Seismic hazard analysis of Sinop province, Turkey using probabilistic and statistical methods

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Using 4.0 and greater magnitude earthquakes which occurred between 1 January 1900 and 31 December 2008 in the Sinop province of Turkey this study presents a seismic hazard analysis based on the probabilistic and statistical methods. According to the earthquake zonation map, Sinop is divided into first, second, third and fourth-degree earthquake regions. Our study area covered the coordinates between 40.66°– 42.82°N and 32.20°– 36.55°E. The different magnitudes of the earthquakes during the last 108 years recorded on varied scales were converted to a common scale (M_w). The earthquake catalog was then recompiled to evaluate the potential seismic sources in the aforesaid province. Using the attenuation relationships given by Boore *et al.* (1997) and Kalkan and Gülkan (2004), the largest ground accelerations corresponding to a recurrence period of 475 years are found to be 0.14 g for bedrock at the central district. Comparing the seismic hazard curves, we show the spatial variations of seismic hazard potential in this province, enumerating the recurrence period in the order of 475 years.

1. Introduction

Considering the development and improvement activities in recent years, Sinop province has become a host to important projects for Turkey. It is one of the most populated cities in the country and hosts Turkey's first nuclear power plant in the region. Thus, construction activities need to be done as reliably as the seismic hazard of region permits (figure 1). The most important seismic activity which could affect the area is right directional North Anatolian Fault Zone (NAFZ). NAF which is one of the most important strike-slip fault systems known in the world has close resemblance with San Andreas Fault at California, USA. When the epicenter map covering the years 1900–2011 was examined, Sinop is shown in the highly active regions of the country.

Since earthquake occurrence cannot be prevented, governments and organizations should work towards minimizing the damage caused by earthquakes. The most important work in order to reduce damage is the preparation a seismic hazard map that will serve as a basis for the development of earthquake-resistant construction techniques. For setting the parameters for designing earthquake-resistant structures, using the probabilistic and statistical methods for determining seismic hazard estimation will be important and useful. In this study, we aimed at determining the seismic hazards in the Sinop province using the probabilistic and statistical methods.

Probabilistic Seismic Hazard Analysis (PSHA) is an estimate of exceedance probability in a given time period about levels of ground motion at different locations. The first step in establishing a

Keywords. Turkey; seismic hazard; North Anatolian Fault; probabilistic.

Figure 1. Tectonic sketch of the Arabia/Eurasia collision zone. Eastern Black Sea basin is located directly north of the tectonic escape of Anatolia. Dotted frame indicates the surveyed area. MBSH: Mid Black Sea High, NAF: North Anatolian Fault, EAF: East Anatolian Fault. Thick black arrows indicate motion of main crustal blocks with respect to Eurasia (modified from Rangin *et al.* 2002).

reliable earthquake catalog is to compile records of earthquakes from past years and examine the tectonic structure. The seismicity parameters of source zones and earthquake forming capacities can be calculated by checking every record from earthquake source zones in the study area. Attenuation relationships are important parameters for the calculation of the hazard analysis. More than one attenuation relationships were used in this study. This helped us to compare the obtained results.

Seismic hazard analysis can be done in two ways—Deterministic Seismic Hazard Analysis (DSHA) and the PSHA. In this study, PSHA was used. The first step of the DSHA approach is the determination of the biggest earthquake that occurred in the past from the seismic sources in the study area. If the earthquake catalog is not old enough or if there are some deficiencies in the catalog then the value of the biggest earthquake can be increased to 0.54 units. The second step is to select the most appropriate attenuation relationship that fits the characteristics of the region. Largest ground acceleration constituted on the bedrock at the project area caused by the biggest earthquake in terms of instrumental magnitude on the seismic source located a certain distance from the project

area is calculated by attenuation relationships (Abrahamson and Silva 1997; Sadigh *et al.* 1997). Many such seismic hazard studies are available today.

Ogata (1988) discussed several classes of stochastic models to study the origin and magnitudes of earthquakes. This study selects a statistical model for the standard activity of earthquake series by comparing several possible models using likelihood methods. In the next section, some possible stochastic models for seismic activity derived from empirical studies, mainly of aftershock statistics, are reviewed and discussed.

The Epidemic Type Aftershock-Sequences (ETAS) model is a point process representing the temporal activity of earthquakes in a certain geophysical region for which a method for fast and accurate computation of data is required. The present numerical procedures put the parameter estimation of the ETAS model to practical use in a large number of occurrence records (Bansal and Ogata 2010; Ogata 2011; Bansal *et al.* 2012).

The basis of statistical methods for the determination of seismic hazards was first developed by Cornell (1968). Previously, only the least squares regression analyses were used (Chiaruttini and

Siro 1981; Johnston 1996; Giardini *et al.* 1997; Gasperini and Ferrari 2000). However, a number of methods have been developed later. In our knowledge, the first general orthogonal regression (GOR) method to be applied to magnitude conversions is the Chi-square regression (CSQ), proposed by Stromeyer *et al.* (2004). Lolli and Gasperini (2012) provide a comparison among general orthogonal regression methods applied to earthquake magnitude conversions. Such conversions were usually done by empirical regressions using the ordinary least squares method (e.g., Chiaruttini and Siro 1981; Johnston 1996; Giardini *et al.* 1997; Gasperini and Ferrari 2000), which assumes that the uncertainty of the independent variable is negligible, and by the simple orthogonal regression approach (Ambraseys 1990; Gutdeutsch *et al.* 2002), which assumes that both variables have the same uncertainty. As such, assumptions are not fully appropriate for magnitude data sets, the use of GOR methods, which assume a different uncertainty for each of the two variables, are generally preferable. There are strict analogies among these three methods even though their formulations may appear quite different (Lolli and Gasperini 2012).

Turkey is an important area in terms of seismic risk. For this reason, a large number of seismic risk analyses must be conducted in the central settlement areas. In a study in the Antalya region, time and space windows proposed by Deniz and Yüçemen (2005) for earthquakes with moment magnitudes ≥ 4.5 , were used. As described by Deniz and Yüçemen (2005), the earthquakes that fall into the space and time windows defined for the magnitude level of a preceding earthquake with larger magnitude are classified as aftershocks of this event. If a larger magnitude earthquake occurs in a later time and space window of a smaller magnitude earthquake, this event is classified as the foreshock of the larger magnitude earthquake. To implement the space and time windows proposed by Deniz and Yüçemen (2005) and Deniz (2006), the magnitudes of earthquakes in the whole catalog should be converted to moment magnitude scale. This is achieved by using the equation derived by Deniz (2006) based on earthquakes recorded in Turkey. In a similar study, earthquake risk in the Eskişehir region was estimated using the stochastic methods by Genç (2004).

Studies have been conducted using different seismic hazard assessment approaches (i.e., deterministic and probabilistic), different attenuation relationships, and different models for seismic sources, magnitude distribution, and the time of earthquake occurrence. Two different methods are widely used for describing earthquake ground motions in geotechnical engineering. Both probabilistic and deterministic methods have a role in

hazard and risk analyses performed for decision-making purposes. PSHA has allowed uncertainties in size, location, and rate of recurrence of earthquakes, as well as in the variation of ground motion characteristics with earthquake size and location, to be explicitly considered in the evaluation of seismic hazards (Kramer 1996). Also determining the earthquake insurance premium a rate using stochastic methods was made by Deniz (2006). Seismic safety work of underground networks was made by Selçuk and Yüçemen (2000). Conversely, earthquake hazard of the Aegean extension region (West Turkey) was made by Polat *et al.* (2008).

In this study, PSHA methodology based on Cornell (1968) was applied for Sinop city and PGA values 10% probability of exceedance in 50 years at rock sites were determined by using the attenuation relationships proposed by Boore *et al.* (1997) and Kalkan and Gülkan (2004). Finally, PGA zonation maps were created for the study area by the CRISIS software (CRISIS 2003) prepared on the basis of Geographic Information System.

2. Geology and tectonic

Paleozoic metamorphic rocks constitute the main formations at Sinop. Metamorphic series around the Boyabat and Duraan districts are spread over a wide area on the east and south-west direction. Upper Cretaceous flysch and limestone occur at the south of Türkeli-Gerze line. This segment generally consists of layers of thick sandstone, marl and marly limestone. Eocene flysch series consists of thin-bedded, poorly cemented sandstone and marl around the Ayancık and Erfelek. The Neogene flysch at the Karasu Valley, southwest of the city center, consists of coarse-grained conglomerates and gres. At the west of the Sinop province and north of the Gerze, there are Pleistocene-aged series covering large areas consisting of sand and clay beds. Upper cretaceous volcanic rocks are found in some places at the Cape Sinop (Boztepe) and the northwest of the Boyabat district.

The study area is located at the Pontides, one of Turkey's tectonic units. Pontids are a part of Alpine mountain formation which starts from Czechoslovakia, Carpathians and passes through Romania, Yugoslavia and Bulgaria and eastward along the Black Sea shores to the Little Caucasus, Iran and extending to the Indian platform. According to the theories of plate tectonics, Alpine mountain formation system was formed by the collision of island arcs and continents (Dewey and Bird 1970). Alpine system which is a collision orogenic belt is a result of the extinction of the former Tethys Ocean (Şengör 1982). The island arc series volcanics around the Alpine mountain formation

was developed throughout this entire belt. Ercan and ve Gedik (1983) and Yılmaz (1980), compiled studies about this island arc volcanism at the Pontids that started from Lias and continued until the upper Eocene in various stages. There are not many studies about the volcanism before the Lower Cretaceous. But volcanics that are younger than Lower Cretaceous have been studied in detail and plenty of data has been obtained. In the Pontides, Upper Cretaceous–Eocene aged volcanic rocks have been thought to descend from a subduction zone dipping to the north by Tokel (1972, 1973, 1977, 1981), Stojanov (1973), Peccerillo and Taylor (1975, 1976), Akın (1978), Gedikoğlu (1978), Eğin and Hirst (1979), Gedikoğlu *et al.* (1979, 1982), Özsayar *et al.* (1982), Ercan *et al.* (1983). In this region an ocean called Tethys Ocean began to open up from Malm (Şengör and Yılmaz 1981) and as a result of the subduction zone that occurred by the plunging of crust material of this ocean's northern branch under the Pontian continent, an island arc volcanism developed after the Upper Cretaceous at the Pontian continent (figure 2).

After the collision between Anatolide-Tauride platform in the south and Pontian continent in the north from the Lower Eocene, this subduction zone completed its evolution (Şengör and Yılmaz 1981). In other words, The North Anatolian Tethys Ocean was closed due to the northern movement of the African and Arabian plates after the Upper Cretaceous (Peccerillo and Taylor 1976; Şengör and Yılmaz 1981; Ercan and ve Gedik 1983). Upper Cretaceous aged Hamsaros volcanics, Çokran associate Yemişliçay formation and Eocene aged Tekkeköy formation volcanics are island arc volcanics that descended from this subduction zone. Thus, Peccerillo and Taylor (1975, 1976) opined that Upper Cretaceous–Eocene aged volcanics at all Pontides that cover the study area too, might have been in the group of island arc volcanism. This was proved to be valid and volcanics in the study area was identified in the group of typical island arc volcanism with the help of chemical analysis of major elements, petrographic studies and regional geodynamic reviews. However, Plio-Quaternary aged Akyörük bazalt which is the youngest volcanism at the region is not in the island arc group unlike other volcanics and is thought to have been formed by the crustal thickening after the collision of Pontian continent and Tauride–Anatolide continents or an entirely alkaline volcanism derived from the primordial mantle. The theory of the mantle uplift in mid-plate is more appropriate for explaining the formation of this type of volcanics. Besides, such volcanics are known to be active in the entire Pontian belt until the Upper Quaternary (Ercan and ve Gedik

1983). This subject will have more clarity in the future when the analyses of trace elements and rare earth elements will be studied on this young alkaline formation.

3. Active faults in the study area

Approximately 94 km long section of NAFZ between the Köprübaşı in the east and Kargı in the west, was examined under the name of Köprübaşı–Kargı section (Şaroğlu and ve Yılmaz 1987). NAFZ is very distinct between the Ladik and Havza with N70W direction and loses its distinctness 4 km north of Havza transforming to large number of complex zones (figure 3).

Approximately 9 km west from this section, it becomes morphologically apparent again near the Köprübaşı. The fault tracks the Kızılırmak valley between the Kamil and Kargı. It consists of three sub-sections between the Köprübaşı and Kargı (Şaroğlu and ve Yılmaz 1987) (figure 3).

Between Köprübaşı and Çaygüneyi, there are many independent fractures with N75W trend inside a zone which is 24 km long and 4 km wide. This zonal structure is entirely related to ophiolitic units that the fault passed through. Between Çaygüneyi and Alanşeyhi, approximately 37 km long section is located. There is no detailed information about this section (Şaroğlu and ve Yılmaz 1987). Between Alanşeyhi and Kamil, there is a zone which consists of a few notable E–W trending fractures that are approximately 33 km long. Between Alanşeyhi and Tahtaköprü the fault tracks the Kocaçaydere valley along 14 km. There are different aged lithological units which stand side by side along the fault valley (Şaroğlu and ve Yılmaz 1987). There were 10 earthquakes with their instrumental magnitudes 6.0 or higher in the region (figure 3). We limit our study area to the years between 1900 and 2008 as given in table 1.

4. The creation of earthquake catalog

The Republic of Turkey Prime Ministry Disaster and Emergency Management Presidency (RTPMDMP 2009a) earthquake database and International Seismological Center (2009) records were used for earthquake catalogs. From these records earthquakes that occurred between 1 January 1900 and 31 December 2008 were taken into consideration.

Moment magnitude (M_w) was used in this study. The magnitude of the smallest earthquake that can cause seismic hazard is identified as 4.5 according to moment magnitude. Conversion to M_w scale of earthquake records which different

Figure 2. Geological map of Sinop region (Özdemir 2005).

institutions offered on different magnitude scales (body wave magnitude (M_b), duration magnitude (M_d), surface wave magnitude (M_s), and local magnitude (M_l)) constitutes important problems.

Considering that different institutions use different measurement devices and different calculation methods, earthquake magnitudes also become different. Therefore, conversion of magnitude scales

Figure 3. Active faults in the study area (Şaroğlu and ve Yılmaz 1987) and distribution of earthquakes with instrumental magnitudes 6.0 and higher in the study area between 1900 and 2008.

Table 1. There were 10 earthquakes with instrumental magnitudes 6.0 or higher in the region RTPMDEMP (2009a).

Date	Time (GMT)	Latitude	Longitude	Depth (km)	Magnitude	Location
25.06.1910	19:26:00.00	41.0000	34.0000	0	Ms = 6.2	Osmancık-Corum
24.01.1916	06:55:00.00	40.2700	36.8300	10	Ms = 7.1	Almus-Tokat
11.12.1942	02:39:00.00	40.7600	34.8300	40	Ms = 6.1	Laçın-Çorum
20.12.1942	14:03:00.00	40.7000	36.8000	16	Ms = 7.0	Erbaa-Tokat
26.11.1943	22:20:00.00	41.0500	33.7200	10	Ms = 7.2	Tosya-Samsun
01.02.1944	03:22:00.00	41.4100	32.6900	10	Ms = 7.2	Gerede-Bolu
26.10.1945	13:56:00.00	41.5400	33.2900	50	Ms = 6.0	Daday-Kastamonu
13.08.1951	18:33:00.00	40.8800	32.8700	10	Ms = 6.9	Kurşunlu-Çankırı
07.09.1953	03:59:00.00	41.0900	33.0100	40	Ms = 6.4	Kurşunlu-Çankırı
11.01.1997	06:42:00.30	40.5500	35.2500	10	Md = 6.0	Mecitözü-Çorum

into each other cannot be made with analytical methods. This situation requires the development of empirical equations. Standard least squares method and orthogonal regression methods are the most commonly used empirical relationships. Standard least square method only considers the error which is caused by random earthquakes. However, determination of earthquake magnitudes depends on many factors. For this reason, it is not possible to determine magnitudes without an error. In this case, using the orthogonal regression method is more appropriate which can also be used on the previous seismic hazard analysis studies conducted

in Turkey. As a result of the analysis of earthquakes on nationwide scale in the last century with related method, the obtained conversion equations (Deniz and Yüçemen 2005) are given below.

$$M_w = 2.25xM_{B-ave} - 6.14$$

$$M_w = 1.27xM_{D-ave} - 1.12,$$

$$M_w = 1.57xM_{L-ave} - 2.66$$

$$M_w = 0.54xM_{S-ave} - 2.81. \quad (1)$$

In equation (1), ‘ave’ sub-icon represents the average earthquake magnitudes given according to the same scale on different data sources for every earthquake.

There are several stochastic models which are considered dependent or independent to previous earthquakes on the estimation process of the earthquake occurrences. The Poisson model is the most widely used of these models. For earthquake events to build up a Poisson process, they must meet the following conditions first; earthquakes are independent in time, which means earthquake occurrences in any year does not affect re-occurrence. Earthquakes are independent in space. It means an earthquake which occurs in any source area will not affect earthquake occurrence in another source area. There is zero possibility of being two separate earthquakes in the same place at the same time. According to Poisson model: the possibility of n number earthquake that is bigger than m_0 lower magnitude limit in the studied area on t time period is given with the equation below:

$$P_n(t) = e^{-\lambda t} \cdot \frac{(\lambda t)^n}{n!}$$

In this equation, $P_n(t)$ is the possibility of n number event during the t time, n is the number of events and λ is the number of earthquakes on unit time period (generally 1 year) in a studied area.

In this study, Poisson model was used. To ensure the independent condition of this model, preliminary earthquakes and aftershocks were excluded from the analysis. There are a lot of methods to separate the preliminary and aftershocks from the main shocks in the literature (Gardner and Knopoff 1974; Prozorov and Dziewonski 1982; Savage and Rupp 2000; Kagan 2002). Preliminary and aftershocks show similar spatial and temporal distributions around the main shocks. Based on the studies of Deniz and Yüçemen (2005) in this study, all of the earthquakes inside a particular time and distance window are considered as aftershocks to a main shock which is recorded on a level of a particular earthquake magnitude. In assessing an earthquake as a preliminary earthquake, there must exist another, bigger magnitude earthquake inside the time and distance window identified for its own level of magnitude. This biggest magnitude earthquake is assumed as the main shock. As an exception, all the earthquakes whose magnitudes are higher than 6.0 inside the particular time and distance window are considered as main shocks. Time and distance windows (Deniz and Yüçemen 2005) that are used in this study are given in table 2.

Table 2. Time and distance windows used in the identification of aftershocks (Deniz and Yüçemen 2005).

Magnitude	Distance (km)	Time (day)
4.5	35.5	42
5.0	44.5	83
5.5	52.5	155
6.0	63.0	290
6.5	79.4	510
7.0	100.0	790
7.5	125.9	1326
8.0	151.4	2471

5. Seismic sources

In this study, 101 earthquakes during the 18-year time period were used; 71 of these earthquakes (figure 4) were considered as main shocks. 37 earthquakes from these main shocks were identified as source zone earthquakes and 34 earthquakes were evaluated as background field source earthquakes (figure 4). Determined seismic source zones for the whole of Turkey by Deniz (2006) also were considered on the selection of the source zones earthquakes in this study (figure 4).

Although the study area is the Sinop central, it is obvious that seismic hazard cannot be dependent on earthquakes in the examined area. Therefore it is assumed that the earthquake hazard of the region was determined by rectangular area which was limited by 40.66°–42.82°N and 32.20°–36.55°E. 23 seismic sources were identified within this region (figure 4).

To determine the probability distribution of earthquake magnitudes, the correlation proposed by Gutenberg and Richter (1949) is expressed as:

$$\text{Log } N(M) = a - b(M). \quad (2)$$

In this correlation, N is the number of earthquakes with M magnitude or greater than M in a year, a and b are regression coefficients and M is the magnitude of the earthquake.

In the relationship of equation (2), a -coefficient is identified as ‘Annual Average Index of Seismic Activity’ which depends on the size of the region, duration of the observation and earthquake activity in the duration of the observation and b -coefficient is identified as ‘Seismotectonic parameter’ which varies according to the tectonic characteristics of the region.

Using the least square method for source zone and background field source earthquakes, a and b coefficients on equation (2) relationship were calculated separately for each source zone from the

Figure 4. Main shocks in the study area, seismic sources are identified within this region and seismic source zones.

M –Log $N(M)$ curve (figure 5). High seismic activity in the region that corresponds to a small coefficient of b , shows that the voltage is discharged continuously. However, graph of the magnitude–recurrence relation Ezinepazar–Kırıkkale fault source zone appears to be less than the amount of the earthquake (figure 5b).

6. Attenuation relationship

In this study, attenuation relationship proposed by Kalkan and Gülkan (2004) and Boore *et al.* (1997) was used. According to Kalkan and Gülkan (2004) and Boore *et al.* (1997) due to the use of equations of attenuation relations, the development of different faults according to the specifications is due to different ground conditions. Researchers recommend that in these kinds of studies coefficients for the different soil conditions in the same attenuation relationship should be used by changing. On the other hand, examination of local soil conditions of the area emerges as another subject of study. Thus, coefficients for the hard soil will be used for attenuation relationship in our study. Every attenuation relationship will be taken as $V_s = 700$ m/s. Thereby results obtained from the attenuation relationships can be compared.

6.1 Kalkan and Gülkan (2004)

Kalkan and Gülkan included in their study done in 2004, moment magnitude values of 4.0 and greater of 57 earthquakes which occurred in Turkey between the years 1976 and 2003, the equation was obtained using the 223 horizontal component record from the 112 strong-motion measurement:

$$\ln Y = 0.393 + 0.576 (M_W - 6) - 0.107 (M_W - 6)^2 - 0.899 \ln(r) - 0.200 \ln(V_S/V_A), \quad (3)$$

where Y is the horizontal component of the largest ground acceleration in terms of gravitational acceleration (in grams) and M is the moment magnitude.

They identified the standard deviation of $\ln Y$ in terms of Peak Ground Acceleration (PGA) as $\sigma_{\ln Y} = 0.612$. The variable r is calculated using the following equation:

$$r = (r_{cl}^2 + h^2)^{\frac{1}{2}}, \quad V_A = 1112 \text{ and } h = 6.91,$$

where r_{cl} is identified as the shortest distance in kilometers between the expected location of the largest ground acceleration with the projection of rupture surface to earth. The calculated values of other parameters in equation (3) are given in table 3 (figure 6).

Figure 5. Magnitude–frequency relationship. (a) NAFZ source zone, (b) Ezinepazarı–Kırıkkale Fault source zone (EKFZ), and (c) Background source zone (BSZ).

Here average V_S value for rock was taken to be 700 m/sec, for hard soil to be 400 m/sec and for soft soil to be 200 m/sec (Kalkan and Gülkan 2004).

6.2 Boore *et al.* (1997)

Boore *et al.* in their study done in 1997 included 271 records belonging to the 20 shallow focused earthquakes that occurred in North America between the years 1940 and 1992. Magnitudes of these earthquakes vary between 5.5 and 7.5 according to Mw. However, a number of ground motion measurements caused by earthquakes

smaller than 6.0 are limited. In the original study, alternative analyses were conducted which classified earthquakes according to their fault mechanism. However, in our study attenuation relationships obtained by using all the earthquakes with moment magnitudes of 4.0 and greater were given. Attenuation relationships suggested for hard soil up to 80 km are expressed as

$$\ln Y = b_1 + b_2 (M - 6) + b_3 (M - 6)^2 + b_5 \ln r + b_v \ln \left(\frac{V_S}{V_A} \right), \quad (4)$$

Table 3. The coefficient values in attenuation relationships developed by Kalkan and Gülkan (2004) and Boore et al. (1997).

Period (sec)	Developers	b_1	b_2	b_3	b_5	b_V	V_A	h (km)	$\sigma_{\ln Y}$
Peak ground	Kalkan and Gülkan (2004)	0.393	0.576	-0.107	-0.899	-0.200	1112	6.91	0.612
acceleration (PGA)	Boore et al. (1997)	-0.313	0.527	0.000	-0.778	-0.371	1396	5.57	0.495

Figure 6. Peak ground acceleration values attenuation–relation proposed by Kalkan and Gülkan (2004).

where Y is the horizontal component of the largest ground acceleration in terms of gravitational acceleration (in grams) and M is the moment magnitude.

They were identified standard deviation of $\ln Y$ as $\sigma_{\ln Y} = 0.495$. Boore et al. (1997 with erratum) variable is calculated with this equation below:

$$r = (r_{cl}^2 + h^2)^{\frac{1}{2}}.$$

In this equation, r_{cl} is identified as the shortest distance in km between the expected location of the largest ground acceleration with the projection of rupture surface to earth. The calculated values of other parameters in equation (4) are given in table 3 (figure 7).

7. Estimated seismic hazard values for Sinop province

For making the analysis of seismic hazard in the study area and creating the iso-acceleration maps, a computer program CRISIS 2003 (Ordaz et al. 2003) was used. Using the different attenuation relationships, iso-acceleration maps were acquired

for Sinop province corresponding to the recurring period of 475 years (Solomos et al. 2008). The program uses Poisson and characteristic earthquake models to consider the occurrence and distribution of earthquakes and the seismicity of the sources along with attenuation relationships to define the ground motion at the site. Civil engineers identified a situation concerning 50-year life proximity of the buildings. In this case, the economic life of a structure which has had 50 years of exposure to a major earthquake probability is 0.10. Seismic hazard maps are also plotted for PGA and MSK corresponding to a return period of 475 years (10% probability of exceedance in 50 years) considering the combination composed of the most likely assumptions. These maps are shown in figures 8 and 9. All of the seismic hazard calculations are conducted using the software CRISIS 2003.

7.1 Kalkan and Gülkan (2004)

The largest acceleration value calculated for the recurring period of 475 years was found to be 0.14 g at the Sinop city center. Acceleration value in south of the study area also was obtained as 0.40 g (figure 8).

Figure 7. Peak ground acceleration values attenuation–relation proposed by Boore *et al.* (1997).

Figure 8. Iso-acceleration map of Sinop province corresponding to recurring period of 475 years calculated according to Kalkan and Gülkan (2004).

7.2 Boore *et al.* (1997)

The largest acceleration value calculated for the recurring period of 475 years was found to be 0.12 g at the Sinop city centre. This value increases southwards from city center and reaches 0.29 g in the area closest to the seismic source (figure 9).

Saraydüzü district is located in the closest proximity to NAFZ. Durağan district is located

in the northeast of Saraydüzü and Boyabat district is located northwest of it. Seismic hazard analyses were made using the attenuation relationships by Boore *et al.* (1997) and Kalkan and Gülkan (2004) results are shown, respectively in figure 10. Saraydüzü district has more earthquake risk for the recurring period of 475 years considering Boyabat and Durağan districts.

Figure 9. Iso-acceleration map of Sinop province corresponding to recurring period of 475 years calculated according to Boore *et al.* (1997).

Figure 10. Calculated earthquake hazard curves for Boyabat, Durağan and Saraydüzü districts.

8. Discussions and conclusions

This study aims to estimate the earthquake hazard of Sinop province by using the probabilistic and statistical methods to study earthquakes whose instrumental magnitudes are 4.0 and greater occurring between the dates 1 January 1900

and 31 December 2008. The four stages of this procedure represent the characterization of seismic sources zones, estimation of seismic hazard parameters, selection of appropriate attenuation relationships, and evaluation of the hazard for the sites of interest. These seismic source models have been modified taking the advantage of recent

neotectonic and seismic data for Sinop province. The previous studies performed by several researchers cover Sinop province.

We investigated 101 earthquakes that had instrumental magnitudes 4.0 and greater than 4.0 inside the 108-year period in our study area. 71 of these earthquakes were considered as the main shocks. 37 earthquakes were considered as the source zone earthquakes and the remaining 34 earthquakes were assessed as the background field source earthquakes. The data on historical and instrumentally recorded earthquakes for Sinop province and surrounding vicinity, collected from the Earthquake Research Department of the General Directorate of Disaster Affairs of Turkey (RTPMDOMP 2009b) were considered as a basis of seismic hazard calculations.

Four seismic sources were selected to assess the seismic hazard of Sinop. These are NAFZ, EKFZ, and BFZ, which are illustrated in figure 5. As a result, nationwide analysis of earthquakes in the last century obtained conversion equations (Deniz and Yüçemen 2005). The Turkish specification suggests that the data defined above should be used for seismic studies of large engineering structures. The coefficients of the G-R law between magnitudes and their cumulative frequencies of occurrence.

In this study, attenuation relationships by Boore *et al.* (1997) and Kalkan and Gülkan (2004) were used. Seismic hazard curves corresponding to the recurring period of 475 years for the Sinop central, Saraydüzü, Boyabat and Durağan districts according to two attenuation relationships were obtained. According to these attenuation relationships, the correlation given by Kalkan and Gülkan (2004) between the calculated acceleration values for Sinop center, Saraydüzü, Boyabat and Durağan districts suggests a large quantity.

For Sinop central:	
Attenuation relationship	Largest acceleration value corresponding to recurrence period of 475 years (g)
Boore <i>et al.</i> (1997)	0.12
Kalkan and Gülkan (2004)	0.14

For Saraydüzü district:	
Attenuation relationship	Largest acceleration value corresponding to recurrence period of 475 years (g)
Boore <i>et al.</i> (1997)	0.19–0.29
Kalkan and Gülkan (2004)	0.24–0.40

For Boyabat district:	
Attenuation relationship	Largest acceleration value corresponding to recurrence period of 475 years (g)
Boore <i>et al.</i> (1997)	0.12–0.22
Kalkan and Gülkan (2004)	0.14–0.29

For Durağan district:	
Attenuation relationship	Largest acceleration value corresponding to recurrence period of 475 years (g)
Boore <i>et al.</i> (1997)	0.15–0.22
Kalkan and Gülkan (2004)	0.19–0.34

Using two different attenuation relationships, the largest ground acceleration corresponding to the recurrence period of 475 years is found to be 0.14 g for bedrock on the central district. When computing the seismic hazard curves of other mentioned districts, it can be said that Saraydüzü district has greater probability of seismic hazard than other districts.

Based on the probabilistic seismic hazard analysis, the following conclusions are drawn: The attenuation models introduced by Boore *et al.* (1997) and Kalkan and Gülkan (2004) gave more realistic solutions for the Sinop province and its vicinity. For the province of Sinop, the hazard is mainly dominated by NAFZ. The analyses indicate that the mean PGA value for the city center of Sinop is about 0.12 g by Boore *et al.* (1997) and 0.14 g by Kalkan and Gülkan (2004) 10% probability of exceedance in 50 years. The seismic hazard maps produced by this study agree with the one prepared by the National Disaster Organization for the whole country, but it provides more detailed values for the investigated region.

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