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PSHA of Van province for performance assessment using spectrally matched strong ground motion records

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Within the framework of the performance based earthquake engineering, site specific earthquake spectra for Van province has been obtained. It is noteworthy that, in probabilistic seismic hazard assessment, as a first stage data from geological studies and records from the instrumental period were compiled to make a seismic source characterization for the study region. The probabilistic seismic hazard curves were developed based on selected appropriate attenuation relationships, at rock sites, with a probability of exceedance 2, 10 and 50% in 50 yrs period. The obtained results are compared with the spectral responses proposed for seismic evaluation and retrofit of building structure in Turkish Earthquake Code (2007), section 7. The acceleration response spectrums obtained from probabilistic seismic hazard analysis are matched to adjust earthquake accelerograms recorded during the 2011 Van earthquakes by using SeismoMatch v2.0 software. The aim of this procedure is to obtain a set of reasonable earthquake input motions for the seismic evaluation of existing buildings.

Keywords. Earthquake spectra; seismic hazard; strong ground motion; performance-based assessment.

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1. Introduction

Seismic hazard analysis of the earthquake-prone Eastern Anatolia region of Turkey has become more important due to its growing strategic importance as a global energy corridor and closer integration with the European Union. In this study, Van province is selected as the study area. The town of Van, capital of province, has a population 400,000 (including the surroundings) as of the year 2000. The town is located 5 km from lake Van.

The seismicity of Van has been evaluated using a performance-based earthquake engineering approach in this study. Performance-based earthquake engineering seeks to improve seismic risk decision-making through assessment and design methods that have a strong scientific basis and that express options in terms that enable stakeholders to make informed decisions. Given the inherent uncertainty and variability in seismic response, a performance-based methodology should be formalized within a probabilistic basis.

The framework has four main analysis steps: hazard, structural/nonstructural, damage, and loss analysis. The first assessment step entails a hazard analysis, through which one or more ground motion intensity measures (IM) is evaluated. For standard earthquake intensity measures (such as peak ground acceleration or spectral acceleration) is obtained through conventional probabilistic seismic hazard analyses. Typically, IM is described with an associated mean annual probability of exceedance, which is specific to the location and design characteristics of the facility (Moehle and Deirlein 2004).

In performance based design and assessment method, it is possible to determine in quantities the damage levels that may arise under the design ground motion within the structural system elements. It is checked whether this damage stays under the acceptable damage levels for each related element. Acceptable damage limits are defined in a way to be consistent with the foreseen performance targets at various earthquake levels (Aydınoğlu 2007; Doran *et al.* 2011; Kutanis and Boru 2014). Site-specific design spectra for the region have a great importance to determined buildings performance under an earthquake hazard.

The demand spectra that were used for determining the performance of buildings systems have shown the maximum response to earthquake ground motion during an earthquake. In performance based design and assessment methods, the earthquake demand is calculated first. It is then necessary to determine the structural performance by comparing these demand values to deformation capacity for the selected performance levels (Işik and Kutanis 2015). There will be significant changes in the demand displacement of buildings. Therefore, damage estimates and building performance will better reflect real values for the buildings, which did not meet the demand displacement (Işik *et al.* 2016). According to section 2 of the Turkish Earthquake Code (TEC'07), the demand spectra used to determine seismic performance of an existing building based on a probability of exceedance of 10% in 50 yrs (figure 1).

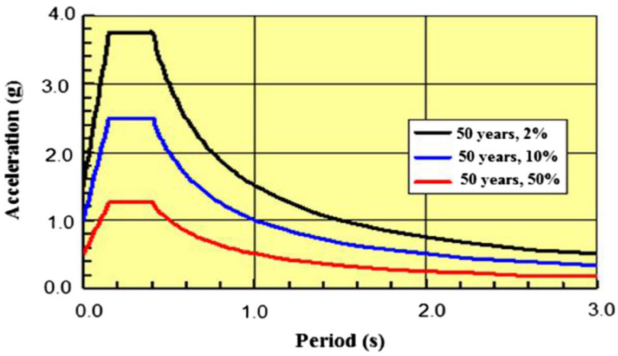

Figure 1. The earthquake spectrum curves for different exceedance probability.

However, the design is made with the statistical earthquake parameters given in this code and obtained according to geographical locations of constructions. However, since the acceleration values given in the standards cannot clearly meet the actual physical conditions in which the structures exist, it is understood from the various studies that the design made may not reflect the expected situation (Yunatçı and Çetin 2007; Yalçın *et al.* 2013; Işik and Kutanis 2015; Harman and Küyük 2016; Işik *et al.* 2016). In all of these studies, the calculated spectrum unique to the field seems to be incompatible with the spectrum that the code gives. Therefore, a site-specific probabilistic seismic hazard analysis (PSHA) is carried out to review the potential risk of the study region in this study. This will make the results more realistic.

The sensitivity of different parameters used in probabilistic seismic hazard calculation is investigated by different logic tree runs with alternative magnitude sets, source zone models and attenuation relations, and with different sets of values for the seismicity parameters. The logic tree algorithm permits several values for each parameter and results in error estimates (fractiles) of the hazard (Grünthal and Wahlström 2001). One example of logic tree for PSHA is given in figure 2.

2. Tectonic settings and seismicity of Van and surrounding areas

General tectonic setting of Eastern Anatolia is mainly controlled by the collision of northerly moving Arabian plate against Anatolian plate along a deformation zone known as Bitlis Thrust Zone (figure 2). The collision leads to the westward extrusion of the Anatolian plate along the two notorious transform faults with different sense of slip, the dextral North Anatolian Fault and the sinistral East Anatolian Fault zones, which join each other in Karlıova Triple Junction (KTJ) in Eastern Anatolia (figure 2). In the eastern side of KTJ; however, the collision deformation is largely accommodated within the Eastern Anatolian Block through distributed NW–SE trending dextral faults and NE–SW trending sinistral faults representing escape tectonics, and shortening of the continental lithosphere along the Caucasus thrust zone. East–west trending Mush-Lake Van and Pasinler ramp basins constitute other conspicuous

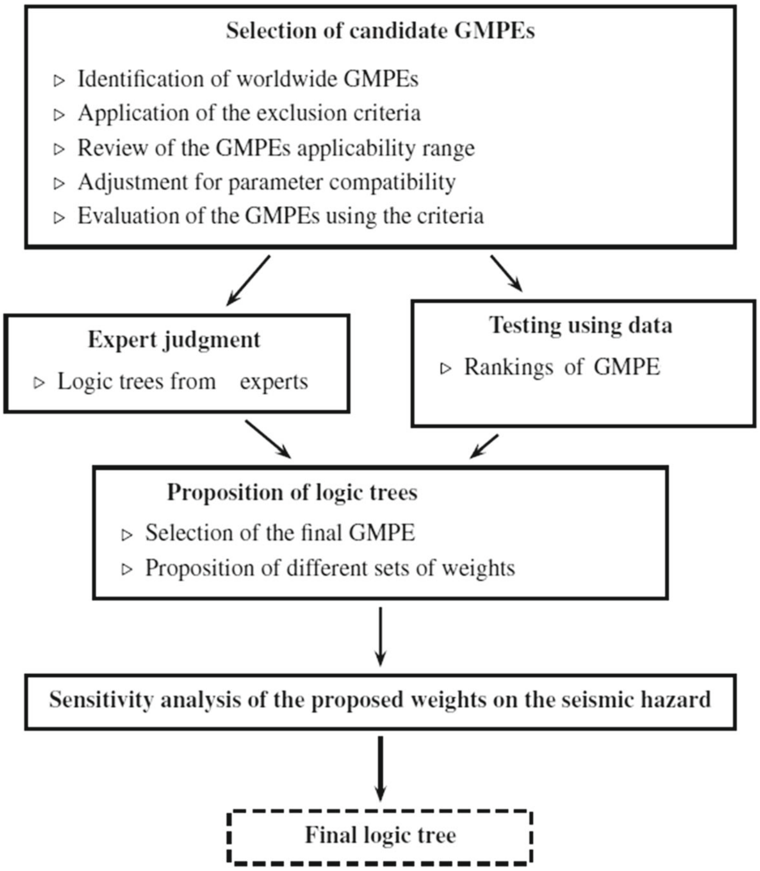

Figure 2. Logic tree setting up procedure for ground motion prediction equations (Delavaud *et al.* 2012).

tectonic properties within the Eastern Anatolian borders (Sengör *et al.* 1985; Barka and Kadinsky-Cade 1988; McClusky *et al.* 2000; Reilinger *et al.* 2006; Utkucu *et al.* 2013).

The East Anatolian Fault Zone is a 550 km long, approximately northeast-trending, sinistral strike-slip fault zone (figure 3) that comprises a series of faults arranged parallelly, sub-parallelly or obliquely to the general trend. The Bitlis Suture is a complex continent–continent and continent–ocean collisional boundary that lies north of fold-and-thrust belt of the Arabian platform and extends from south-eastern Turkey to the Zagros Mountains in Iran (Lyberis *et al.* 1992; Bonnin *et al.* 1988; Homke 2007; Piper *et al.* 2008; Stern and Johnson 2008). The area to the east of Karlıova triple junction is characterized by a N–S compressional tectonic regime (figure 4). Conjugate strike-slip faults of dextral and sinistral character parallel to the north and east Anatolian fault zones are the dominant structural elements of the region. Some of these structures include Agrı Fault, Bulanık Fault, Çaldıran Fault, Ercis Fault, Horasan Fault, Iğdır Fault, Malazgirt Fault, Süphan Fault, Balıklıgölü Fault Zone, Baskale Fault, Çobandede Fault Zone, Dumlu Fault Zone, Hasan Timur Fault Zone, Kavakbası Fault, Kagızman Fault Zone, Doğubayazıt Fault Zone, Karayazı Fault, Tutak Fault Zone, Yüksekova-Semdinli Fault Zone and the North-east Anatolian Fault Zone (figure 4) (Bozkurt 2001). Aydemir *et al.* (2014) investigated the faults and possible structural elements that may have caused the devastating earthquake that occurred on October 23, 2011. This possible long fault zone starting from the Nemrut Mountain in the west may exist through to the east of Lake Van (Aydemir *et al.* 2014).

The faults are seismically active and form the source for many earthquakes. Some of the major earthquakes in the 20th century are September 13, 1924 Pasinler ($M = 6.8$), 1975 Lice ($M = 6.6$), November 24, 1976 Çaldıran ($M = 7.3$), October 30, 1983 Horasan-Narman ($M = 6.8$), May 5, 1986 ($M = 5.8$) and June 6, 1986 Doğanşehir ($M = 5.6$) earthquakes.

Van Centre is in first degree of seismic zones in current seismic hazard map of Turkey (figure 5). Figure 5 indicates first and second degree seismic zones.

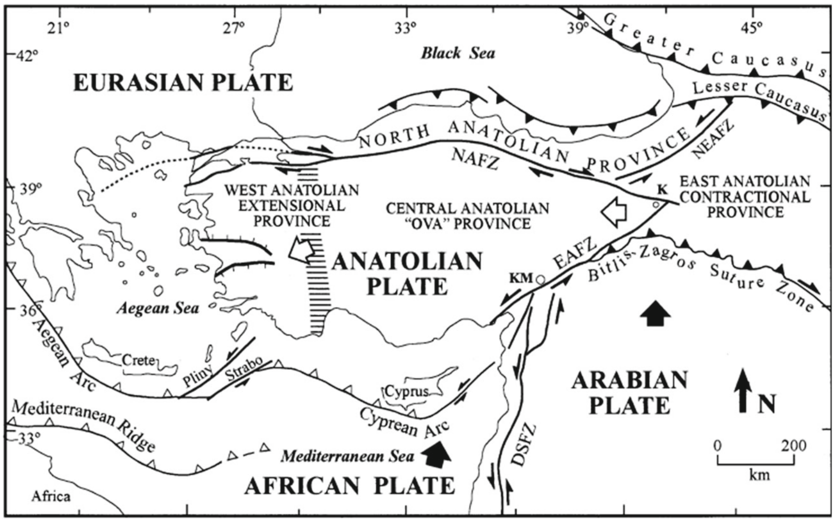

Figure 3. Tectonic map of Turkey including major structural features (from Bozkurt 2001).

3. Seismicity parameters

On any given fault within any given region, earthquakes occur at irregular intervals in time, and one of the basic activities in seismology has long been the search for meaningful patterns in the time sequences of earthquake occurrence (Dowrick 2003). Amongst the number of recurrence laws that have been proposed, in this study, Gutenberg and Richter law was used due to the fact that there is no available evidence to determine whether the Gutenberg–Richter or some other recurrence laws are correct. During any given interval of time, the general underlying pattern or distribution of size of events is that first described by Gutenberg and Richter (1944), who derived an empirical relationship between magnitude and frequency of the form

$$\log N = a - b \cdot M \tag{1}$$

where N is the number of shocks of magnitude at least M per unit time and unit area, and a and b are seismic constants for any given region (Dowrick 2003).

The parameter a, which is related to the size of the investigated region, observation period and earthquake activities during the observation period is defined as Average Annual Seismic Activity Index. The parameter b, which varies according to the tectonic specifications of the investigated region is defined as Seismotectonic Parameter (Özmen 2013).

The core of the study is Van City Center. Therefore, Gutenberg–Richter relation was calculated according to Van City Center. While making those calculations for Van City, an area of 70.650 km^2, which was 150 km radius from the Van City Center was taken into account.

In a seismic hazard modeling study of Van, recurrence rates are estimated by using historical and digital records. After the compilation of collected data, a plot of 'M' against 'log N' was constructed and the best-fit line of the form of equation (1) was determined by regression analysis (figure 6). In probabilistic seismic hazard analysis, magnitude–frequency relationship is calculated for Van province as $\log N = 5.8248 - 0.8344M$.

4. Site-specific design spectra for Van province

In the standard methodology of seismic hazard analysis, attenuation relationships are used and obtained results are used in order to form the hazard spectrum in the frequency intervals of a range of ground motion. Seismic hazard calculations can be defined with the equation given below, as an application of the theorem of total probability (McGuire 2004)

$$H(a) = \sum_i v_i \int\int P[A > a|m, r] \times f_{M_i}(m) f_{R_i}|_{M_i}(r, m) dr dm \tag{2}$$

in this equation, $H(a)$, stated as hazard, is the annual frequency of the earthquake that produces 'A' magnitude, which is a higher value than 'a'. Here, 'A' is the peak momentum, velocity or displacement.

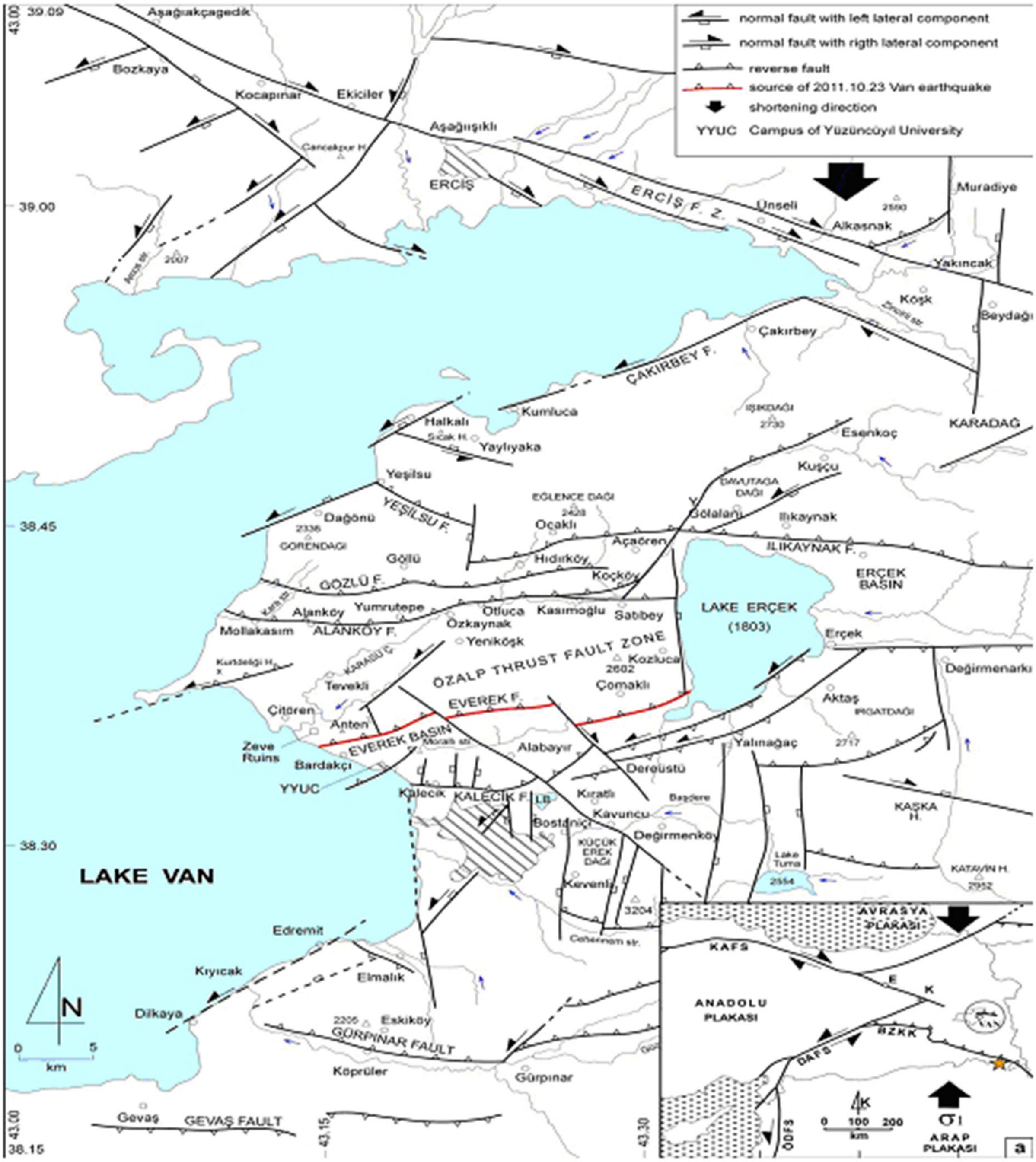

Figure 4. Active faults of Eastern Anatolian Province (Koçyiğit 2013).

Total ($\sum$) symbol indicates that it involves all the sources; v_i indicates the annual occurrence ratio of the earthquakes, which are larger than M_{oi} magnitude in I earthquake source. $f_{M_i}(m)$ and $f_{R_i}|_{M_i}(r;m)$ indicate the magnitude of the earthquake and stochastic density functions of the distance, respectively. $P[A{>}a|m,r]$ states the probability of forming a ground motion magnitude, which is an 'A' bigger than 'a' in the investigated settlement area of an earthquake.

Earthquake sources may be linear (faults) or areal sources. The features of their source geometry and whether the earthquake source is linear or areal, present differences in the calculation of $f_{R_i}|_{M_i}$. For linear sources, $P[A > a|m,r]$ is calculated with the formula below

$$\ln A = C_1 + C_2 M + C_3 \ln R + C_4 R + \varepsilon; \quad \varepsilon \approx N\left(0, \sigma_\varepsilon^2\right). \tag{3}$$

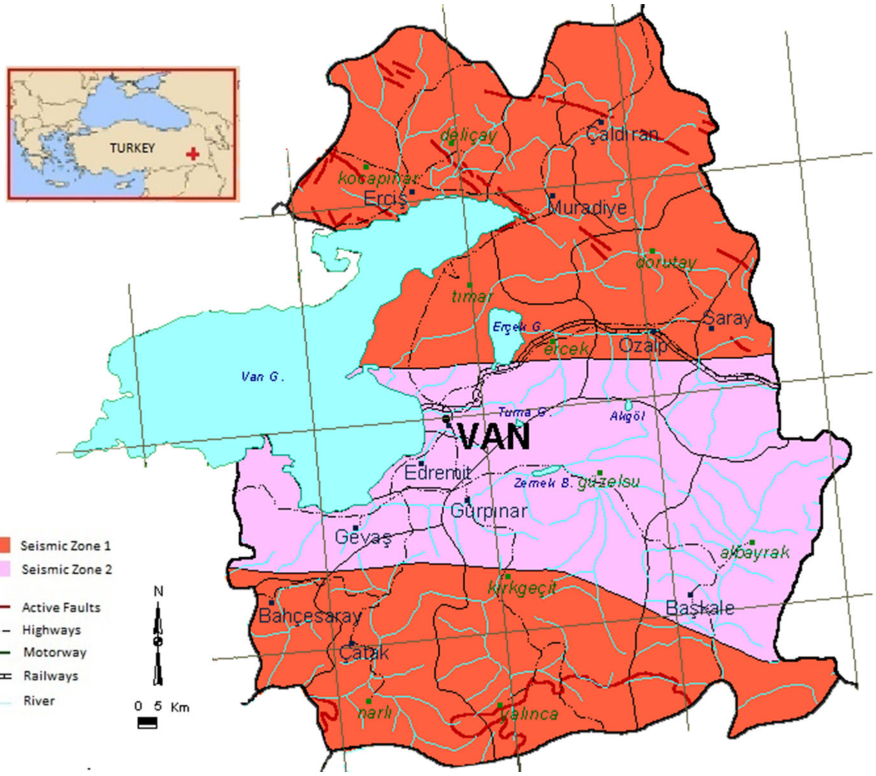

Figure 5. Seismic hazard map of Van region where the red areas indicate the first degree zone with a minimum effective acceleration of 0.40 g and the pink areas mark the second degree zone with a minimum acceleration of 0.30 g.

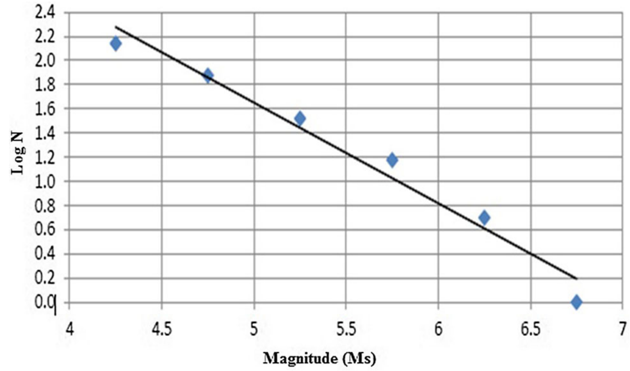

Figure 6. Gutenberg–Richter magnitude–frequency relationship for earthquakes from Van and surrounding data.

Here, R can be calculated in various forms as distance, for example, the closest distance to the fault crack, the closest distance to the horizontal projection of the fault crack, etc. In the case that the source is taken areal, it is calculated with $P[A > a|m, r]$ relation.

$$\ln A = C_1 + C_2 M + C_3 \ln (R + RZEROA) + C_4 R + \varepsilon; \quad \varepsilon \approx N(O, \sigma_\varepsilon^2). \tag{4}$$

Here, R is the focal length and it is calculated with horizontal distance and focal depth (d). In the formulas above, C_1, C_2, C_3, C_4, $RZEROA$ and σ_ε are constants independent from M and R.

The seismic hazard analysis approach is based on the model developed originally by Cornell (1968), who quantified it in terms of the probability of exceedance of the design level peak ground acceleration (PGA). The procedure for conducting a probabilistic seismic hazard analysis includes seismic source characterization, size distribution and rate of occurrence determination for the source, ground motion estimation and, lastly, probability analysis.

In the current study, since the neotectonic faults are not identified in the research area clearly, earthquake sources are characterized as area source zones. Area seismic sources are often defined where specific fault data are not known, but seismicity does exist. Area sources assume that the rate of occurrence is uniform throughout. Therefore, every location within the area has equal probability that an event will occur.

One of the most significant steps to determine the earthquake hazard of a region is to define the borders of the region on which earthquake data will be evaluated. For this reason, the faults which cause an earthquake are supposed to be known while evaluating the earthquake potential of any region. Earthquake sources can also be detected according to the historical earthquake records (palaeoseismology). These data were used during the determination of earthquake sources which may affect Van and closer regions around.

All seismic sources, that can generate strong ground shaking in Van and surroundings, are classified into 12 areal seismic zones: (1) Malazgirt, (2) Suphan, (3) Erciş, (4) Çaldıran, (5) First, (6) HasanTimur, (7) Second, (8) Third, (9) Lake Van Southern Boundary fault, (10) Fourth, (11) Başkale, and (12) Bitlis Zagros Suture zone (figure 7).

In the design of earthquake resistant buildings, simulating the earthquake motion, essential for the design is getting important. Since the design defines earthquake motion as ground motion characteristics, the calculation methods of ground motion parameters are needed. In the calculation of ground motion, attenuation relationships which state a

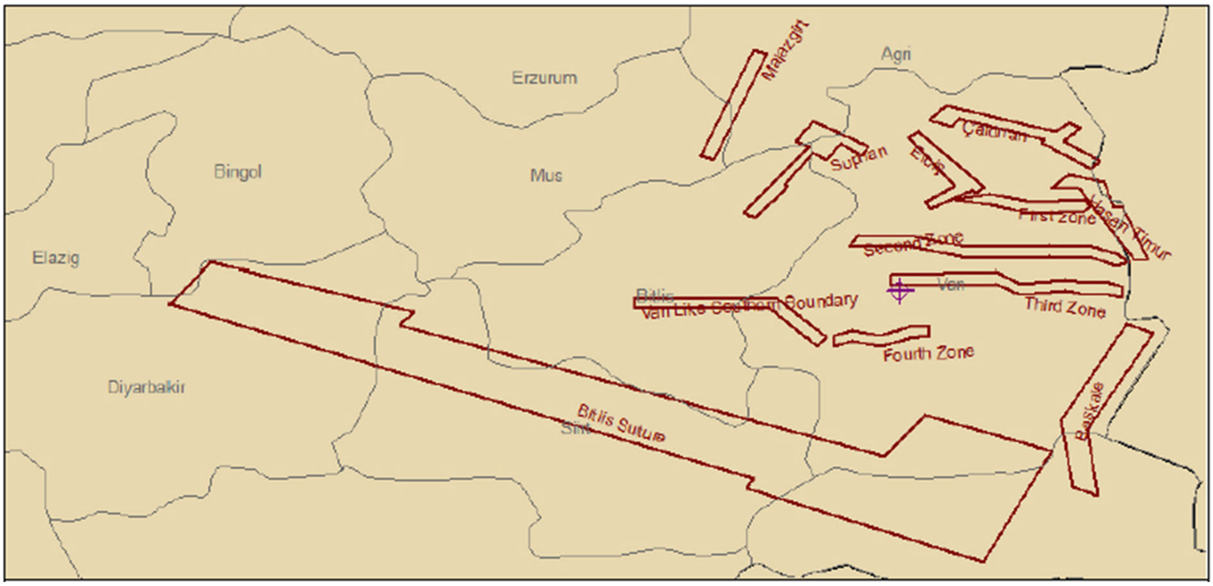

Figure 7. Earthquake areal zones in Van and surroundings.

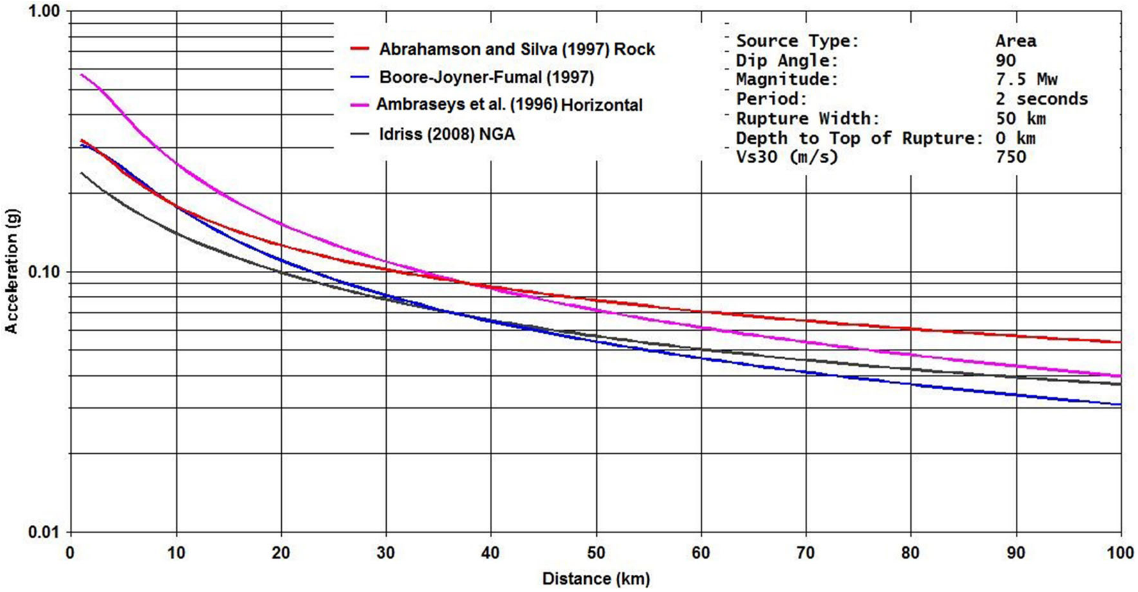

Figure 8. Abrahamson and Silva (1997), Boore *et al.* (1997), Ambraseys *et al.* (1996), and Idriss (2008) attenuation relationships for rock sites.

specific ground motion parameter in terms of magnitudes that intensely affect that parameter. Attenuation relationships play a vital role in the seismic hazard analysis used in seismic design (Kutanis 2005).

Attenuation relationships which are used in earthquake hazard studies are the measurement of ground motion related to the source, diffusion area and regional characteristics. Attenuation relationships used in earthquake hazard studies determine the ground motion parameters such as maximum acceleration, strength and spectral acceleration, according to earthquake source parameter, diffusion and soil properties

$$Y = f\,(M, R, P_i) \tag{5}$$

Y is the desired ground motion parameter, M is the magnitude of the earthquake, R is the measurement of the distance of the project site from the source, and P defines the other parameters used in order to characterize the earthquake source, wave diffusion and/or local land conditions. Attenuation relationships are developed through regression analysis from the databases of recorded strong motions (Yağcı 2016).

In Eastern Anatolia region, previously recorded strong ground motion acceleration records are limited. Therefore, in the current analysis, worldwide applicable three empirical attenuation relationships are utilized to perform the seismic hazard analysis. Attenuation relationships for rock sites employed in this study are Abrahamson and Silva (1997), Boore *et al.* (1997), Ambraseys *et al.* (1996), and Idriss (2008) (figure 8).

After the compilation of the seismic hazard analysis data, the procedure for conducting a probabilistic seismic hazard analysis, by using

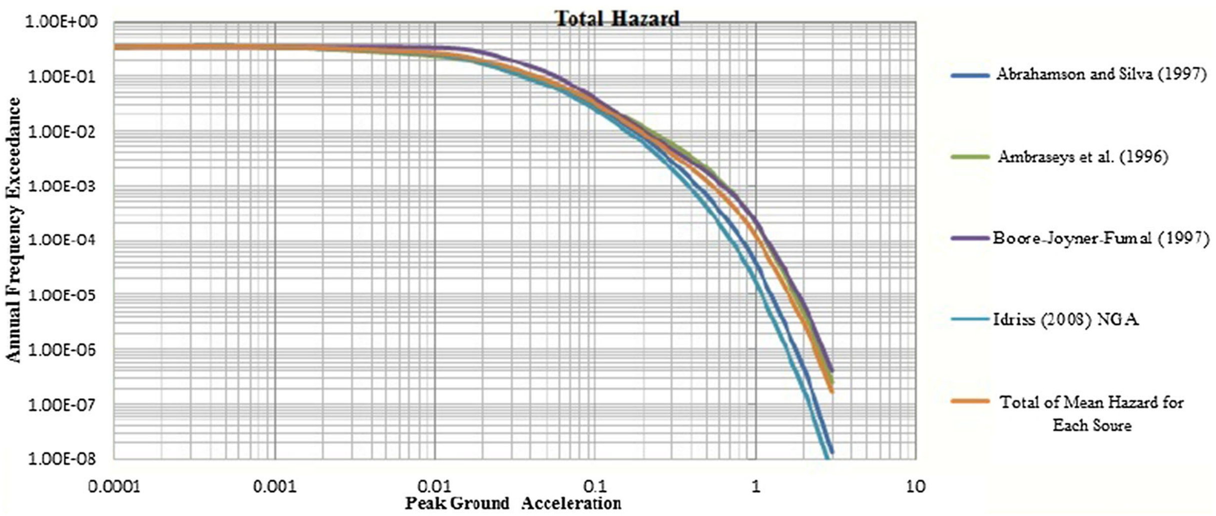

Figure 9. Peak ground acceleration (PGA) at Van with varying return periods.

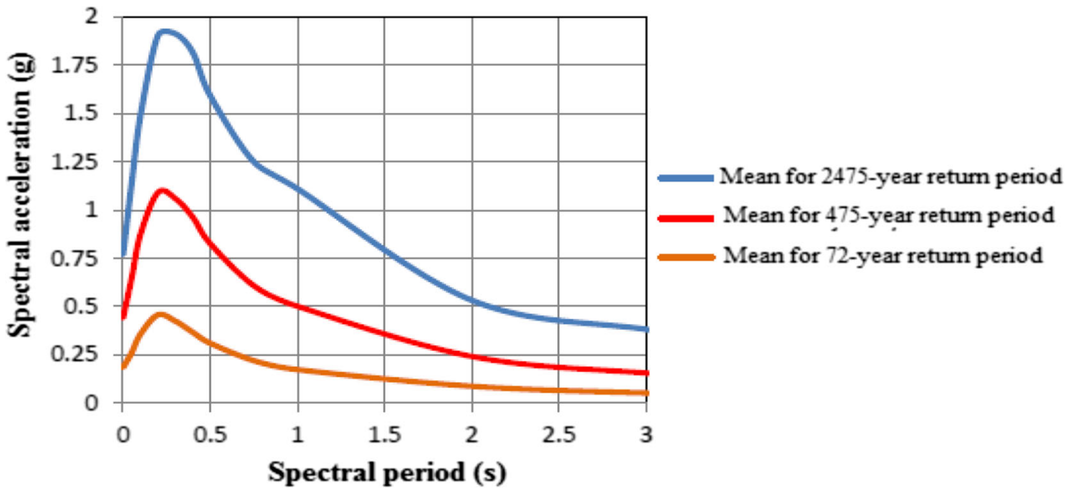

Figure 10. Spectral responses at 5% damping for the return period of 72, 474.6 and 2474.9 yrs.

EZ-FRISK software was employed to produce the PGA as a function of return periods (figure 9) and uniform probability response spectra for selected return periods (figure 10). The results of probabilistic seismic hazard analysis for Van are presented in terms of spectral responses at 5% damping for the return periods of 72, 474.6 and 2474.9 yrs (figure 10). The results are compared with N–S and E–W component taken from Muradiye station after the earthquake, which occurred on

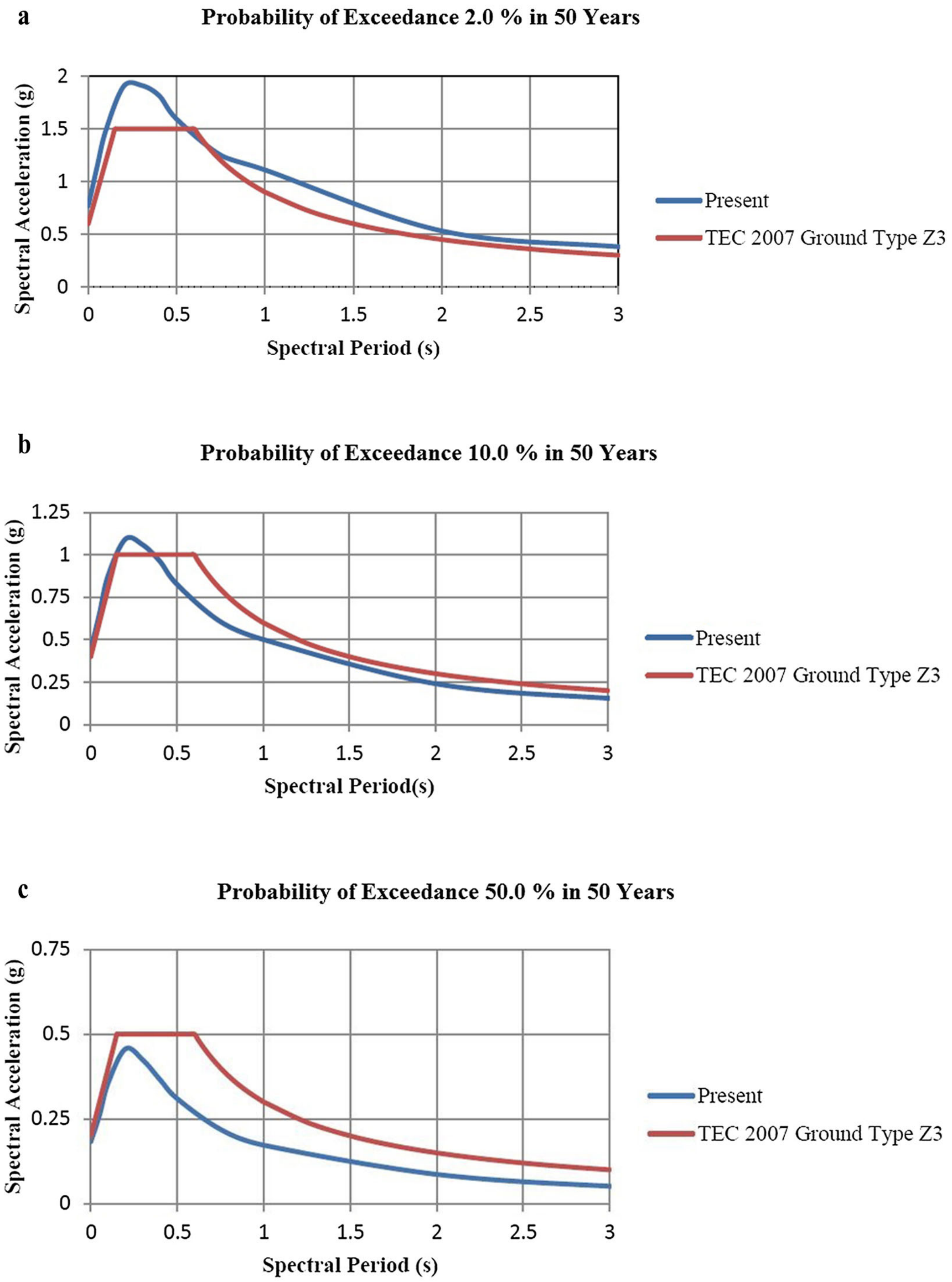

Figure 11. (**a**) Comparison of spectral responses at 5% damping for the return period of 2474.9 yrs in Van. (**b**) Comparison of spectral responses at 5% damping for the return period of 474.6 yrs in Van. (**c**) Comparison of spectral responses at 5% damping for the return period of 72 yrs in Van. (**d**) Comparison of October 23, 2011 Muradiye Station N–S and E–W components, TEC 2007 Ground Type Z3 and present study. (**e**) Comparison of November 9, 2011 Muradiye Station N–S and E–W components, TEC 2007 Ground Type Z3 and present study.

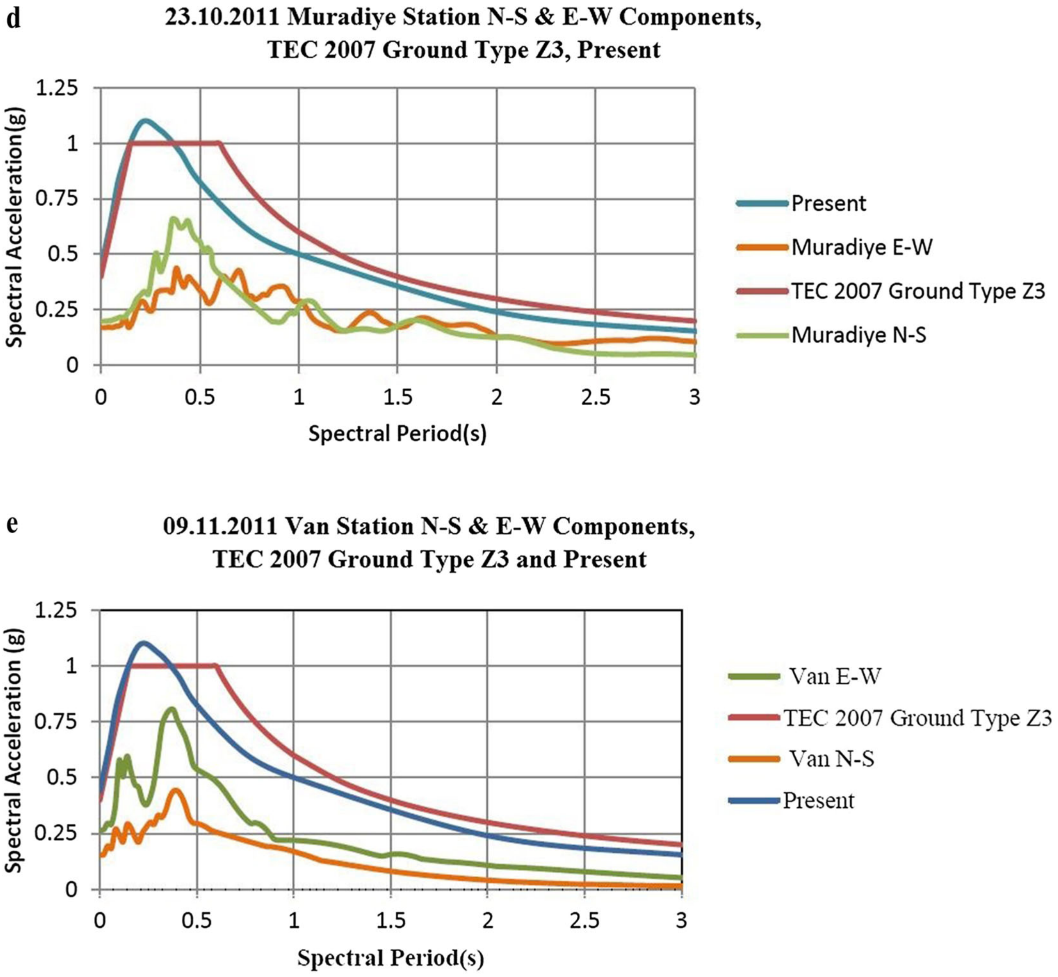

Figure 11. (*Continued.*)

October 23, 2011 in Van, N–S and E–W component taken from Van station after the earthquake which occurred on November 9, 2011 in Van and the spectral responses proposed for seismic evaluation and retrofit of building structure in Turkey Earthquake Code (2007), section 7.

The obtained results are compared with N–S and E–W component taken from Muradiye station after the earthquake which occurred on October 23, 2011 in Van, N–S and E–W component taken from Van station after the earthquake which occurred on November 9, 2011 in Van and the spectral responses proposed for seismic evaluation and retrofit of building structure in Turkey Earthquake Code (2007), section 7 (figure 11).

5. Determination of ground motion records for Van

Abrahamson (1992) and Hancock *et al.* (2006) made records of ground motions in the province of Van in SeismoMatch software program, which allows matching a specific response spectrum with an earthquake acceleration record by using ripples algorithm. The SeismoMatch software program gives users opportunity to simulate series accelerations with a target spectrum at the same time. Thus, ground motion records of earthquakes occurred on the territory, are matched with response spectrum that is created by compiling geological data and records of instrumental period of a region. Ground motion records, which will be used in the performance analysis of the existing structures in the province of Van, was formed by matching of E–W and N–S components of Van earthquakes (October 23, 2011 and November 9, 2011) with acceleration response spectrum that was obtained as a result of seismic risk analysis through the SeismoMatch v1.3.0 software program.

The acceleration response spectrum that was computed as a result of probabilistic seismic risk analysis for the province of Van with the help of the software program, SeismoMatch, was shown

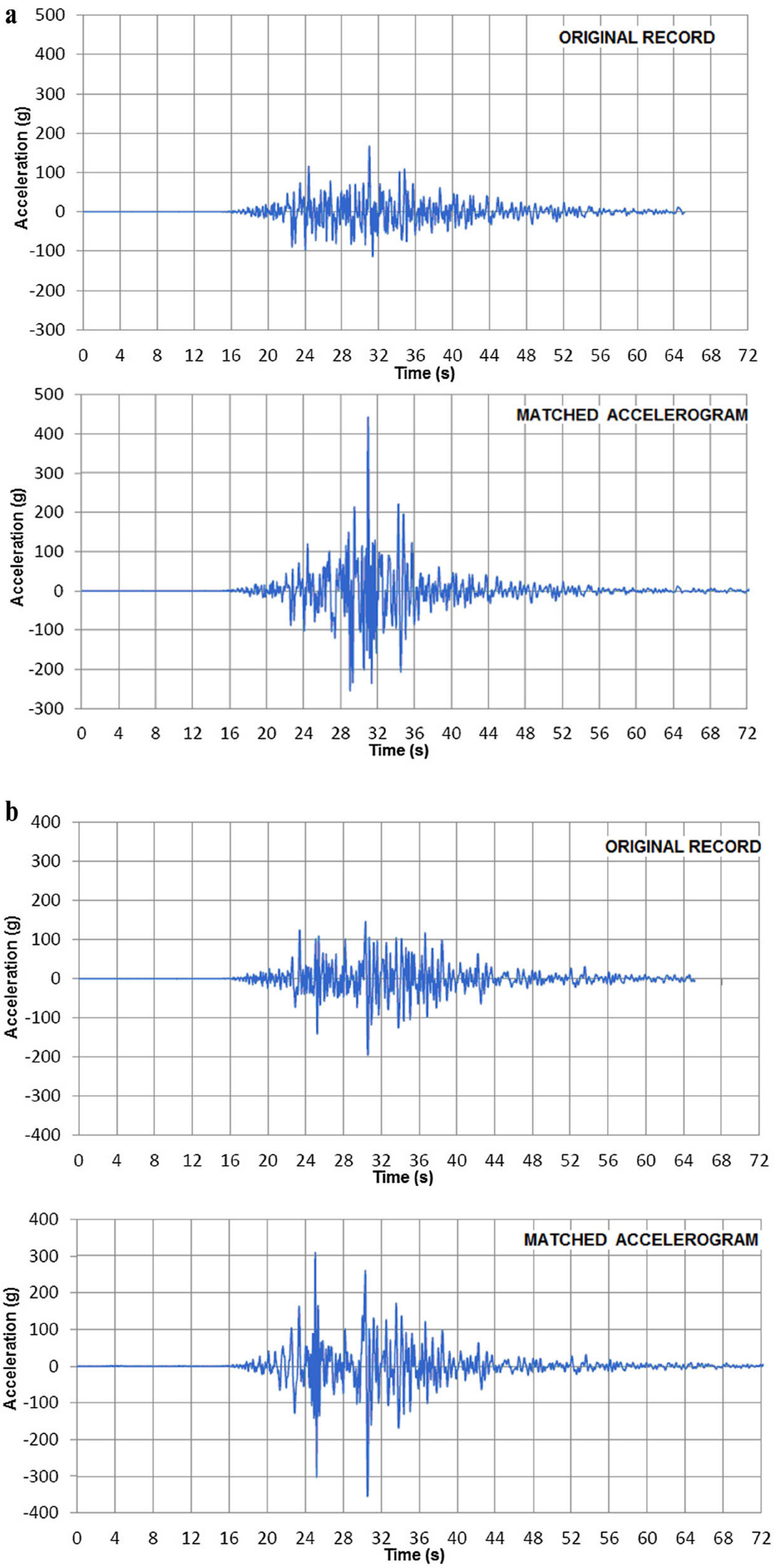

Figure 12. (**a**) The comparison of ground motion records that was obtained by using the SeismoMatch software program with E–W component that was received from Van Muradiye Station of October 23, 2011 earthquake in Van. (**b**) The comparison of ground motion records that was obtained by using the SeismoMatch software program with N–S component that was received from Van Muradiye Station of October 23, 2011 earthquake in Van.

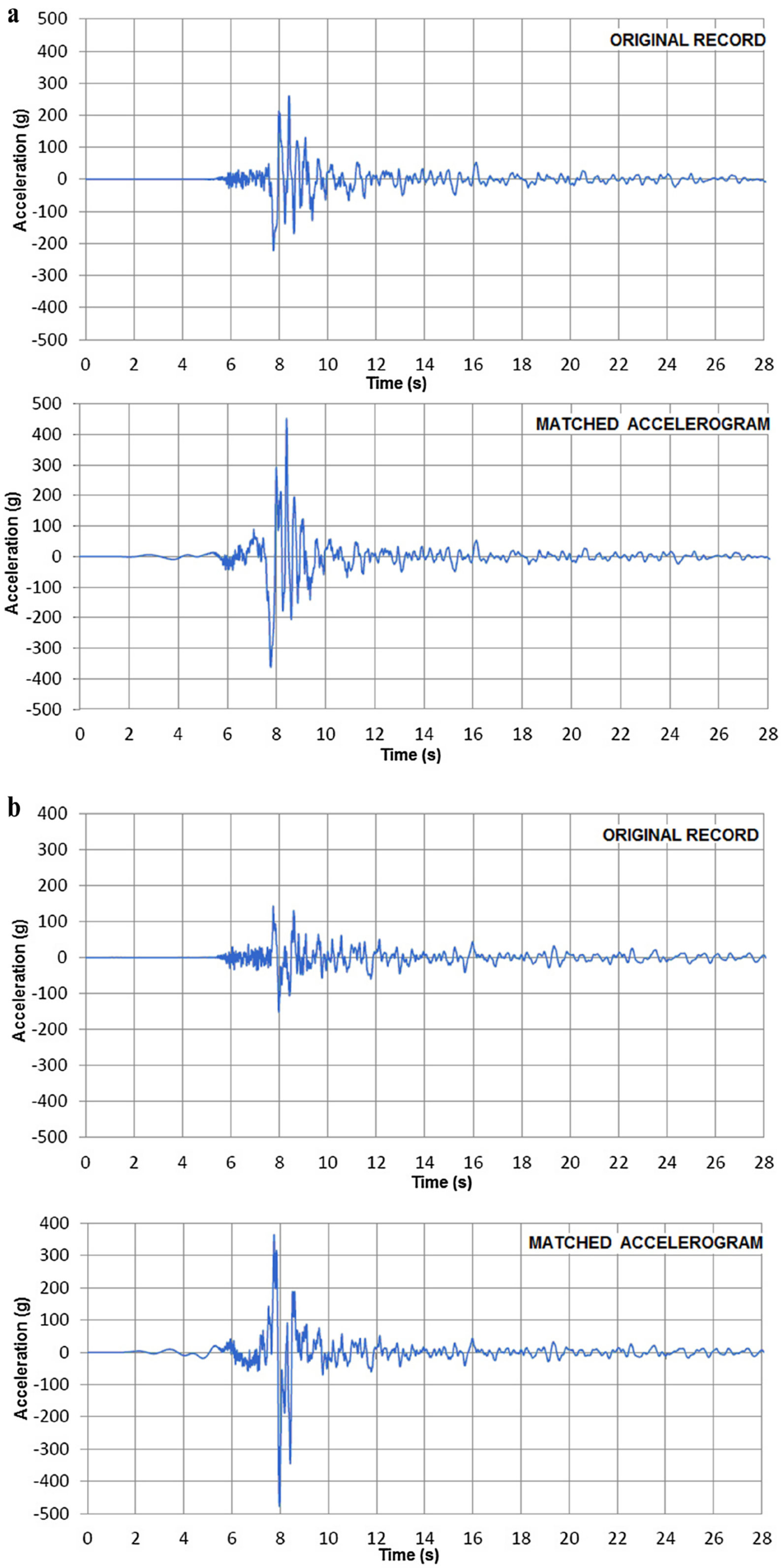

Figure 13. (**a**) The comparison of ground motion records that was obtained by using the SeismoMatch software program with E–W component that was received from Van Central Station of November 9, 2011 earthquake in Van. (**b**) The comparison of ground motion records that was obtained by using the SeismoMatch software program with N–S component that was received from Van Central Station of November 9, 2011 earthquake in Van.

as generalized ground accelerograms that were created by matching the E–W component (figure 12a) and N–S component (figure 12b) for the October 23, 2011 earthquake in Van, with E–W component (figure 13a) and N–S component (figure 13b), for the November 9, 2011 earthquake in Van (data received from Van Muradiye Station).

6. Results and conclusions

By utilizing available data and the use of improved methods, a probabilistic seismic hazard of Van province in Turkey was determined. As a first step of the performance based earthquake engineering, it is well understood that the Code proposed spectra are not sufficient to represent earthquake demand in the performance evaluation. The results of this work will form the basis for the replacement of the existing earthquake design spectra in evaluation of earthquake performances of the existing buildings in Van province. In this study, since active faults are not identified clearly, regional areas were used as an earthquake source zones. Future work will increase the resolution of the seismotectonic model by adding specific active faults. The obtained results are compared with the spectral responses proposed for seismic evaluation and retrofit of building structure in Turkish Earthquake Code (2007), section 7. Using the response spectrum obtained from probabilistic seismic hazard analysis will make obtained data for Van and other regions which are under a threat of earthquakes.

The spectral responses obtained from probabilistic seismic hazard analysis was compared with E–W and N–S components of Van earthquakes (October 23, 2011 and November 9, 2011) and Turkish Earthquake Code (2007) spectral curves. Then by using spectral matching methodology, the relevant time histories were calculated in order to use in the performance evaluation of existing structures.

It was considered that the spectral curves calculated from updated local earthquake sources in probabilistic manner are more realistic than code proposed spectral curves. Therefore, in spectral matching methodology, spectral responses obtained from probabilistic seismic hazard analysis was selected as a target spectrum and for the source accelerogram, October 23, 2011 earthquake Van Muradiye Station records and November 9, 2011 earthquake Van Central Station records were used. The results of this study will form the basis for the replacement of the existing earthquake design spectra in evaluation of earthquake performances of the existing buildings in Van province.

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