values is the corrected value [24].

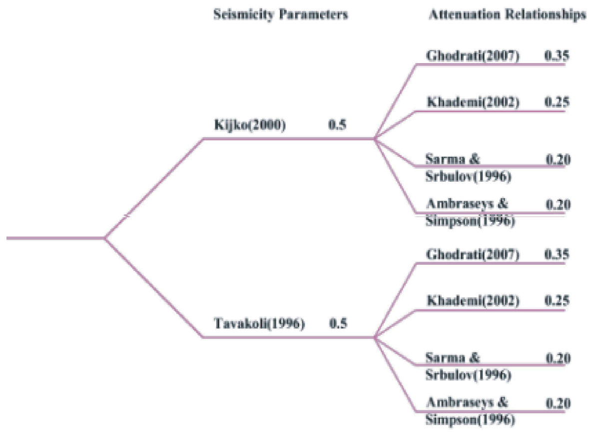

Fig. 11: Applied logic tree

Seismic parameters obtained by Tavakoli [1] were calculated for each seismotectonics province and therefore compensate for the inaccuracy of the assumption made on uniformity of seismic properties in the region of 200 km radius around Babol. The time span used in Tavakoli's study was limited to duration of 1927 to 1995. Considering the advantages and disadvantages of Kijko and Tavakoli methods, it is obvious that the application of both methods in the calculations and using the logic tree method is most beneficial.

Figure 11 shows the logic tree that considered the uncertainty in attenuation relationships and seismicity parameters. Each branch is weighted by the product of the weight assigned to it and seismic hazard can then be assessed at each end node.

Probabilistic Seismic Hazard Assessment of Babol City: In order to the seismic hazard analyze, the whole area of Babol city and its vicinity was subdivided into a grid of 8×7, total of 56 sites, with eight vertical and seven horizontal lines that the distance between every two subsequent vertical lines is 400 m and the distance between every two subsequent horizontal lines is 300 m. Then, the seismic hazard regarding the region faults and the seismic sources of the region are modeled and with the required parameters for the seismotectonic model, the calculated seismicity parameters by each of the two methods and peak values of the strong ground motion that have been calculated for each of attenuation relationships are introduced separately to SEISRISK III [13]. The program outputs are mixed by logic tree coefficients as shown in Figure 10. Finally, the output of program was the anticipated Peak Ground Acceleration in g over the bedrock (PGA) with 10 and 2% probability of exceedence during life cycles of 50 years, or for the return periods of 475 and 2475 years, respectively, (that are introduced hazard levels in the Seismic Rehabilitation Code for Existing Buildings in Iran for 56 sites of Babol city (the points of the introduced mesh). Iso-acceleration zoning map of Babol city structure for each hazard level is represented in Figures 12 and 13.

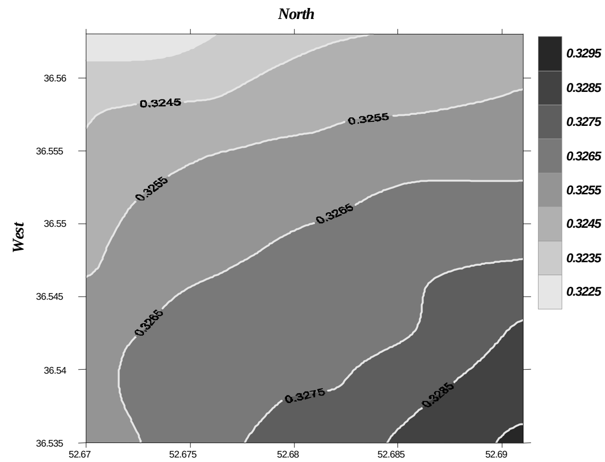

Fig. 12: Final seismic zoning map (PGA over bedrock) of Babol using logic tree for 475 year return period

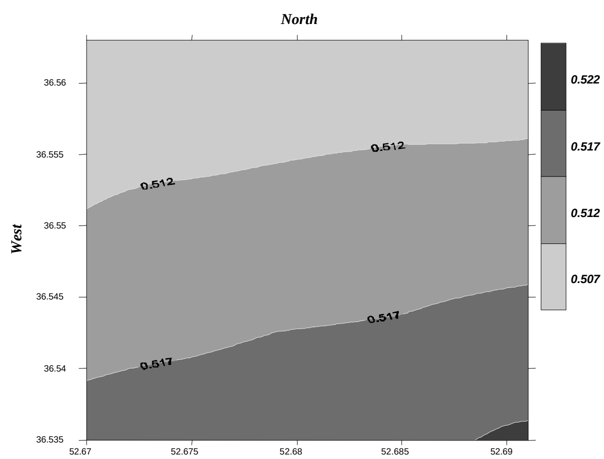

Fig. 13: Final seismic zoning map (PGA over bedrock) of Babol using logic tree for 2475 year return period

These figures show that in the whole area of Babol city the peak ground acceleration is greater than 0.32g and the south Eastern parts of Babol city have the highest peak ground acceleration (PGA = 0.33 g), for the 10% probability of exceedance. The comparison of the calculated values in this study in the return period of 475 years with the proposed design acceleration of the Iranian Code of Practice for Seismic Resistant Design of Buildings (BHRC 2005) for this area (PGA = 0.30 g), shows that the proposed values of this code are not conservative and should be increased.

CONCLUSIONS

In this study, zoning maps of the horizontal peak ground acceleration over the bedrock in different parts of Babol city is presented according to two hazard levels that show PGA values for 10 and 2% probability of being exceeded during life cycles of 50 years (Figures 12 and 13). The significant results of this study can be summarized as:

- Generation of a preliminary seismic zoning map (PGA over bedrock) that can be used, with caution, as a guide for determining the design earthquake,
- Production of an updated and complete earthquake catalogue considering both historical and instrumental events for Babol city and its vicinity,
- Utilization of different worldwide attenuation relationships using the logic tree method.

The PGA in the interested area ranges from 0.32 to 0.33g for a return period of 475 years and from 0.507 to 0.527g for a return period of 2475 years. These values show that in the whole area of Babol city the peak ground accelerations is greater than 0.32g for the return period of 475 years, while the comparison these values with the proposed design acceleration of the Iranian Code of Practice for Seismic Resistant Design of Buildings (BHRC) for this area (PGA = 0.30 g), shows that the proposed values of this code are not conservative and should be increased.

This PGA can cause major structural damages in important structures and lifeline systems. The minimum acceleration values are expected in the north of Babol where soil deposits are thick while maximum acceleration values are expected in the south eastern of Babol where soil deposits are thin (Figure 12 and Figure 13).

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Appendix

Table A.1: Earthquake catalogue

No.	Date(yyyy/mm/dd)	Time(UTC)	Latitude	Longitude	Depth(km)	Magnitude	Distance(km)	Reference
1	874		37.20	54.20		Ms:6	53	AMB
2	1127		36.30	53.60		Ms:6.8	87	AMB
3	1301		36.10	53.10		Ms:6.7	62	AMB
4	1436		37.20	54.20		Ms:5.3	154	AMB
5	1470		37.10	54.60		Ms:5.5	183	AMB
6	1498		37.20	54.20		Ms:6.5	53	AMB
7	1687		36.30	52.60		Ms:6.5	28	AMB
8	1825		36.10	52.60		Ms:6.7	50	AMB
9	1901/05/20	12:29:00.0	36.39	50.48		Ms:5.4	198	AMB
10	1903/01/02	00:07:15.0	36.50	54.90	25	Ms:5	200	MEA
11	1917/10/24	11:00:00.0	36.94	54.31		Ms:5.3	152	AMB
12	1924/09/27	10:12:00.0	37	53	16	Ms:4.9	57	MEA
13	1930/10/02	15:32:00.0	35.76	51.99		Ms:5.2	106	AMB
14	1932/05/20	19:16:11.0	36.50	53.50		Ms:5.4	74	MEA
15	1935/04/11	23:14:00.0	36.36	53.32		mb:6.8	61	AMB
16	1944/04/05	18:06:02.0	36.70	54.50	13	mb:5.4	164	BER,M
17	1952/05/20	00:00:00.0	36.60	53.40	12	Ms:5.4	65	ULM
18	1952/10/09	19:12:19.0	36.65	54.33		Ms:4.6	148	NOW
19	1953/04/18	06:22:34.0	36.83	54.41	12	mb:4.8	158	BER,M
20	1957/03/16	00:43:48.0	34.91	52.87	46	mb:5.5	180	NOW
21	1957/07/02	00:42:00.0	36.07	52.47		mb:7	55	AMB
22	1958/10/06	09:29:22.0	37.41	54.47	3	Ms:5	186	NOW
23	1962/07/28	09:02:00.0	36.60	54.80	11	Ms:4.5	190	MEA
24	1962/12/08	09:02:54.0	36.55	54.79	15	Ms:4.8	190	EHB
25	1964/02/08	06:28:27.0	37.10	51.04	40	mb:4.6	159	ISC
26	1964/12/01	08:21:53.0	36.80	54.57	33	mb:4.6	172	ISC
27	1965/05/07	01:03:05.0	36.17	54.82	62	mb:4.6	197	ISC
28	1966/10/03	17:05:08.0	35.80	53.44	14	mb:4.9	106	ISC
29	1966/11/08	03:14:11.0	36.10	50.75	15	mb:4.8	180	EHB
30	1967/02/16	11:55:32.0	35.40	51.90	144	mb:4.5	144	ISC
31	1967/11/10	02:50:52.0	36	53.89	5	mb:5	124	ISC
32	1968/07/29	16:03:43.0	36.72	53.85	14	mb:4.8	107	ISC
33	1968/12/12	18:54:47.0	35.80	53.49	27	mb:4.9	109	ISC
34	1969/01/26	02:25:53.0	36.74	54.49	10	mb:4.7	164	EHB
35	1970/04/03	20:53:54.0	37.07	54.70	26	mb:5	190	EHB
36	1971/08/09	02:54:38.0	36.20	52.76	30	mb:5.2	38	EHB
37	1971/10/15	14:19:32.0	37.33	54.59	41	MS:5	192	ISC
38	1972/02/23	23:13:47.0	36.21	53.46	73	mb:4.6	79	ISC
39	1972/08/08	00:44:55.0	36.51	52.77	42	mb:4.8	9	ISC

Table A.1: Continued

No.	Date(yyyy/mm/dd)	Time(UTC)	Latitude	Longitude	Depth(km)	Magnitude	Distance(km)	Reference
40	1973/09/17	04:06:01.0	36.54	51.11	10	mb:4.7	141	EHB
41	1974/11/05	20:02:19.0	36.22	52.92	15	mb:4.6	42	EHB
42	1975/03/13	17:33:12.0	37.08	50.70	27	mb:4.4	187	ISC
43	1975/11/06	04:09:32.0	36	53.15	6	mb:4.6	73	ISC
44	1976/06/01	02:17:34.0	37.52	54.52	34	mb:4.4	197	ISC
45	1977/05/25	11:01:46.0	34.84	52.01	23	mb:5.3	197	EHB
46	1978/03/02	11:42:16.0	37.18	54.46	58	mb:4.6	174	ISC
47	1979/02/22	05:07:17.0	35.20	52.10	33	mb:4.6	157	ISC
48	1979/03/18	05:19:53.0	36.34	52.65	33	mb:4.5	23	ISC
49	1979/03/25	02:32:25.0	34.87	52.45	26	mb:4.6	185	EHB
50	1980/12/19	16:54:18.0	35.25	52.38		mb:4.5	145	ISC
51	1981/08/04	18:53:59.0	36.45	51.27		mb:4.7	127	ISC
52	1982/02/05	23:37:12.0	36.13	53.68	33	mb:4.5	101	ISC
53	1982/05/15	17:36:08.0	35.47	54.07	15	mb:4.5	172	EHB
54	1982/10/25	16:54:50.0	35.11	52.31	15	MS:5.4	161	EHB
55	1983/03/25	11:57:49.0	36.04	52.29	20	Mw:5.5	66	EHB
56	1983/12/20	22:21:04.0	36.85	50.85	15	mb:4.8	168	EHB
57	1983/12/21	00:07:28.0	36.93	51.32	33	mb:4.4	129	ISC
58	1985/07/08	17:02:35.0	36.27	53.71	33	mb:4.7	97	ISC
59	1985/10/14	15:28:33.0	35.58	52.66	15	mb:4.7	106	EHB
60	1985/10/29	13:13:41.0	36.68	54.77	15	Mw:6.1	188	EHB
61	1986/03/26	15:18:09.0	36.01	53.68	34	mb:4.6	107	ISC
62	1987/11/25	02:09:38.0	35.67	53.07	33	mb:4.4	102	ISC
No.	Date(yyyy/mm/dd)	Time(UTC)	Latitude	Longitude	Depth(km)	Magnitude	Distance(km)	Reference
63	1988/01/13	05:56:57.0	37.27	54.40	15	mb:4.9	174	EHB
64	1988/08/22	21:23:38.0	35.32	52.34	23	Mw:5.3	138	EHB
65	1989/09/13	07:01:32.0	37.24	54.23	30	mb:5.1	158	EHB
66	1990/01/20	01:27:12.0	35.90	52.97	30	Mw:6	75	EHB
67	1991/01/22	12:04:25.0	35.44	52.32	33	mb:4.5	126	ISC
68	1991/08/23	22:14:21.0	35.99	53.27	42	mb:5	81	ISC
69	1991/09/08	04:20:31.0	35.38	53.36	15	mb:4.4	142	EHB
70	1992/09/22	14:05:56.0	36.29	52.72	35	mb:5.1	28	EHB
71	1993/03/08	19:13:21.0	36.54	51	15	mb:4.4	151	EHB
72	1993/06/09	17:33:37.0	34.83	53.32	31	mb:4.7	197	ISC
73	1993/06/19	17:01:55.0	36.75	54.83	15	mb:4.5	194	EHB
74	1993/06/30	23:05:37.0	35.17	53.56	25	mb:4.6	170	EHB
75	1993/08/19	10:04:30.0	35.17	52.10	16	mb:4.6	160	EHB
76	1993/10/18	01:28:24.0	36.55	53.78	33	mb:4.5	99	ISC
77	1994/03/15	21:46:15.0	36.85	54.82	33	mb:4.4	195	ISC
78	1994/06/04	10:38:57.0	36.72	54.76	53	mb:4.7	188	ISC
79	1994/07/11	20:57:39.0	37.43	54.42	30	mb:4.7	184	EHB
80	1994/11/21	18:55:18.0	36.05	51.91	44	mb:4.5	88	ISC
81	1995/06/26	21:12:54.0	36.60	51.19	22	MS:4.2	134	ISC
82	1997/08/26	00:44:51.0	36.59	53.06	43	mb:4.4	34	ISC
83	1997/09/16	12:15:33.0	36.83	54.10	30	mb:4.4	131	EHB
84	1997/11/03	06:59:30.0	36.27	54.48	15	mb:4.5	164	EHB
85	1998/01/09	19:06:13.0	36.38	52.15	15	mb:4.6	51	EHB
86	1999/08/10	19:33:59.0	36.16	54.65	20	mb:4.4	182	EHB
87	1999/11/19	04:40:25.0	37.32	54.41	31	Mw:5.4	177	EHB
88	1999/12/09	22:20:37.0	36.45	53.57	15	mb:4.5	80	EHB
89	2000/08/16	12:53:02.0	36.71	54.37	25	Mw:4.9	153	EHB
90	2001/05/16	07:24:29.0	36.26	52.66	26	MS:4.4	31	ISC
91	2003/03/30	19:08:17.0	37.36	54.42	30	MS:4.7	180	ISC
92	2003/06/21	15:00:05.0	35.63	52.86	24	mb:4.5	102	ISC
93	2004/05/28	12:38:45.0	36.26	51.57	27	Ms:6.4	104	EHB
94	2004/10/07	21:46:15.2	37.40	54.58	17	ML:6.2	195	IIEES

Table notification:

AMB: Ambraseys, N. N., Melville, C. P.

BER, M: Berberian, Geological and Mining Survey of Iran

EHB (Mag. Ref.: MEA)

ISC: International Seismological Center, UK

IIEES: International Institute of Earthquake Engineering and Seismology

MOS: Moscow, USSR

MEA: Riad and Meyers, 1985

NOW: Nowroozi

ULM: Catalog of earthquakes compiled by V.1. Ulomov; Russian Academy of Sciences, Moscow