Nat Hazards (2008) 44:51–64
DOI 10.1007/s11069-007-9141-2

ORIGINAL PAPER

An investigation of seismicity for western Anatolia

Nilgün Sayil · İlhan Osmanşahin

Received: 12 September 2006 / Accepted: 27 April 2007 / Published online: 4 July 2007

Abstract In order to investigate the seismicity of western Anatolia limited with the coordinates of 36°–40° N, 26°–32° E, Gutenberg–Richter magnitude–frequency relation, seismic risk and recurrence period have been computed. The data belonging to both the historical period before 1900 ($I_0 \geq 5.0$ corresponding to $M_S \geq 4.4$) and the instrumental period until the end of 2006 ($M_S \geq 4.0$) has been used in the analysis. The study area has been divided into 13 sub-regions due to certain seismotectonic characteristics, plate tectonic models and geology of the region. All the computations have been performed for these sub-regions, separately. According to the results, a and b values in the computed magnitude–frequency relations are in the intervals 3.19±0.17 – 5.15±0.52 and 0.42±0.05 – 0.66±0.07, respectively. The highest b values have been determined for sub-regions 3 and 12 (Demirci-Gediz and Gökova Gulf-Muğla-Gölhisar). The lowest b values have also been determined for sub-regions 1 and 9 (Balıkesir and Bodrum-İstanköy). Finally, seismic risk and recurrence period computations from a and b values have shown as expected that sub-regions 1 and 9 which have the lowest b values and the highest risks and the shortest-recurrence periods.

Keywords Anatolia · Seismicity · Recurrence period · Poisson model

N. Sayil (✉)
Engineering Faculty, Department of Geophysics,
Karadeniz Technical University,
Trabzon 61080, Turkey
e-mail: sayil@ktu.edu.tr

İ. Osmanşahin
Engineering Faculty, Department of Geophysics,
Istanbul University,
Avcılar-Istanbul 34850, Turkey
e-mail: isahin@istanbul.edu.tr

1 Introduction

Statistical earthquake occurrence models have get more importance while amount of the available earthquake data increase. These models allow one to reduce the large data sets of earthquake occurrences to statistical parameters for any region. They can be used to predict earthquake occurrences, recurrence periods, maximum ground motions and earthquake hazard at a given region (Cornell 1968). Several statistical models have been proposed to represent the process of earthquake occurrence. The most common model is Poisson model, which assumes spatial and temporal independence of all earthquakes including great earthquakes: i.e. the occurrence of an earthquake does not affect the likelihood of a similar earthquake at the same location in the next time unit.

Although most of the earthquake generation models currently used for seismic hazard evaluation assume a Poisson (Cornell 1968; Caputo 1974; Shah and Movassate 1975) or other memory-less distributions, studies in the last few decades have concluded that the large earthquakes in many regions are temporally dependent (Bufe et al. 1977; Sykes and Quittmeyer 1981; Papazachos 1989; Stein et al. 1997; Parsons et al. 2000). Two kinds of time-dependent models have been suggested: the slip-predictable model and time-predictable model.

A few other probabilistic models have been used to represent earthquake sequences as strain energy release mechanisms. Hagiwara (1975) has proposed a Markov model to describe an earthquake mechanism simulated by a belt-conveyer model. A Weibull distribution is assumed by Rikitake (1975) for the ultimate strain of the Earth's crust to estimate the probability of earthquake occurrences. Knopoff and Kagan (1977) have used a stochastic branching process that considers a stationary rate of occurrence of main shocks and a distribution function for the space–time location of foreshocks and aftershocks.

Bağcı (1996) investigated seismic risk of western Anatolia between 36°–41° N and 25°–31° E using the Poisson model for earthquake data (1930–1990). Altınok (1991) evaluated the seismic risk of west Anatolia by the application of Semi-Markov model. Sayıl and Osmanşahin (2004, 2005) and Sayıl (2005) applied time-and magnitude-predictable model to the Marmara Region, west and east Anatolia for long-term earthquake prediction.

The subject of this study is to estimate the probability of earthquake occurrences and recurrence periods by using Poisson model from historical and instrumental data for selected characteristic sub-regions in western Anatolia.

2 Seismotectonics of the region

One of the most seismically active regions in the world is the Alpine-Himalayan Belt which extends from the Azores to Indonesia. Anatolia locates in the most active section of this belt in the eastern Mediterranean and involves several important tectonic structures such as North Anatolian Fault Zone (NAFZ), East Anatolian Fault Zone (EAFZ), North-East Anatolian Fault Zone (NEAFZ) and Bitlis Thrust Belt (BTB) shown in Fig. 1. Previous studies about this section have brought out that the Anatolian (which is a part of Eurasian), Arabian and African plates joined and formed a triple junction structure (Karliova Junction, KJ, in Fig. 1) in the east Anatolia (McKenzie 1972; Ketin 1977; Osmanşahin 1983; Özer 1983; Osmanşahin et al. 1986; Kenar et al. 1996). Western Anatolia is one of the four major neotectonic provinces in Anatolia (Şengör et al. 1985).

The seismicity in western Anatolia is high (Fig. 2) and displays swarm-type activity with remarkable clustering of low-magnitude earthquakes in time and space (Üçer et al.

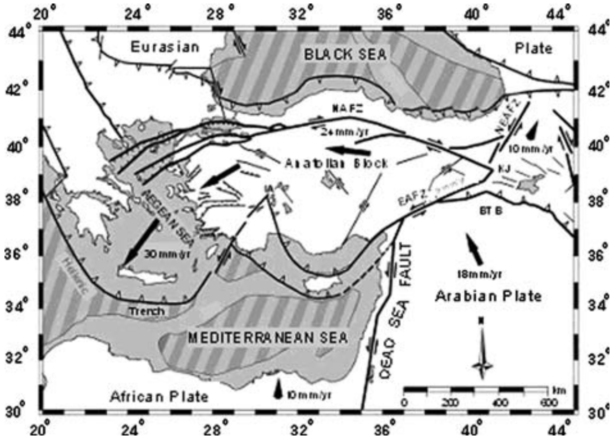

Fig. 1 Plate tectonics model of Anatolia and surrounding area (The Institute of Mineral Research and Exploration, Ankara, Turkey)

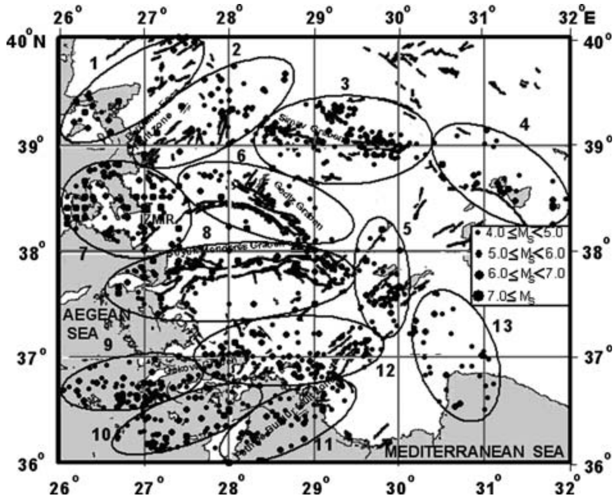

Fig. 2 Epicentral map and selected 13 sub-regions of western Anatolia

1985). Focal mechanisms of earthquakes in western Anatolia indicate that intra-plate deformations arising from vertical movements are occurring inside of the Aegean-Anatolian block. Most of the fault-plane solutions in western Anatolia represent normal faulting, indicative of crustal extension. Tensional axes for these solutions are nearly horizontal and perpendicular to the general east–west trend of graben structure. The Arabian plate moves northward, and forces the smaller Anatolian plate westward between the North and the East Anatolian Fault Zones as from Karliova triple junction. McKenzie (1972, 1978) showed that this motion is transferred into the Aegean in a southwesterly direction, resulting in the northern Aegean being dominated by dextral strike-slip faulting of northeasterly strike. This faulting type has been seen in the recent strong earthquakes, and confirmed by neotectonic observations.

3 Data

Both historical (since BC-496, $I_0 \geq 5.0$ corresponding to $M_S \geq 4.4$) and instrumental period (until the end of 2006, $M_S \geq 4.0$), data obtained from the catalogues and bulletins of international data centres given in Tables 1 and 2 have been used in this study. Homogeneity of the data is very important in the analysis. In order to ensure homogeneity, all of the magnitudes have been taken as surface wave magnitude (M_S). These magnitudes have been determined by seismologists who compiled the catalogues either from recordings of long-period seismometers, or through the use of experimental scaling relations. Possible discrepancies between the magnitudes computed by different authors for the same earthquake are small, and do not affect the results much in any case.

In this study, the experimental scaling relation between surface (M_S) and body wave magnitudes (m_b) has been estimated by using 204 earthquakes of $M_S \geq 4.0$ and $m_b \geq 3.0$ taken from the dataset in the instrumental period (Fig. 3, Eq. (1)). Likewise, the correlation between intensity and magnitude has been determined from the data of 115 earthquakes ($M_S \geq 4.4$) occurred in the instrumental period (Fig. 3, Eq. (2)). Computed $M_S - I_0$ and $M_S - m_b$ relations are consistent with those of Ambraseys (2001) and Bath (1966), respectively.

$$M_s = 1.40m_b - 2.33 \quad (1)$$

$$M_s = 0.47I_o + 2.05 \quad (2)$$

An important criterion for the analysis is completeness of the data. Namely, the data must include all of the earthquakes that occurred in a certain seismogenic region during a specific time–period with magnitudes larger than a specific minimum (cut-off) magnitude. According to this statement, the smallest magnitude from which earthquakes were reliably reported in the catalogues (historical and instrumental period) used has been chosen as a minimum magnitude (M_{min} = 4.0 in our case for all sub-regions) in each region. Maximum magnitude value (M_{max}) is magnitude of the biggest earthquake for each sub-region.

Table 1 Some of the historical period earthquake catalogues for Turkey and surrounding area

By (Researcher)	Symbol	Year
Pınar and Lahn	PL	1952
Ergin et al.	EGU	1967
Karnik	VKR	1968
Öcal	ON	1968
Alsan et al.	ATB	1975
Dewey	DJW	1976
Ayhan et al.	AASÜ	1987
Ambraseys and Jacson	AJ	1981
Soysal et al.	SSKA	1981
Papazachos and Comminakis	PC	1982
Gündoğdu and Altınok	GA	1986
Westaway	WR	1990
Ambraseys and Finkel	AF	1995
Ambraseys	AN	2001

Table 2 Instrumental period earthquake catalogues made use to form data

Data centre	Symbol	Working period
British Association for the Advancement of Science	BAS	1913–1917
International Seismological Summary	ISS	1918–1963
Bureau Central International	BCI	1953–1963
International Seismological Centre	ISC	Continue
U.S. Coast and Geodetic Survey	USCG	Continue
Bosphorus University, Kandilli Observatory	ISK	Continue

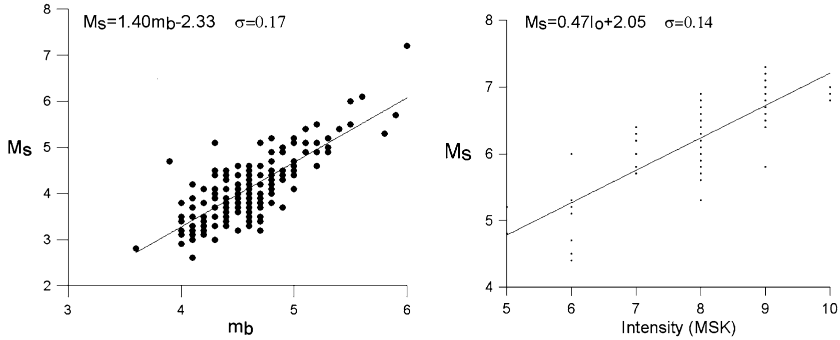

Fig. 3 Correlations of $M_s - m_b$ and $M_s - I_0$ used in this study

Another important criteria is to select the main shocks from dataset. Namely, the dataset has to be cleared from after- and for-shocks to be able to use it in Gutenberg-Richter relationship. Thus, after- and for-shocks have been rejected from dataset.

4 Definition of the method

Since magnitude–frequency relations are formed as the basis of the earthquake occurrence, it is used for the criterion of earthquake activity as times ago. In the investigation of earthquake occurrence frequencies, it seems that they exhibit usually a linear relation. An equation to represent the relation between the magnitude and earthquake occurrence frequencies has been suggested by Gutenberg and Richter (1954). The general form of this well-known equation is:

$$\mathrm{LogN(M)} = \mathrm{a} - \mathrm{bM}, \tag{3}$$

where N(M) (cumulative frequency), is the number of earthquakes equal or larger than M magnitude. Gutenberg–Richter relation does not become linear for all magnitudes. Therefore, the magnitude interval (M_1, M_2) in which the logN(M) is linear must be known. So that, the relation is undetermined for the large earthquakes since they are a few number. On the other hand, it must be sure that earthquake array is complete for the small earthquakes. Parameters (a) and (b) in the magnitude–frequency relation are constants. Parameter (a) depends on the observation period, the order of the region interested and the seismic activity, and defines a mean annual seismic activity index. Parameter (b) is related to the physics of the earthquakes and gives slope of the linear relation. According to the analysis of worldwide data, it has been noted that b values considerably change as depending on the geological age of the seismotectonic belt (Miyamura 1962). In general, low b-values are related to high stress-drop, high b-values are related to high heterogeneity of material and crack density (Weeks et al. 1978; Urbancic et al. 1992; Wiemer and Katsumada 1999).

For (M, LogN) dataset, a and b-values are commonly computed by using the linear least square approximation. According to this method, parameters (a) and (b) are found by Eq. (4);

$$\sum_{i=1}^{n} \mathrm{LogN_i} = \mathrm{an} - \mathrm{b}\sum_{i=1}^{n} \mathrm{M_i}$$

$$\sum_{i=1}^{n} \mathrm{M_i} \cdot \mathrm{LogN_i} = \mathrm{a}\sum_{i=1}^{n} \mathrm{M_i} - \mathrm{b}\sum_{i=1}^{n} \mathrm{M_i^2}, \tag{4}$$

where n is the number of group. Other parameters are as described in Eq. (3). The earthquake occurrence probability with the specific magnitude in a specific period could be determined by using a and b values obtained from Eq. (4). Equation (5) could be obtained from the relation between cumulative and normal frequency. Equation 6 is obtained by dividing the relation of magnitude and frequency to the specified time-period (T_1). Equation (7) is obtained by logarithm of Eq. (6). Equations (8) and (9) are obtained from Eq. (7).

$$\mathrm{a'} = \mathrm{a} - \mathrm{Log(bln10)}, \tag{5}$$

$$\frac{\mathrm{N(M)}}{\mathrm{T_1}} = \frac{10^{\mathrm{a-bM}}}{\mathrm{T_1}}, \tag{6}$$

$$\mathrm{Log(N(M)T_1) = a - bM - LogT_1 \Rightarrow n(M\rangle M_1) = 10^{a-bM-LogT_1}}, \tag{7}$$

$$\mathrm{a'_1 = a' - LogT_1}, \tag{8}$$

$$\mathrm{n(M) = 10^{a'_1-bM}}. \tag{9}$$

The annual mean number n of earthquakes ($M \geq M_1$) with specific magnitude equal and larger than M_1 value in a specific time can be estimated by using these relations. In any regions, occurrence risk in T years of an earthquake with any magnitude M for observation interval of T_1 year is calculated by Eq. (10) and recurrence period of an earthquake is estimated by Eq. (11) (Tabban and Gencoğlu 1975).

$$\mathrm{R(M) = 1 - e^{-n(M)T}} \tag{10}$$

$$\mathrm{Q} = \frac{1}{\mathrm{n(M)}} \tag{11}$$

5 Analysis for western Anatolia

5.1 Definition of seismogenic sub-regions

A seismogenic sub-region must include seismically homogenous fault segment where every point is assumed as having the same probability for a future earthquake. Sub-regions are mainly defined by two fundamental characteristics. These are a seismic profile and the tectonic regime of the region. Sub-regions should be defined as characteristic seismic areas which are as homogenous as possible. Marking the boundaries between sub-regions is quite difficult in the seismically complex regions like Anatolia. The boundary between sub-regions of different seismic potential should be located close to the highest concentration around the hard core of the more active ones. In these cases, all the possible characteristics such as the distribution of epicentres, the type of faulting, geomorphological conditions, seismicity and the largest event should be taken account. Under the points of this view, study area has been divided into 13 sub-regions (Fig. 2).

5.2 Computation of seismic risk and recurrence period

In this study, the linear least square method (Eq. (4)) has been applied to obtain a and b parameters in Eq. (3) for each sub-region shown in Fig. 2 using the earthquakes of $M_S \geq 4.0$ occurred from BC-496 to the end of 2006. Distribution of the earthquakes with the magnitude increment of 0.5 and cumulative frequency values for each sub-region have been given in Table 3, and the computed a and b values for these sub-regions are in Table 4. Figure 4 shows the magnitude–frequency relations.

Seismic risk and recurrence period values have been estimated by using a and b parameters given in Table 4. In the computations, magnitudes of $M_S \geq 5.0$ and increment interval of 0.5 were chosen, and Eqs. 5, 8, 9 and 10 for seismic risk and Eq. (11) for recurrence period are used. Observational time interval (T_1 year) has been determined by the completeness condition (Table 4, second column) of each sub-region. Maximum magnitude value (M_{max}) has been selected as magnitude of the biggest earthquake for each sub-region. Computations have been done for decades in the next 100 years. The results are given in Table 5. Figure 5 shows the standardized residuals of the predicted seismic risk values.

6 Discussion and conclusions

In this study, seismicity of western Anatolia has been investigated by means of computations of the magnitude–frequency relation, seismic risk and recurrence period, and the

Table 3 Cumulative frequencies (N_i) with the magnitude increment of 0.5 for the earthquakes occurred in each sub-region

Magnitudes (M_S)	Cumulative frequencies (N_i) for each sub-region												
	1	2	3	4	5	6	7	8	9	10	11	12	13
4.0–4.4	32	47	139	31	78	27	110	99	84	68	69	106	39
4.5–4.9	26	29	41	20	32	16	97	64	43	32	33	58	18
5.0–5.4	18	17	32	16	11	11	80	45	28	25	22	25	7
5.5–5.9	8	8	7	5	4	6	39	20	7	13	12	6	3
6.0–6.4	6	5	5	4	2	4	20	10	5	8	7	3	0
6.5–6.9	5	2	1	2	0	2	8	5	3	5	4	1	0
7.0.7.4	2	0	1	1	0	0	4	2	2	2	2	0	0
7.5–7.9	0	0	0	0	0	0	0	0	1	0	0	0	0

Table 4 a and b values with a standard errors estimated by the linear least square method for each sub-region

Sub-regions	Completeness date (d/m/yr)	Earthquake number	a	b
1 Balıkesir	12.10.1845	32	3.39 ± 0.19	0.43 ± 0.03
2 Bergama-Sındırgı	04.04.1903	47	3.85 ± 0.17	0.52 ± 0.03
3 Demirci-Gediz	30.04.1904	139	4.78 ± 0.41	0.66 ± 0.07
4 Bolvadin-Afyonkarahisar	16.10.1862	31	3.50 ± 0.20	0.47 ± 0.03
5 Dinar-Çivril	04.10.1914	78	4.06 ± 0.43	0.57 ± 0.07
6 Manisa-Salihli	03.11.1862	27	3.19 ± 0.134	0.44 ± 0.02
7 İzmir-Sakız Island	01.01.1639	110	5.15 ± 0.37	0.65 ± 0.06
8 Sisam Is.-Aydın-Denizli	21.06.1846	99	4.59 ± 0.17	0.58 ± 0.03
9 Bodrum-İstanköy	27.08.1886	84	3.30 ± 0.21	0.42 ± 0.03
10 Bozburun-Sombeki Island	18.10.1844	68	4.10 ± 0.14	0.53 ± 0.02
11 Fethiye-Rodos Island	28.02.1852	69	3.90 ± 0.07	0.50 ± 0.01
12 Gökova Gulf-Muğla-Gölhisar	24.08.1920	106	4.51 ± 0.43	0.66 ± 0.07
13 Antalya Gulf	08.07.1925	39	3.60 ± 0.47	0.52 ± 0.08

results tried to be interpreted and related with the active tectonic of region. The map in Fig. 2 showing the main faults and epicentre distribution demonstrate quite high seismic activity in the region. At the result of these observations, the study area has been separated to 13 sub-regions (Fig. 2). Magnitude–frequency relations have been determined by the data sets ($M_S \geq 4.0$) in different observation intervals for each sub-region. Then seismic risk and recurrence periods for the time periods of decades in the next 100 years and

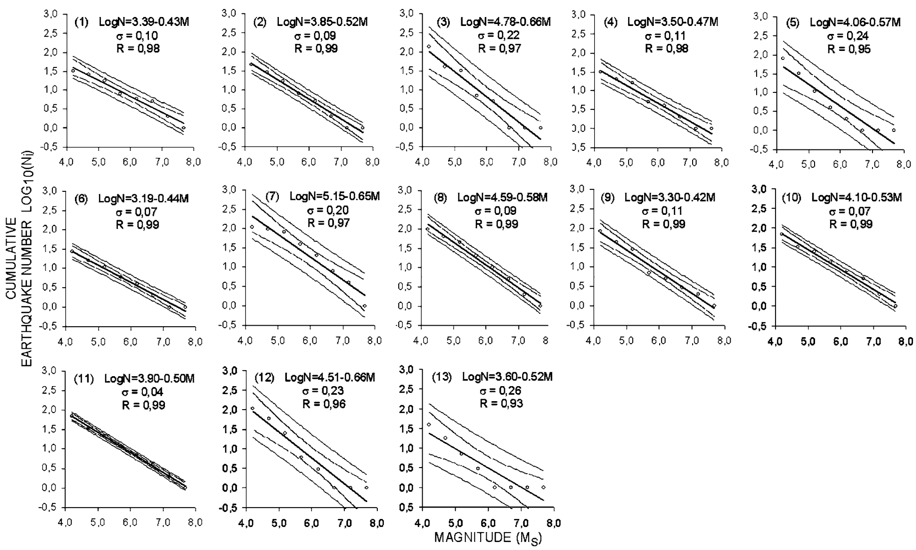

Fig. 4 Magnitude-frequency relations computed by the linear least square method. Thick line shows the estimated relation. Broken and thin lines show confidence interval band of 95% and prediction interval band. σ and R are standard deviation and correlation coefficient, respectively

Table 5 Seismic risk and recurrence period values estimated by using a and b values for the earthquakes of $5.0 \leq M_S \leq M_{max}$ with the magnitude increment of 0.5 in observation interval (T_1 year) of each sub-region. Maximum magnitude value (M_{max}) is magnitude of the biggest earthquake for each sub-region

Sub-regions	Magnitudes (M_S)	Seismic risk R(M)% period (year)										Recur. period Q (year)
		10	20	30	40	50	60	70	80	90	100	
1 (T_1 = 162 year) M_{max} = 7.2	5.0	66.4	88.7	96.2	98.7	99.6	99.9	100	100	100	100	9
	5.5	48.5	73.5	86.4	93.0	96.4	98.1	99.0	99.5	99.7	99.9	15
	6.0	33.3	55.5	70.3	80.2	86.8	91.2	94.1	96.1	97.4	98.3	24
	6.5	21.9	39.0	52.3	62.8	70.9	77.3	82.2	86.1	89.2	91.5	41
	7.0	14.0	26.0	36.3	45.2	52.9	59.5	65.1	70.0	74.2	77.8	67
2 (T_1 = 104 year) M_{max} = 6.9	5.0	76.4	94.4	98.7	99.7	99.9	100	100	100	100	100	7
	5.5	54.7	79.5	90.7	95.8	98.1	99.1	99.6	99.8	99.9	100	13
	6.0	35.3	58.1	72.9	82.5	88.7	92.7	95.3	96.9	98.0	98.7	23
	6.5	21.3	38.0	51.2	61.6	69.8	76.2	81.3	85.3	88.4	90.9	42
3 (T_1 = 103 year) M_{max} = 7.1	5.0	85.7	98.0	99.7	100	100	100	100	100	100	100	5
	5.5	59.8	83.8	93.5	97.4	98.9	99.6	99.8	99.9	100	100	11
	6.0	34.7	57.4	72.2	81.8	88.1	92.2	94.9	96.7	97.8	98.6	24
	6.5	18.1	32.9	45.0	55.0	63.1	69.8	75.2	79.7	83.4	86.4	50
	7.0	08.7	08.9	17.0	24.4	31.1	37.3	42.8	47.9	52.6	56.8	107
4 (T_1 = 145 year) M_{max} = 7.0	5.0	59.6	83.7	93.4	97.3	98.9	99.6	99.8	99.9	100	100	11
	5.5	41.0	65.2	79.5	87.9	92.9	95.8	97.5	98.5	99.1	99.5	19
	6.0	26.4	45.9	60.2	70.7	78.5	84.2	88.4	91.4	93.7	95.4	33
	6.5	16.4	30.1	41.5	51.1	59.1	65.8	71.4	76.1	80.0	83.3	56
	7.0	09.9	18.8	26.8	34.1	40.6	46.4	51.7	56.5	60.8	64.7	96
5 (T_1 = 93 year) M_{max} = 6.2	5.0	50.2	75.2	87.6	93.8	96.9	98.5	99.2	99.6	99.8	99.9	8
	5.5	50.2	75.2	87.6	93.8	96.9	98.5	99.2	99.6	99.8	99.9	14
	6.0	30.3	51.5	66.2	76.4	83.6	88.6	92.0	94.5	96.1	97.3	28

Table 5 continued

Sub-regions	Magnitudes (M_S)	Seismic risk R(M)% period (year)										Recur. period Q (year)
		10	20	30	40	50	60	70	80	90	100	
6 (T_1 = 145 year) M_{max} = 6.9	5.0	48.8	73.8	86.6	93.1	96.5	98.2	99.1	99.5	99.8	99.9	15
	5.5	33.2	55.4	70.2	80.1	86.7	91.1	94.1	96.0	97.4	98.2	25
	6.0	21.6	38.5	51.8	62.2	70.4	76.8	81.8	85.7	88.8	91.2	41
	6.5	13.6	25.4	35.6	44.4	51.9	58.5	64.1	69.0	73.3	76.9	68
7 (T_1 = 368 year) M_{max} = 7.2	5.0	90.2	99.0	99.9	100	100	100	100	100	100	100	4
	5.5	67.2	89.2	96.5	98.8	99.6	99.9	100	100	100	100	9
	6.0	41.3	65.6	79.8	88.2	93.0	95.9	97.6	98.6	99.2	99.5	19
	6.5	22.5	40.0	53.5	64.0	72.1	78.4	83.2	87.0	89.9	92.2	39
	7.0	11.5	21.7	30.7	38.7	45.7	52.0	57.5	62.4	66.7	70.5	82
8 (T_1 = 161 year) M_{max} = 7.2	5.0	79.9	96	99.2	99.8	100	100	100	100	100	100	4
	5.5	55.3	80.0	91.0	96.0	98.2	99.2	99.6	99.8	99.9	100	9
	6.0	33.2	55.4	70.2	80.1	86.7	91.1	94.1	96.0	97.3	98.2	20
	6.5	18.3	33.2	45.5	55.4	63.6	70.3	75.7	80.1	83.8	86.7	45
	7.0	9.6	18.3	26.2	33.3	39.7	45.5	50.8	55.5	59.8	63.7	98
9 (T_1 = 121 year) M_{max} = 7.7	5.0	69.5	90.7	97.2	99.1	99.7	99.9	100	100	100	100	6
	5.5	51.6	76.5	88.6	94.5	97.3	98.7	99.4	99.7	99.9	99.9	14
	6.0	35.7	58.7	73.4	82.9	89.0	92.9	95.5	97.1	98.1	98.8	23
	6.5	23.6	41.6	55.4	65.9	74.0	80.1	84.8	88.4	91.1	93.2	37
	7.0	15.1	28.0	38.9	48.1	56.0	62.6	68.3	73.1	77.2	80.6	61
	7.5	9.5	18.1	25.9	33.0	39.4	45.1	50.4	55.1	59.4	63.2	100

Table 5 continued

Sub-regions	Magnitudes (M_S)	Seismic risk R(M)% period (year)										Recur. period Q (year)
		10	20	30	40	50	60	70	80	90	100	
10 (T_1 = 163 year) M_{max} = 7.2	5.0	76	94.2	98.6	99.7	99.9	100	100	100	100	100	7
	5.5	53.9	78.8	90.2	95.5	97.9	99.0	99.6	99.8	99.9	100	13
	6.0	34.3	56.9	71.7	81.4	87.8	92.0	94.7	96.5	97.7	98.5	24
	6.5	20.4	36.7	49.6	59.9	68.1	74.6	79.8	83.9	87.2	89.8	44
	7.0	11.7	22.0	31.1	39.1	46.2	52.5	58.1	63.0	67.3	71.1	81
11 (T_1 = 155 year) M_{max} = 7.2	5.0	75.7	94.1	98.6	99.7	99.9	100	100	100	100	100	7
	5.5	54.9	79.7	90.8	95.9	98.1	99.2	99.6	99.8	99.9	100	13
	6.0	36.1	59.2	73.9	83.3	89.4	93.2	95.7	97.2	98.2	98.9	22
	6.5	22.3	39.6	53.0	63.5	71.6	77.9	82.9	86.7	89.6	91.9	40
	7.0	13.2	24.7	34.6	43.3	50.8	57.3	62.9	67.8	72.1	75.7	71
12 (T_1 = 87 yr) M_{max} = 6.7	5.0	70.3	91.2	97.4	99.2	99.8	99.9	100	100	100	100	4
	5.5	43.3	67.8	81.8	89.7	94.1	96.7	98.1	98.9	99.4	99.7	17
	6.0	23.3	41.2	54.9	65.4	73.5	79.6	84.4	88	90.8	93	30
	6.5	11.7	22	31.1	39.1	46.2	52.5	58	62.9	67.3	71.1	80
13 (T_1 = 82 year) M_{max} = 5.5	5.0	64.3	87.3	95.5	98.4	99.4	99.8	99.9	100	100	100	11
	5.5	43.3	67.8	81.7	89.6	94.1	96.7	98.1	98.9	99.4	99.7	18

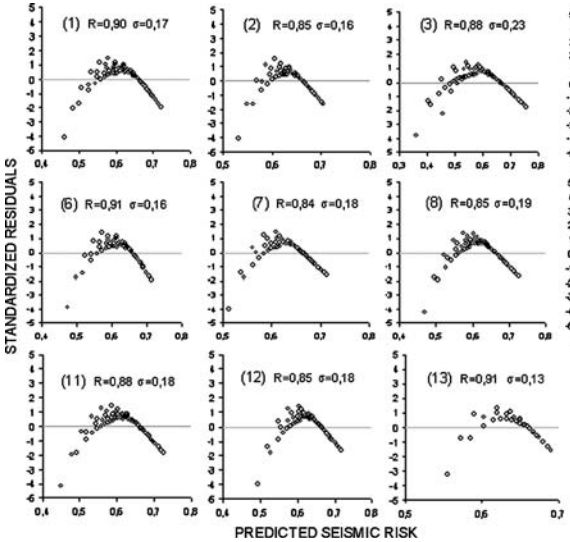

Fig. 5 The standardized residuals versus the predicted seismic risk for each sub-region. σ and R are standard deviation and correlation coefficient, respectively

magnitude interval of $5.0 \leq M_S \leq 7.5$ have been estimated from a and b values computed to determine the magnitude–frequency relations.

In twos of the highest and lowest b-values were determined as 0.66 ± 0.07, 0.66 ± 0.07 for sub-regions 3, 12, and as 0.43 ± 0.03, 0.42 ± 0.03 for sub-regions 1, 9, respectively. As it is well-known, the high b value implies that the high seismic activity had rolled in that region.

According to the seismic risk estimations, the highest-earthquake occurrence probability of $M_S \geq 7.0$ in the next 100 years is 80.6% (σ = 0.20, R = 0.87) for sub-region 9 and 77.8% (σ = 0.17, R = 0.90) for sub-region 1. Recurrence times for the earthquakes with the same magnitude have been found as 61 and 67 years in these sub-regions. The highest-occurrence probability and recurrence time of an earthquake with $M_S \geq 7.5$ in the next 100 years have been found as 63.2% (σ = 0.20, R = 0.87) and 100 years for sub-region 9, respectively. Sayıl and Osmanşahin (2005) had applied the regional time- and magnitude-predictable model at the same sub-regions of western Anatolia by using earthquakes with the magnitude $M_S \geq 5.5$ to compute the occurrence probabilities and the recurrence intervals of large earthquakes. The conclusions of present study agree with the results of the regional time- and magnitude-predictable model.

In conclusion, the large earthquakes have occurred in western Anatolia like its other regions and will occur in the future. For this reason, seismicity studies should be continued for minimizing the losses of life and property caused by earthquakes. Therefore, the tectonics features and active faults and activity of the region should be defined carefully and followed continuously.

References

Alsan E, Tezuçan L, Bath M (1975) An earthquake catalogue for Turkey for the interval 1913–1970. Report Kandilli Observatory, Istanbul and Uppsala Univ, Sweden

Altınok Y (1991) Assessment of the seismic risk of western Anatolia by Semi-Markov model. Geophysics 5:135–140

Ambraseys NN, Jacson JA (1981) Earthquake hazard and vulnerability in the northeastern Mediterranean: the Corinth earthquake sequence of February–March 1981. Disaster 5:355–368

Ambraseys NN, Finkel CF (1995) The seismicity of Turkey and adjacent areas, a historical review, 1500–1800. Eren Press, Istanbul

Ambraseys NN (2001) Reassesment of earthquakes, 1900–1999, in the eastern Mediterranean and the middle east. Geophys J Intern 145:471–485

Ayhan E, Alsan E, Sancaklı N et al (1987) An earthquake catalogue of Turkey and surrounding area (1881–1980). Boğazici Univ, Istanbul

Bağcı G (1996) Earthquake occurrences in western Anatolia by Markov model. Geophysics 10:67–75

Bath M (1966) Earthquake energy and magnitude. Phys Chem Earth 7:115–165

Bufe CG, Harsh PW, Burford RO (1977) Steady-state seismic slip: a precise recurrence model. Geophys Res Letters 4:91–94

Caputo M (1974) Analysis of seismic risk. Nato Advanced Study Institutes Series, Appl Sci 3, Noordhoff-Leiden

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 58:1583–1606

Dewey JW (1976) Seismicity of northern Anatolia. Bull Seismol Soc Am 66:843–868

Ergin K, Güçlü U, Uz Z (1967) An earthquake catalogue of Turkey and surrounding area (A.D. from 11 years to ends of 1964). Istanbul Tech Univ Faculty of Mining 24, Istanbul

Gündoğdu O, Altınok Y (1986) Earthquake data set of Turkey and surrounding area, 1900–1986. Istanbul Univ Engineering Faculty, Department of Geophysics, Istanbul

Gutenberg B, Richter CF (1954) Seismicity of the earth and related phenomena. Second Printed, Princeton University Press, Princeton

Hagiwara Y (1975) A stochastic model of earthquake occurrence and the accompanying horizontal land deformations. Tectonophysics 26:91–101

Karnik V (1968) Seismicity of the European area, Part I, Academic Praha, Publishing House of the Czechoslovak Academy of Sciences

Kenar Ö, Osmanşahin I, Özer MF (1996) Seismicity and tectonics of eastern Anatolia. Bull IISEE 30:59–76

Ketin I (1977) General geology 1. Istanbul Tech. Univ., Faculty of Mining publication, Istanbul

Knopoff L, Kagan Y (1977) Analysis of the theory of extremes as applied to earthquake problems. Geophys J R Astr Soc 82

Miyamura S (1962) Magnitude-frequency relations and its bearing to geotectonics. Proc Jpn Ac 38:27–30

McKenzie DP (1972) Active tectonics of the Mediterranean region. Geophys J R Astr Soc 30:109–185

McKenzie DP (1978) Active tectonics of the Alpine-Himalayan Belt: the Agean Sea and surrounding regions. Geophys J R Astr Soc 55:217–254

Osmanşahin I (1983) Seismicity of southeastern Anatolia and Caucasus (in Turkish). Dissertation Karadeniz Tech Univ Inst of Graduate Studies, Trabzon Turkey, p 62

Osmanşahin I, Eksi F, Alptekin O (1986) Seismicity and active tectonics of eastern Anatolia (in Turkish). Bull Earthq Res Inst of Turkey 52:5–41

Öcal N (1968) Seismicity and earthquake geography of Turkey (An earthquake catalogue of Turkey for the interval 1950–1960). Istanbul Univ, Kandilli Observatory, Istanbul

Özer MF (1983) Seismicity of the eastern part of north Anatolia Fault (in Turkish). Dissertation Karadeniz Tech Univ Inst of Graduate Studies, Trabzon Turkey, p 71

Papazachos BC (1989) A time-predictable model for earthquake generation in Greece. Bull Seismol Soc Am 79:77–84

Papazachos BC, Comminakis PE (1982) A catalogue of earthquake in Greece and surrounding area for the period 1901–1980. Univ of Thessaloniki, Geophys Lab 5, Greece

Parsons T, Toda S, Stein RS (2000) Heightened odds of large earthquakes near Istanbul: an interaction-based probability calculation. Science 288:661–665

Pınar N, Lahn E (1952) An earthquake catalogue of Turkey. Ministry of Public Working and Settlement, Department of Construction, 96

Rikitake T (1975) Statistics of ultimate strain of the earth's crust and probability of earthquake occurrence. Tectonophysics 26:1–21

Sayıl N, Osmanşahin I (2004) An Application of the time- and magnitude-predictable model to long-term earthquake prediction in the Marmara region. The 16th. International Geopyhsical Congress and Exhibition of Turkey, Cultural Center of Min Tech Res, Ankara, pp 107–111

Sayıl N (2005) An application of the time- and magnitude-predictable model to long-term earthquake prediction in eastern Anatolia. J Seismol 9:367–379

Sayıl N, Osmanşahin I (2005) An Application of the time- and magnitude-predictable model for the long-term earthquake prediction in the Western Anatolia. International Symposium on the Geodynamics of Eastern Mediterranean: Active Tectonics of the Aegean Region, Kadir Has Univ, İstanbul, 15–18 June 2005

Şengör AMC, Görür N, Şaroğlu F (1985) Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: Strike-Slip Deformation, Basin Formation and Sedimentation Soc Econ Paleontol. Mineral., Special Publication 37:227–264

Shah HC, Movassate M (1975) Seismic risk analysis of California state water project. Proc of Fifth European Conf on Earthq Eng 2:156

Soysal H, Sipahioğlu S, Kolçak D et al (1981) Historical earthquake catalogue of Türkiye and its surrounding. Tübitak, TBAG 341, Ankara

Stein RS, Barka AA, Dietrich JH (1997) Progressive failure on the north Anatolian fault since 1939 by earthquake stress triggering. Geophys J Intern 128:594–604

Sykes LR, Quittmeyer RC (1981) Repeat times of great earthquakes along simple plate boundaries. Maurice Ewing Ser 4:297–332

Tabban A, Gencoğlu S (1975) Earthquake and its parameters. Bull Earthq Res Inst of Turkey 11:7–83

Urbancic TI, Trifu CI, Long JM et al (1992) Space-time correlations of b value with stress changes associated with the 1999 November 12, Düzce (Turkey) Earthquake (Mw = 7.1). Geophys J Intern 153:229–241

Üçer SB, Crampin S, Evans R et al (1985) The MARNET radio linked seismometer network spanning the Marmara Sea and the seismicity of western Turkey. Geophys J R Astr Soc 83:17–30

Weeks J, Lockner D, Byerlee J (1978) Change in b-values during movement on cut surfaces in granite. Bull Seismol Soc Am 68:333–341

Westaway R (1990) Present-day Kinematics of the Plate Boundary Zone between Africa and Europe, from the Azores to the Aegean. Earth Planet Sci Lett 96:393–406

Wiemer S, Katsumata K (1999) Spatial variability of seismicity parameters in aftershock zones. J Geophys Res 104:13135–13151