Probabilistic Seismic Hazard Assessment for Izmir, Turkey

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Abstract—Izmir, the third largest city and one of the major economic centers in Turkey, has more than three million residents and one-half million buildings. The city, located in a seismically active region in western Anatolia, was a subject of the 1997 RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disaster) project. In this paper, the seismic hazard of Izmir is investigated through probabilistic seismic hazard assessment. First, the seismic setting of Izmir is presented. Considering the statistics of earthquakes that took place in the region during the period 1900–2005, a simple seismic hazard model is used to facilitate the assessment. To account for modeling uncertainties associated with the values of seismicity parameters, a logic tree procedure is employed in carrying out the seismic hazard computations. The resulting weighted average seismic hazard, presented in terms of peak ground acceleration and associated probability of exceedence, could be considered the "best estimate" of seismic hazard for Izmir. Accordingly, for a return period of 475 years, for rock sites, a PGA value of 0.34 g is calculated. This PGA hazard estimate is close to the current code-recommended design acceleration level for Izmir.

Key words: Seismic hazard assessment, seismic hazard analysis, earthquake, Izmir.

1. Introduction

Heavy destruction caused by recent earthquakes in Turkey has increased interest in seismic hazard and risk assessment of urban areas in Turkey (Schneider and Schauer, 2005). Various researchers have reported that the seismic risk exposure of Izmir is very high (Emre *et al*., 2005; Ilhan *et al*., 2004; RADIUS, 1997; Korkmaz *et al*., 2009). Following the RADIUS investigation in 1997, an earthquake master plan for Izmir was published by the Metropolitan Municipality of Izmir (MMI, 2000). Recent studies (Erdik *et al*., 2004; Korkmaz *et al*., 2009) indicate that this third largest city in Turkey, with its rapidly increasing population and built environment, is facing very high seismic risk.

The pioneering study on seismic hazard estimation was carried out by Cornell (1968). While Cornell's work still describes the procedure adequately, Gupta (2002) provides the current state-of-the-art format of seismic hazard analysis in detail.

The current earthquake zoning map of Turkey is based on the study of Gulkan *et al*. (1993). Later, Erdik *et al*. (1999) and Bommer *et al*. (2002) contributed, in particular to the seismic zoning part of the analysis, and Gulkan and Kalkan (2002) developed a domestic earthquake attenuation model consisting of a set of equations based on the records of the 1999 Marmara and Duzce earthquakes. None of these studies specifically focus on the seismic hazard or seismic loss in the Izmir metropolitan area, but obviously results of some of the latter studies are utilized as tools in our study, too.

In what follows, the seismic hazard of Izmir is investigated by presenting the seismic setting, considering the statistics of earthquakes that have taken place in the region and employing a logic tree procedure to account for modeling uncertainties associated with the values of seismicity parameters in our study.

The current study contributes to previous studies by providing extensive information on the seismicity and seismic hazard in Izmir and its surrounding region. First, all of the historic and instrumented era earthquake event records currently available in the international databases were taken into consideration. The earthquakes were usually reported by different sources using different magnitude scales. This problem was resolved through cross-checking the

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earthquake records and by running a series of statistical analyses to determine which level of magnitude on a selected scale corresponds to which level of magnitude on a target scale. Through this process, an earthquake database with a single consistent magnitude was obtained. Then the seismic source zones affecting the region were established based on spatial clustering of earthquake epicenters. Due to the complexity and interlacing of the fault zones in the region, almost none of the seismic sources could be defined exactly in the form of well-defined, distinct fault lines (DENIZ, 2006). Furthermore, due to shallow dip angles of most of the fault zones, earthquake epicenters associated with a given fault zone varied in the latitude-longitude coordinate system for different focal depths. Due to these complications, it was not possible to find the perfect fault match as a line for each earthquake in the database. For these reasons, in this study, the seismic sources are defined as areas instead of well-defined lines or narrow regions. In the literature, there are open-source seismic hazard analysis codes (such as Seisrisk III by BENDER and PERKINS, 1987) which can be modified to take into consideration the seismic source zone boundary uncertainty. Such an approach could be used for the determination of the variation of seismic hazard near the boundary of two neighboring source zones. This method is shown to result in smooth changes in the seismic hazard, especially near seismic zone boundary regions (YUCEMEN and GULKAN, 1994).

2. Seismic Setting

Izmir is located in a very active seismic region in western Anatolia. Earthquakes in the Aegean Graben System and the Aegean Trench (AKINCI et al., 2000) dominate the seismicity of the region. Both historic and instrumental records indicate that large earthquakes occur frequently in the Izmir region. Figure 1 (EMRE et al., 2005) shows the locations of the major earthquakes that occurred in the region between 1900 and 2005. In 1944 a magnitude $M_S = 6.8$ earthquake occurred near the Gulf of Edremit, 125 km north of Izmir. One of the most severe earthquakes in the region happened in 1953 and had a magnitude of $M_S = 7.2$ and epicentral distance of 170 km (N). In

1974, during an earthquake of magnitude $M_S = 5.2$ at an epicentral distance of approximately 10 km (NNE), 47 apartment buildings were damaged and two people died in Izmir city center. In 1992, an earthquake with magnitude of $M_S = 6.0$ and epicentral distance of approximately 50 km (SSW) caused damage to 100 buildings (ILHAN et al., 2004; RADIUS, 1997). In 2003, an $M_w = 5.8$ earthquake occurred 50 km southwest of Izmir but caused no damage in the city. Most recently, in 2005, a sequence of three earthquakes with $M_S = 5.5$, 5.9, and 5.9 occurred in the same region as the 2003 event and, likewise, caused no damage.

3. Seismic Hazard Model

Probabilistic seismic hazard evaluation is related to occurrence frequency of earthquakes at different magnitudes. In the following, the Poisson occurrence model for the seismic hazard environment (GUTENBERG and RICHTER, 1956; CORNELL, 1968; FREUND, 1992; NAEIM and KELLY, 1999) is explained. Using the Poisson model, occurrence probabilities for different magnitude earthquakes and over different time periods can be found.

3.1. Poisson Model

The magnitude–frequency relationship suggested by GUTENBERG and RICHTER (1956) is

$$\text{Log}(N) = a - b \cdot M \qquad (1)$$

where, N: cumulative number of earthquakes with magnitude M or greater; a: a parameter representing the seismic activity of the source region; b: a parameter associated with the distribution of earthquake magnitudes in the region. Frequency density function of the earthquake magnitudes can be obtained from Eq. 1, parameters of which can be calculated as follows:

$$\beta = b \cdot \ln 10 \qquad (2)$$

$$k = \left[1 - e^{-(M_{max} - M_{min})} \right]^{-1} \qquad (3)$$

The exceedence probability for magnitude M_1, i.e., probability of occurrence of at least one earthquake
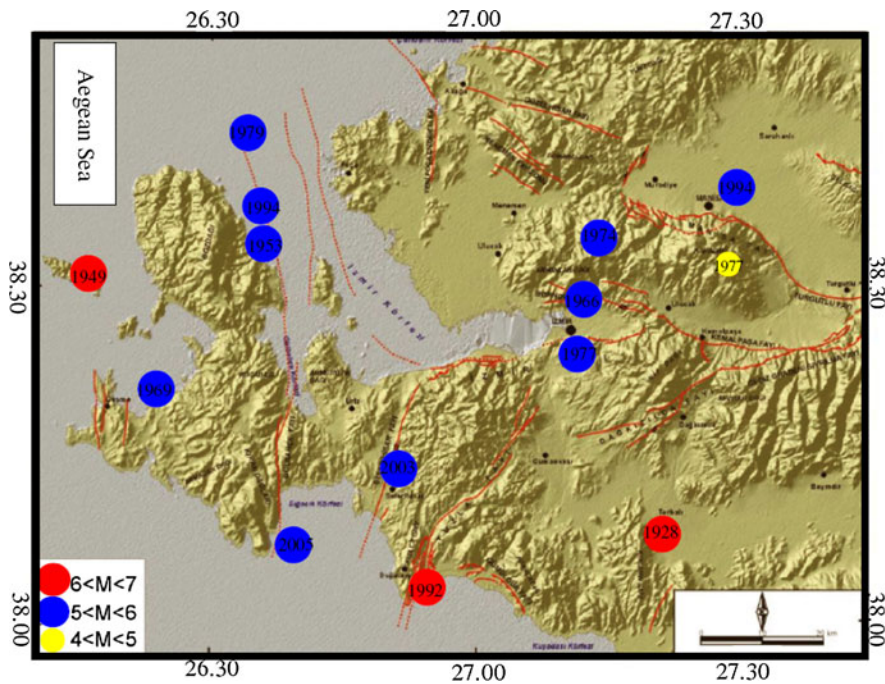
Figure 1
Izmir map with significant earthquakes between 1900 and 2005 (modified from EMRE *et al.*, 2005)

with magnitude M_1 or higher, in t years can be calculated as:

$$P_f(M \geq M_1) = 1 - e^{-n(M \geq M_t)t} \qquad (4)$$

where $n(M \geq M_1)$ is the annual number of earthquakes with magnitude M_1 or greater.

4. Probabilistic Seismic Hazard Analysis

As the time of occurrence, magnitude, and location of future earthquakes are not known with certainty, seismic hazard analyses must be performed in a probabilistic manner. The key steps of probability-based seismic hazard analysis are the delineation of seismic sources (to the extent possible), assessment of the earthquake occurrence characteristics for each seismic source, selection of appropriate ground motion prediction model(s) including attenuation and local site effects and identification of the site characteristics.

Different sources of uncertainties exist in seismic hazard representation models. For one, at the current level of understanding of earthquake initiation, it is not possible to predict earthquake occurrence with certainty. Similarly, attenuation expressions are limited in their prediction capabilities. However, using long-term observations and large data sets, statistical models could be used to estimate the event occurrences and ground motion attenuations. Then, there are biases associated with data interpretation differences and model selection.

Many researchers working in probabilistic modeling of seismic hazard separate the sources of uncertainties into two groups, namely the so-called aleatory and the epistemic. While this uncertainty representation decision is not a requirement, it is used in this study to keep the approach compatible with various widely available research efforts. However, a logic tree approach is taken at the end of the process to introduce expert judgment, which is based on quality and relevance of respective databases and attenuation relationships, via giving importance weights into the final decision. The result is presented as a "best estimate" and depends on the weights used in the logic tree.

5. The Earthquake Database

Earthquake catalogs are the most important sources of information in forming the seismic database to be used in seismic hazard analyses. However, the information presented in the catalogs cannot be used directly and has to be processed. Generally, earthquake magnitudes are reported in different magnitude scales and it is desirable to form a unified catalog by converting the different magnitude scales into a single one. The implementation of the Poisson model requires the elimination of the spatial and temporal dependencies created by fore and aftershocks. Another problem is the fact that earthquake catalogs are often biased, due to less than complete reporting of small magnitude earthquakes as compared to larger magnitude earthquakes. In performing the seismic hazard analysis for Izmir, these problems are handled as follows:

A comprehensive seismic data base is compiled which contains the earthquakes that have occurred within 250 km of the city center (coordinates 27.15°E longitude and 38.40°N latitude) in the last century. It is assumed that the seismic hazard for the Izmir region is due to the seismic activity occurring in a rectangular region bounded between 24.15°–30.15°E longitudes and 36.15°–40.65°N latitudes. In preparing this seismic database, four different sources of seismicity data were utilized. These were the catalogs provided by the Earthquake Research Department of General Directorate of Disaster Affairs of Turkey (GDDA-ERD), Kandilli Observatory and Earthquake Research Institute of the Bogazici University (KOERI), International Seismological Centre (ISC) and the United States Geological Survey (USGS). The data in these catalogs were provided in different magnitude scales and it was necessary that they be converted to a single scale. Magnitude values reported in the seismic database are converted to their equivalent moment magnitude values. The moment magnitude (M_w) scale was selected since, in recent years, this scale has become the most preferred one. The minimum value of M_w is set to 4.5 and earthquake magnitudes reported in different scales, namely, surface wave magnitude (M_S), local magnitude (M_L), body wave magnitude (M_b), and duration magnitude (M_d) are converted to M_w by using the empirical equations developed by DENIZ (2006). These equations were obtained by applying the orthogonal regression procedure to earthquakes that occurred in Turkey during the last 100 years. In the corresponding procedure, the error in both regression variables was taken into consideration. In the standard least squares regression methodology, on the other hand, only the error in the response variable is considered and large magnitude earthquakes are usually underestimated. In the same study, for the saturation problem of some earthquake magnitudes (for instance, M_S) detailed analyses were carried out. Besides, the distributions of earthquakes due to different earthquake catalogs within the same earthquake scale and among different magnitude scales were investigated (DENIZ and YUCEMEN, 2010). As a result, we found that the surface wave magnitude results of KOERI were overestimating the earthquake magnitude with respect to the other data sources. To overcome this problem, the so called intra-scale conversion relationships were developed and the earthquake catalog was homogenized before converting all the magnitudes into moment magnitude (DENIZ and YUCEMEN, 2010).

In order to satisfy the assumptions of the Poisson process, it is necessary that earthquake clusters should be identified and dependent events (fore and after shocks) be eliminated from the earthquake data set. This is achieved by using the space and time windows, also specified by DENIZ (2006), which were obtained based on an extensive literature survey. The corresponding space and time windows are magnitude-dependent and get larger as the assumed main shock magnitude increases. In this approach, DENIZ (2006) stated that if an earthquake of magnitude m occurring after a larger magnitude earthquake remains within the space–time windows corresponding to the larger magnitude earthquake, the earthquake with magnitude m is accepted to be an aftershock. For foreshock identification, a similar approach is utilized as follows: If the event of magnitude m precedes a larger earthquake within a space and time vicinity given for m, this event is accepted to be the foreshock of the larger earthquake. Thus, for both different magnitude levels and for the fore and aftershock activity at a selected main shock

magnitude level, different space and time windows are utilized.

Incompleteness in the earthquake catalogs is also taken into account. For this purpose, an analysis of catalog completeness is performed and artificially completed rates (i.e. complete number of events over a particular time period) are obtained based on the method proposed by STEPP (1973).

6. Delineation of the Seismic Source Zones

As the delineation of seismic source zones depends highly on the judgment of experts, the number and layout of seismic source zones might change between different studies (for example, GULKAN et al., 1993; BOMMER et al., 2002). In this study, the configuration given by BOMMER et al. (2002) is adopted with some local modifications to take into account recent findings related to the boundaries of known active tectonic regions, as well as identification of new active tectonic regions (KOCYIGIT, 2005). The resulting seismic source zones, are tabulated in Table 1. In the same table, the expected maximum earthquake magnitudes are also given. The expected maximum earthquake magnitudes were determined based on the statistics of past earthquakes, empirical estimation of earthquake magnitude using the fault length (WELLS and COPPERSMITH, 1994) and subjective expert opinion (KOCYIGIT, 2005).

For earthquakes that cannot be related to any of the 10 seismogenic provinces, background seismicity regions are defined. There exist background seismicity regions both inside and outside of the main seismic source zones listed in Table 1. For both the main zones and the background zones, a lower bound of 4.5 in moment magnitude is chosen for the earthquakes to be hazardous to engineered structures. The configuration of seismic source zones is displayed in Fig. 2.

The earthquakes in the finalized seismic data base are distributed among these 10 main and 4 background seismic source zones according to the location of their epicenters, and are used to predict the seismicity parameters of each seismic source zone. For the estimation of the parameters of the linear magnitude–recurrence relationship (mainly b,

Table 1

Seismic source zones and the expected maximum earthquake magnitude values used in the study

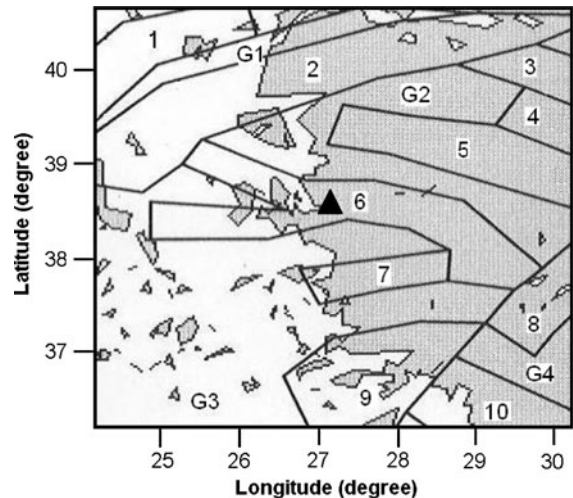| Number	Seismic source zone	$(M_w)_{max}$
1	North Anatolian fault system- segment A	8.0
2	North Anatolian fault system- segment C	7.4
3	İnönü-Eskişehir fault zone	7.1
4	Kütahya fault zone	6.9
5	Simav-Akşehir fault zone	7.2
6	Alaşehir-İzmir (Gediz) Graben	7.2
7	Büyük Menderes Graben	7.1
8	Çameli-Burdur fault zone	7.1
9	Gökova fault zone	7.8
10	Finike fault zone	7.2
G1	Background 1	5.3
G2	Background 2	5.4
G3	Background 3	5.9
G4	Background 4	5.6

Figure 2

Configuration of the seismic source zones listed in Table 1. *Triangle marks* the location of metropolitan Izmir

the parameter of the exponential magnitude distribution) the least squares regression and maximum likelihood methods are applied, both to the original (incomplete) and artificially completed data sets, creating four different combinations.

In the literature, both the least squares regression and maximum likelihood methods are used for recurrence modeling. Actually, the standard method gives equal weight to all data. The standard least squares regression is based on the minimization of

the sum of squares of the discrepancies between the observed and estimated values. On the other hand, the maximum likelihood method is based on the maximization of the likelihood of obtaining the recurrence relationship parameters as close as possible to the observed data. Therefore, in the maximum likelihood method, cumulative distribution is useless and observations at each discrete magnitude level are required. For large number of observations, assuming the validity of the GR relationship, outcomes of the two methods are expected to coincide. In our database, the parameter of the exponential magnitude distribution due to the standard least squares regression is found to be greater than the parameter of the exponential magnitude distribution, due to the maximum likelihood method for only some of the seismic source zones (as shown in Tables 3, 4). For the rest, the opposite is true. Hence, utilizing any one of the methods in place of the other somehow either overestimates or underestimates the hazard of the corresponding source zone. Using both methods and superposing the results, as we did, regulates smaller range estimates of the parameter of the exponential magnitude distribution. The weight of the standard least squares regression is 0.4, whereas the weight of the maximum likelihood method is 0.6 as given in Table 2.

Table 2

Alternative assumptions and assigned subjective probabilities

Alternative assumptions	Subjective probability
All earthquakes	0.5
Main shocks only	0.5
Incomplete catalogs	0.4
Artificially completed catalogs	0.6
Standard least squares regression for the recurrence relationships	0.4
Maximum likelihood method for the recurrence relationships	0.6
PGA as earthquake intensity measure	
Attenuation relationship of GULKAN and KALKAN (2002)	0.6
Attenuation relationship of BOORE et al. (1997)	0.4
Attenuation uncertainty, $\sigma_{\ln Y} = 0.447$	0.1
Attenuation uncertainty $\sigma_{\ln Y}$ equal to reported value	0.6
Attenuation uncertainty, $\sigma_{\ln Y} = 0.707$	0.3

7. Attenuation Relationships

Peak ground acceleration is selected as the earthquake severity parameter. In order to estimate earthquake hazard in terms of this parameter, the attenuation relationships of GULKAN and KALKAN (2002) and BOORE et al. (1997) for rock sites (Vs30 = 700 m/s.) are used. These equations are, respectively,

$$\ln Y = -0.682 + 0.253 \times (M - 6) + 0.036 \\ \times (M - 6)^2 - 0.562 \times \ln r + 0.202 \qquad (5)$$

$$\ln Y = -0.242 + 0.527 \times (M - 6) - 0.778 \times \ln r \\ + 0.301 \qquad (6)$$

where: $r = \sqrt{r_{cl}^2 + h^2}$; Y = horizontal component of the peak ground acceleration (PGA) in g; M = moment magnitude; r_{cl} = the closest horizontal distance to the surface projection of the rupture in km; h = fictitious depth, computed by regression analysis as 4.48 and 5.57 km, respectively for Eqs. 5 and 6. The standard deviation, $\sigma_{\ln Y}$ was reported as 0.562 and 0.520 and the soil conditions were considered through the constants at the ends of Eqs. 5 and 6 by GULKAN and KALKAN (2002) and BOORE et al. (1997) for rock sites, respectively. The soil conditions were considered by using the last constants as "0.202" and "0.301" in the attenuation relationships of GULKAN and KALKAN (2002) and BOORE et al. (1997) for rock sites, respectively. In the present study, the different horizontal component definitions were neglected while implementing the predictive models to PSHA.

The first equation is obtained by analyzing the local attenuation characteristics in Turkey. It is based on the ground motions recorded during the 1999 Marmara and Duzce earthquakes with strike-slip mechanisms. There are some other attenuation relationships based on domestic studies besides GULKAN and KALKAN (2002), a few of which were KALKAN and GULKAN (2004), OZBEY et al. (2004), and ULUSAY et al. (2004). On the other hand, the second equation is used widely both in recent international and domestic studies. Both are selected based on subjective judgment. A sensitivity analysis can also be performed in order to observe the variation in the seismic hazard results while changing only the attenuation equation but keeping the other parameters constant.

Table 3

Seismicity parameters of the seismic source zones (using data set as is)

No.	Seismic source zone	All earthquakes				Only main shocks			
		Standard least squares regression		Maximum likelihood method		Standard least squares regression		Maximum likelihood method	
		β	λ(obs.)	β	λ(obs.)	β	λ(obs.)	β	λ(obs.)
1	North Anatolian fault system- segment A	1.583	0.676	1.301	0.676	1.242	0.362	1.464	0.362
2	North Anatolian fault system- segment C	1.579	1.629	1.674	1.629	1.276	0.790	1.243	0.790
3	İnönü-Eskişehir fault zone	1.658	0.343	1.161	0.343	1.423	0.200	2.441	0.200
4	Kütahya fault zone	1.918	0.171	1.918	0.171	1.722	0.133	1.722	0.133
5	Simav-Akşehir fault zone	1.964	2.257	1.939	2.257	1.393	0.762	1.211	0.762
6	Alaşehir-İzmir (Gediz) Graben	2.204	1.657	1.462	1.657	1.944	1.048	1.326	1.048
7	Büyük Menderes Graben	1.545	0.467	2.855	0.467	1.266	0.295	1.186	0.295
8	Çameli-Burdur fault zone	1.950	0.943	1.837	0.943	1.365	0.333	1.391	0.333
9	Gökova fault zone	2.123	3.095	1.633	3.095	1.890	1.657	1.407	1.657
10	Finike fault zone	1.865	0.781	1.494	0.781	1.539	0.467	1.455	0.467
G1	Background 1	2.059	0.133	2.694	0.133	2.408	0.095	2.947	0.095
G2	Background 2	1.328	0.962	1.328	0.962	1.762	0.667	2.372	0.667
G3	Background 3	2.563	3.952	1.985	3.952	2.419	2.781	1.964	2.781
G4	Background 4	2.464	1.590	2.464	1.590	2.395	1.200	2.395	1.200

Table 4

Seismicity parameters of the seismic source zones (using data set corrected for completeness)

No.	Seismic source zone	All earthquakes				Only main shocks			
		Standard least squares regression		Maximum likelihood method		Standard least squares regression		Maximum likelihood method	
		β	λ(obs.)	β	λ(obs.)	β	λ(obs.)	β	λ(obs.)
1	North Anatolian fault system- segment A	1.756	0.952	2.040	0.952	1.344	0.467	1.559	0.467
2	North Anatolian fault system- segment C	1.699	2.400	3.062	2.400	1.380	1.138	2.162	1.138
3	İnönü-Eskişehir fault zone	1.669	0.343	1.669	0.343	1.445	0.207	1.445	0.207
4	Kütahya fault zone	2.263	0.288	2.993	0.288	1.913	0.192	2.855	0.192
5	Simav-Akşehir fault zone	2.083	2.762	2.809	2.762	1.504	0.940	1.695	0.940
6	Alaşehir-İzmir (Gediz) Graben	2.326	2.188	2.395	2.188	2.050	1.330	2.075	1.330
7	Büyük Menderes Graben	1.516	0.430	3.454	0.430	1.350	0.336	1.294	0.336
8	Çameli-Burdur fault zone	2.053	1.013	2.125	1.013	1.328	0.289	1.439	0.289
9	Gökova fault zone	2.236	5.001	3.247	5.001	2.013	2.659	2.579	2.659
10	Finike fault zone	2.114	1.299	2.855	1.299	1.774	0.804	2.924	0.804
G1	Background 1	3.129	0.228	3.129	0.228	2.408	0.169	2.947	0.169
G2	Background 2	2.025	1.204	2.025	1.204	2.290	0.978	2.290	0.978
G3	Background 3	2.828	5.155	2.828	5.155	2.842	4.248	2.842	4.248
G4	Background 4	2.464	2.710	2.464	2.710	2.395	1.996	2.395	1.996

8. Best Estimate Seismic Hazard for Izmir

In order to reflect the influence of various assumptions discussed above and to account for the uncertainties in the values of seismicity parameters, the logic tree procedure is applied as described below. The alternative assumptions are listed in Table 2, together with the subjective probabilities assigned to

them. These probabilities quantify the likelihood of each assumption being valid as compared to the alternative assumptions. Seismic hazard computations are carried out for each one of the resulting $2^4 \times 3 = 48$ combinations. Multiplying the seismic hazard results computed for each one of the 48 combinations with the corresponding joint probability (multiplication of the probabilities of the selected

alternatives) of that combination, then summing the results, gives a weighted average seismic hazard value. Tables 3 and 4 list seismicity parameters of the source zones, obtained using the available data set as-is and after correcting it for completeness, respectively.

The resulting seismic hazard curve in terms of PGA is called as the "best estimate" seismic hazard for Izmir and is shown in Fig. 3. Certainly, one may find another hazard curve if different weights are assigned to different analysis cases. The weights we have given to different analysis cases reflect the bounds of our databases. When considering all earthquakes, versus considering only the main shocks, a 50% probability is assigned to each. The catalog completed artificially is given 60% weight, while the as-is catalog (which is incomplete) is given 40% weight. Based on these "best estimate" hazard curves and for a return period of 475 years, a PGA value of 0.34 g is calculated for rock sites in metropolitan Izmir. In earthquake engineering studies related to urban earthquake vulnerability estimation and seismic risk mitigation, it is important to be able to estimate spectral response parameters and not just peak ground acceleration. The probabilistic spectral response estimates could be obtained by replacing the attenuation model for PGA with an attenuation model for response spectra (for example, as provided by BOORE et al., 1997 or GULKAN and KALKAN, 2002) and then carrying out a probabilistic hazard estimation process similar to that shown here. In this study for Izmir and the surrounding region, the hazard level is represented in the form of PGA only.
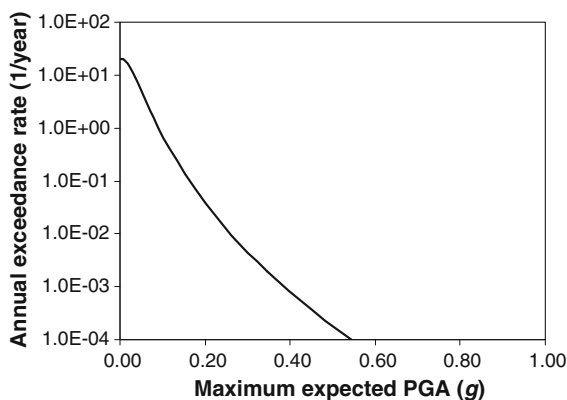
Corresponding to a return period of 475 years (10% probability of exceedance in 50 years), a seismic hazard map was also plotted, considering the analysis combination composed of the most likely assumptions. This map is shown in Fig. 4. All of the seismic hazard calculations are carried out using CRISIS2003 software (ORDAZ et al., 2003). As can be seen from Fig. 4, metropolitan Izmir is in the vicinity of the highest seismic hazard level within the region. Figure 5 and Table 5 illustrate the contribution of earthquake magnitude and distance pairs to the seismic hazard of Izmir city center for a PGA level of 0.34 g on rock sites. It has been computed that approximately 95% of the contribution to this hazard level, 10% probability of exceedance in 50 years, comes from earthquakes with magnitudes lower than 6.2 and within 75 km of the city center. The corresponding seismic source zone is the Alaşehir-İzmir (Gediz) Graben.

9. Summary and Conclusion

The present study focuses on a probabilistic seismic hazard analysis and evaluation for the metropolitan city of Izmir in western Anatolia, Turkey. The region is one of the most active tectonic regions of Turkey. First, the seismicity of the region

Figure 3
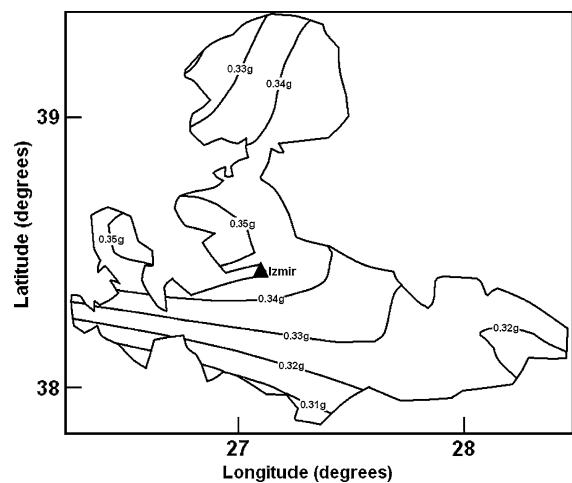Best estimate seismic hazard curve for Izmir city center, in terms of peak ground acceleration (g) on rock sites

Figure 4
Seismic hazard map corresponding to a return period of 475 years obtained based on the combination of the most likely assumptions, in terms of peak ground acceleration (g) on rock sites
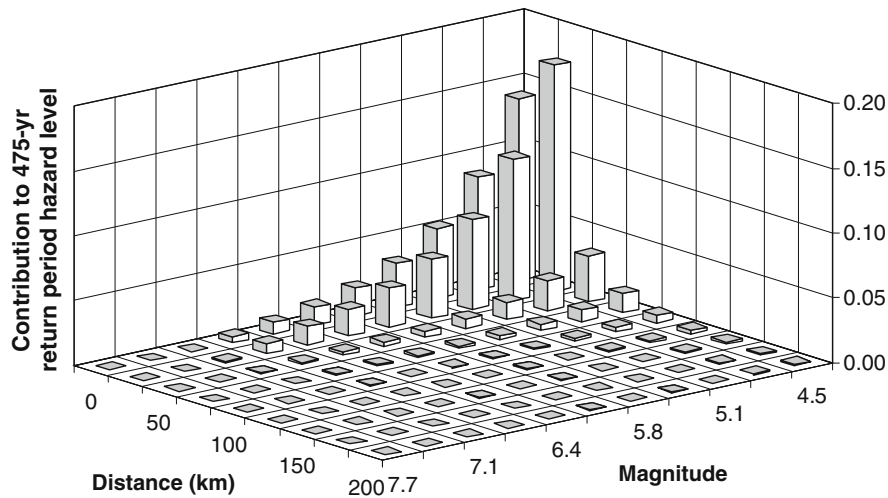
Figure 5

Contribution of earthquake magnitude and epicentral distance pairs to the 10% of exceedance probability over 50 years, i.e. hazard level of PGA = 0.34 g, on rock sites for Izmir city center (see Table 5)

Table 5

Disaggregation of seismic hazard (in terms of probability of occurrence), as a function of earthquake magnitude and epicentral distance pairs, for Izmir city center at PGA level of 0.34 g on rock sites

Magnitude	Distance (km)								
	0	25	50	75	100	125	150	175	200
4.5	0.141	0.175	0.035	0.015	0.006	0.003	0.002	0.001	0.001
4.8	0.087	0.109	0.023	0.009	0.004	0.002	0.001	0.001	0.001
5.1	0.054	0.069	0.014	0.005	0.002	0.001	0.001	0	0
5.5	0.034	0.045	0.008	0.003	0.001	0.001	0.001	0	0
5.8	0.022	0.030	0.005	0.002	0.001	0	0	0	0
6.1	0.014	0.021	0.004	0.001	0	0	0	0	0
6.4	0.009	0.014	0.003	0.001	0	0	0	0	0
6.8	0.005	0.008	0.002	0.001	0	0	0	0	0
7.1	0	0.001	0	0	0	0	0	0	0
7.4	0	0	0	0	0	0	0	0	0
7.7	0	0	0	0	0	0	0	0	0

is presented and a simple probabilistic representation of hazard is given, based on statistics obtained from earthquakes that happened between 1900 and 2005. A more comprehensive seismic hazard calculation is made by taking into consideration the influences of different seismic sources in the region separately. Two ground motion estimation models are used to estimate the ground motion intensity expressed in terms of peak ground acceleration on rock sites. A logic-tree combination approach is used to take alternative assumptions into consideration. The result could be considered a "best estimate" seismic hazard assessment for Izmir.

Accordingly, for a return period of 475 years, for rock sites, a PGA value of 0.34 g is calculated. Note that the current seismic hazard zonation map used in the Turkish seismic design code (MPWS, 2007) recommends a design acceleration value of 0.4 g for Izmir. Ground motion is obviously a natural phenomenon, and a design acceleration value itself does not mean much regarding the seismic vulnerability of the building stock in a region. The seismic vulnerability, on the other hand, is man-made and depends on the characteristics of the available building stock, such as material and workmanship quality, construction control, structural irregularities, etc.

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