Nat Hazards (2010) 54:949–965
DOI 10.1007/s11069-010-9517-6

ORIGINAL PAPER

Probabilistic seismic hazard assessment for Lake Van basin, Turkey

Levent Selcuk · Azad Saglam Selcuk · Turgay Beyaz

Received: 16 October 2008 / Accepted: 2 March 2010 / Published online: 18 March 2010

Abstract The seismic hazard for the Lake Van basin is computed using a probabilistic approach, along with the earthquake data from 1907 to present. The spatial distribution of seismic events between the longitudes of 41–45° and the latitudes of 37.5–40°, which encompasses the region, indicates distinct seismic zones. The positions of these zones are well aligned with the known tectonic features such as the Tutak-Çaldıran fault zone, the Özalp fault zone, the Gevaş fault zone, the Bitlis fault zone and Karlıova junction where the North Anatolian fault zone and East Anatolian fault zone meet. These faults are known to have generated major earthquakes which strongly affected cities and towns such as Van, Muş, Bitlis, Özalp, Muradiye, Çaldıran, Erciş, Adilcevaz, Ahlat, Tatvan, Gevaş and Gürpınar. The recurrence intervals of $M_s \geq 4$ earthquakes were evaluated in order to obtain the parameters of the Gutenberg–Richter measurements for seismic zones. More importantly, iso-acceleration maps of the basin were produced with a grid interval of 0.05 degrees. These maps are developed for 100- and 475- year return periods, utilizing the domestic attenuation relationships. A computer program called Sistehan II was utilized to generate these maps.

Keywords Lake Van Basin · Peak ground acceleration · Probabilistic approach · Return period

L. Selcuk (✉) · A. S. Selcuk
Architectural-Engineering Faculty, Department of Geological Engineering,
Yuzuncu Yil University, 65080 Van, Turkey
e-mail: lselcuk@hotmail.com

A. S. Selcuk
e-mail: azadsaglam@gmail.com

T. Beyaz
School of Engineering, Department of Geological Engineering, Pamukkale University,
20017 Kinikli, Denizli, Turkey
e-mail: tbeyaz@pau.edu.tr

1 Introduction

Turkey has suffered with a number of large earthquakes that have killed many thousands of people and caused economic losses in densely populated areas. Turkey's recent tectonic elements include active fault systems such as the North Anatolian fault zone, Aegean Graben System, Eastern Anatolian fault zone and Bitlis thrust zone. The East and Southeast Anatolian regions are structurally more complex than the other regions of Turkey (see Bozkurt 2001). Prior geological studies conducted in the area indicate that neotectonic activity in Eastern Anatolia dates back to Serravalian (10–14 Ma ago). A N-S trending compression regime, resulting from the collision of the Arabian and Anatolian Plates, prevailed 12 Ma ago and gave rise to the development of extensional and strike-slip fault systems in front of the suture belt (Şaroğlu and Güner 1981; Şengör et al. 1985; Koçyiğit 1985; Dewey et al. 1986; Şaroğlu and Yılmaz 1986). Some recent studies suggest this tectonic regime was dominant between the end of the Late Miocene and at the end of Early Pliocene (Koçyiğit et al. 2001). The Lake Van basin is located between the Karlıova Joint and Zagros fault zone, north of the Bitlis suture belt (Fig. 1a). In this region, several other strike-slip faults parallel to the main structural elements were described in detail (Koçyiğit et al. 2001; Koçyiğit 2002). Lake Van basin is also a tectonically active basin due to the seismicity of these faults. Therefore, it is a region where destructive earthquakes could occur anytime.

In order to mitigate earthquake damage in this region, adequate planning controls and design codes are necessary. These require an evaluation of the magnitude of future earthquakes. Such an evaluation is normally based on a statistical analysis of historical earthquakes. Probabilistic Seismic Hazard Analysis (PSHA) is one method of analysis. In the probabilistic approach, the earthquake epicenter is modeled as a point in the spatial source zones that are seismically homogeneous. Most importantly, a use of probabilistic concepts has allowed for uncertainties in the size, location and rate of recurrence of earthquakes. Furthermore, uncertainties in the variations of ground motion characteristics with earthquakes size and location are explicitly considered in the assessment of seismic hazards (Kramer 1996).

In regard to the use of the probabilistic approach for the seismic hazard analysis of Turkey, the first extensive study was carried out by Erdik et al. (1985). Their study included the use of historical and instrumental earthquake records correlated with the neotectonic elements of Turkey. The present seismic hazard zonation map of Turkey was produced by the General Directorate of Disaster Affairs of Turkey based on the report by Gülkan et al. (1993). Gülkan et al. (1993) effectively used the same methodology in regard to source regionalization as was employed by Erdik et al. (1985) (Kayabalı 2002). The most recent seismic hazard map was produced by Kayabalı (2002). This study includes 14 seismic sources with the major fault zones such as Eskisehir, Tuz gölü and Ecemiş.

The present study covers Eastern Turkey, a region including major tectonic elements longer than 50 km in length and capable of generating earthquakes greater than 6.0 in magnitude, such as those of Tutak-Çaldıran, Varto, Bahçesaray and Gevaş, none of which were accounted for in previous seismic studies of Turkey. This study investigates the seismicity of settlements in the Lake Van basin in detail, including the cities of Van, Muş and Bitlis and the towns of Özalp, Muradiye, Çaldıran, Erciş, Adilcevaz, Ahlat, Tatvan, Gevaş and Gürpınar. About 1,000,000 people live in these settlements (TSI 2006). In these areas, characterized by high population density and high earthquake risk, the construction of multi-story buildings continues. However, the projection of a region using the maximum ground acceleration in design of earthquake-resistant structures is a conventional

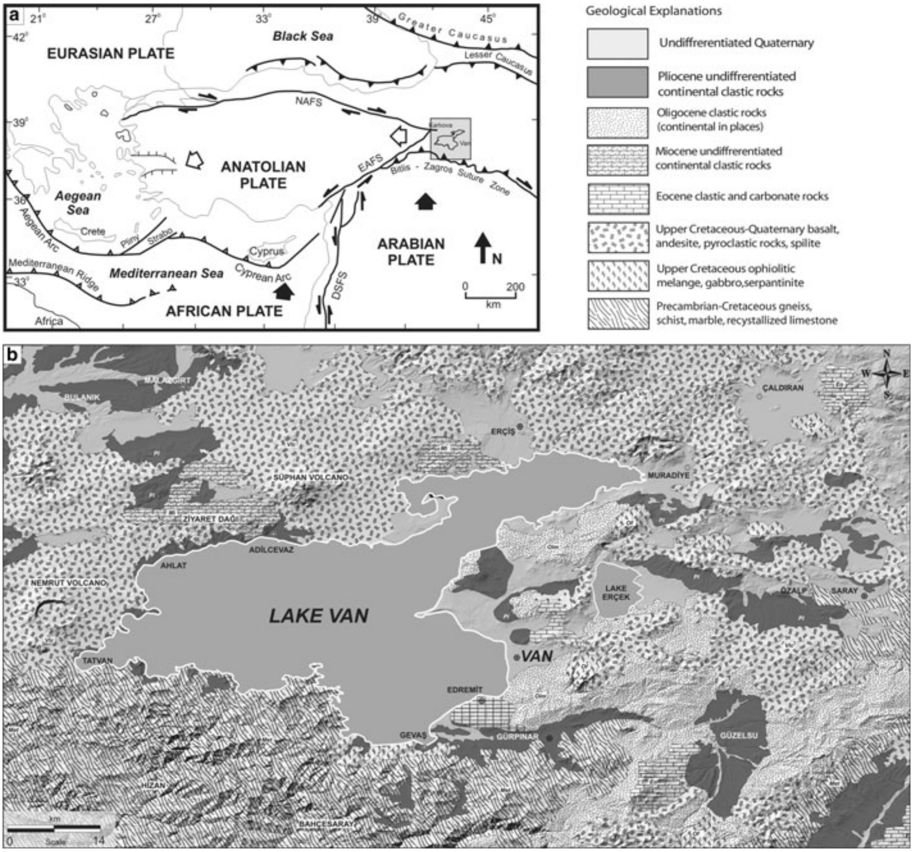

Fig. 1 **a** Simplified tectonic map of Turkey showing major neotectonic structures and neotectonic provinces (modified from Şengör et al. (1985)). DSFZ: Dead Sea Fault Zone, EAFZ: East Anatolian Fault Zone, NAFZ: Nort Anatolian Fault Zone, *heavy lines with half arrows* are strike-slip faults with *arrows* showing relative movement sense. *Heavy lines with filled triangles* indicate an active subduction zone, *Heavy lines with open triangles* show major fold and thrust belt. **b** Geological map of The Lake Van Basin and its surroundings

application. For this purpose, a zonation study for the seismicity of the region was conducted and Gutenberg–Richter relations of different source zones were obtained. Using the attenuation relations obtained by various researchers, iso-acceleration maps for return periods of 100 and 475 years were constructed for the region.

2 Geological context

The bedrock in the Lake Van basin (12,522 km^2) consists of the metamorphic rocks of the Bitlis mountain ridge (with elevations higher than 3,000 m) to the south of the lake; Pliocene-Quaternary deposits, carbonates and sandstones to the east, and volcanic deposits to the north and west, and the semi-active volcanoes Nemrut volcano (3,050 m) and Süphan volcano (4,434 m) in the vicinity of the lake (Schweizer 1975; Lemcke 1996). Pliocene-Quaternary sediments include shore-sand and lacustrine sediments interfingering with fluviatile sediments. These sediments consist of uncemented sand with gravels of different particle shape and diameter, and loose, unconsolidated carbonaceous-clay layers. The thickness of these units is as much as 150 m (Selçuk and Çiftçi 2007). Many settlements (Van city and the towns of Gevaş, Gürpınar, Özalp, Muradiye, Çaldıran and Erciş) are located over these young sediments (Fig. 1b). Archaeological and paleoseismological records indicate that many earthquakes occurred since the civilizations began to form over these materials. The Urartian cities were damaged and were re-built several times at these locations (Çiftçi et al. 2004).

3 Seismicity background and fault zones

Historical and instrumental earthquake records indicate that earthquakes with magnitudes (M_s) of 4.0–7.3 have occurred in Lake Van basin (DAD 2007). Since the beginning of the 1900s, 14,606 people lost their lives and 70,364 buildings were heavily damaged by the earthquakes occurred in the region (Table 1). The Çaldıran earthquake ($M_s = 7.3$) was the latest and most destructive earthquake to occur in the region. This earthquake caused great loss of life and economic damage around the city center of Van. Following the Çaldıran earthquake, no other strong earthquakes have occurred in the region. Over a 100-year period, a total of 634 earthquakes with magnitudes of 4.0 or greater were recorded in historical and instrumental documentation. Some of these important earthquakes are shown with their fault-plane solutions in Table 2 and Fig. 2.

As shown in Fig. 2, the Bitlis Thrust Belt is located in the south part of the study area. This belt was formed by the closure of the southern branch of Neotethian Ocean between the Arabian and Eurasian plates. The Bitlis-Zagros Thrust Belt extends between Kahramanmaraş and Yüksekova and is composed of southern-dipping thrust faults. This zone comprises a region of 1,500 km in length and 60 km in width. The Lake Van basin just north of the Bitlis suture belt is located between the Karlıova junction in the west and the Zagros fault zone in the east. Studies conducted by various researchers in the area between the Karlıova junction and the Zagros fault zone describe several strike slip fault zones similar to the main structural elements in the region (Şengör et al. 1985; Koçyiğit et al. 2001; Koçyiğit 2002; Yılmaz et al. 1987; Şaroglu et al. 1992). These fault zones were marked on the digital elevation model (DEM) image, and the fault systems were compared to topography and geology.

3.1 Gevaş strike-slip fault zone

The Gevaş strike-slip fault zone is dominated by right lateral strike-slip character extends along the southern border of Lake Van (Fig. 2). The Gevaş fault is located between Gevaş and Gürpınar towns (Ketin 1977) and it clearly appears on the DEM image (Fig. 2). Additionally, a plot of earthquake epicenters superimposed on the DEM shows that a number of earthquakes, including the several $M_s \geq 5.0$ events which have recently damaged the city of Van, are associated with this fault zone.

3.2 Tutak: Çaldıran right lateral strike-slip fault zone

The Çaldıran fault at the northeast of the Lake Van basin is one of the most important faults in the region. This fault produced an earthquake of $M_s = 7.3$ which killed 3,840 people and demolished 9,552 buildings in 1976. This earthquake also caused significant

Table 1 The damaging historical and instrumental earthquakes at Lake Van basin and its surroundings (DAD 2007)

Date (d/m/y)	Magnitude (M_s)	Location	Deaths	Injured	Buildings affected by earthquakes	Lat (N)	Long (E)	Depth (km)	Mercalli intensity scale
28.04.1903	6.7	Malazgirt	2,626	–	4,500	39.10	42.50	–	IX
13.05.1924	5.3	Çaykara	50	–	700	40.00	42.00	30	–
13.09.1924	6.9	Pasinler	310	–	4,300	39.96	41.94	10	–
06.05.1930	7.2	Hakkari	2,514	–	3,000	37.98	44.48	70	X
15.12.1934	4.9	Bingöl	12	–	200	38.85	40.55	–	–
10.09.1941	5.9	Van	194	–	600	39.45	43.32	20	VIII
20.11.1945	5.8	Van	–	–	1,000	36.63	43.33	10	–
31.05.1946	5.7	Varto	839	349	1,986	39.29	41.21	60	VIII
17.08.1949	7.0	Karlıova	450	–	3,000	39.60	40.60	40	IX
04.02.1950	4.6	Kığı	20	–	100	39.50	40.60	30	–
03.01.1952	5.8	H.kale	133	–	701	39.95	41.67	40	VIII
07.07.1957	5.1	Basköy	–	–	300	39.37	40.46	60	–
25.10.1959	5.0	Hınıs	18	–	300	39.25	41.63	50	–
26.02.1960	4.0	Bitlis	–	–	80	38.49	41.52	40	–
10.02.1962	4.0	Mus	–	–	97	38.70	41.45	–	–
04.09.1962	5.3	Iğdır	1	22	–	39.96	44.13	40	–
24.03.1964	4.0	Siirt	1	–	100	37.95	42.00	–	–
31.08.1965	5.6	Karlıova	–	–	1,500	39.30	40.79	33	–
07.03.1966	6.2	Varto	14	75	1,100	39.20	41.60	26	VIII
12.07.1966	4.0	Varto	12	–	90	39.17	41.56	–	–
19.08.1966	6.9	Varto	2,394	1,489	20,007	39.17	41.56	26	IX
26.07.1967	6.2	Pülümür	97	268	1,282	39.54	40.38	30	VIII
24.09.1968	5.1	Bingöl	2	40	–	39.20	40.20	8	–
22.05.1971	6.7	Bingöl	878	700	5,617	38.85	40.52	3	VIII
16.07.1972	5.2	Van	1	–	400	38.30	43.30	46	–
24.11.1976	7.3	Çaldıran	3,840	497	9,552	39.12	44.16	10	IX
02.04.1976	4.8	D. Beyazıt	5	13	236	39.91	43.76	14	VI
25.03.1977	4.8	Lice	8	17	210	38.58	40.03	29	–
27.03.1982	5.2	Bulanık	–	–	424	39.23	41.90	38	–
13.04.1998	4.8	Karlıova	–	–	69	39.32	41.05	–	–
01.05.2003	6.0	Bingöl	184	515	8,142	38.94	40.51	–	VIII
03.03.2004	5.0	Bingöl	–	–	–	39.05	40.33	–	–
25.01.2005	5.6	Hakkari	3	–	82	37.64	43.82	–	–
12.03.2005	–	Karlıova	–	–	760	39.42	40.87	–	–
14.03.2005	–	Bingöl	–	–	–	39.42	40.82	–	–
10.12.2005	–	Bingöl	–	–	–	39.40	40.85	–	–
Total			14,606	3,985	70,364				

Table 2 Significant earthquakes and their fault plane solutions at Lake Van Basin and its surroundings

No.	Reference of Fault plane solution on Fig. 2	Location of epicenters	Date (d/m/y)	Epicenter		Magnitude	
				Lat.N°	Long.E°	M_s	M_w
1	FPS-1 (c)	Varto	07/03/1966	39.10	41.40	6.2 (e)	6.2 (g)
2	FPS-2 (c)	Varto	19/08/1966	39.20	41.60	6.9 (f)	6.7 (g)
3	FPS-3 (c)	Karlıova	20/08/1966	39.30	41.16	6.3 (b)	6.3 (g)
4	FPS-4 (c)	Tur-Iran Border	29/04/1968	39.20	44.30	5.3 (d)	5.6 (g)
5	–	–	06/09/1975	38.47	40.72	6.7 (d)	6.5 (g)
6	FPS-5 (a)	Çaldıran	24/11/1976	39.10	44.00	7.3 (b)	7.0 (g)
7	FPS-6 (a)	Tur-Iran Border	26/05/1977	38.70	44.32	5.4 (f)	5.6 (a)
8	–	Varto	27/03/1982	39.23	41.9	5.1 (d)	5.5 (g)
9	FPS-7 (a)	Erzurum	30/10/1983	39.97	41.94	5.2 (a)	5.5 (a)
10	–	Gevaş	03/12/1984	37.97	43.15	5.7 (d)	5.9 (g)
11	FPS-8 (a)	Erzurum	07/11/1985	39.75	41.68	4.2 (a)	4.8 (g)
12	FPS-9 (a)	Çaldıran	20/04/1988	38.97	44.00	5.1 (d)	5.5 (g)
13	FPS-10 (a)	Gevaş	25/06/1988	38.44	43.08	5.0 (a)	5.5 (a)
14	FPS-11 (a)	Karlıova	13/04/1998	39.18	41.10	4.8 (a)	5.2 (a)
15	–	Horasan	03/12/1999	40.36	42.35	5.5 (d)	5.7 (d)
16	FPS-12 (a)	Gevaş	15/11/2000	38.30	42.92	–	5.6 (d)
17	FPS-13 (a)	Pasinler	10/07/2001	39.94	42.07	–	5.4 (d)
18	–	Bingöl	01/05/2003	39.01	40.46	6.4 (d)	6.4 (g)
19	–	Tercan	25/03/2004	39.93	40.81	5.4 (d)	5.6 (d)
20	FPS-14 (a)	D. Beyazıt	01/07/2004	39.65	43.83	4.8 (a)	5.1 (a)
21	FPS-15 (a)	Hakkari	25/01/2005	37.72	43.72	5.6 (a)	5.8 (a)
22	FPS-16 (a)	Karlıova	14/03/2005	39.35	40.89	5.7 (a)	5.8 (a)
23	–	Karlıova	06/06/2005	39.22	41.08	5.4 (a)	5.6 (a)
24	FPS-17 (a)	Karlıova	02/07/2006	39.49	40.78	4.9 (a)	5.0 (a)

(a) Harvard cmt, (b) Ambraseys (2001), (c) McKenzie (1972), (d) USGS-pde and ISC catalog, (e) Ambraseys and Jackson (1998), (f) Jackson and McKenzie (1984), (g) Converted from equations in Table 3

loss of life and economic damage around the city of Van. During the Çaldıran earthquake, a surface rupture of N70W trend and 53 km length was formed. A lateral slip of 3.50 m, a vertical slip of 0.50 m and compression and swellings of 70–80 cm were measured (Ambraseys 2001; Arpat et al. 1976; Tabban 2000). The lineament of the Çaldıran fault zone is clearly visible on the DEM image; however, if one marks the epicenters of earthquakes with $M_s \geq 4.0$, it becomes evident that the earthquakes in this region are clustered on the Çaldıran fault and in its southern part. The epicenters of these earthquakes are clustered in the south and they have depths between 33 and 57 km; this may indicate a dip component in the southern end of the Çaldıran fault zone.

3.3 Other strike-slip faults

The Varto right-lateral strike slip fault is one of the active faults in the region. The DEM image (Scale: 1/250,000) shows that this fault strike N35W form a lineament along the Bingöl and Bilican volcanoes. Plotting the epicenters on the DEM image suggests that the

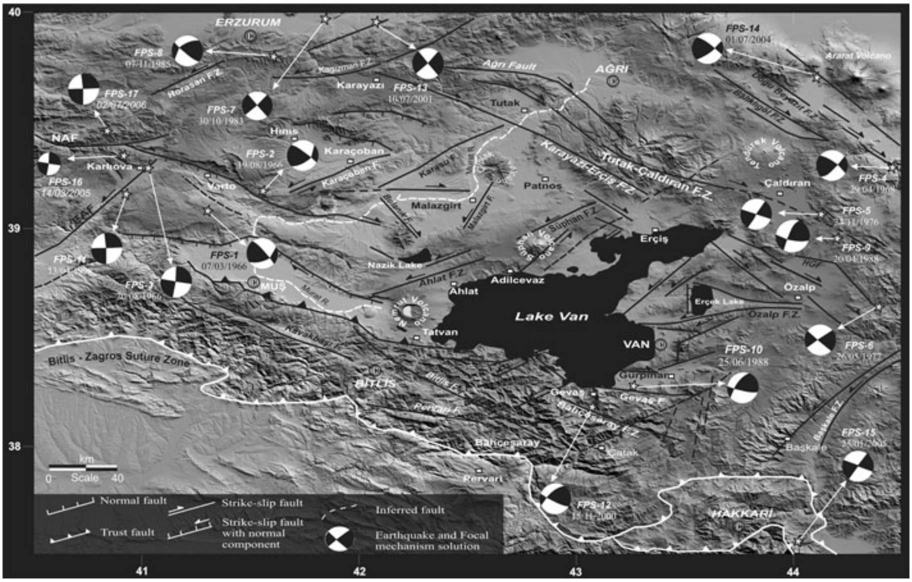

Fig. 2 Seismotectonic map of Van and its surroundings FZ, fault zone; F, fault; R, river; NAF, North Anatolian Fault; EAF, East Anatolian Fault; HFZ, Hasan Timur Fault; FPS, fault plane solution, reference number at Table 2

Varto fault continues until the Bilican volcano (Figs. 2, 3). Also present in this region is the NE-SW trending left lateral Malazgirt fault of 20 km in length, in the area between the Karlıova junction and Muradiye, and the Süphan fault of 30 km in length in the area between Erciş and Adilcevaz. In addition, E-W and NW-SE trending strike-slip fault systems are the main structural elements shaping the tectonic structure of the region. The strike-slip Özalp fault is the best example of these structural elements. This fault starts from the east of the town of Özalp and continues 60 km toward the west. Additionally, there are other fracture lines in the region, such as the Tutak-Çaldıran fault, Bahçesaray fault zone, Gürpınar fault and Edremit fault. It can be inferred from the distribution of epicenters of earthquakes with $M_s = 4.0$ or greater that some of these faults are still active.

4 Probabilistic seismic hazard analysis (PSHA)

4.1 Seismic source models

Seismic source characterization has three fundamental steps: (1) Identification of all seismic sources that can generate strong ground shaking in the region; (2) identification of the maximum size of the earthquakes for each seismic source and (3) characterization of each seismic source in terms of earthquake recurrence rates for all magnitudes of significance to the site hazard. These parameters are characterized for input into the PSHA (Cornell 1968; SSHAC 1997). In order to identify seismic sources, the data used in the present study were obtained from several earthquake catalogs (Records of Earthquake Research Department in General Directorate of Disaster Affairs of Turkey, DAD, catalogs of International Seismological Center, ISC and United States Geological Survey, USGS).

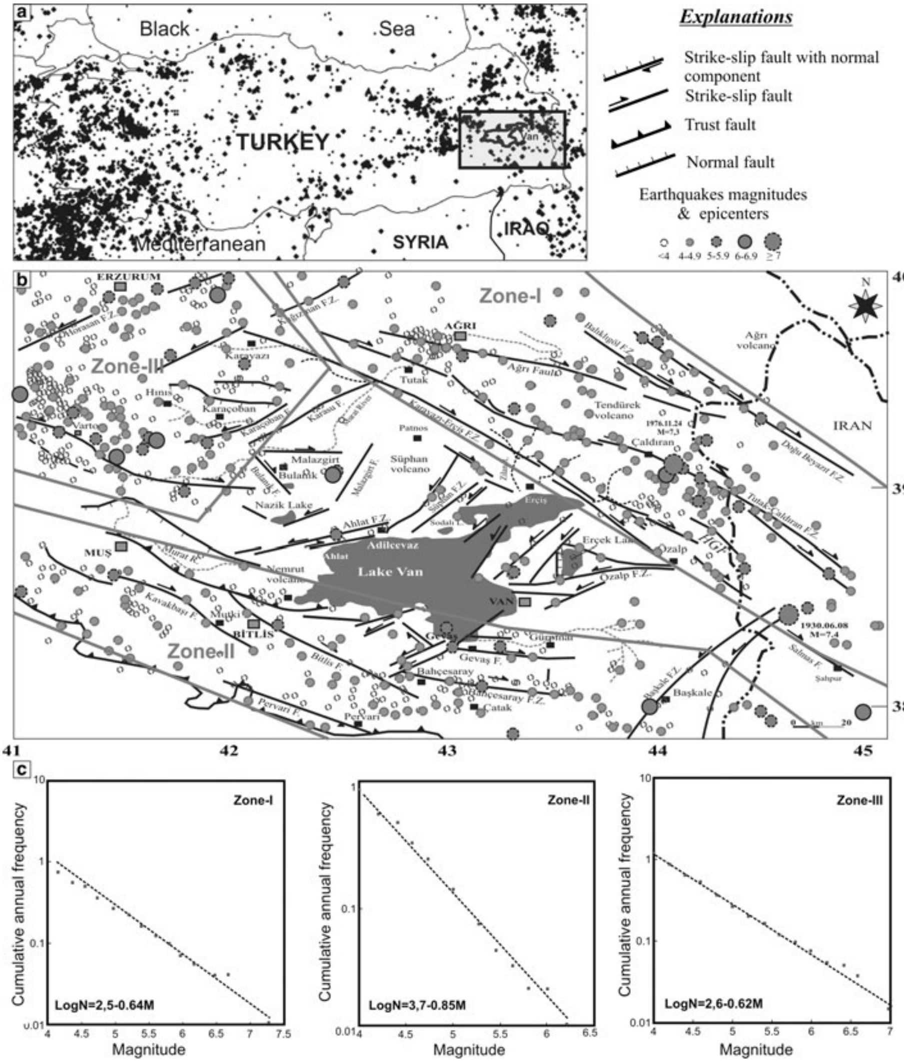

Fig. 3 **a** Epicenter distribution of earthquakes in Turkey from 1900 to present (data from the Earthquake Research Center, General Directorate of Disaster Affairs of Turkey). **b** Map showing earthquake data in source zones, and fault zones used in hazard model (modified from Koçyiğit A. (2002)) *FZ* fault zone, *F* fault, *R* river, *HGZ* Hasan Timur Fault Zone. **c** Magnitude–cumulative frequency plots and Gutenberg–Richter equations for three zones used in the hazard analysis

In the new dataset, the data with the same date of occurrence, magnitude and locations were eliminated from the initial data. A basic assumption of seismic hazard methodology holds that earthquake sources are independent, so catalogs that are used to estimate future seismic activity must be free of dependent events such as foreshocks and aftershocks; therefore, foreshocks and aftershocks were also eliminated from initial data (Gardner and Knopoff 1974). Among different magnitudes reported for the establishment of the catalog (e.g., moment magnitude, M_w, surface wave magnitude, M_s and body wave magnitude, M_b), the surface wave magnitude (M_s) was selected since it was proposed by Bolt (1989)

Table 3 Empirical forms of the relationship between the reported M_w, and the reported M_s, M_b, M_d and M_L values for Turkish earthquakes

Relationship by	Empirical equations
Yılmazturk and Bayrak (1997)	$M_S = 1.112(\pm 0.041)M_L - 0.779(\pm 0.193)$
Zare and Bard (2002)	$M_w = 0.76M_L + 1.13$
Yılmazturk and Bayrak (1997)	$M_S = 0.554(\pm 0.171)M_w + 3.240(\pm 0.227)$
Kalafat (2002)	$M_S = (M_D - 1.59)/0.67$
Ulusay et al. (2004)	$M_w = 0.6798M_S + 2.0402$
Ulusay et al. (2004)	$M_w = 1.2413M_b - 0.8994$
Ulusay et al. (2004)	$M_w = 0.9495M_D + 0.4181$
Ulusay et al. (2004)	$M_w = 0.7768M_L + 1.5921$

for magnitudes $M_s \geq 4$ and it is commonly used in attenuation relations. However, since other magnitude scales are also used in attenuation relations developed for Turkey, analyses were evaluated at different magnitude scales with necessary instrumental magnitude conversions. For example, Beyaz (2004) and Ulusay et al. (2004) used moment magnitude, M_w in their attenuation equations. The equations for conversion of earthquake magnitudes used in the present work are given in Table 3.

Once the epicenters and magnitudes of all earthquakes for a region are obtained from earthquake catalogs, the next step is the determination of seismic source zones. Earthquake epicenters were marked on the previously prepared DEM image. The epicenters of these earthquakes are shown to be clustered along the major tectonic lines and closely related with the borders of fault systems in the region. For the purpose of present study, the map of active faults prepared by Koçyiğit (2002) was used as a reference map. Figure 3b shows the epicenter distributions and active faults of Lake Van Basin. The seismic source zones were developed using these epicenter distributions of earthquakes, tectonic boundaries and fault information. The maximum size of the earthquakes for each of the zones was estimated from the past seismicity.

An earthquake occurrence model is the most important part of seismic hazard assessment. An earthquake occurrence model describes the recurrence of events in time within each seismic source zones. A linear regression analysis was carried out to estimate the coefficients of the Gutenberg–Richter relationship between magnitudes and their cumulative frequency of occurence. This equation is expressed by Gutenberg and Richter (1944) as follows:

$$\mathrm{Log}N = a - bM \quad (1)$$

where N: number of earthquakes, M: earthquake magnitude, a and b are regression coefficients. The parameters of Gutenberg–Richter magnitude frequency relations were computed for each source zone (Table 4).

4.1.1 Zone I: seismicity along the Tutak: Çaldıran fault zone

A number of 114 earthquakes with $M_s \geq 4.0$ were recorded in the northeastern part of the Lake Van region since 1907. NW-SE trending right lateral strike-slip faults are the main structural elements in the region. The Balıklıgöl fault of 100 km in length, the Tutak-Çaldıran fault zone, the Doğubeyazıt fault of 50 km in length, Karayazı-Erciş fault zone

Table 4 Parameters for seismic zones

Source zones	Number of earthquakes between 1907 and 2007 ($M \geq 4.0$)	Annual rate of earthquakes ($M \geq 4.0$)	Maximum magnitude	*a*-value	*b*-value
Zone I	114	1.14	7.3	2.50	0.64
Zone II	85	0.85	6.0	3.70	0.85
Zone III	118	1.18	7.0	2.60	0.62

and the Hasan Timur fault zone are the major faults in this region. According to the Gutenberg–Richter relation, derived from the available earthquake data, the recurrence interval of an earthquake with a magnitude of 6.0 was found to be about 25 years, while that with a magnitude greater than 7.3 is found as 175 years.

Tutak-Çaldıran fault zone is most effective fault in zone I. The 1976 Çaldıran earthquake is associated with a lateral slip of 3.50 m. With a very basic calculation, for this amount of slip to accumulate in 175 years, the slip rate on that fault should be about 20 mm/year. In other words, the same amount as the slip rate of the North Anatolian fault. Following the 1976 Çaldıran earthquake of $M_s = 7.3$, no other strong earthquake was recorded in the same region (Fig. 3b).

4.1.2 Zone II: seismicity in Bitlis thrust belt

A total of 85 earthquakes occurred in the area at the southern part of Lake Van basin. In addition to low-magnitude quakes recorded during the instrumental period, particularly within the lake and shores in the south, earthquakes with moderate magnitudes were also recorded between 2000 and 2007. These data also imply that Lake Van is tectonically controlled. Using the Gutenberg–Richter relation, the return period of an earthquake with a magnitude of 6.0 is 25 years. The Bitlis thrust belt to the basins's south is the most effective structural element. This zone has a length of 1,500 km and is approximately 60 km in width. The E-W and NW-SE trending Pervari fault, Bitlis fault, Bahçesaray and Gevaş faults form the other main structural lines in this region.

4.1.3 Zone III: seismicity in east segment of North Anatolian fault zone

A total of 118 moderate to large earthquakes were recorded in the northwestern part of the Lake Van basin between 1907 and 2007. The Bulanık fault, Kavakbaşı fault, Karaçoban fault, Kağızman fault zone and Horasan (Erzurum) fault are the main structural elements in the region (Fig. 3b). Using the earthquake data for the region, Gutenberg–Richter parameters were computed. The recurrence of an earthquake with magnitude of 6.5 is about 13 years.

Historical earthquakes in these three regions heavily damaged settlements areas in the Lake Van basin. Buildings in these areas, built on the Quaternary fluvial and lacustrine deposits, are multi-story and of low quality. Therefore, damage may be possibly high during an earthquake.

4.2 Ground motion model (attenuation relationship)

The ground motion model used in PSHA is referred to as an attenuation relationship. In most attenuation models, peak ground acceleration (PGA) is calculated on the basis of magnitude (M), distance (R) and local soil conditions (e.g., rock, soil). The PGA most commonly used for the assessment of earthquake hazards is the most important parameter in designing earthquake-resistant structures. Since previously recorded strong ground acceleration records are very limited in Turkey, the PGA attenuation relationship developed from acceleration records of earthquakes occurring outside Turkey. Recently, an attenuation relationship for rock sites was developed by Beyaz (2004), given in the following form. This equation is used in the probabilistic seismic hazard analysis as a principle input (Beyaz 2004).

$$\mathrm{LogPGA} = 2.581 + (2.9 \times 10^{-2} \times (M_w)^2) - (1.305 \times \mathrm{Log}(r + 7)) \quad (2)$$

where M_w is the moment magnitude and r is the epicentral distance (in kilometers). However, some recent domestic attenuation relations are also used in the seismic hazard analysis. The most important thing is that these domestic attenuation relations let us consider the rock and soil ground condition (e.g., Ulusay et al. 2004) (Table 5).

4.3 Approach and results of hazard analysis

Numerous seismic hazard forecasting models were developed within the last several decades. The simplest of those models is the Poisson model. The model assumes that earthquake events have no memory, and an earthquake in the source zone occurs independently from both location and time. The time-dependent (with memory) models are time-estimated, rock-estimated and Semi-Markov models. Among these memory models, the most commonly used is the characteristic earthquake model (Youngs and Coppersmith 1985). However, fault zones studied in detail (e.g., San Andreas fault) and uncertainties arising only from characteristic earthquakes do not allow these models to substitute for the Poisson model. On the other hand, the Poisson model is widely used and is a reasonable assumption in regions where data are sufficient only to provide an estimate of average recurrence rate (Cornell 1968). The Poisson model is described by the following equation;

$$p_r[N = n|v, t] = (e^{-vt}(vt)^n)/n! \quad (3)$$

where P_r is the probability of n events that occur in an interval of time, t. v is the mean rate of occurrence (or the expected number of events in a unit time period).

In present study, we used the computer program SISTEHAN-II for computing the probabilistic seismic hazard for Lake Van Region, modified with the most recent attenuation relations. Due to its simplicity and widespread use in seismic hazard studies, the Poisson process was employed in SISTEHAN-II as the stochastic model. The computer

Table 5 Attenuation relationships employed in the study

Reference	σ	Empirical form of the relationship
Joyner and Boore (1988)	0.26	$\mathrm{logPGA} = 0.43 + 0.23(M_s - 6) - \log(r) - 0.0027(r)$
Gülkan and Kalkan (2002)	0.562	$\mathrm{lnPGA} = -0.682 + 0.258(M_w - 6) + 0.036(M_w - 6)^2 - 0.562\ln(r)\ 0.297\ln(V_S/V_A)$ $r = \sqrt{r_{cl}^2 + h^2}$ $V_A = 1{,}381$ and $h = 4.48$
Ulusay et al. (2004)	0.63	$\mathrm{PGA} = 2.18e^{(0.0218(33.3M_w - \mathrm{Re} + 7.8427\mathrm{SA} + 18.9282\mathrm{SB})}$ SA:0, SB:0 (rock), SA:1, SB:0 (Soil) and SA:0, SB:1 (soft soil)
Beyaz (2004)	0.712	$\mathrm{logPGA} = 2.581 + (2.9 \times 10^{-2} \times (M_w)^2) - (1.305 \times \mathrm{Log}(r + 7))$

PGA the peak ground acceleration, M_s, M_w magnitudes, r epicentral distance, σ standard deviation program also incorporates the ‘‘earthquake location uncertainty’’ approach in such a way that each seismic source taken into consideration for the hazard analysis is extended outward from the center, resulting in a 50% increase in the original area of the seismic source, thereby yielding a smooth transition from the seismic zone to a non-seismic one (Kayabalı 2000).

Standard methods of Probabilistic Seismic Hazard Analyses give rise to calculation of earthquake magnitude, its location and recurrence interval as well as ground motion levels with different return periods. In this study, ground acceleration values with return periods of 100 and 475 years were compiled by using the computer program SISTEHAN II. To develop the probabilistic seismic hazard maps, interpolation by the ordinary kriging method was performed on the data (Figs. 4, 5). Considering the 50-year lifespan of engineered structures, it would be valuable for engineers to evaluate maps prepared for earthquake-resistant structural design for a return period of 100 years (Fig. 4). The Turkish building code prepared for earthquake regions requires that buildings with a building importance coefficient of $I = 1$ must consider earthquakes with an exceedance probability of 10% within a 50-year period (return period of 475 years).

In the ground acceleration contour map prepared using the attenuation relationship of Beyaz (2004), the ground acceleration values around the Lake Van Basin for a return period of 475 years ranges from 0.05 to 0.25 g (Fig. 5).

Since some settlement areas around Lake Van Basin sit on fluvial and lacustrine deposits of 100–150 m thickness (soft soil), these values obtained for rock conditions during an earthquake could be greater than accelerations obtained for rock sites. During

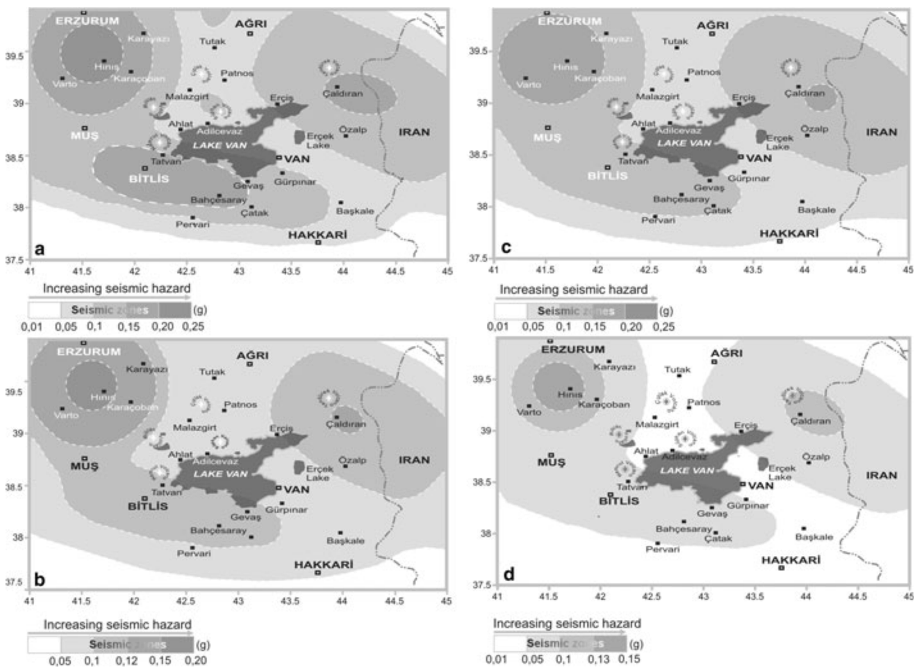

Fig. 4 Maps showing peak ground acceleration contour lines on rock and soil site conditions for return period of 100 years (utilizing the attenuation relationships **a** Joyner and Boore (1988) **b** Gülkan and Kalkan (2002) **c** Ulusay et al. (2004) for soil site condition **d** Beyaz (2004))

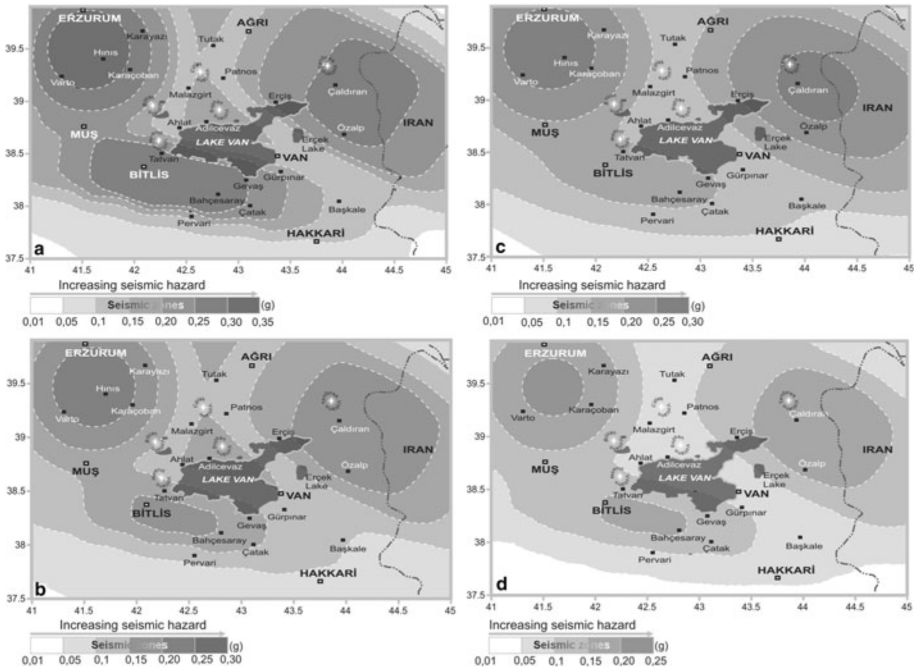

Fig. 5 Maps showing peak ground acceleration contour lines on rock and soil site conditions for the return period of 475 years (utilizing the attenuation relationships **a** Joyner and Boore (1988) **b** Gülkan and Kalkan (2002) **c** Ulusay et al. (2004) for soil site condition **d** Beyaz (2004))

some earthquakes, such as the 1985 Mexico City and 1989 San Francisco Bay area earthquakes, relatively small rock accelerations resulted in great accelerations on the surface of soft deposits. In the present study, soil site conditions in hazard analysis were also considered, with two alternatives. One is the domestic attenuation relations derived from Turkish strong motion data for soil and soft soil sites. In this regard, Ulusay et al. (2004) developed an attenuation equation of PGA for soil and soft soil conditions of Turkey. The second procedure is the appropriate prediction relations for PGA. Figure 6 shows that the peak accelerations between rock and soft rock conditions were combined with each other based on calculations of data obtained from several earthquakes (Idriss

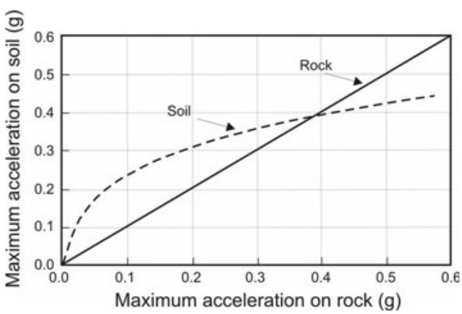

Fig. 6 Approximate relationships between peak acceleration on rock and soil site conditions (Idriss 1990)

1990). Considering these approaches, ground acceleration values obtained for return period of 475 years for soil sites are ranging from 0.20 to 0.35 g at the region.

This technique used above for seismic hazard assessment has been developed for the estimation of seismic hazards at individual sites. In fig. 7, probabilities of the given peak ground acceleration values are computed within time intervals of 50, 100 and 250 years for six sites. The probability of exceedance for PGA value of 0.10 g at rock site conditions is less than 0.50 (%50) during 100 years at six sites. However, the results are higher than 0.50 (%50) during 250 years at the city of Muş and the towns of Çaldıran, Gevaş, Erciş and Tatvan. The maximum PGA values at rock site conditions were 0.14 g for the city of Muş, 0.24 g for Çaldıran, 0.14 g for Gevaş, 0.13 g for Erciş and 0.14 g for Tatvan.

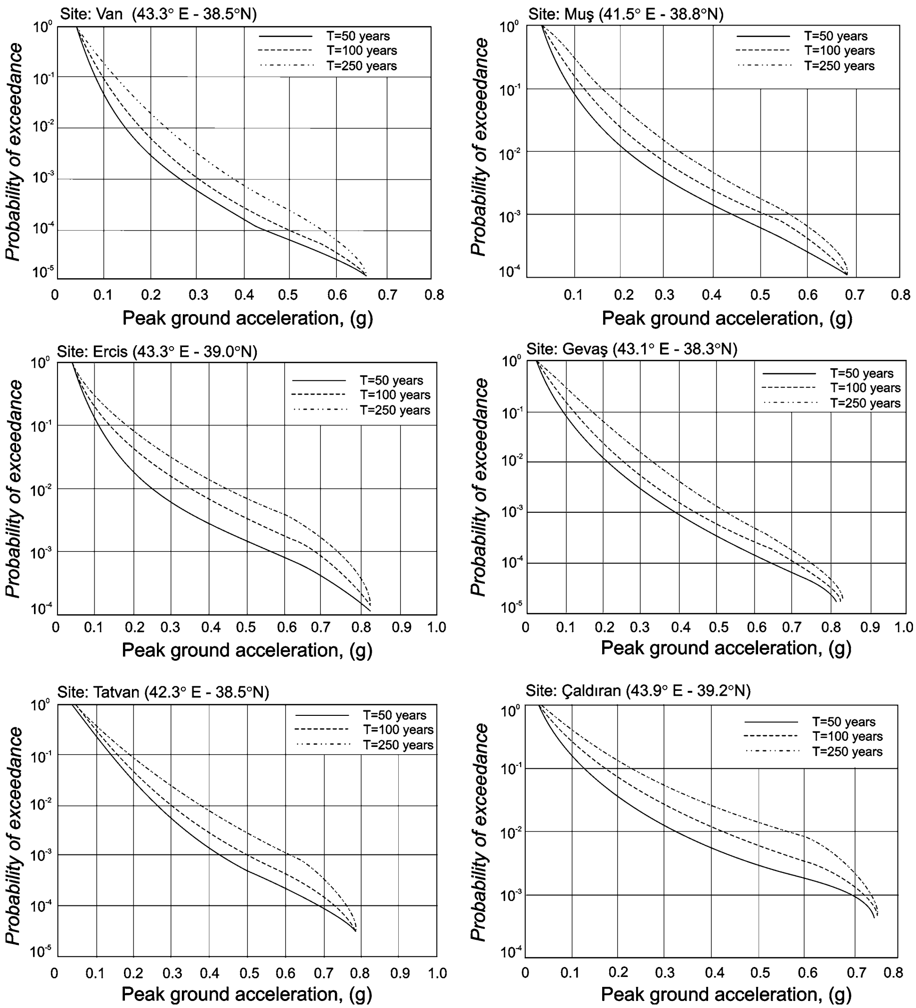

Fig. 7 Plots showing probabilities of exceedance at time intervals of 50, 100 and 250 years for the cities of Van, Muş and the towns of Erciş, Gevaş, Tatvan, Çaldıran

5 Conclusion and discussion

The Lake Van basin and its surroundings host several active fault systems and have faced significant seismic activity during the historical and instrumental period. In the present study, ground acceleration contour maps with return periods of 100 and 475 years were constructed. The ground acceleration map of the 475-year return period is proposed as the new seismic hazard map of Lake Van Region. In the new hazard map, the highest estimated levels of seismic hazard of region are found in the Northeast and Northwest part of Lake Van, where PGA values for rock sites in excess of 0.25 g are reached, and within lake and its shores, where PGA values in the range of 0.10–0.20 g are obtained. High values are also observed in the southwest part of Lake Van. The city of Van, the towns of Başkale, Gürpınar, Ahlat and the southeast part of the Lake appear as areas of the lowest seismic hazard. Settlement areas around Lake Van Basin fall within the 1st and 2nd degree earthquake regions of the Turkey Earthquake Hazard Map. Data obtained from the region and soil site conditions in the region indicate that the region comes under the 1st degree earthquake risk. However, settlement areas around the cities of Van, Muş and Bitlis continue to suffer from earthquakes occurring in these three seismic source zones. Since settlement areas are still built on fluvial and lacustrine deposits and buildings are multistory and low quality, an earthquake could incur significant loss of life and property damage. However, the probability of exceedance for PGA value of 0.10 g at rock site conditions is greater than 0.50 (%50) during 250 years at these settlement areas. For these reasons, communities in the Lake Van basin should adopt project structure regulations proposed for 1st degree earthquake regions.

In the present study, we have applied several domestic and imported attenuation equations to account for soil and rock site conditions. Although hazard maps for rock sites generally yield similar results, there are also some differences. The attenuation relations obtained by different researchers yield different results since they use different earthquake magnitude scales. Conversion equations among M_b, M_d, M_l, M_s and M_w magnitudes used for Turkish earthquakes should be updated on the basis of recent seismic records, and this will provide more precise conversions for earthquake magnitudes and more accurate assessments of the data. However, it should be kept in mind that the moment magnitude scale (M_w) is the most suitable scale for acquiring more accurate results since it has no saturation problems. Since the duration of an earthquake has an effect on earthquake damage, it is scientifically very important to take seismic records with both moment magnitude (M_w) and duration magnitude (M_d) scales.

References

Ambraseys N (2001) Reassessment of earthquakes, 1900–1999, in the Eastern Mediterranean and the Middle East. Geophys J Int 145:471–485

Ambraseys N, Jackson JA (1998) Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region. Geophys J Int 133:390–406

Arpat E, Saroğlu F, Iz HB (1976) Çaldıran Earthquake, Yeryuvarı ve Insan 1977 2:29–41

Beyaz T (2004) Development of a new attenuation relationship of seismic energy for Turkey using the strong motion records free of soil effect. Ankara University, PhD Thesis, 2004 Ankara

Bolt BA (1989) The nature of earthquake ground motion. In: Naeim F (ed) The seismic design handbook. Van Nostrand Reinhold, NY

Bozkurt E (2001) Neotectonics of Turkey—a synthesis. Geodinamica Act 14:3–30

Çiftçi Y, Selçuk L, Özvan A, Akkaya İ, Şengül A, Bülent A (2004) Seismic risk analysis for the settlement in the basin of Lake Van. 5th International Symposium on Easternmediterranen Geology, Thessaloniki, Greece

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

DAD (2007) Earthquake Research Department of Gen. Direct. of Disaster Affairs of the Ministry of Public Works and Settlement 2007. http://www.deprem.gov.tr

Dewey JF, Hempton MR, Kidd WSF, Şaroğlu F, Şengör AMC (1986) Shortening of continental lithosphere: the neo-tectonics of Eastern Anatolia—a young collision zone; Collision Tectonics. Geol Soc Special Publ 19:3–36

Erdik M, Doyuran V, Gülkan P, Akkas N (1985) A probabilistic assessment of the seismic hazard in Turkey. Tectonophysics 117:295–344

Gardner JK, Knopoff L (1974) Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian? Bull Seismol Soc Am 64:1363–1367

Gülkan P, Kalkan E (2002) Attenuation modelling of recent earthquakes in Turkey. J Seismol 6:397–409

Gülkan P, Kocyigit A, Yucemen MS, Doyuran V, Basoz N (1993) Earthquake zoning map of Turkey based on most recent data: METU Earthquake Engineering Research Center, Report No. 93-01, 156 pp (in Turkish)

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

Idriss IM (1990) Response of soft soil sites during earthquakes, proceedings, H. Bolton Seed Memorial Symposium, Bitech Publishers, Vancouver, British Columbia 2:273–289

Jackson J, McKenzie DP (1984) Active tectonics of the Alpine- Himalayan belt between western Turkey and Pakistan. Roy Astron Soc Geophys J 77:185–264

Joyner WB, Boore DM (1988) Measurement, characterization and prediction of strong ground motion. Earthq Eng Soil Dyn 2:43–102

Kalafat D (2002) Empirical quantification of earthquake magnitudes in seismic belts: Abstracts of Active Tectonic Research Group of Turkey Workshop (ATAG-6), MTA, Ankara, 105–108 (in Turkish)

Kayabalı K (2000) Sistehan II: a computer program for seismic hazard analysis. Geosound 37:15–42

Kayabalı K (2002) Modeling of seismic hazard for Turkey using the recent neotectonic data. Eng Geol 63:221–232

Ketin İ (1977) Short explanation for geological prospections between Van Lake and Iran Border. Bull Geol Soc Turkey 20:79–85

Koçyiğit A (1985) Karayazı Fault. Geol SocTurkey Bull 28:67–72

Koçyiğit A (2002) Neotectonics and seismicity of East Anatolian.Workshop-2002 on the Geology of East Anatolian. Van, Turkey

Koçyiğit A, Yılmaz A, Adamia S, Kuloshvili S (2001) Neotectonics of East Anatolian Plateau (Turkey) and Lesser Caucasus: implication for transition from thrusting to strike-slip faulting. Geodynamic Acta 14:177–195

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

Lemcke G (1996) Pala oklimarekonstruktion am Van See (Ostanatolien, Turkei). Dissertation, Swiss Federal Institute of Technology (Zurich) 11786:182

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

Şaroğlu F, Güner Y (1981) Doğu Anadolu'nun jeomorfolojik gelişimine etki eden opener; jeomorfoloji, tektonik, volkanizma ilişkileri. Turkish Geol Bull 24:39–51 (in Turkish)

Şaroğlu F, Yılmaz Y (1986) Geological evolution and basin models in neo-tectonic period in Eastern Anatolia. Miner Res Explor Inst Turkey Bull 107:74–94

Şaroglu F, Emre O, Kuscu I (1992) Active fault map of Turkey. General directorate of mineral and research exploration of Turkey Publication

Schweizer G (1975) Untersuchungen zur Physiogeographievon Ostanatolienund Nordwestiran. Geomorphologische, klima- und hydrogeographischeStudien im Vansee- und Rezaiyehsee-Gebiet. Tubinger Geographische Studien 60

Selçuk L, Çiftçi Y (2007) Microzonation of the plio-Quaternary soils: a study of the liquefaction risk potential in the Lake Van Basin, Turkey. Bull Eng Geol Env 66(2):161–176

Şengör AMC, Görür N, Şaroğlu F (1985) Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: Biddle KT,Christie-Blick N (eds) Strike-slip faulting and basin formation. Soc Econ Paleontol Min Sp Pub 37:227–264

SSHAC (Senior Seismic Hazard Analysis Committee) (1997) Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts. US Nuclear Regulatory Commission report CR-6372, Washington, DC

Tabban A (2000) Kentlerin Jeolojisi ve Deprem Durumu, Chamber of Geological Engineers, no: 56 (in Turkish)
TSI (2006) Turkish Statistical Institute 2006, http://www.turkstat.gov.tr/Start.do
Ulusay R, Tuncay E, Sönmez H, Gökçeoğlu C (2004) An attenuation relationship based on Turkish strong motion data and iso-acceleration map of Turkey. Eng Geol 74:265–291
Yılmaz Y, Şaroğlu F, Güner Y (1987) Initiation of the neo-magmatism in East Anatolia. Tectonophysics 134:177–199
Yılmazturk A, Bayrak Y (1997) Temporal and spatial distribution of seismic energy released by global earthquakes. Earthq Res Bull 75:17–53 (in Turkish)
Youngs RR, Coppersmith KJ (1985) Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. Bull Seism Soc Am 75:939–964
Zare M, Bard PY (2002) Strong motion data set of Turkey: data processing and site classification. Soil Dyn Earthq Eng 22:703–718