Determination of Regional Seismic Design Parameters following the 2011 M7.2 Van Earthquake

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ABSTRACT

Van is a major Eastern Anatolian city, located on the east of the eponymous lake basin, and surrounded by the Van, East Anatolian and Bitlis Fault zones. In 2011, this urban area was hit severely by an **M**7.2 earthquake and a swarm of aftershocks due to the Van Fault zone. This east-west direction extended thrust fault zone, passing 20 km north of the city's center, is approximately 40 km in length. The main shock and aftershocks resulted in the collapse of many non-ductile buildings leaving a death toll of 600 in Van and its surroundings. This region falls in second-degree hazard zone (in a scale of first thru fifth, the first-degree hazard zone has the highest seismic hazard) according to the national seismic hazard map (Gülkan et al., 1993). This study re-examines the seismic hazard of the region using a probabilistic approach based on an updated regional earthquake catalog including events from 1901 to 2011 that occurred within 200 km of the city. To quantify the regional exposure on a set of hazard maps with return periods of 475 and 2,475 years (respectively, 2% and 10% probability of exceedance within 50 years), a total of four local and global ground motion prediction equations were used in a combinatorial approach to account for epistemic uncertainty. The resultant high-resolution (0.002° by 0.002°) hazard maps provide peak horizontal ground acceleration (PGA) and spectral acceleration values at 0.2, 1, and 2 seconds, appropriate to obtain smooth design spectrum. A procedure to obtain a smooth design spectrum from a uniform hazard spectrum is given in the FEMA-356 guidelines (ASCE 2000). The maximum PGA values computed on engineering rock for 475 and 2,475 years return periods are 0.44 g and 0.76 g, respectively at the city center. The hazard results of this study can be used directly as design ground motion level for evaluating existing infrastructure and design of new buildings and other structural systems in Van and its surroundings.

1. INTRODUCTION

On October 23, 2011 moment magnitude (M) 7.2 earthquake occurred in Van province (Fig. 1). It occurred at a shallow focal depth of 7.2 km (4.5 mi) causing heavy shaking across much of eastern Turkey and lighter tremors across neighboring parts of the South Caucasus and Levant. According to Disasters and Emergency Situations Directorate of Turkey (AFAD), the earthquake killed 604 and injured are 4,152. At least 11,232 buildings sustained damage in the region, 6,017 of which were found to be uninhabitable.

Seismic activity of province of Van and its surroundings is under the influence of South Anatolian Fault and Van and Bitlis-Zagros Fault Zones. This region is within the second-degree earthquake zone according to the national seismic hazard map (in a scale of first thru fifth, the first-degree hazard zone has the highest seismic hazard) (Gülkan et al., 1993). In the light of these recent events, and considering regional tectonics and historical earthquakes, this study aims to re-define the parameters necessary for engineering calculations for earthquake-resistant design of buildings and structural systems in Van and its surroundings. For this objective, the information complied on active faults and past earthquakes is examined within stochastic formulations to determine and render the seismic hazard of the region on series of maps. At the end, a set of bedrock design spectra is presented for Van City Center.

2. TECTONIC SETTINGS

The easternmost part of Turkey lies within the complex zone of continuing continental collision between the Arabian Plate and the Eurasian Plate. The overall shortening that affects this area is accommodate partly by thrusting along the Bitlis-Zagros fold and thrust belt and partly by a mixture of sinistral strike-slip on SW-NE trending faults and dextral strike-slip on NW-SE trending faults (Bayrak et al., 2009). The epicenter of the October 23, 2011 event is in this compressional belt, located north of Van, is just east of Lake Van (Fig. 1). According to the USGS, the earthquake's focal mechanism indicates oblique thrust faulting, consistent with the expected tectonics in the region of the Bitlis-Zagros Fault Zone and Van Fault Zone, where thrust mechanisms dominate (Selcuk et al., 2010; Emre et al., 2012). The size of the rupture has been estimated as 60 km x 20 km, consistent with the observed distribution of aftershocks, on a WSW-ENE orientated fault plane with a dip of about 35°. An offset of about 2 m (6 ft 7 in) has been estimated at 10–15 km (9.3 mi) depth, but there is no visible rupture of the ground surface. The rupture lasted for about 50 seconds (Akansel et al., 2013).

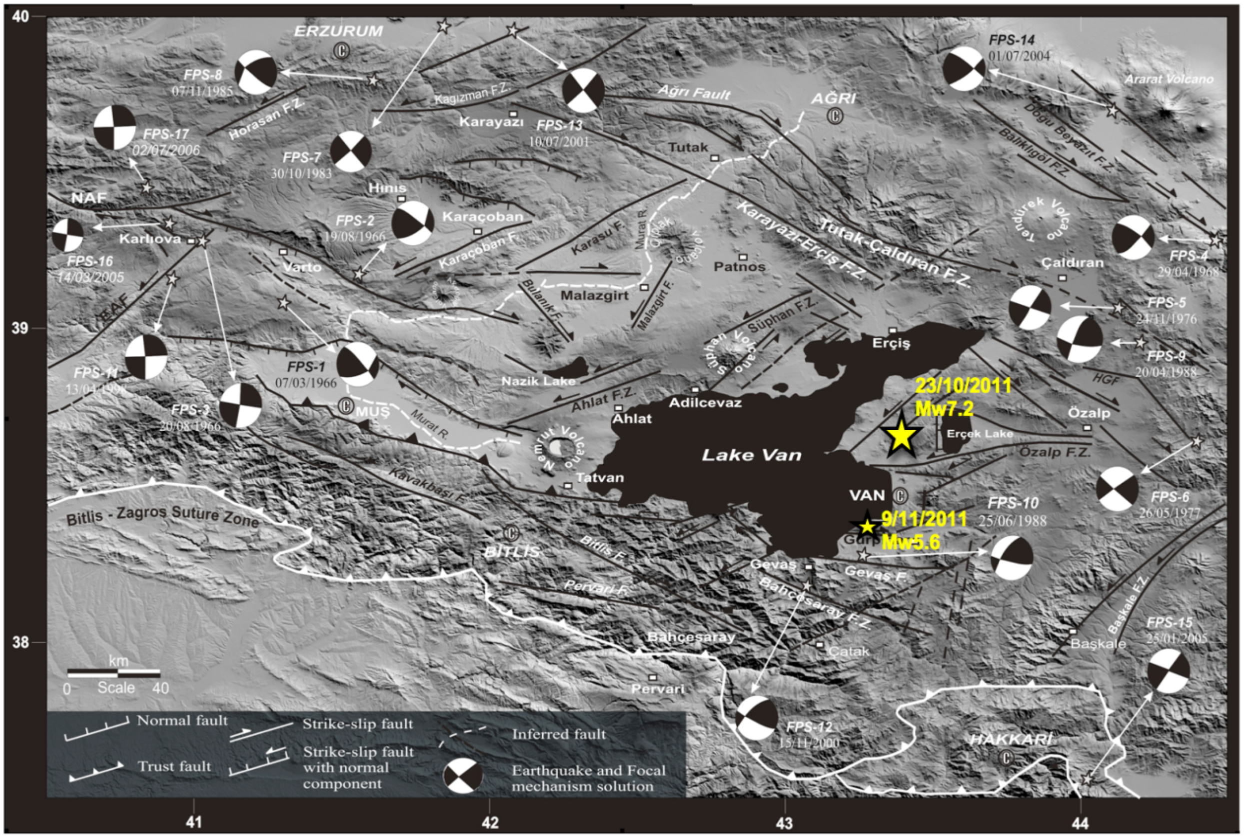

Figure 1. Active faults around Van and its surroundings; 2011 **M**7.2 main shock and **M**5.6 aftershock are marked with star sign (map is modified from Selcuk et al., 2010).

The strongest aftershock (**M**5.6) at a shallow depth of 4.8 km (3.0 mi) occurred on November 9, 2011 about three weeks after in Edremit district of Van province and resulted in further structural damages to those structures that had been already lost strength and stiffness as a result of strong shaking due to the main shock.

This region has been exposed to many devastating earthquakes in the past. Ambraseys and Jackson, (1998) reports an event with Ms > 7.0 that occurred in 1646 around Van province. Most recent damaging event in and around Van was the 1976 Ms 7.3 Çaldıran-Muradiye earthquake, which took about 3,000 lives.

3. PROBABILISTIC SEISMIC HAZARD ASSESSMENT

Based on our current state of knowledge about seismicity and tectonic environment of Van province and its surrounding area, regional probabilistic seismic hazard analysis is performed using smoothed-gridded seismicity model. This model assumes that historical large earthquakes have in general taken place in locations where epicenters of smaller earthquakes have accumulated (Frankel, 1995; Kafka and Walcott, 1998; Kafka, 2002), and based on the earthquake catalog and characterizes the hazard from earthquakes between **M**4.5 – 7.2. As a recurrence forecasting process, we used the Poisson equation (time independent) to estimate the probability of being exceeded over a finite time interval. Use of time-dependent models with confidence is hampered by short-term completeness of the earthquake catalog.

3.1 Earthquake Catalog

The earthquake catalog includes events from instrumental period. The study area is defined as a rectangle, bounded by 41° – 46° latitude and 37° – 40° longitude. This area covers approximately 200 km radius of Van City Center. The magnitude, epicenter coordinates of all events within this region that occurred between 1901 and 2011 with **M** ≥ 4.5 are depicted in Figure 2. Magnitude scales of all events were converted to **M** through a set of empirical equations derived based on Turkish earthquakes. These equations are given in Yücemen and Deniz (2006).

In compiling the catalog of earthquakes, fore- and after-shocks were removed using the de-clustering methodology (Gardner and Knopoff 1974). This simple algorithm requires no tuning parameters, thus the results are easily reproducible. In addition, events before 1901 were excluded due to catalog incompleteness. For the 110-year time period between 1901 and 2011, plotting the cumulative number of events against time tested the catalog completeness. We computed completeness levels of **M**4.5 or greater since 1964 and **M**5.0 or greater since 1901. These are one of the input parameters of probabilistic seismic hazard analysis.

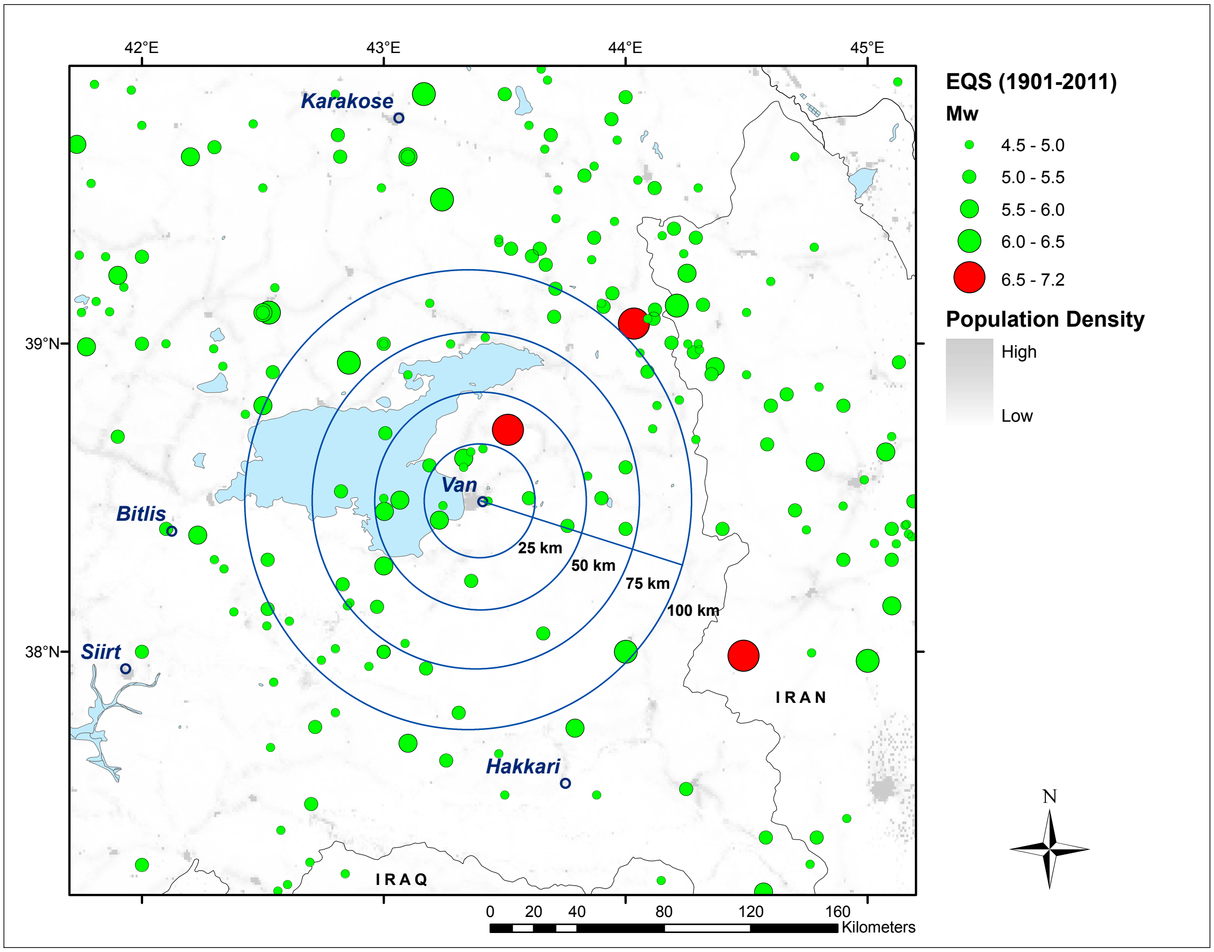

Figure 2. Earthquakes (**M** ≥ 4.5) occurred within instrumental period (1901 to 2011); grey color shows population density based on Landsat data; epicenter locations of **M** ≥ 6.5 earthquakes are shown with red dots.

3.2 Earthquake Recurrence

For the computation of smoothed-gridded seismicity, a catalog having discrete independent earthquakes was associated with the Gutenberg-Richter (G-R) earthquake recurrence relation (Gutenberg and Richter 1949):

$$log(N) = a - b\mathbf{M} \qquad (1)$$

where N is the annual number of earthquakes of magnitude equal to or greater than **M**. 10^a is the mean yearly number of earthquakes of magnitude greater than or equal to a pre-established threshold, and b describes the relative likelihood of large and small earthquakes. As the number of larger magnitude earthquakes decreases compared to those of smaller magnitudes, the *b* value increases.

For the entire region, the *b* value was estimated as 0.8 using maximum likelihood method (Weichert 1980) based on the 110-year catalog. This method accounts for variable completeness. No uncertainty associated with the *b* value was considered. Thereafter, the values for *a* were computed for each sub-domain and spatially smoothed over a grid of 0.05° x 0.05° in latitude and longitude using a two-dimensional Gaussian filters with a decay of 50 km.

3.3 Smoothed Seismicity Model

The contribution of background events to hazard is calculated using the smoothed-gridded seismicity model (Frankel 1995). This model addresses the aleatoric uncertainty in the location of future earthquakes, thus allowing spatially stationary seismicity while eliminating the subjectivity in delineation of areal sources. This seismicity model requires a de-clustered earthquake catalog for computation of Poissonian earthquake recurrence rates. In this model, events that are not assigned to specific faults are assumed to be potential seismogenic sources and are spatially gridded to cells. First we count the number of earthquakes n_i with magnitude greater than M_{ref} in each cell *i* of a grid with spacing of 0.05° in latitude and 0.05° in longitude. This count represents the maximum likelihood estimate of the parameter *a* for that cell (Weichert 1980; Bender 1983) for earthquakes above M_{ref}. The values of n_i are converted from cumulative values (number of events above M_{ref}) to incremental values (number of events from M_{ref} to M_{ref} $+\Delta M$) using the Hermann formula (Hermann 1977). The grid of n_i values is then smoothed spatially by multiplying by a Gaussian function with correlation distance *c*. For each cell *i*, the smoothed value $\tilde{n}_i$ is obtained from (Frankel 1995):

$$\tilde{n}_i = \frac{\sum_j n_j e^{-\Delta_{ij}^2/c^2}}{\sum_j e^{-\Delta_{ij}^2/c^2}} \tag{3}$$

In this equation, $\tilde{n}_i$ is normalized to preserve the total number of events, and Δ_{ij} is the distance between the i^{th} and j^{th} cells. The sum is taken over cells *j* within a distance of 3*c* of cell *i*. The annual probability of exceeding specified ground-motions is calculated for a grid of sites using

$\tilde{n}_i$ from Eq. (3). For each site, the values of $\tilde{n}_i$ are binned by their distance from that site, so that N_k denotes the total of $\tilde{n}_i$ values for cells within a certain distance increment of the site. Now the annual rate $\lambda(u > u_0)$ of exceeding ground-motion u_0 at a specific site is determined from a sum over distance and magnitude (Frankel 1995):

$$\lambda(u > u_0) = \sum_k \sum_l 10^{[\log(N_K/T) - b(M_l - M_{ref})]} P(u > u_0 | D_k, M_l) \qquad (4)$$

where k is the index for the distance bin and l is the index for the magnitude bin; T is the time in years of the earthquake catalog used to determine N_k. The first factor in the summation is the annual rate of earthquakes in the distance bin k and magnitude bin l. $P(u > u_0 | D_k, M_l)$ is the probability that u at the site will exceed u_0, for an earthquake at distance D_k with magnitude M_l (D_k is fixed for each bin). This probability is dependent on the attenuation relation and the standard deviation (variability) of the ground-motion for any specific distance and magnitude. For this model, values are computed from the magnitude 4.5 and larger earthquakes since 1901.

3.4 Ground Motion Prediction Equations

In the post-1999 period, a number of ground-motions were recorded in Turkey. This data was combined with existing national ground-motion library to develop a local GMPE to be used for regional hazard assessments (Gülkan and Kalkan, 2002). This GMPE has the same form as Boore et al., (1997) with different coefficients and updated later considering a larger data set (Kalkan and Gülkan, 2004). In this study, three Next Generation Attenuation (NGA) relations (Campbell and Bozorgnia, 2008; Boore and Atkinson, 2008; Chiou and Youngs, 2008) are also used in addition to the GMPE of Kalkan and Gülkan to compute the ground motions by considering epistemic uncertainty. Figure 4 compares the recorded PGA data from **M**7.2 Van earthquake with the predictions by Kalkan and Gülkan; grey colored area bounds the 16th and 84th percentile predictions. As shown, recorded data (maximum of two horizontal components of recordings) is well predicted within 100 km of fault; beyond that data shows faster attenuation due to regional low Q_0 (Toksoz et al., 2010).

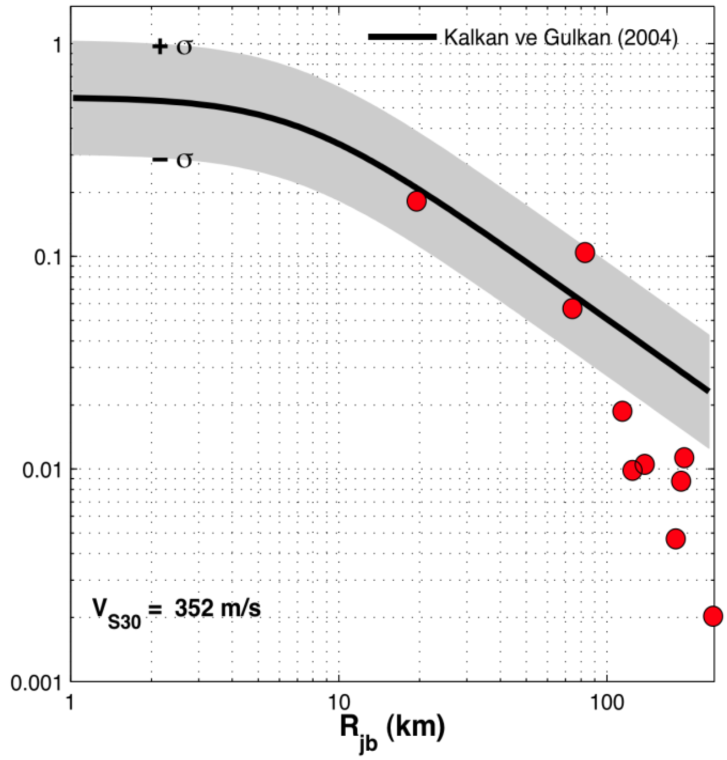

Figure 3. 2011 **M**7.2 Van earthquake peak ground motion data in unit of g, and its comparison with predictions of Kalkan and Gülkan (2004) GMPE (R_{jb} = Joyner-Boore distance measure).

4. RESULTS

The seismic hazard is computed for PGA and spectral acceleration (SA) ordinates at 0.2 s and 1.0 s considering a firm rock site-condition (V_{S30} = 760 m/s). The most recent USGS seismic hazard code is used for the seismic hazard computations (Petersen et al., 2008). The spectral periods at 0.2 s and 1.0 s are selected because they are frequently used to construct smooth design spectrum. Seismic hazard was computed for 2% and 10% probabilities of being exceeded in 50 years corresponding to return periods of 2475 and 475 years, respectively. Table 1 tabulates the values of PGA and SA values at those return periods. Figure 7 plots the three hazard curves, which show the value of expected ground motion with given annual frequency. For Van, national seismic hazard map of Turkey gives a PGA value of 0.39, which is very close to 0.44 g computed for 475 years return period. Figures 4-6 render the mean seismic hazard values mapped for PGA, SA at 0.2 and 1.0 s at 2% probability of exceedance level within 50 years. Also shown in these figures are the locations of earthquakes.

Table 1. Seismic design values computed for Van City Center at different recurrence intervals (PE: probability of exceedance)

DESIGN BASIS ACCELERATION VALUES FOR DIFFERENT RETURN PERIODS

	10% PE in 50 years 475 year	2% PE in 50 years 2475 year
PGA	0.44g	0.76g
SA (0.2s)	0.77g	1.46g
SA (1.0s)	0.24g	0.50g

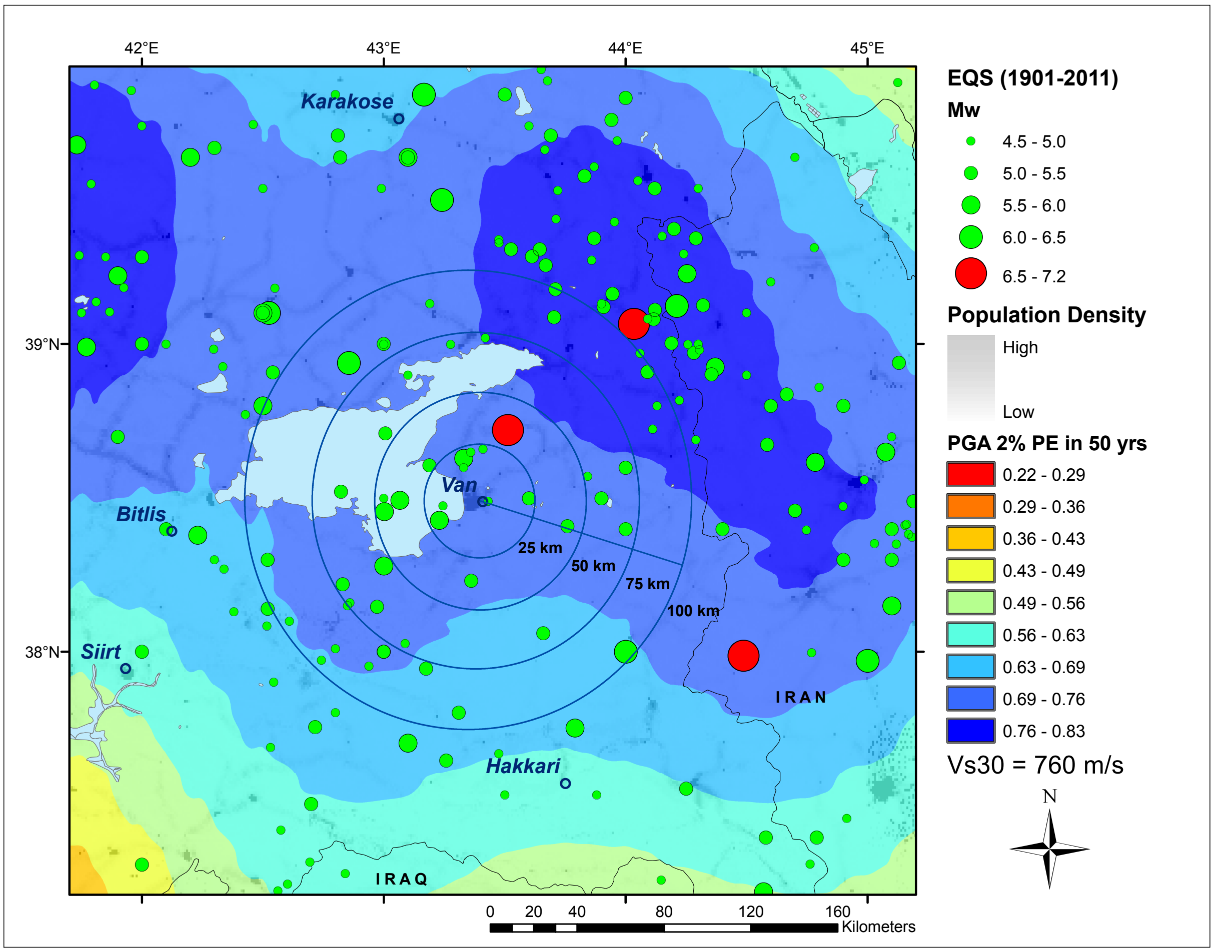

Figure 4. Probabilistic seismic hazard map for PGA computed for 2,475 years return period event.

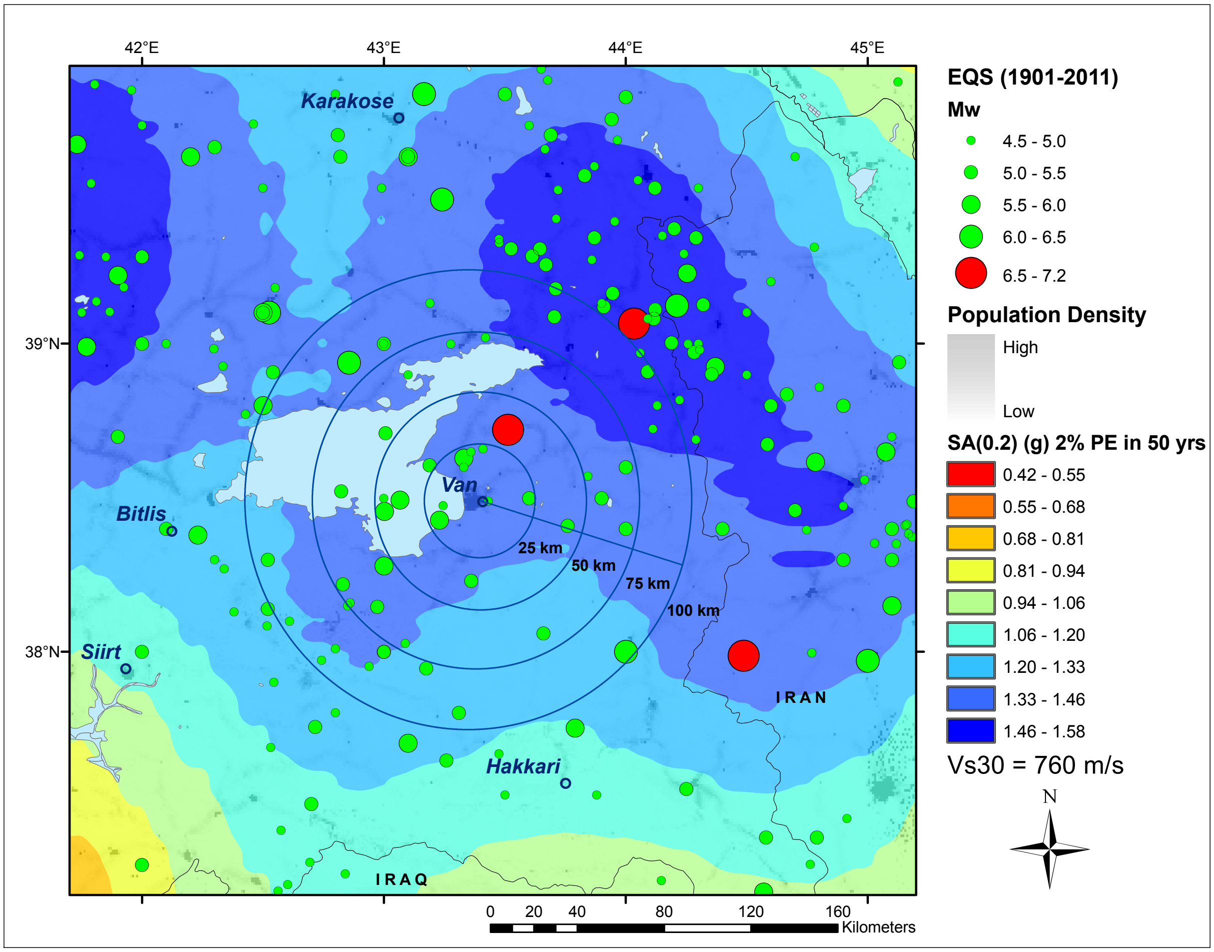

Figure 5. Probabilistic seismic hazard map for SA(0.2 s) computed for 2,475 years return period event.

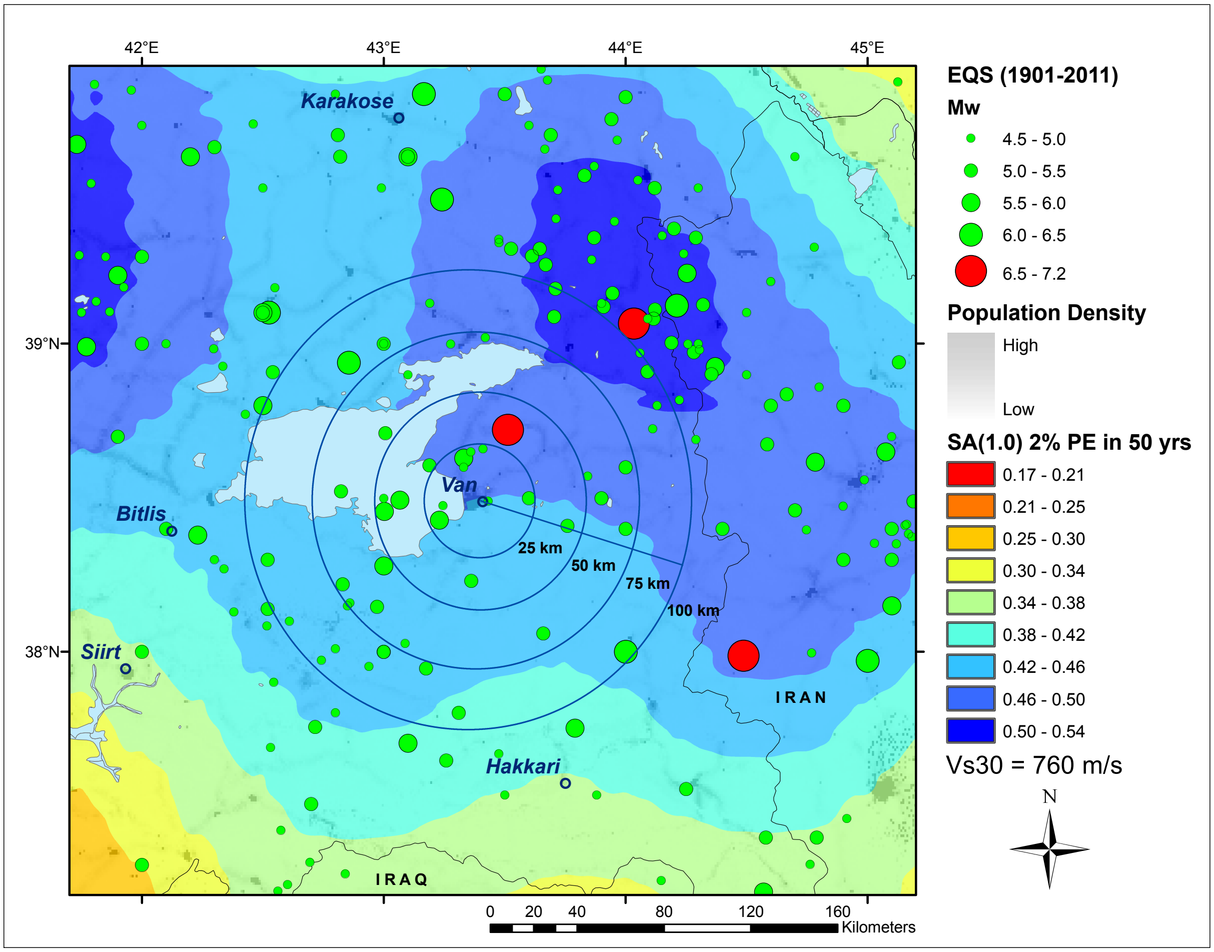

Figure 6. Probabilistic seismic hazard map for SA(1.0 s) computed for 2,475 years return period event.

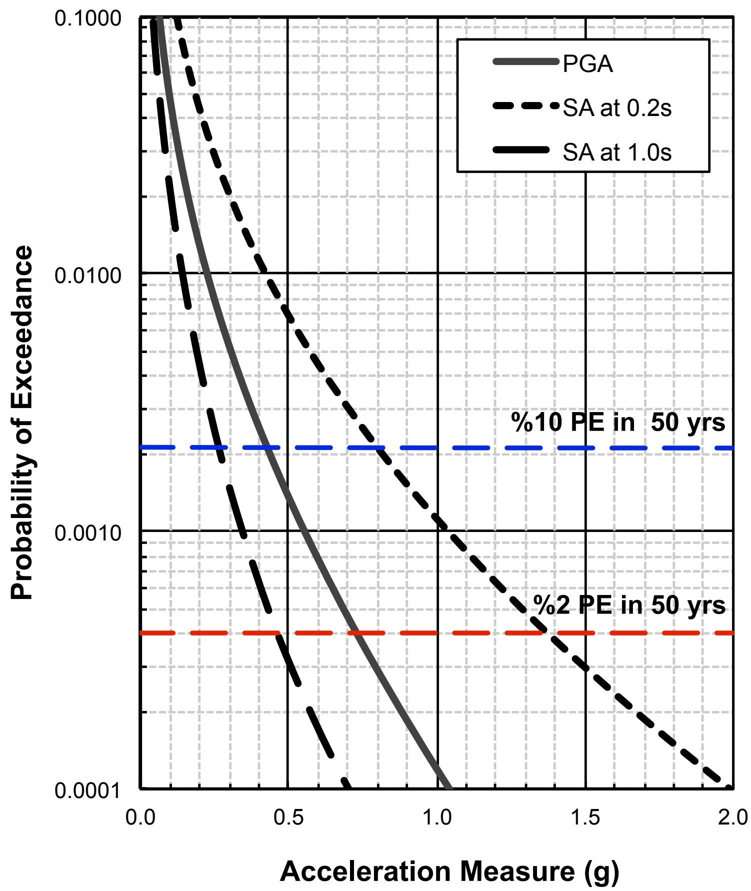

Figure 7. Hazard curves for PGA, SA at 0.2 and 1.0 s (dashed blue line is for 475, and dashed red line is for 2,475 years return period event; PE: probability of exceedance).

5. SUMMARY

In this study, stochastic methods are used to determine the earthquake hazard in Van province and its surrounding area. The seismic hazard is computed considering tectonic settings of the study area and the historical earthquake catalog free from dependent events. Different assumptions and uncertainties in the parameters are assessed within the logic tree. The global GMPEs selected are those of Boore and Atkinson (2008), Chiou and Youngs (2008) and Campbell and Bozorgnia (2008), which are also based on earthquakes recorded in Turkey. In addition, a domestic predictive model by Kalkan and Gülkan (2004) is also used. Within the logic-tree, relative weight of the domestic GMPE is set to 0.5, and the remaining weight of 0.5 is equally distributed (0.5 / 3 = 0.167) among other three imported GMPEs. Without considering the local geological conditions, the seismic hazard is computed considering engineering rock

(V_{S30} = 760 m/s) conditions. The largest peak ground acceleration is computed as 0.76 g at 2% probability of exceedance level within 50 years, corresponding to 2,475 years return period. The maximum PGA values computed on engineering rock for 475 years return period is 0.44 g at Van City Center.

For practical applications, design spectra are presented as smooth curves or straight lines. Smoothing is justified because of the difficulties in determining the exact frequencies and mode shapes of structures during severe earthquakes when the behavior is most likely nonlinear. In this study, three different bedrock spectra are presented in Figure 8 for Van City Center. These are MCE (Maximum Credible Earthquake) spectrum considering 2,475 years return period event, 2/3xMCE spectrum, typically used for design, and a spectrum corresponding to the 475 years return period event, also known as a Design Basis Earthquake (DBE). These spectra are derived by using the results tabulated in Table 1 and following the procedure prescribed in FEMA-356 (ASCE 2000).

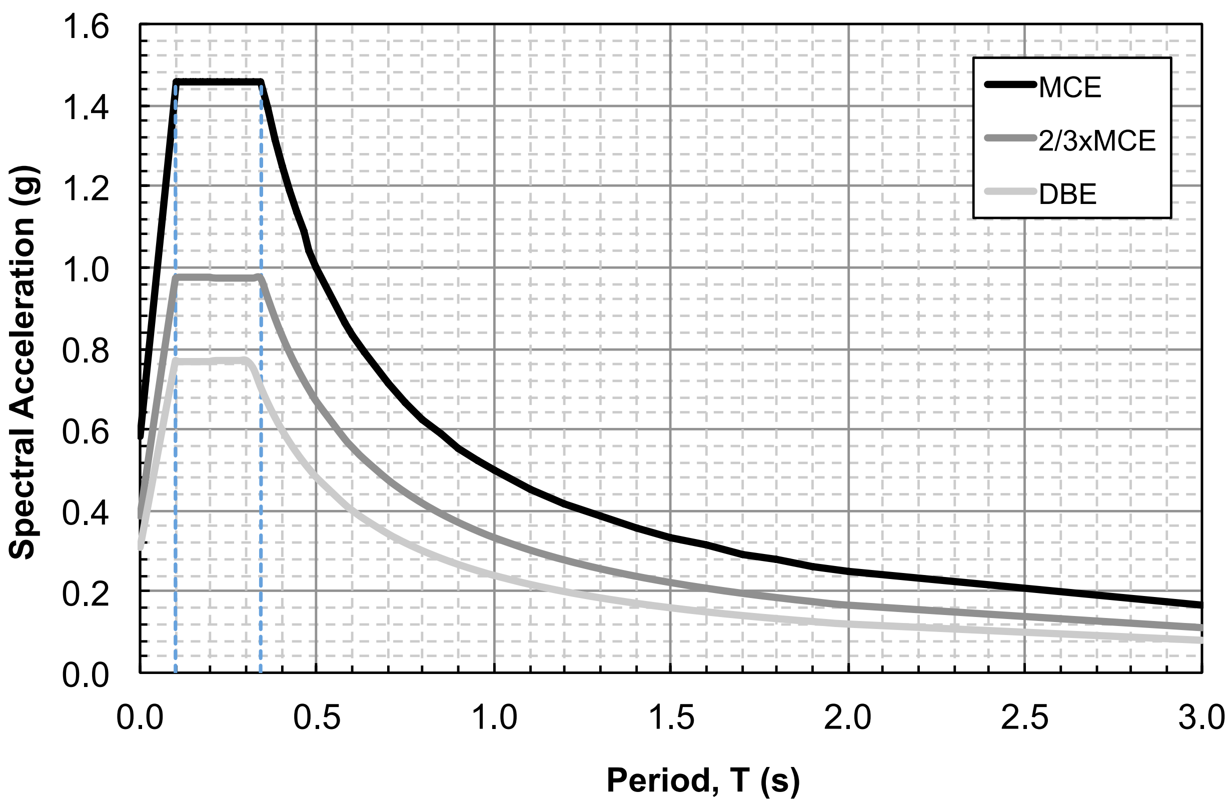

Figure 8. Bedrock smooth design spectra for 2,475 (MCE), 2/3xMCE and DBE for Van City Center.

The results presented herein can be used directly as design ground motion level for evaluating existing infrastructure and design of new buildings and other structural systems in Van and its surroundings. For sites underlined by soft geological conditions, the acceleration values given here should be modified.

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