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ORIGINAL PAPER

Probabilistic seismic hazard assessment of Muğla, Turkey

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Abstract

Muğla Province, which has been selected as the study area, is located in the Aegean Extension Region (AER), where seismic motions are widely observed. Moreover, the AER is the most active part of the Eastern Mediterranean Region in terms of seismic activity, and this seismicity has been continuing increasingly. This study aims to determine the seismic hazard of Muğla Province and its surroundings by using the probabilistic seismic hazard method. The earthquake dataset including 19,824 seismic records that were used in the research was obtained from the national and international earthquake catalogs. The data about the active fault zones in the study area were acquired from the General Directorate of Mineral Research and Exploration. The seismic source zones were generated as homogeneous areas as possible taking into account the active fault zones. The earthquakes in seismic source zones were eliminated based on the time and distance frames. The annual recurrence relationships of the source zones were determined using the least-squares method taking into account the earthquakes with a magnitude of 5 or above. The peak acceleration values on the bedrock were calculated using the attenuation relationships of the selected local and global ground motion prediction models. The calculations were performed using the SEISRISK III software package utilizing the homogeneous Poisson Process Model according to the exceedance probability of 10% for 50 years (corresponding to the return period of 475 years). The peak acceleration values on bedrock were found to range between 0.11 and 0.42. The study revealed that the Gökova fault zone (Zone 4) was the most active source in terms of the seismic hazard in the region and that the seismic hazard of the southwestern part of the region was greater compared to other parts.

Keywords Muğla · Probabilistic seismic hazard analysis · SEISRISK III · Peak acceleration on bedrock

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1 Introduction

The purpose of seismic hazard analyses is to construct buildings and facilities that can meet a certain level of shocks caused by earthquakes by avoiding excessive damage to the load-bearing system of these buildings and facilities. It is required to predict the level of potential shocks that the building may face to construct these buildings and facilities safely. The level of these shocks can be defined by the design ground motion, which is characterized by using certain ground motion parameters (İnce 2005). The time, location, magnitude, and other characteristics of future earthquakes in a seismically active region cannot be predicted. Determining the impacts of earthquakes that may occur in a certain period on the construction site, particularly, the maximum possible values of the parameters related to the ground motion that may cause destructive effects on the building, is one of the most challenging and important problems of geotechnical earthquake engineering. Some of the studies in the literature on this subject are summarized below.

In the study conducted by Erdik et al. (1985), the seismic hazard map of Turkey was generated using probabilistic methods. Deniz and Yücemen (2005) studied the seismic data in various scales regarding the earthquakes that occurred in Turkey, and they obtained experimental equations that convert the seismic intensity of these earthquakes to the moment magnitude scale by using orthogonal regression methods (total least-squares method). Finally, they investigated the seismic hazard of the Antalya region using stochastic (random) methods. They generated regional seismic sources by analyzing seismic data of the study area with a diameter of 250 km where Antalya is in the center for an observation period of one hundred years. Using national and international ground motion prediction models (ground attenuation relations), they modeled the seismic hazard of the study area for 475 years based on the Poisson Process Model and obtained the peak acceleration values.

In their study on the integrated earthquake risk of the Odunpazarı Municipality of the Eskişehir Düzgün and Yücemen (2007) used and revised the seismic source zones that were already generated by Bommer et al. (2002). Orhan et al. (2007) examined the earthquakes affecting the region for 100 years to determine the seismic hazard of Eskişehir Province by using probabilistic methods. In their study on determining the seismic hazard of the Marmara Region, Sayıl and Osmanşahin (2007) used the records of earthquakes with an instrumental magnitude of 4 and above for the period 1900–2004, as well as the records of the earthquakes that occurred in historical periods. Other studies on the subject are listed below.

Orhan et al. (2007), Yalçın et al. (2008), Güzel (2009), Dipova ve Cangir (2011), Kartal et.al. (2011), Ocak (2011), Unutmaz et al. (2011), Tosun and Seyrek (2012), Akol and Bekler (2013), Işık (2013), Levendoğlu (2013), Ram and Guoxin (2013) Kartal et al. (2014) Özmen and Erkan (2014) Rehman et al. (2014).

In her Ph.D. study, İnce (2005) conducted the micro-zoning of the Old City Districts of Istanbul (Fatih and Eminönü districts), and she generated the site amplification, liquefaction and landslide hazard maps. The seismic hazards of the region were calculated by a stochastic method using seismic source zones determined in the Global Seismic Hazard Assessment Program (GSHAP) (1999). The maximum possible horizontal acceleration values that might be observed in the region were calculated using the SEIS-RISK III seismic hazard estimation program (Bender and Perkins 1987) for a period of

50 years according to the exceedance probabilities of 10% and 40%. Then, the peak and spectral acceleration maps were generated for the ground and bedrock.

Erdik et al. (2006) analyzed tectonic and seismic data of Turkey in detail, and they identified active fault zones in the region. The researchers generated regional seismic sources of the study area to calculate the probabilistic seismic hazards based on the country.

In the study, the short-period earthquakes group, which included all minor earthquakes, and the long-period earthquakes group, which included all major earthquakes, were used. The missing data were generated by combining both data groups to obtain a homogeneous database. Then, this homogeneous dataset was used to determine the seismicity of seismic sources. Seismic hazards for the buildings were assessed for their economic life of 50 years by calculating the maximum horizontal acceleration values using the SEISRISK III software for earthquakes within the periods of 72, 475 and 2475 years, respectively. Then, the peak and spectral acceleration maps were generated.

Ansal et al. (2011) aimed to create a model to determine site amplification and characteristics of a site-specific design earthquake. In this study, they compared the spectral acceleration records of the 1999 Kocaeli earthquake with the spectral acceleration values generated by the Shake91 software (Idriss and Sun 1992) and the NEHRP (1997) spectral acceleration values for the return periods of 475 and 2475 years.

In the present study, the probabilistic seismic hazard of Muğla Province was calculated using the SEISRISK III software utilizing the homogeneous Poisson Process Model developed by Bender and Perkins (1987). The Gökova fault zone and the Fethiye–Burdur fault zone stand out as the significant fault zones in the region. The attenuation relationships suggested by Boore et al. (1997), Campbell and Bozorgnia (2008) and Kalkan and Gülkan (2004) were used to determine the peak ground acceleration values on the bedrock for the 50-year economic life of the buildings for an exceedance probability of 10%.

1.1 Probabilistic seismic hazard

As defined in Fig. 1, the probabilistic earthquake hazard analysis can be conducted in four steps. In the first step, seismic sources that may affect the region are determined (seismic source zoning). In the next step, seismicity or earthquake recurrence–time distribution (recurrence relationships) is revealed. In the third step, the ground motion caused by an earthquake of any magnitude occurring at any point in the source zone is determined based on attenuation relationships. In the fourth step, which is the final one, the exceedance probability of the ground motion parameter in a certain period is obtained by earthquake occurrence models after the uncertainties related to earthquake location, earthquake magnitude and ground motion estimation are combined (Kramer 1996).

1.2 Modeling the seismic hazard

The probabilistic seismic hazard analysis method, which was first introduced by Cornell (1968), provides successful results. The model takes into account the uncertainties in the magnitude, locations and frequency of earthquakes together with the changes in their magnitudes and locations, and the characteristics of ground motion while modeling the seismic hazard. The purpose of seismic hazard analysis is to systematically combine data of previous earthquake events from various disciplines using statistical methods and to determine the probabilities of seismic activities that can be expected at

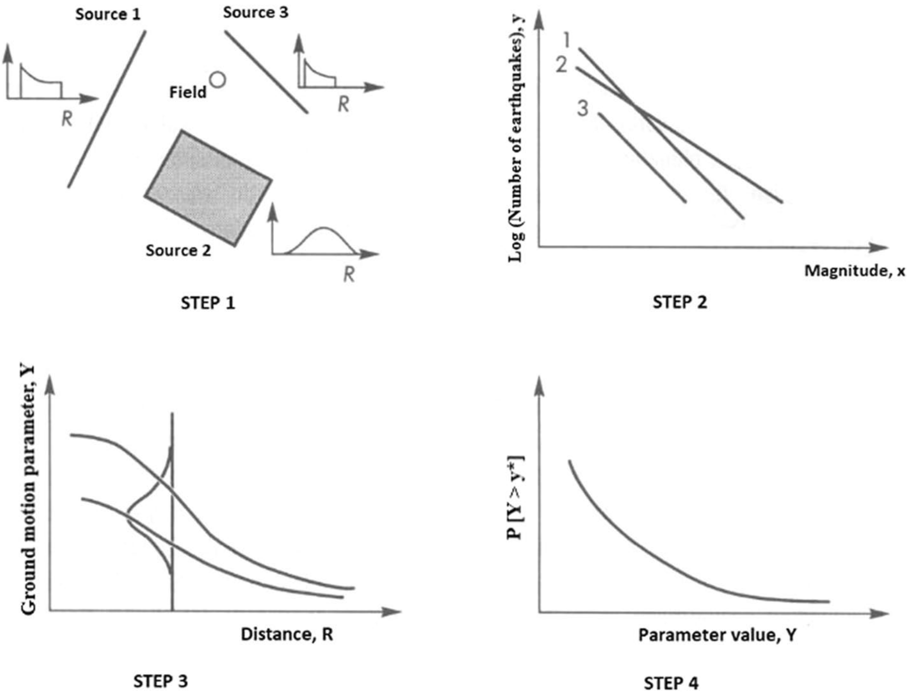

Fig. 1 Four steps of the probabilistic seismic hazard analysis (Kramer 1996)

the construction site in a certain location in the future (Yücemen 2008). These analyses provide the peak ground acceleration value or spectral acceleration value for a period. Homogeneous Poisson Process Model and Relative Likelihood (Recurrence) Model are commonly used for modeling seismic hazards.

1.2.1 Homogeneous Poisson process model

The Poisson Process developed by Cornell (1968) is the simplest model. The earthquakes should meet the conditions of independence, regularity and stability to meet the criteria of this model. In the Poisson Process Method, the occurrence of earthquakes due to a certain seismic source can be expressed using the following equation (Kramer 1996; Meral and Meral 2002; Yücemen 2008):

$$P_{\mathrm{A}}(n/m,t) = \left[\exp\left(-\lambda_{\mathrm{A}}(m)t\right)n\right]/n! \tag{3.10}$$

where $P_A(n/m, t)$ is the probability of the occurrence of n earthquakes with a magnitude of $M \geq m$ in the time frame of t. $-\lambda_{\mathrm{A}}(m)$ denotes the average occurrence rate. The number of earthquakes with a magnitude of $M \geq m$ expected to occur in the time frame of T is calculated as follows:

$$E_{\mathrm{A}}\left(\frac{n}{m},t\right)=\lambda_{\mathrm{A}}(m) \tag{3.11}$$

The probability of the occurrence of at least one earthquake with a magnitude of $M \geq m$ in the time frame of t is expressed as follows:

$$P(n>0|m,t)=1.0-\exp\left[\lambda_{\mathrm{A}}(m)\right] \tag{3.12}$$

The average recurrence interval (return time) of an earthquake, $\mathrm{RI}_{\mathrm{A}}(m)$, is expressed as the inverse of the occurrence rate.

$$\mathrm{RI}_{\mathrm{A}}(m)=1/\lambda_{\mathrm{A}}(m) \tag{3.13}$$

The probability of at least one earthquake with a magnitude greater than z within a period of t years can be calculated using the Simple Poisson Process Method as follows;

$$P_E(A>z,t)=1-\exp\left[-v(A>z)t\right] \tag{3.14}$$

or

$$R_t=P_E(z)=1-\exp\left[-V_z t\right] \tag{3.15}$$

where $V_z = V(A > z)$ denotes the annual frequency of ground motions with a magnitude greater than z occurring in a site. The average return period (RP) for a strong level of ground motion is defined as the inverse of V_z:

$$\mathrm{RP}=1/V_z \tag{3.16}$$

In practice, the results of probabilistic seismic hazard analysis are expressed using one or some of the parameters of $P_E(z)$, P, and V_z.

2 Description of the study area

Muğla, which is a very rich province in terms of its historical and touristic texture and has many natural beauties, has been selected as the study area (Fig. 2). The region is one of the leading provinces in Turkey in terms of tourism revenue. However, it is one of the regions with a high risk in terms of seismic activity. There are many grabens, gulfs and faults within the borders of the Muğla Province. Also, the province has faced many earthquakes in the past that caused the loss of life and property. Estimating the seismic hazard and its effects on such an important region, and determining the measures that can be taken are considered to be important for the region.

2.1 Geological features of the region

The units and structures reflecting the basic geological features of the Western Taurus Mountains are outcropped in the region. It has been known for many years that Palaeozoic–Mesozoic and Tertiary aged rock units of various origins outcropped as autochthonous and allochthonous units in the region (Bozcu et al. 2007). The Lycian nappes among the allochthonous units lie between the Menderes Massif in the north and the Bey Mountains autochthon in the south.

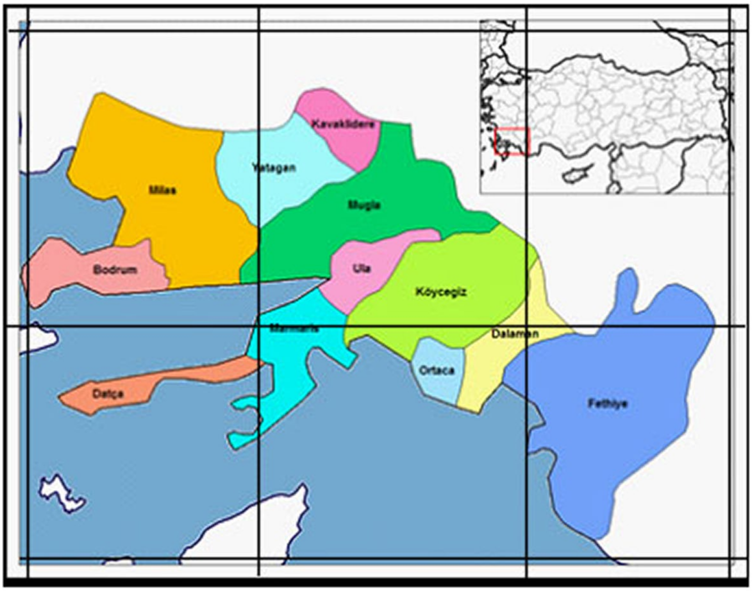

Fig. 2 The map of the Muğla province

The units which are known as the Tavas nappe, Bodrum nappe and Marmaris ophiolite nappe outcrop as the allochthonous units belonging to the Lycian nappes. Tectonically, these nappes are located on the Eocene aged Elmalı formation in the region. The allochthonous units in the study area are unconformably covered by Plio-Quaternary sediments (Şenel et al. 1991, 1996; Bozcu et al. 2007).

They form a light metamorphic unit in the Bodrum Peninsula. The basis of this unit is composed of the Paleozoic aged conglomerate-sandstone-shale alternation. The Mesozoic aged units are prominent with Triassic-Lias aged dolomitic limestones, Lias aged silty-marly limestones and Cenomanian aged pelagic limestones together with the Upper Cretaceous-Paleocene aged wild flysch overlying all these sediments.

Cenozoic rock units begin with Oligocene aged sediments. After Oligocene Epoch, violent magmatism formed plutonic and volcanic rocks at various ages in the peninsula (Şenel et al. 1991, 1996).

Widespread calc-alkaline volcanism was active in the region, it resulted in the formation of tuff-agglomerate deposits, andesitic, trachyandesitic, latitic and dacitic lavas. After a significant period, this calc-alkaline volcanism, which was formed by the crustal material, gradually turned into alkaline olivine basaltic formations made up of the mantle. Thus, the second volcanic phase began. As a result, the alkali-type basaltic, trachybasaltic and trachytic lavas were formed in the form of dykes. After the end of volcanism in the Upper Miocene, limestones formed in the Lower Pliocene are observed. Then, travertines, talus, alluviums and pumice fragments and tuffs possibly from the neighboring Kos Island by air are observed from the Quaternary period (Şenel et al. 1991, 1996).

2.2 Tectonic structure of the region

Anatolia, which has been affected by the earthquake dynamics related to the motions of the African continent and the Arabian Peninsula as well as the continental motions of Europe and Asia, has faced major earthquakes. Although it is not a part of the North Anatolian Fault (NAF) system, which is the largest faulting system, the Aegean (Western Anatolia) Region has a widespread seismic activity, and it is one of the regions that show the greatest dynamism in the world.

The region, which has faced earth crust motions, namely the escape mechanism, and the subduction relationships have a very complex structure both kinematically and dynamically. Numerous tectonic and seismo-tectonic models have been suggested to explain the seismological structure of Western Anatolia (Dewey and Şengör 1979; Şengör 1987; Seyitoğlu and Scott 1992, 1996; Koçyiğit et al. 1999). However, there is no generally accepted model since the dynamic and kinematic structure related to the deformation in the region is extremely complicated. There are numerous studies on the seismic activity in the region and its seismic hazard (Barka and Reilinger 1997; Şalk et al. 2000; Kahraman et al. 2008, 2011).

The Aegean Extension Region (AER) is the result of the collision of the Eurasian and Arabian plates. As a result of this collision, the compression in Eastern Anatolia has moved to the west by the Northern Anatolian fault; thus, the depression trenches were formed. Also, the AER is the most active part of the Eastern Mediterranean Region in terms of seismic activity, and this seismicity continues increasingly. Two neotectonic structures stand out in the Aegean Extension Region. The first characteristic is that the Aegean Subduction Zone (ASZ), which is located in the north of the African Plate, subducts beneath the Anatolian Plate. The other significant tectonic characteristic of the region is the North Anatolian Fault Zone in the north. As shown in Fig. 3, the plate motion of the Western Anatolia relative to the European plate can be defined as a counter-clockwise rotation with a velocity of 24 mm/year (Korkmaz 2012).

The counter-clockwise motion of the Western Anatolia-Aegean Block, which is known to face seismic activities frequently throughout history, is thought to be associated with the movement of the Eurasian, Arabian and African plates. The reason for the seismic activity of the region is the motion of the Aegean Block to the south as a result of the collision of the Eurasian plates with the African/Arabian and Indian plates moving to the north. As shown in Fig. 4, this motion occurs within the boundaries of the North Anatolian Fault (NAF) in the north, and the East Anatolian Fault, the Cyprus Arc, and the Hellenic Arc in the south (Barka and Reilinger 1997; Rockwell et al. 2001).

2.3 Active faults in Muğla Province and its vicinity

In a study conducted by the General Directorate of Mineral Research and Exploration (MTA), five active fault systems were identified in Muğla and its vicinity. The faults in the tectonic systems in the region generally lie in the E–W direction, and particularly they have a lateral and strike-slip fault mechanism. Figure 5 shows the map of active faults in Muğla Province and its vicinity.

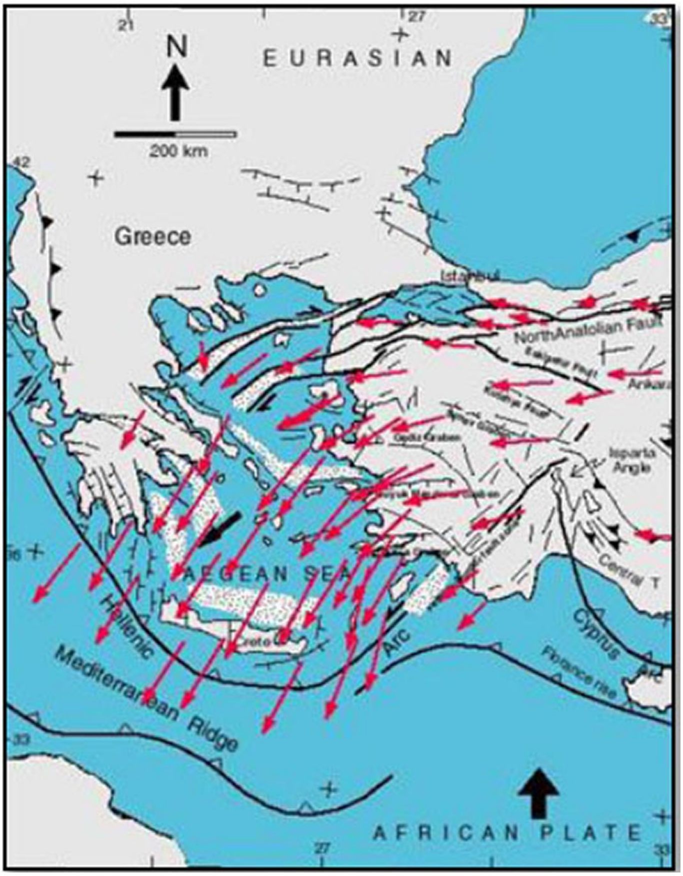

Fig. 3 The mechanism of the displacement of the Aegean Region and its surroundings (Barka and Reilinger 1997)

The following seismic structures affect Muğla Province:

- Büyük Menderes Fault Zone,
- Karaova-Milas Fault Zone,
- Muğla-Yatağan Fault Zone,
- Gökova Fault Zone,
- Fethiye-Burdur Fault Zone.

Büyük Menderes Fault Zone Büyük Menderes Fault Zone (graben), which lies between the Denizli Province and the Aegean Sea, has a length of about 200 km. The east end of the graben intersects Gediz graben near the Pamukkale district. The west end of this graben is divided into two branches near the Germencik district. While its north branch continues toward the Kuşadası district, the south branch turns to the southwest and enters the Aegean Sea. The main fault of this graben lies across its northern edge and inclines southwards. Numerous earthquakes have occurred on Büyük Menderes

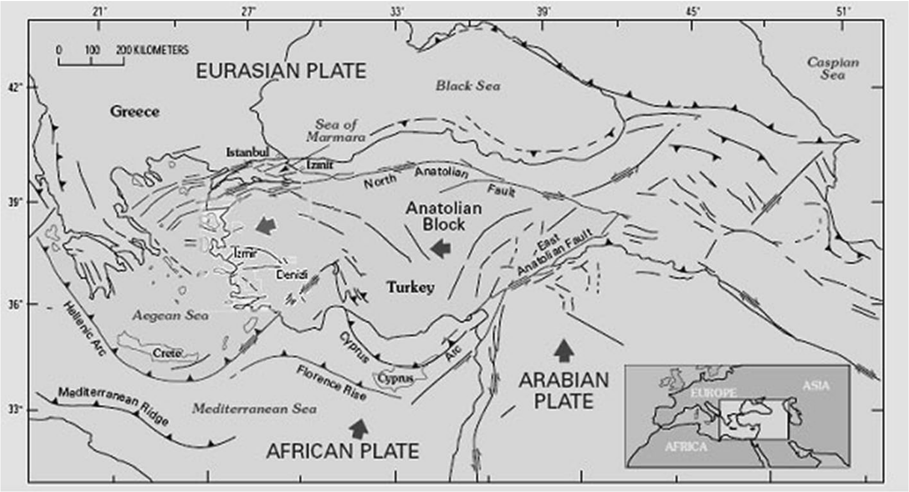

Fig. 4 Ground motions in Turkey and their directions (Rockwell et al. 2001)

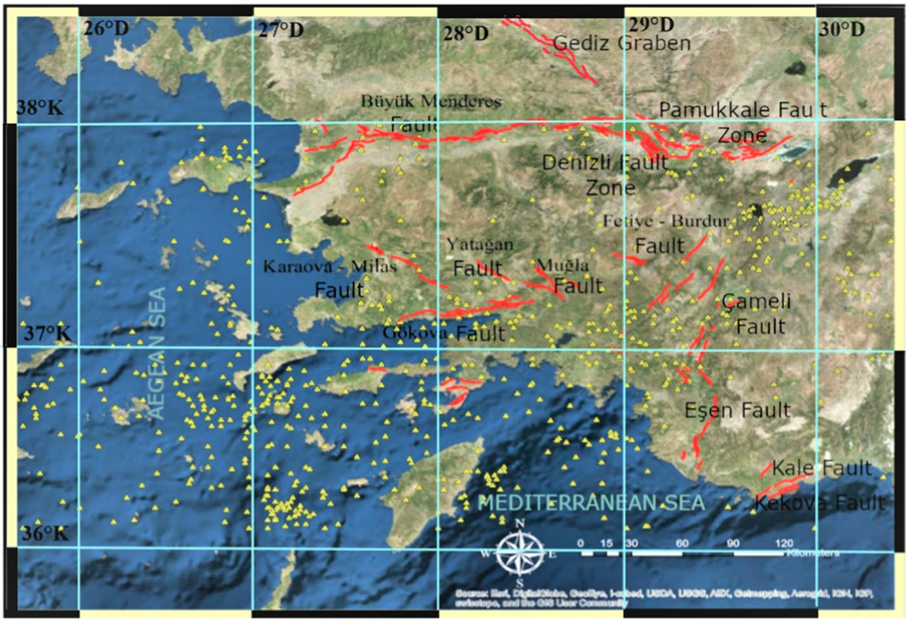

Fig. 5 Active fault zones in the Muğla Province and its vicinity (MTA)

graben throughout history (Ambraseys and Finkel 1995). Its current seismic activity is intensified in the vicinity of the Denizli Province.

Muğla-Yatağan Fault Zone Muğla-Yatağan Fault Zone intersects the eastern end of the Gökova fault zone with an angle of 50 degrees. This fault zone is composed of two parallel faults lying between 15 km to the northeast of Muğla and the Yatağan district in the NW–SE direction. Each of these faults has a length of about 40 km. A 32-km-long section of this fault zone between the villages of Ortayaraş and Gökpınar shows normal fault characteristics with a local strike-slip component toward the left. The fault has brought limestone and talus side by side in the east of Düğerek Village. Also, the fault intersects Pliocene sediments in the vicinity of Salihpaşalar Village (Demirtaş et al. 2012).

Karaova-Milas Fault Zone This fault zone is composed of parallel fault sets with an NW–SE direction. It can be also observed by the metamorphic rocks exhumed between Karaova and the Milas district. This fault zone, which has a length of about 20 km, is regarded as a potentially active fault since it controls the morphology.

Gökova Fault Zone This fault zone lies across the northern edge of the Gulf of Gökova. It starts near the Ula Town in the east of the Gulf of Gökova in the east and continues to the southwest of İstanköy Island. The length of this fault is about 180 km. The Gökova Fault Zone is composed of a few normal fault sequences parallel to each other with an arc shape. This fault zone continues completely under the sea to the west of Ören. This basin is a typical example of active extensional basins, such as Gediz and Büyük Menderes in Western Anatolia (Ersoy 1991).

Fethiye-Burdur Fault Zone In the study of Dumont et al., Fethiye-Burdur Fault Zone was defined as a left-lateral strike-slip fault with a normal component. This fault zone is regarded as the north-east extension of the east wing of the Hellenic arc (Erdik et al. 2006). Minor and medium-magnitude seismic activities are widespread across this fault zone.

2.4 Seismicity of Muğla Province and its vicinity

There has been a significant seismic activity in Muğla and its vicinity in terms of seismicity of both the historical and instrumental periods. A total of 19,824 earthquakes have occurred within the last century in the area bounded by the coordinates of 35.5–38.5 degrees North and 26.0–31.0 degrees East (AFAD 2014; UDIM 2014; USGS 2014). The seismic activities in the region have been observed to increase in Muğla-Bodrum, Yatağan and the Gulf of Gökova in recent years. The most significant earthquakes affecting the region in recent history are the 1957 Fethiye earthquakes, which occurred at 7-h intervals and caused great damage and loss in the area between Rhodes Island and Fethiye, as well as on the Dodecanese Islands. The magnitude of the first earthquake, which occurred on April 24, 1957 (M_s= 6.8), was relatively minor but it affected a wide area. The magnitude of the second earthquake, which occurred on April 25, 1957 (M_s = 7.1), was greater, and it caused greater damage but affected a narrower area compared to the first one. The last major earthquake that occurred in the region was the Marmaris earthquake on October 5, 1999. This earthquake occurred due to the breaking of a secondary fault in the north of Marmaris. The faulting mechanisms that create inland earthquakes reveal the general domination of strike-slip faults in the region. The earthquake occurrence pattern in the region is rather complicated. The earthquake occurrence pattern in the land is generally observed as an earthquake series, and these earthquake series contain intensive seismic activities. However, the Dodecanese Islands generally constitute the border of the Aegean-Anatolian Plate. The

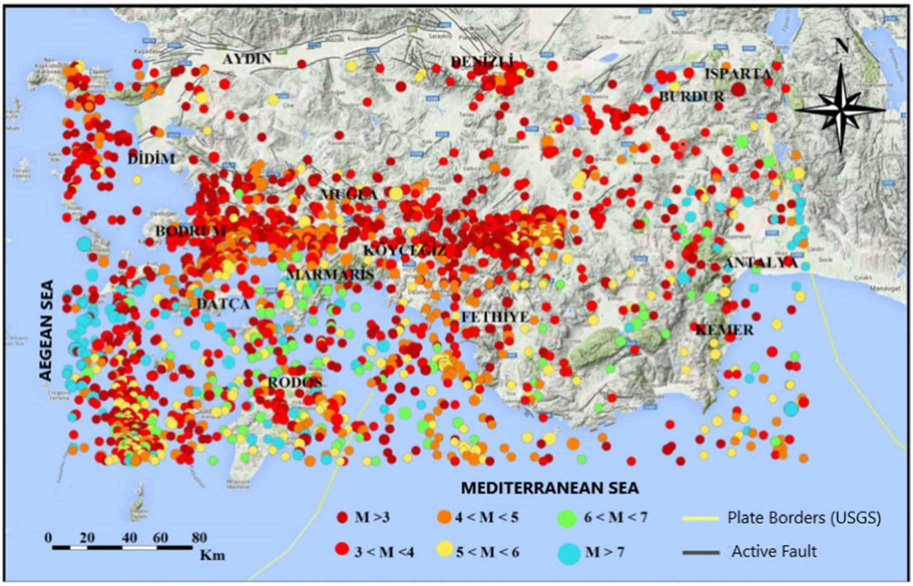

Fig. 6 The seismicity of Muğla Province and its vicinity (1900–2014)

Table 1 Historical earthquakes in Muğla (UDİM 2014)

Year	Magnitude	Epicenter
1887	7	Köyceğiz/Muğla
1885	8	Fethiye/Muğla
1852	7	Fethiye/Muğla
1851	9	Fethiye/Muğla
155	10	Fethiye/Muğla

thrust and oblique faulting, which cause thrust in both vertical and horizontal directions, can cause major earthquakes in the region.

While shallow-focus earthquakes caused by tensional stress occur in the center and interior of the Aegean-Anatolian plate, and earthquakes caused by compressional stress occur at the edges. The tensional stress expands due to the formation of normal faults and causes expansion within the plate. Figure 6 shows the seismicity of Muğla and its vicinity in the instrumental period. The details about the magnitude, focal depth, fault type and coordinates of these earthquakes with a magnitude greater than 5 are given in Table 2.

The seismic records of Muğla Province and its vicinity reveal that five major earthquakes occurred since 155 AD. Table 1 shows the historical earthquakes and their magnitudes.

Table 2 The details about the magnitude, focal depth, fault type and coordinates of 155 earthquakes extracted from the leading and aftershocks with a magnitude greater than 5

Date	Latitude	Longitude	Depth (km)	M_w	Location
25.6.2012	36.4422	28.9422	27.0	5.7	ÖLÜDENİZ OFFSHORE-MUGLA (MEDITERRANEAN SEA)
14.6.2012	36.3907	29.0555	19.7	5.0	BOGAZICI-FETHIYE (MUGLA) [SOUTH WEST 11.9 km]
10.6.2012	36.4528	28.9160	21.3	6.8	ÖLÜDENİZ OFFSHORE-MUGLA (MEDITERRANEAN SEA)
27.1.2012	36.3177	25.1792	22.9	5.6	TWELVE ISLANDS YUNANİSTAN
8.5.2011	36.6960	27.1145	6.2	5.3	TWELVE ISLANDS (MEDITERRANEAN SEA)
4.12.2009	37.9152	28.7873	4.1	5.3	TEKKEKOY-SARAYKOY (DENIZLI) [North East 2 km]
26.6.2009	36.5773	25.2478	27.5	5.0	MEDITERRANEAN SEA
16.11.2007	37.0230	29.2637	5.0	5.2	EMECIK-CAMELI (DENIZLI) [North East 2.8 km]
31.8.2007	36.8898	26.2773	44.0	5.5	MEDITERRANEAN SEA
10.4.2007	37.9980	30.9378	5.5	5.0	ESINYURT-GELENDOST (ISPARTA) [South West 3.5 km]
11.1.2005	37.0190	27.7387	14.2	5.2	MAZIKOY-BODRUM (MUGLA) [North West 2.8 km]
4.8.2004	37.0900	27.6500	18.0	5.8	MUMCULAR-BODRUM (MUGLA) [South West 2.1 km]
3.8.2004	37.0700	27.7000	7.0	5.2	YENIKOY-BODRUM (MUGLA) [South East 2.9 km]
13.9.2003	36.5300	26.6700	91.0	5.0	MEDITERRANEAN SEA
5.10.1999	36.8000	28.1400	23.0	5.5	HISARONU-MARMARIS (MUGLA) [West 0.5 km]
9.7.1998	37.9500	26.7400	21.0	5.6	AEGEAN SEA
2.4.1996	37.7800	26.6400	12.0	5.1	SISAM ADASI (AEGEAN SEA)
11.3.1991	37.0100	30.9600	113.0	5.5	TEKKEKOY-SERIK (ANTALYA) [South West 0.8 km]
15.1.1991	37.1200	29.4800	1.0	5.8	GOLHISAR (BURDUR) [South West 3.4 km]
21.11.1990	37.0000	29.5800	20.0	5.1	ALTINYAYLA (BURDUR) [East 3.2 km]
28.8.1990	36.2700	27.2200	41.0	5.2	TWELVE ISLANDS (MEDITERRANEAN SEA)
12.2.1990	36.2000	27.1000	7.0	5.1	MEDITERRANEAN SEA
24.11.1989	36.7100	26.6100	11.0	5.0	MEDITERRANEAN SEA
27.4.1989	37.0400	28.1700	12.0	5.7	KIRAN- (MUGLA) [South West 3.8 km]
24.2.1989	37.7300	29.3300	10.0	5.1	MENTESE-HONAZ (DENIZLI) [South East 2.5 km]
24.8.1988	36.5900	26.2900	26.0	5.1	MEDITERRANEAN SEA

Table 2 (continued)

Date	Latitude	Longitude	Depth (km)	M_w	Location
5.10.1987	36.2400	28.2700	27.0	5.3	MEDITERRANEAN SEA
19.6.1987	36.8000	28.1800	85.0	5.1	HISARONU-MARMARIS (MUGLA) [East 3.1 km]
11.10.1986	37.9400	28.5600	5.0	6.0	YORE-KUYUCAK (AYDIN) [North East 2.3 km]
23.12.1985	36.8100	26.6200	25.0	5.0	MEDITERRANEAN SEA
5.2.1984	37.2100	28.6700	30.0	5.1	CAKMAK- (MUGLA) [North East 3 km]
27.9.1983	36.9900	26.9000	192.0	6.0	TWELVE ISLANDS (MEDITERRANEAN SEA)
18.4.1982	36.6500	27.1100	155.0	5.1	TWELVE ISLANDS (MEDITERRANEAN SEA)
11.5.1981	36.7800	28.0800	22.0	5.0	TURGUTKOY-MARMARIS (MUGLA) [North West 2.3 km]
26.4.1981	36.5300	30.6500	76.0	5.8	CAMYUVA-KEMER (ANTALYA) [South East 8.8 km]
4.10.1980	37.0000	28.8000	26.0	5.1	CAYHISAR-KOYCEGIZ (MUGLA) [North West 5.2 km]
16.2.1979	36.6600	25.8200	40.0	5.2	MEDITERRANEAN SEA
27.10.1977	37.8700	27.8800	16.0	5.8	YILMAZKOY- (AYDIN) [North West 1.8 km]
12.11.1975	36.2800	28.1500	64.0	5.8	RODOS ADASI (MEDITERRANEAN SEA)
20.9.1975	36.1400	30.7300	40.0	5.5	MEDITERRANEAN SEA
30.4.1975	36.1900	30.7400	61.0	5.7	ANTALYA KÖRFEZI (MEDITERRANEAN SEA)
24.12.1974	37.5400	29.9100	24.0	5.2	CELTEK-YESILOVA (BURDUR) [North East 1.5 km]
9.7.1974	36.5700	28.4800	49.0	5.3	MEDITERRANEAN SEA
12.3.1974	36.7600	26.4000	45.0	5.0	MEDITERRANEAN SEA
20.1.1972	36.6400	27.2300	34.0	5.1	TWELVE ISLANDS (MEDITERRANEAN SEA)
12.11.1971	36.6100	27.0900	23.0	5.0	TWELVE ISLANDS (MEDITERRANEAN SEA)
16.10.1971	36.6300	28.5400	61.0	5.1	DALYAN OFFSHORE-MUGLA (MEDITERRANEAN SEA)
9.9.1971	37.3400	30.1800	49.0	5.5	AKCAOREN-KEMER (BURDUR) [South East 7.1 km]
29.6.1971	37.5100	29.8700	29.0	5.0	BASKUYU-YESILOVA (BURDUR) [North West 0.8 km]
8.6.1971	37.5500	29.7900	11.0	5.1	KARAATLI-YESILOVA (BURDUR) [North 3.3 km]
12.5.1971	37.6400	29.7200	30.0	5.8	BAYINDIR-YESILOVA (BURDUR) [South West 3.6 km]

Table 2 (continued)

Date	Latitude	Longitude	Depth (km)	M_w	Location
8.3.1971	37.4900	29.8400	36.0	5.0	CUVALLI-YESILOVA (BURDUR) [South West 3.2 km]
22.2.1971	37.2400	30.3000	47.0	5.3	BOZOVA-KORKUTELI (ANTALYA) [North East 3.1 km]
6.9.1969	36.7300	28.3500	72.0	5.3	GÜNLÜCE OFFSHORE-MUGLA (MEDITERRANEAN SEA)
27.4.1969	36.5400	28.2100	33.0	5.0	MEDITERRANEAN SEA
23.3.1969	37.9000	27.6000	5.0	5.2	DAGKARAAGAC-GERMENCIK (AYDIN) [South West 0.7 km]
14.1.1969	36.1100	29.1900	22.0	5.9	KALKAN OFFSHORE -ANTALYA (MEDITERRANEAN SEA)
5.12.1968	36.6000	26.9200	31.0	5.7	TWELVE ISLANDS (MEDITERRANEAN SEA)
4.12.1968	36.5000	27.0200	32.0	5.0	TWELVE ISLANDS (MEDITERRANEAN SEA)
11.11.1968	36.6100	27.1500	23.0	5.1	TWELVE ISLANDS (MEDITERRANEAN SEA)
31.10.1968	36.6200	27.0100	2.0	5.4	TWELVE ISLANDS (MEDITERRANEAN SEA)
6.10.1968	36.9600	26.3800	17.0	5.0	MEDITERRANEAN SEA
20.2.1968	36.2000	27.1000	64.0	5.0	MEDITERRANEAN SEA
26.10.1967	37.2200	29.0500	46.0	5.3	ALPA-TAVAS (DENIZLI) [North West 0.6 km]
18.6.1967	36.7800	29.3200	35.0	5.0	SOGUTLUDERE-FETHIYE (MUGLA) [South East 1.7 km]
1.6.1967	36.8100	29.2600	43.0	5.3	SOGUTLU-FETHIYE (MUGLA) [South East 4.3 km]
4.4.1967	36.6800	29.2700	24.0	5.0	YAKACIK-FETHIYE (MUGLA) [East 0.5 km]
25.9.1966	37.7700	29.9700	44.0	5.1	ULUPINAR-(BURDUR) [North West 2.2 km]
9.5.1966	37.0500	30.9800	132.0	5.1	TONGUCLU-SERIK (ANTALYA) [South East 2.2 km]
7.5.1966	37.7500	27.7900	9.0	5.3	BOYDERE-KOCARLI (AYDIN) [North 2.4 km]
4.5.1966	37.7400	27.7100	37.0	5.1	TASKOY-KOCARLI (AYDIN) [North East 0.8 km]
2.1.1965	36.4600	26.1000	59.0	5.3	MEDITERRANEAN SEA
18.7.1964	36.1300	26.0100	99.0	5.3	MEDITERRANEAN SEA
30.1.1964	37.4100	29.8900	59.0	5.6	KAGILCIK-KARAMANLI (BURDUR) [North East 2.3 km]
29.9.1963	36.4400	29.0000	60.0	5.0	ÖLÜDENİZ OFFSHORE-MUGLA (MEDITERRANEAN SEA)
26.7.1963	36.8400	28.7600	80.0	5.3	GOLBASI-ORTACA (MUGLA) [South East 1 km]

Table 2 (continued)

Date	Latitude	Longitude	Depth (km)	M_w	Location
11.3.1963	37.9600	29.1400	40.0	5.6	KARAHAYIT- (DENIZLI) [East 3.1 km]
23.5.1961	36.7000	28.4900	70.0	6.2	DALYAN OFFSHORE-MUGLA (MEDITERRANEAN SEA)
27.2.1961	36.5600	27.0000	70.0	5.3	TWELVE ISLANDS (MEDITERRANEAN SEA)
23.2.1961	36.7300	27.2200	40.0	5.2	TWELVE ISLANDS (MEDITERRANEAN SEA)
26.1.1960	37.0000	28.9300	72.0	5.4	SAZAK-KOYCEGIZ (MUGLA) [North East 4.6 km]
12.7.1959	36.0300	26.2800	80.0	5.3	MEDITERRANEAN SEA
25.4.1959	36.9400	28.5800	30.0	5.9	ZAFERLER-KOYCEGIZ (MUGLA) [South West 4.4 km]
4.9.1958	36.5600	26.7200	40.0	5.4	MEDITERRANEAN SEA
30.6.1958	36.2900	27.3200	100.0	5.5	TWELVE ISLANDS (MEDITERRANEAN SEA)
27.5.1958	36.8000	26.7600	160.0	5.3	TWELVE ISLANDS (MEDITERRANEAN SEA)
9.5.1958	36.6100	27.6000	67.0	5.4	MESUDIYE-DATCA (MUGLA) [South East 10.5 km]
25.4.1957	36.4200	28.6800	80.0	6.7	MEDITERRANEAN SEA
24.4.1957	36.4300	28.6300	80.0	6.5	MEDITERRANEAN SEA
9.2.1957	36.7500	26.4400	40.0	5.3	MEDITERRANEAN SEA
5.2.1957	36.3700	28.8800	60.0	5.4	ÖLÜDENİZ OFFSHORE-MUGLA (MEDITERRANEAN SEA)
6.9.1956	36.0300	25.8800	10.0	5.2	MEDITERRANEAN SEA
9.7.1956	36.6900	25.9200	10.0	7.0	MEDITERRANEAN SEA
16.7.1955	37.6500	27.2600	40.0	6.5	YUVACA-SOKE (AYDIN) [South East 0.3 km]
25.8.1954	37.2900	29.9600	40.0	5.2	KAYALIKOY-KARAMANLI (BURDUR) [South East 3.1 km]
1.5.1954	37.8100	26.9500	54.0	5.6	SISAM ISLAND (AEGEAN SEA)
2.1.1954	36.9800	27.1200	140.0	5.5	TWELVE ISLANDS (MEDITERRANEAN SEA)
22.10.1952	36.8300	27.6000	40.0	5.4	GÖKOVA KÖRFEZI (MEDITERRANEAN SEA)
9.6.1952	36.8300	27.6400	20.0	5.2	GÖKOVA KÖRFEZI (MEDITERRANEAN SEA)
5.11.1951	36.0000	29.0000	30.0	5.4	MEDITERRANEAN SEA
2.2.1951	36.8300	30.5400	120.0	5.7	HACISEKILILER-KONYAALTI (ANTALYA) [South East 2.7 km]

Table 2 (continued)

Date	Latitude	Longitude	Depth (km)	M_w	Location
27.5.1944	36.2300	27.2500	40.0	5.6	TWELVE ISLANDS (MEDITERRANEAN SEA)
5.1.1944	36.4200	27.6700	70.0	5.7	TWELVE ISLANDS (MEDITERRANEAN SEA)
20.11.1943	36.5500	28.3600	35.0	5.6	MEDITERRANEAN SEA
16.10.1943	36.4500	27.9400	120.0	5.8	MEDITERRANEAN SEA
11.1.1943	36.5500	27.2600	26.0	5.5	TWELVE ISLANDS (MEDITERRANEAN SEA)
21.6.1942	36.1200	27.2000	40.0	5.2	MEDITERRANEAN SEA
13.12.1941	37.1300	28.0600	30.0	6.3	DAGPINAR- (MUGLA) [North 4.1 km]
21.9.1941	37.5000	28.2900	70.0	5.5	YESILKOY-KAVAKLIDERE (MUGLA) [North West 2.1 km]
13.7.1941	37.6600	26.0900	60.0	5.9	TWELVE ISLANDS (MEDITERRANEAN)
23.6.1941	37.9500	27.8100	10.0	5.2	KARAGOZLER-INCIRLIOVA (AYDIN) [North East 1.3 km]
23.5.1941	37.0700	28.2100	40.0	6.0	KIRAN- (MUGLA) [North East 1.1 km]
13.3.1939	36.0000	29.0000	15.0	5.3	MEDITERRANEAN SEA
2.1.1939	36.3000	30.7000	33.0	5.5	ANTALYA GULF (MEDITERRANEAN SEA)
12.8.1936	37.4400	29.4400	130.0	5.3	YENIKOY-ACIPAYAM (DENIZLI) [North East 2.9 km]
28.4.1936	36.1500	26.3500	115.0	5.3	MEDITERRANEAN SEA
18.3.1935	36.0800	27.3000	83.0	6.0	MEDITERRANEAN SEA
9.11.1934	36.6300	25.7700	80.0	5.8	MEDITERRANEAN SEA
15.5.1933	36.3500	26.8000	10.0	5.2	MEDITERRANEAN SEA
23.4.1933	36.7700	27.2900	30.0	6.2	TWELVE ISLANDS (MEDITERRANEAN SEA)
7.12.1932	36.7100	27.3300	60.0	5.3	DATÇA OFFSHORE-MUGLA (MEDITERRANEAN SEA)
22.8.1930	36.2000	27.5000	100.0	5.2	DATÇA OFFSHORE -MUGLA (MEDITERRANEAN SEA)
11.11.1929	36.6800	26.2100	15.0	6.1	MEDITERRANEAN SEA
10.4.1928	37.4000	26.1000	30.0	5.3	TWELVE ISLANDS (MEDITERRANEAN SEA)
8.12.1926	36.0000	27.0000	15.0	5.3	MEDITERRANEAN SEA
26.6.1926	36.5000	27.5000	15.0	5.5	MEDITERRANEAN SEA

Table 2 (continued)

Date	Latitude	Longitude	Depth (km)	M_w	Location
26.6.1926	36.5400	27.3300	100.0	7.2	TWELVE ISLANDS (MEDITERRANEAN SEA)
16.3.1926	37.5000	29.0000	15.0	6.9	MEDET-TAVAS (DENIZLI) [South West 1.7 km]
18.12.1925	37.4000	30.4000	15.0	5.3	KECILI-BUCAK (BURDUR) [North East 1.3 km]
1.9.1925	37.5600	29.1700	130.0	5.5	AYDOGDU-TAVAS (DENIZLI) [North 5.4 km]
8.7.1925	37.4000	30.5000	15.0	5.2	SUSUZ-BUCAK (BURDUR) [North West 4.4 km]
17.3.1925	37.2000	26.2000	15.0	5.3	TWELVE ISLANDS (MEDITERRANEAN SEA)
6.12.1922	37.5000	29.0000	15.0	5.4	MEDET-TAVAS (DENIZLI) [South West 1.7 km]
17.8.1922	36.0000	28.0000	15.0	5.3	MEDITERRANEAN SEA
3.6.1922	36.4900	28.6500	30.0	5.2	MEDITERRANEAN SEA
20.4.1922	36.4000	26.2000	150.0	5.4	MEDITERRANEAN SEA
27.1.1921	36.0000	28.0000	15.0	5.5	MEDITERRANEAN SEA
15.11.1920	36.0000	25.8000	120.0	5.6	MEDITERRANEAN SEA
28.9.1920	37.8900	28.3500	10.0	5.8	SEVINDIKLI-NAZILLI (AYDIN) [South West 2.9 km]
1.5.1920	37.0000	28.7000	30.0	5.3	YESILKOY-KOYCEGIZ (MUGLA) [North West 0.7 km]
2.4.1920	36.7500	26.6400	10.0	5.6	MEDITERRANEAN SEA
26.10.1919	36.5000	25.5000	20.0	5.3	MEDITERRANEAN SEA
25.10.1919	36.5000	25.5000	10.0	5.9	MEDITERRANEAN SEA
24.8.1919	36.0000	28.0000	15.0	5.5	MEDITERRANEAN SEA
5.4.1919	36.6000	26.7000	15.0	5.4	MEDITERRANEAN SEA
13.11.1918	37.8000	27.3000	35.0	5.4	SOGUCAK-KUSADASI (AYDIN) [North 1.9 km]
16.7.1918	36.0800	26.9900	70.0	6.0	MEDITERRANEAN SEA
27.7.1916	36.5000	25.7000	140.0	5.5	MEDITERRANEAN SEA
3.10.1914	37.7000	30.4000	14.0	6.6	HALICILAR- (BURDUR) [South 0.7 km]
4.4.1911	36.5000	25.5000	140.0	6.7	MEDITERRANEAN SEA
7.8.1910	37.8000	28.7000	30.0	5.5	HACIHIDIRLAR-KARACASU (AYDIN) [NORTH EAST

Table 2 (continued)

Date	Latitude	Longitude	Depth (km)	M_w	Location
8.3.1908	37.8000	27.8000	15.0	5.3	KADIKOY- (AYDIN) [South West 2.6 km]
11.8.1904	37.7000	26.9000	6.0	6.1	SISAM ISLAND (AEGEAN SEA)
1.5.1901	37.8000	27.8000	15.0	5.2	KADIKOY- (AYDIN) [South West 2.6 km]
20.9.1900	37.8000	29.1000	5.0	5.2	DENIZLI (DENIZLI) [North East 2.3 km]

3 Modeling probabilistic seismic hazards of the region

In this study, the SEISRISK III software package (Bender and Perkins 1987), which ran the homogeneous Poisson Process Model with the conditions of spatial and temporal independence, was used to calculate the peak and spectral acceleration parameters of the bedrock in the study area. The geographical coordinates of the seismic zones and the study area were entered using the software. The earthquake occurrence parameters of each zone (the annual occurrence relations depending on the magnitude) were expressed using Gutenberg and Richter (1944) relationship. Appropriate attenuation relationships were used to determine the seismic hazard that the zones might create in the study area. Then, the total magnitude of the ground motion could be determined with the desired probability of exceedance using the probabilistic assessment. The ground motion could be defined by the peak acceleration and spectral acceleration.

3.1 Generating seismic source zones

This study aimed to obtain the seismicity of the region objectively using national and international earthquake catalogs. The earthquake catalogs of the National Earthquake Monitoring Center (UDİM), Disaster and Emergency Management Presidency (AFAD) and the US Geological Survey Center (USGS) were used to collect the number of earthquakes with a magnitude of 5 or above that occurred in Muğla and its vicinity between 1900 and 2014 (Fig. 6). Also, the active fault map prepared by MTA and the seismic activity data of Muğla and its vicinity for the 1900–2014 period were analyzed together, and the region was divided into 7 sub-zones. The following procedure was followed to determine seismic source zones:

- An active fault system was determined for the source zone.
- It was assumed that earthquakes with a magnitude of 6 or above occurred within the source zone while determining the boundaries of the source zone. Then, the boundaries were determined taking into account the spatial and temporal distribution of earthquakes.
- The mainshock earthquakes were separated from foreshocks and aftershocks while determining the boundaries of the source zone; thus, it facilitated determining the seismic zones (Table 2).
- The boundary between source zones with different earthquake potentials was determined close to the active zone.
- It was tried to determine source zones as homogeneous sites as much as possible (Erdik et al. 2006).

Also, the seismic zones suggested in the literature (Erdik et al. 1999, 2006) were evaluated, and the seismic source zones were generated as shown in Fig. 7 without considering the background seismicity for the calculation of the seismic hazard of the study area.

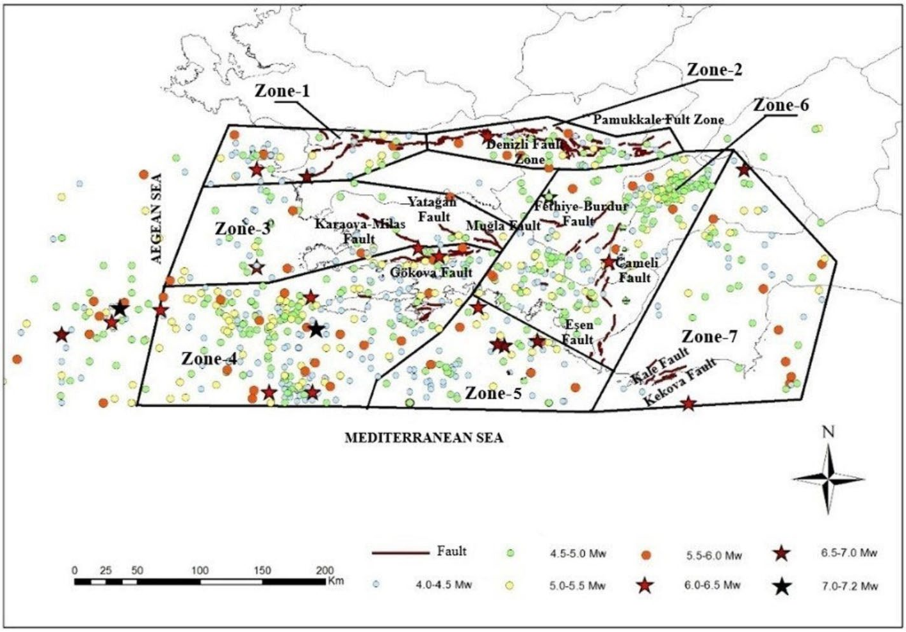

Fig. 7 Earthquake source zones of Muğla Province and its vicinity (Yılmazoğlu , 2015)

Table 3 Time-distance relations (Deniz and Yücemen 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

3.2 Calculation of the recurrence relationships of seismic source zones

Firstly, the study area between the 36.5–37.8 degrees North latitudes and 26.8–29.5 degrees East longitudes was determined to cover Muğla and its vicinity. Then, the earthquakes with a magnitude of $M_w \geq 5.0$ that occurred in the study area were separated from foreshocks and aftershocks according to the time-distance window shown in Table 3. Recurrence relationships were calculated using the least-squares method for each of the seven source zones according to Gutenberg-Richter law. These zones are shown in Figs. 8, 9, 10, 11, 12, 13 and 14, respectively. The Gutenberg-Richter parameters (a and b), fault systems and their characteristics are shown for each source zone in Table 4.

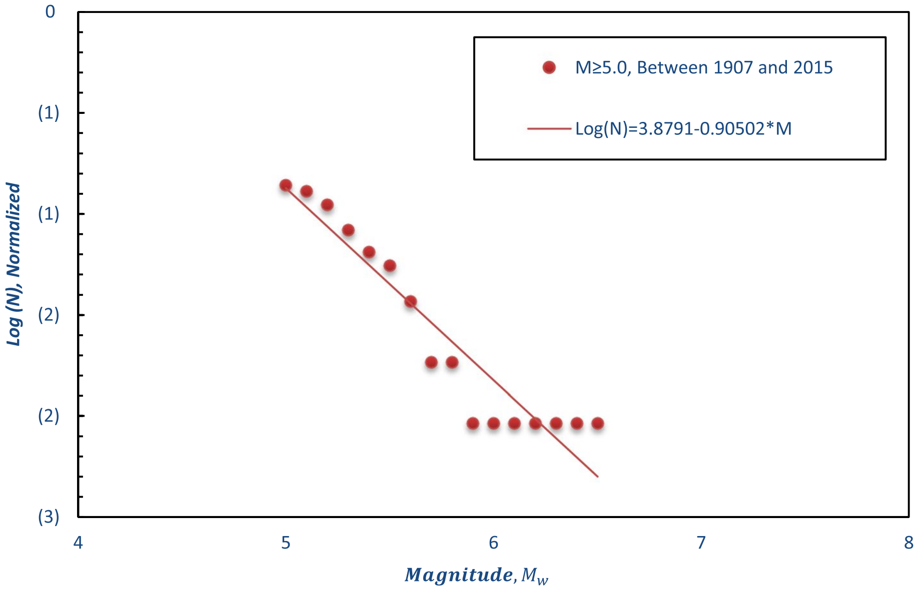

Fig. 8 Source Zone 1 recurrence relationship

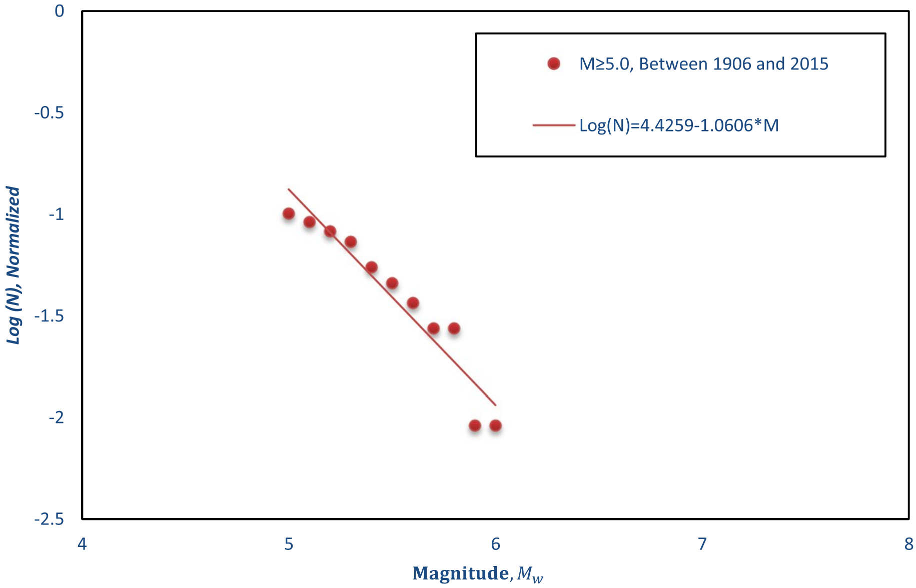

Fig. 9 Source Zone 2 recurrence relationship

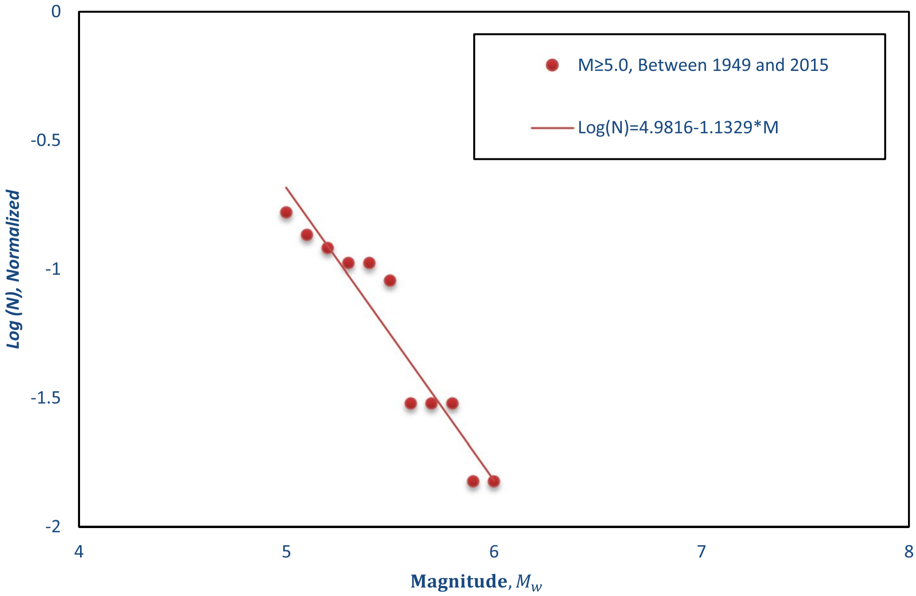

Fig. 10 Source Zone 3 recurrence relationship

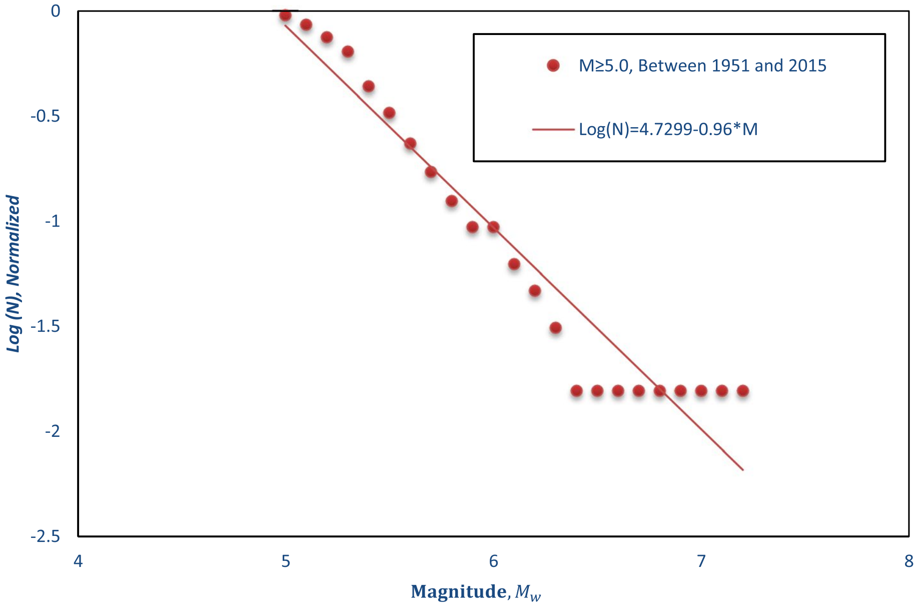

Fig. 11 Source Zone 4 recurrence relationship

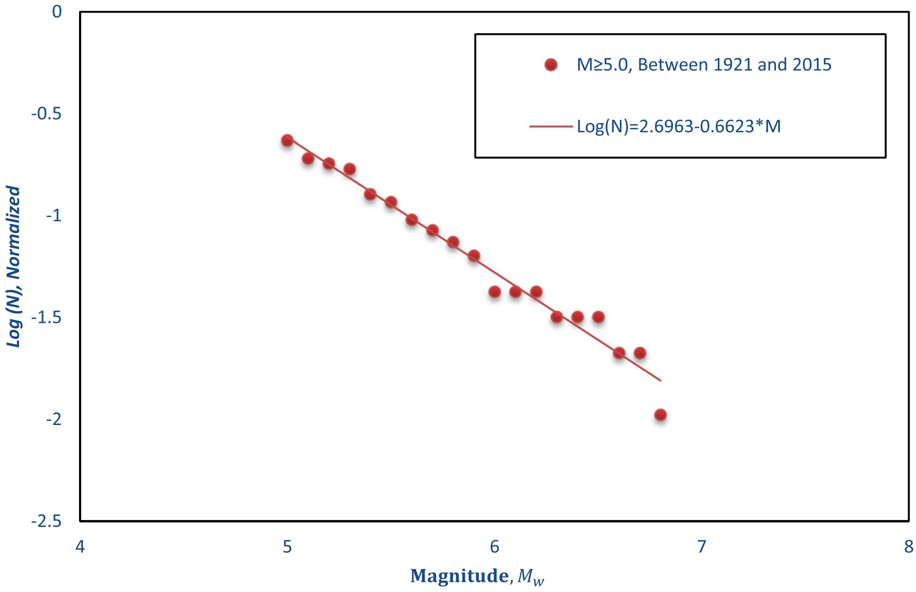

Fig. 12 Source Zone 5 recurrence relationship

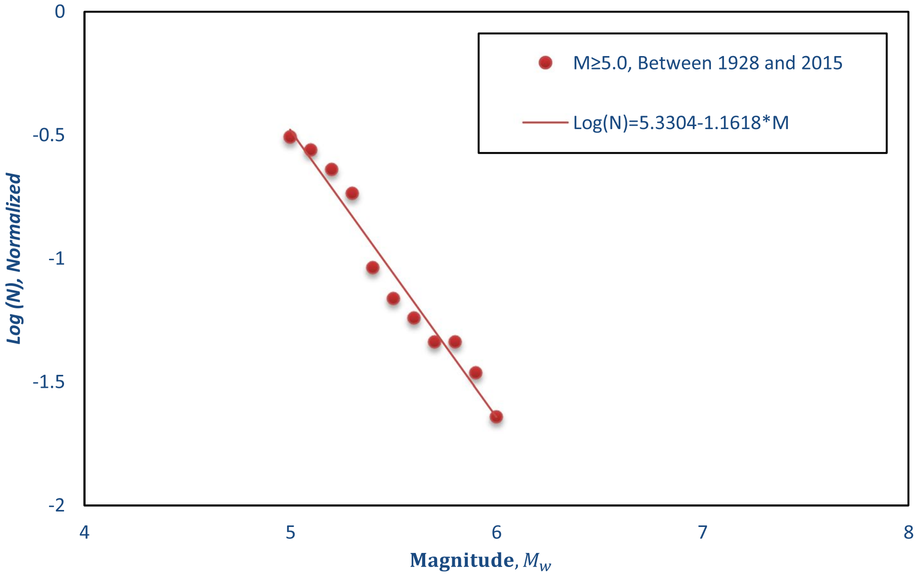

Fig. 13 Source Zone 6 recurrence relationship

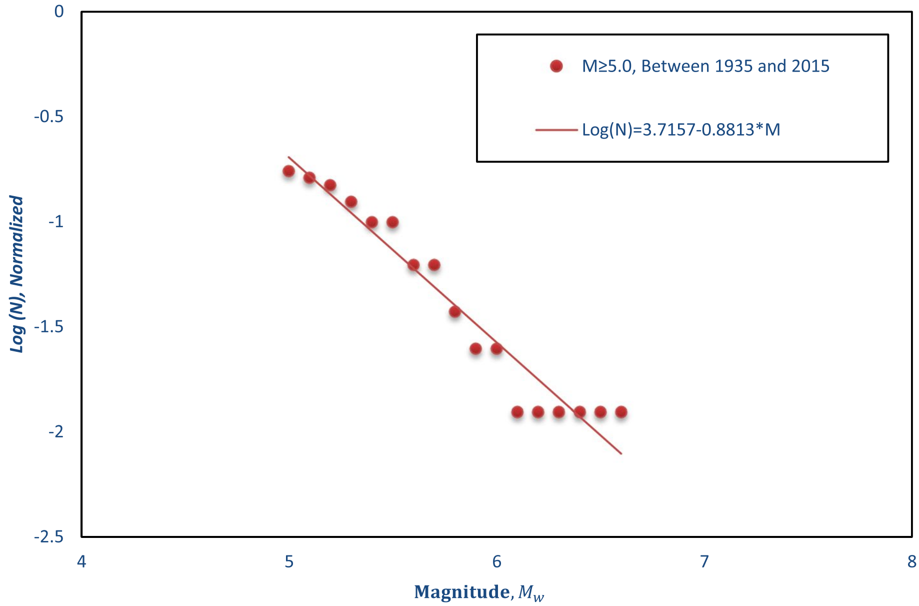

Fig. 14 Source Zone 7 recurrence relationship

Table 4 Fault characteristics and the Gutenberg–Richter parameters of seismic source zones in Muğla and its vicinity

Name of the source zone	Related active fault	Mechanism	*a*	*b*	$M_{\min}$–$M_{\max}$
Zone 1	Menderes fault	Normal	3.86	1.01	5.0–6.5
Zone 2	Menderes fault	Normal	4.4	1.1	5.0–6.0
Zone 3	Karaova-Simav fault	Normal	4.74	1.13	5.0–6.0
	Muğla-Yatağan fault	Lateral strike + normal			
Zone 4	Gökova fault	Normal	5.06	1.04	5.0–7.2
Zone 5	Hellenic Arc	Normal component left lateral strike slip	2.62	0.66	5.0–6.8
Zone 6	Fethiye-Burdur fault	Normal component left lateral strike-slip	5.21	1.16	5.0–6.0
Zone 7	Kale and Kekova faults	Normal faults in the northwest direction	3.56	0.88	5.0–6.6

3.3 Ground motion prediction models (attenuation relationship) used in the analysis

Several models that were particularly developed for Turkey also cover the study area, and they use major ground motion records (Özbey et al. 2003; Kalkan and Gülkan 2004; Çeken et al. 2008). The models developed based on local data are better than the global ones since they reflect the regional differences. Since they are developed using a limited database and have great uncertainties, they provide a lower seismic hazard compared to global models. In the present study, global models were used together with local models. The global ground motion prediction models developed by Boore and Atkinson

(2008), Campbell and Bozorgnia (1997, 2008) and Sadigh et al. (1997) were used, and their average was taken into consideration in the calculations. Although these models were developed for earthquakes in the California region, the USGS confirmed that they could be used also for Europe. The ground characteristics were considered in accordance with the NEHRP (1997) B/C guidelines in the calculation of the ground attenuation relationships.

4 Probabilistic earthquake hazard analysis for the region

Several software packages such as Shake91 (Idriss and Sun 1992), EZ-FRISK (1997), Ordonez (2009), CRISIS2007 (Ordaz et al. 2007) and SEISRISK III (Bender and Perkins 1987) are used to determine the seismic hazard. In the present study, the SEISRISK III software developed by Bender and Perkins (1987) was used to analyze the probabilistic seismic hazard. The geographical coordinates of the study area and seismic zones were determined as 35.5–38.5 North and 26.0–31.0 East, taking Muğla Province as the center. The earthquake occurrence parameters of each zone, i.e., the annual occurrence relationships depending on the magnitude, were expressed using the Gutenberg–Richter law. Then, appropriate attenuation relationships were used to determine the seismic hazard created by the source zones in the study area. Finally, total ground motion magnitudes were calculated for the specified probability of exceedance by probabilistic evaluation. In the study, the seismic sources were defined as areal sources in the software

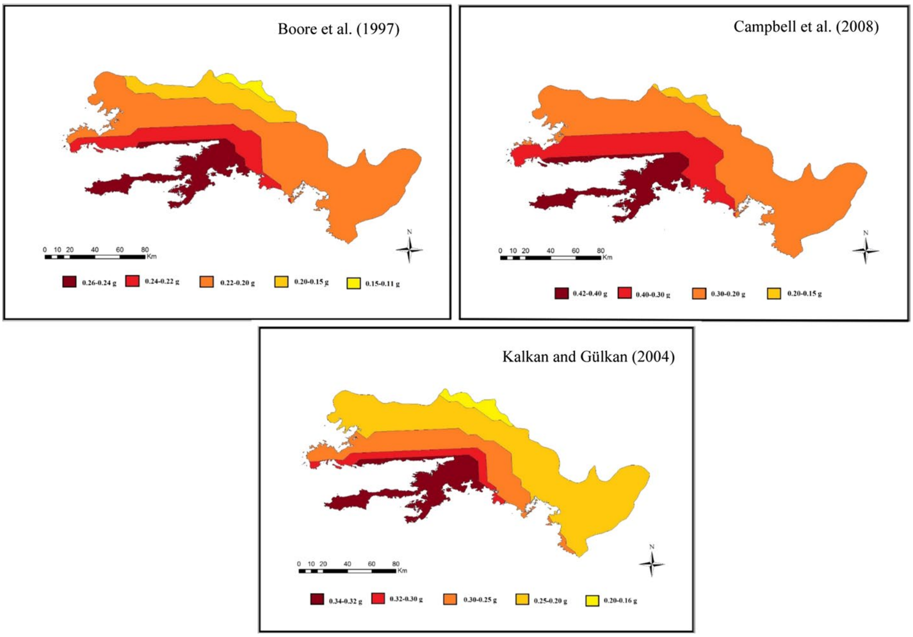

Fig. 15 The PGA map generated based on the exceedance probability of 10% using the attenuation relationships of Boore et al. (1997), Campbell and Bozorgnia (2008), Kalkan and Gülkan (2004) (map from Yılmazoğlu 2015)

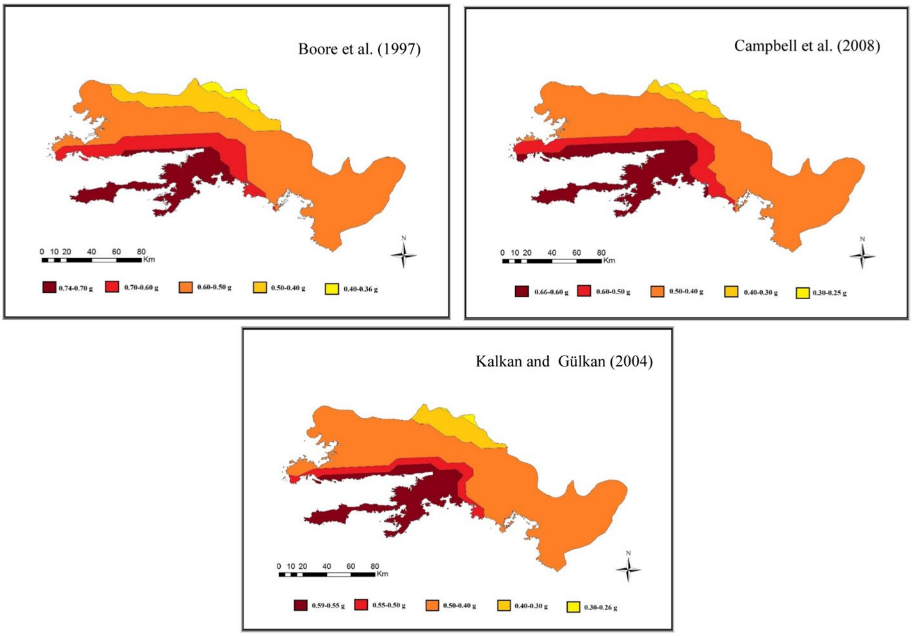

Fig. 16 The map of spectral acceleration with a period of $T=0.2$ s generated based on the exceedance probability of 10% using the attenuation relationships of Boore et al. (1997), Campbell and Bozorgnia (2008), Kalkan and Gülkan (2004) (map from Yılmazoğlu 2015)

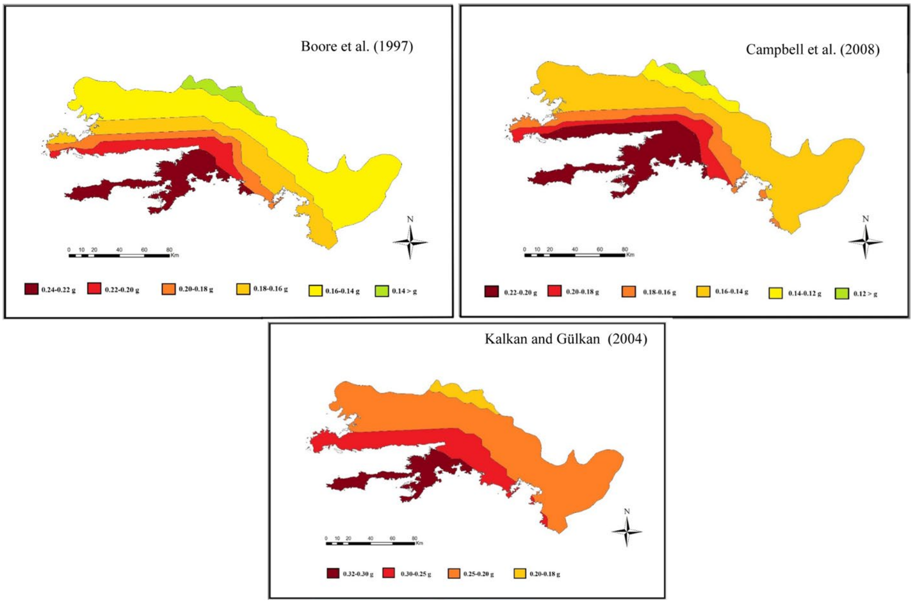

Fig. 17 The map of spectral acceleration with a period of $T=1.0$ s generated based on the exceedance probability of 10% using the attenuation relationships of Boore et al. (1997), Campbell and Bozorgnia (2008), Kalkan and Gülkan (2004) (map from Yılmazoğlu 2015)

using their seismicity parameters. The seismic hazard analyses are conducted to predict the most hazardous earthquakes that may occur throughout the average economic life of the buildings. Turkish Regulation on Buildings to be Constructed in Earthquake Zones (DBYBHY 2007) considers the design seismic motion as the ground motion with a probability of exceedance of 10% for 50 years, i.e., a period of 475 years. Depending on the seismic hazard sensitivity of the study area, it is also possible to consider earthquakes with a probability of exceedance of 40% and a period of 98 years. In the present study, the calculations were made considering the exceedance probabilities of 10% and 40% for a period of 50 years, the economic life of a building. Figure 15 shows the maps of the peak ground acceleration (PGA), Fig. 16 shows the maps of the spectral acceleration with a period of $T = 0.2$ s, and Fig. 17 shows the maps of the spectral acceleration with a period of $T = 1.0$ s.

5 Conclusions

The maximum peak acceleration value on the bedrock based on the exceedance probability of 10% for 50 years was found to range between 0.16 and 0.52 g using the model proposed by Campbell and Bozorgnia (2008). On the other hand, the minimum value was found to range between 0.11 and 0.26 g using the model proposed by Boore et al. (1997). According to the model developed by Kalkan and Gülkan (2004) based on the local data, the peak acceleration value on the bedrock was found to range between 0.16 and 0.34 g. Considering these values, it is seen that the values generated by the local model (Kalkan and Gülkan 2004) range between the values generated by the global ground motion prediction models (Campbell and Bozorgnia (2008); Boore et al. 1997). Examining the obtained values, it is seen that the ground acceleration value on the surface used in the building design is reached on the bedrock. In this case, in the dynamic analysis of soil to be performed on a local basis, it can be expected that the ground acceleration value on the surface will be much higher than the value specified in the regulation. It is believed that the actual ground acceleration value that may affect the building can be calculated more realistically by using the values in these hazard maps, which have been generated considering all the sources that may affect the region. The study also reveals that the Gökova Fault Zone (Zone 4) is the most active source in terms of the seismic hazard in the region and that the seismic hazard of the southwestern part of the region is greater compared to other parts.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

Akol B, Bekler T (2013) Assessment of the statistical earthquake hazard parameters for NW Turkey. Nat Hazards 68:837–853

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

Ansal A, Tönük G, Kurtuluş A (2011) Ground amplification analyses and determination of the characteristics of site-specific design earthquake. In: 1st Turkish earthquake engineering and seismology conference, Ankara, Book of Papers, pp 1–8

Barka A, Reilinger R (1997) Active tectonics of the Eastern Mediterranean Region deduced from GPS, neotectonic and seismicity data. Ann Geofis 40:587–610

Bender B, Perkins DM (1987) SEISRISK III: a computer program for seismic hazard estimation, USGS bulletin 1772. U. S. Government Printing Office, Washington

Bommer JJ, Rodŕiguez CE (2002) Earthquake-induced landslides in Central America. Eng Geol 63(3–4):189–220

Boore DM, Atkinson GM (2008) Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s. Earthquake Spectra 24(1):99–138

Boore DM, Joyner WB, Fumal TE (1997) Equations for estimating horizontal response spectra and peak acceleration from Western North American earthquakes: a summary of recent work. Seismol Res Lett 68(1):128–153

Bozcu M, Yağmurlu F, Şentürk M (2007) Some neotectonic and paleosismological characteristics of Fethiye–Burdur fault zone GB-Turkey. J Geol Eng 31(1):25–48

Campbell KW (1997) Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity and pseudo-absolute acceleration response spectra. Seismol Res Lett 68(1):154–179

Campbell KW, Bozorgnia Y (2008) NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. Earthquake Spectra 24(1):139–171

Çeken U, Beyhan G, Gülkan P (2008) Major ground motion attenuation relationship for Northwestern Anatolia Earthquakes. In: 18th international geophysics congress and exhibition, vol 3B14, pp 1–4. General Directorate of Mineral Research and Exploration, Cultural Site, Ankara

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

Demirtaş R, Yavuz MA, Derin F, Tadık Y (2012) 1:1000 Scale geological—geotechnical investigation report for zoning plan of the settlement area within the boundaries of map sections of O-19-D-02-C, O-19-D-02-D, O-19-D-07-A, O-19-D-07-B in Mesudiye Municipality, Fethiye District, Muğla Province

Deniz A, Yücemen MS (2005) Prediction of earthquake hazard for Antalya territory with scholastic methods. In: Congress on civil engineering problems in Antalya Territory, Book of Papers, pp 540–551

Dewey JF, Şengör AMC (1979) Aegean and surrounding regions complex multiplate and continuum tectonics in a convergent zone. Geol Soc Am Bull I 90:84–92

Dipova N, Cangir B (2011) Investigation of seismicity of antalya settlement area. J Geol Eng 35:27–41

Düzgün HŞ, Yücemen MS (2007) Integrated earthquake risk model in urban areas: Eskişehir example. In: TMMOB chamber of civil engineers disaster symposium, pp 201–211

Erdik M, Doyuran V, Akkaş N, Gülkan P (1985) A probabilistic assessment of the seismic hazard in Turkey, tectonophysics, vol 117. Elsevier Science Publishers B.V, Amsterdam, pp 295–344

Erdik M, Biro YA, Onur T, Şeşetyan K, Birgören G (1999) Assessment of Earthquake hazard in Turkey and neighboring regions, Bogazici University Kandilli Observatory and Earthquake Research Institute, GSHAP Proce

Erdik M, Şeşetyan K, Demircioğlu MB, Durukal E (2006) Earthquake hazard determination for technical regulations regarding constructions of coastal structures, railways and airports by the general directorate of railways. Harbors and Airports Construction, Ministry of Transportation

Ersoy Ş (1991) Stratigraphy and Tectonics of Datça Peninsula. Turk Geol Bull 34:1–14

Güzel M (2009) Combining geological, geophysical and geotechnical data in microzonation studies (North Adana example). Ph.D. Thesis, Çukurova University, Institute of Science, Adana

Gutenberg B, Richter CF (1944) Frequency of earthquakes in California. Bull Seismol Soc Am 34(4):1985–1988

Idriss IM, Sun JI (1992) Shake91: a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits, User's guide. University of California, California

İnce GÇ (2005) Seismic zoning and estimation of damages of Istanbul earthquake. Doctoral Thesis, Yıldız Technical University, Institute of Science, İstanbul/Turkey

Işık E (2013) Seismicity of Bitlis Province. Erciyes University J Inst Sci 29(3):267–273

Kahraman S, Baran T, Saatçı İA, Şalk M (2008) The effect of regional borders when using the Gutenberg–Richter model, case study: Western Anatolia. Pure Appl Geophys 165:331–347

Kahraman S, Baran T, Saatçı İA, Şalk M (2011) Data quality and effect of selection of region boundaries on the earthquake hazard account. In: 1st Turkey earthquake engineering and seismology conference, Ankara

Kalkan E, Gülkan P (2004) Site-dependent spectra derived from ground motion records in Turkey, Earthquake Spectra 20

Kartal et al (2011) With mersinil of Probability and Statistics Methods of Seismic Hazard Prediction, Earthquake Engineering and Seismology Conference 1. Turkey, Ankara

Kartal RF et al (2014) Seismic hazard analysis of Sinop province, Turkey using probabilistic and statistical methods. J Earth Syst Sci 123(3):565–579

Koçyiğit A, Yusufoğlu H, Bozkurt E (1999) Evidence from the Gediz graben for episodic two-stage extension in western Turkey. J Geol Soc Lond 156:605–616

Korkmaz B (2012) Evaluation of probabilistic earthquake hazard for İzmir territory with different methods. Master's Thesis, Gebze Institute of Advanced Technology, Institute of Engineering and Science, Sakarya

Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall Press, Cambridge

Levendoğlu M (2013) Probabilistic seismic hazard analysis of the North Anatolian Fault Line Bolu-Ilgaz section by Creating enhanced seismic source models. Master Thesis, METU, Graduate School of Science, Ankara

Meral A, Meral HC (2002) Earthquake engineering and earthquake resistant structural design. Kozan Ofset, Ankara

NEHRP (1997) Recommended provisions for seismic regulations for new buildings and other structures, FEMA-303, Prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington, DC

Ordaz M, Aguilar A, Arboleda J (2007) Crisis Program for computing seismic hazard. Instituto de Ingenierıa , Universidad Naconal Autónoma de México, UNAM, México

Orhan A, Seyrek E, Tosun H (2007) A probabilistic approach for earthquake hazard assessment of the Province of Eskişehir Turkey. Nat Hazards Earth Syst Sci 7(5):607–614

Ocak RS (2011) Probabilistic analysis of seismic hazard in East Marmara and comparison with Turkish Earthquake specifications. Master Thesis, METU, Institute of Science, Ankara

Ordonez GA (2000) SHAKE 2000: a computer program for the I-D analysis of geotechnical earthquake engineering problems

Özbey C, Sari A, Manuel L, Erdik M, Fahjan Y (2003) Empirical strong Groundmotion attenuation relations for Northwestern Turkey. In: Fifth national conference on earthquake engineering, Istanbul, Turkey

Özmen B, Erkan BBB (2014) Probabilistic earthquake hazard assessment for Ankara and its Environs. Turk J Earth Sci 23:462–474

Ram TD, Wang G (2013) Probabilistic seismic hazard analysis in Nepal. Earthq Eng Eng Vib 12(4):577–586

Regulation on Buildings to be Constructed in Earthquake Zones (DBYBHY, 2007): Turkey, 2007

Rehman et al (2014) Probabilistic Seismic Hazard Analysisfor the City of Quetta Pakistan. Acta Geophys 62:737–761

Republic of Turkey Ministry of Interior, Disaster and Emergency Management Presidency (AFAD). https://www.afad.gov.tr/TR/index.aspx: 4 June 2014

Risk Engineering, Inc.: ez EZ-FRISK User's Manual (1997)

Rockwell T, Barka A, Dawson T, Thorup K, Akyüz S (2001) Paleoseismology of the Gazikoy-Sarossegment of the North Anatolia fault, northwestern Turkey Comparison of the historical and paleoseismic records, implications of regional seismic hazard, and models of earthquake recurrence. Int J Seismol 5(3):433–448

Sadigh K, Chang CY, Egan JA, Makdisi F, Youngs RR (1997) Attenuation relationships for shallow crustal earthquakes based on California strong motion data. Seismol Res Lett 68(1):180–189

Şalk M, Altıner Y, Ergün M (2000) Geodynamics of western Turkey and implications. In: Proceedings of international conference on earthquake hazard and risk in the Mediterranean region I, pp 179–189

Sayıl N, Osmanşahin İ (2007) An Investigation of Seismicity for Western Anatolia. Nat Hazards. https://doi.org/10.1007/s11069-007-9141-2

Seismic Hazard Program (GSHAP) (1999). http://www.seismo.ethz.ch/static/GSHAP/index.html. Accessed 10 July 2014

Seyitoğlu G, Scott BC (1992) The age of the Buyuk Menderes graben (West Turkey) and its tectonic implications. Geol Mag 129:239–242

Seyitoğlu G, Scott BC (1996) The age of Alasehir graben (west Turkey) and its tectonic implications. Geol J 31:1–11

Şenel M, Bilgin AZ, Dalkılıç H, Gedik I, Korucu M, Uğuz MF, Serdaroğlu M (1991) Geology of Eğirdir-Sütçüler-Yenişarbademli and its immediate vicinity (Western Taurus): MTADergisi 113, pp 1–15

Şenel M, Gedik I, Dalkılıç H, Serdaroğlu M, Bilgin AZ, Uğuz MF, Bölükbaşı AS, Korucu M, Özgül N (1996) Stratigraphy of the autochthonous and allochthonous units in the east of Isparta Bend (Western Taurus). MTA J 118:111–160

Şengör AMC (1987) Cross-faults and differential stretching of hanging walls in regions flow-angle normal faulting: examples from western Turkey, in Continental extensional tectonics (Eds: M.P.Coward, J.F. Dewey andP.L. Hancock), London. Geol Soc Spec Publ 28:575–589

Tosun H, Seyrek E (2012) Selection of the appropriate methodology for earthquake safety assessment of dam structures in advances in geotechnical earthquake engineering—soil liquefaction and seismic safety of dams and monuments (edited by Abbas Moustafa). InTech Publishing, Rijeka, Croatia, pp 167–188

UDIM, Bogazici University Kandilli Observatory National Earthquake Monitoring Center Earthquake Research Institute. http://www.koeri.boun.edu.tr/sismo/zeqdb/. Date accessed 30 May 2014

UDİM, Bogazici University Kandilli Observatory National Earthquake Monitoring Center Earthquake Research Institute. http://www.koeri.boun.edu.tr/sismo/Depremler/thistoric.htm, Date accessed 16 July 2014

Unutmaz et al (2011) Comparison of the nonlinear behavior of deep Alluvial Fill with equivalent linear and nonlinear methods 1. In: Conference on seismology and earthquake Turkey, Ankara

USGS (2014) United States Geological Research Center, Earthquake Hazard Program. http://earthquake.usgs.gov/earthquakes/search, USA, Date accessed 30 May 2014

Yalçın İA, Kuruoğlu M, Kayalar AŞ (2008) Soil mechanics and foundation engineering. In: Proceedings of second national congress. Selçuk University, Konya, pp 62–72

Yılmazoğlu MU (2015) Probabilistic eismic hazard for muğla province and investigation of one-dimensional dynamic analysis of local soil behavior. Master's Thesis, Aksaray University, Institute of Science

Yücemen MS (2008) Probabilistic methods in estimation of earthquake hazard, section 14. Basic Earthquake Engineering Principles for Buildings Bizim Büro Printing House, Ankara

Campbell KW, Bozorgnia Y (2008) NGA ground motion model for the geometric Mean Horizontal component of PGA, PGV, PGD and 5% damped linear elastic Response Spectra for periods ranging from 001 to 10 s. Earthq Spectra 24(1):139–171 ((**in addition, this reference was corrected in the text**))