PREPARATION OF A LINE SOURCE MODEL FOR PROBABILISTIC SEISMIC HAZARD ANALYSES OF DÜZCE PROVINCE, TURKEY

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SUMMARY:
The study encompasses the Eastern Marmara Region where the North Anatolian Fault System, one of the most important active fault systems in the world, has a complex segmentation structure and where two recent devastating earthquakes, namely, Kocaeli in 17 August 1999 and Düzce, in12 November 1999 have occurred on this fault system. There are different seismicity maps for the region with different scales and purposes, thus a lineament map was prepared from ASTER satellite images and correlated with the literature in order to prepare a generalized seismic source map for the region. The prepared map including a database of slip rates, lengths and depth of each segment, along with a homogenized and de-clustered earthquake catalogue and four different ground motion prediction models were used for a probabilistic seismic hazard assessment of the Düzce city center, Turkey. A sensitivity analysis in terms of model segmentation and seismicity was performed.

Keywords: Seismic source modeling, probabilistic seismic hazard assessment, Eastern Marmara

1. INTRODUCTION

The North Anatolian Fault System (NAFS) is one of the most important strike slip fault systems in the world where the westward propagating seismic activity starting from the 1939 Erzincan earthquake and most recently including the 1999 Kocaeli and Düzce earthquakes have caused more than ten destructive earthquakes and more than 50,000 casualties during this period (Barka, 1996; MTA, 2003a; MTA, 2003b).

The study area located within the 28.55 - 33.75 latitudes and the 40.00 - 41.20 longitudes encompassing the Eastern Marmara Region and part of Western Black Sea Region has been studied extensively in terms of seismicity. However, the active fault maps prepared for the region have different scales and purposes, thus resulting in different active fault and segmentation models for the NAFS. The utilization of probabilistic seismic hazard assessment requires three main parameters; 1) Seismic source model, 2) Earthquake catalogue and 3) Ground motion prediction equations (Cornell, 1968). The generation of a reliable and utilizable seismic source model is crucial for a PSHA study. Therefore, a total of 10 ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite images were analyzed and lineament extraction was performed. The extracted lineaments were correlated with digitized maps from literature and a seismic source model was prepared for probabilistic seismic hazard assessment. Six seismic sources were delineated and these were investigated in terms of seismicity with the utilization of the earthquake catalogue prepared by the Kandilli Observatory and Earthquake Research Institute (KOERI, 2007). The slip rates of each segment as well as their width (depth) were determined according to literature. Then their source-segment-scenario relationships (SF Bay WG Report, 2003) were determined according to the Youngs and Coppersmith (1985) characteristic model. Finally, probabilistic seismic hazard assessment (PSHA) was performed via utilizing the developed seismic source model along with four different ground motion prediction models (GMPEs), namely Abrahamson and Silva 2008, Campbell and Bozorgnia, 2008, Chiou and Youngs, 2008, and Boore and Atkinson, 2008 (henceforth AS08, CB08, CY08 and BA08, respectively). The PSHA was performed by using Haz43 program developed by Norman Abrahamson for the Düzce city center according to two different soil conditions (i.e., V_{s30} values of 360 m/s and 760 m/s, respectively). The reason for selecting these soil conditions is based on the presence of Plio-Quaternary basin fill deposits and Pre-Pliocene rock formations dominantly in the Düzce province and its vicinity (MTA (General Directorate of Mineral Exploration, Turkey) and AU (Ankara University), 1999). Hazard curves in accordance with the previously stated two V_{s30} values were generated for the aforementioned four GMPEs at each three standard deviation value (0, 1 and 3) for 10% probability of exceedence for 50 years. Finally, sensitivity analysis of the seismic model was performed in terms of seismicity and model geometry was performed, and the results were compared.

2. IMAGE PROCESSING

ASTER satellite image data is highly suitable for lineament extraction in terms of its intermediate-high spatial resolution in Visible Near Infrared (VNIR) (15m) and Short-Wave Infrared (SWIR) (30m) bands as well as high applicability of these data in geological interpretations. Lineament extraction from satellite imagery in conjunction either with the field surveys or as a correlation with the literature is an effective method in the determination of fault (or possible fault) locations in the study area (Gupta, 2003; Koç, 2005; Sarp, 2005). Along with its relatively high spatial resolution, the Digital Elevation Maps (DEMs) produced from ASTER images are another tool for extraction of lineaments.

In this study, Principle Component Analysis (PCA) was chosen to be the manual extraction method for 10 different ASTER scenes. This method is used for decreasing dimensionality in bands of a single image (Richards, 1999). In other words, PCA allows reduction of noise component, determination of correlated bands and thus allowing collection of all bands in as a little band as possible by conversion into uncorrelated bands (Gupta, 2003). Therefore, data on multispectral satellite images such as Landsat or ASTER images can be collected in the first three principle components (PCs), mainly on the first principle component. In this study, the first three PCs were visualized as RGB color composite for each scene and thus as many reduction of data redundancy and noise as possible was obtained along with visualizing the highest possible proportion of data as a single image in RGB composite. At least 97.8% of the total data was visualized by combining the first three principal components in RGB color composite. These RGB (Red-Green-Blue) color composites were overlain on DEM in order to visualize the image in 3-D (Figure 2.1).

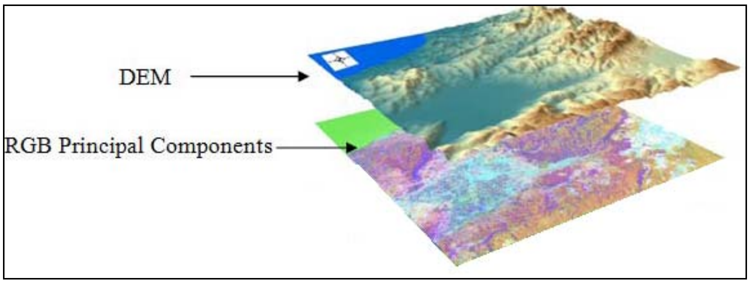

Figure 2.1. RGB PCs and DEM for an example ASTER image of the study area.

A total of 10 ASTER scenes were analyzed according to this methodology, and a total of 2454 lineaments were extracted from images and the length of these line features changed between 85 m and 13133 m with a mean length of 1984 m (Figure 2.2a). The length weighted directional analysis of these lineaments revealed that the dominant direction was oriented between N50°E and N80°E where the highest frequency was accumulated at N70°E direction with total of 282 lineaments oriented in that direction (Figure 2.2b). These lineaments were correlated with the literature in order to compose the seismic source model and segmentation of these sources.

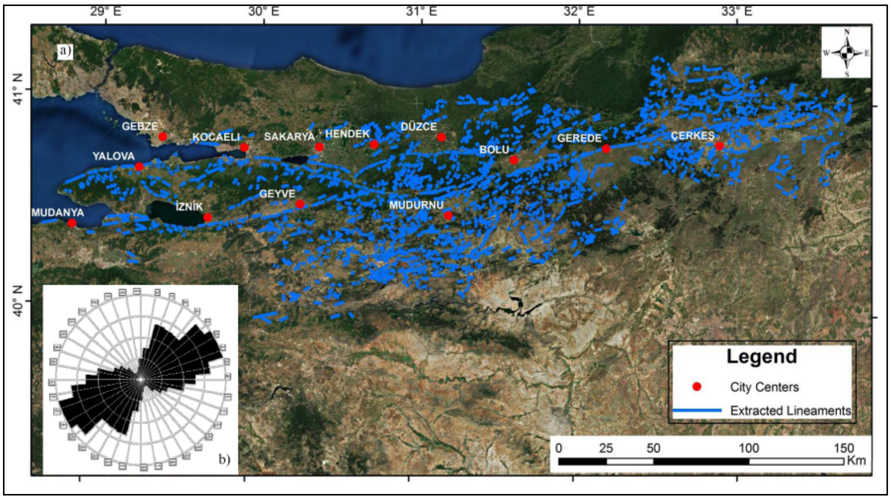

Figure 2.2. a) Extracted lineaments, b) Rose diagram for length weighted directional analysis of the lineaments.

3. CORRELATION WITH THE LITERATURE

The extracted lineaments were correlated with the literature (Ambraseys and Zatopek, 1969; Ambraseys, 1970; Barka and Kadinsky-Cade, 1988; Şaroğlu et al., 1992; Emre et al., 1998; Akyüz et al., 2002; Barka et al., 2002; Harris et al., 2002; MTA, 2003a; Duman et al., 2005; Kondo et al., 2005; Pucci et al., 2007) according to previously mentioned six seismic source zoned determined mainly according to major seismic events. The reasoning behind segmentation and their parameters are given below in detail (see Figure 3.1). The acronyms of the segments shown in Figure 3.1 are given in parentheses throughout the explanations below.

The first seismic segmentation was adopted for the rupture zone of 17 August 1999, Kocaeli earthquake which was reported to have a surface rupture between 125 km and 145 km (Lettis et al., 2002 and Barka et al., 2002). Although there are different segmentation models in the literature (Barka et al., 2002; Langridge et al., 2002; MTA (General Directorate of Mineral Exploration, Turkey), 2003b), the rupture segmentation model proposed by Barka et al. (2002) was adopted and correlated with the extracted lineaments. Five segments were defined, namely: Hersek (K1.H), Karamürsel-Gölcük (K2.KG), İzmit-Lake Sapanca (K3.IS), Sapanca-Akyazı (K4.SA) and Karadere (K5.K). The off-shore continuation of the segments were included in this study according to literature (Emre et al., 1998; Armijo et al., 2002; Barka et al., 2002; MTA, 2003b; Harris et al; 2002; Duman et al., 2005). Hendek Fault which is reported to have ruptured during after-shocks of the main event is also included as a segment to this seismic source and rupture scenarios were modified accordingly.

The surface rupture of the 12 November 1999, Düzce earthquake was reported to be between 30 and 45 km (Duman et al., 2005). The segmentation of this source was adopted according to Duman et al. (2005) where the surface rupture of the earthquake has three distinct segments delineated by the Beyköy and Kaynaşlı restraining step-overs, therefore naming these segments as Eften (D1.E), Dağdibi (D2.D) and Kaynaşlı (D3.K) segments.

Another source zone for the model was determined to be the surface rupture areas of the May 26, 1957 Abant (M3.A); June 22, 1967 Mudurnu earthquakes (M2.M) and western continuation (M1.W) of these events up to Sapanca Lake -from east to west- (Palyvos et al., 2007). The 1967 Mudurnu earthquake is associated with approximately 55 km of rupture zone and the rupture zone overlaps at the eastern part with the 1957 Abant earthquake surface rupture with approximately 25 km (Ambraseys and Zatopek, 1969; Ambraseys, 1970), and the deformation zone continues approximately another 25 km to the west. The 1957 Abant earthquake has an approximate surface rupture between 30 km (Barka, 1996) and 40 km (Ambraseys and Zatopek, 1969) located between Lake Abant and near Dokurcun.

As the area of interest for this study (Düzce) is located towards the east of the Marmara region as well as within the western Black Sea region, one of the most important earthquakes that occurred at the east of this location; i.e. February 1^{st}, 1944, Bolu-Gerede earthquake; was also included in this study. The base map for this source was the study by Barka and Kadinsky-Cade (1988) where the rupture zone was delineated into three segments between Lake Abant and Bayramören (Ketin, 1969; Öztürk et al., 1985) namely; western (B1.W), divide (B2.D) and eastern (B3.E) segments.

The Geyve-İznik Fault Zone which is defined as a seismically quiescent (seismic gap) zone (Barka and Kadinsky-Cade, 1988; Barka, 1992) is adopted as three segments (identified as Middle Strand by Barka and Kadinsky-Cade, 1988) starts from the west at the rupture zone of the 1967 Mudurnu earthquake as a branch and continues until Gemlik Bay in the west, namely: Gemlik (G1.Gm), İznik (G2.İ) and Geyve (G3.Ge) segments from west to east.

The final fault source included in this study is the Çınarcık Fault which has been mapped by different researchers as an on land fault bounding the northern shore of the Çınarcık Peninsula (Şaroğlu et al., 1992; Emre et al., 1998; MTA, 2003b) and also as an offshore fault following the trace of the northern trend of the Çınarcık Peninsula (Barka and Kadinsky-Cade, 1988; Barka et al., 2002). This source was included in the model as two segments as west (C1.W) and east (C2.E).

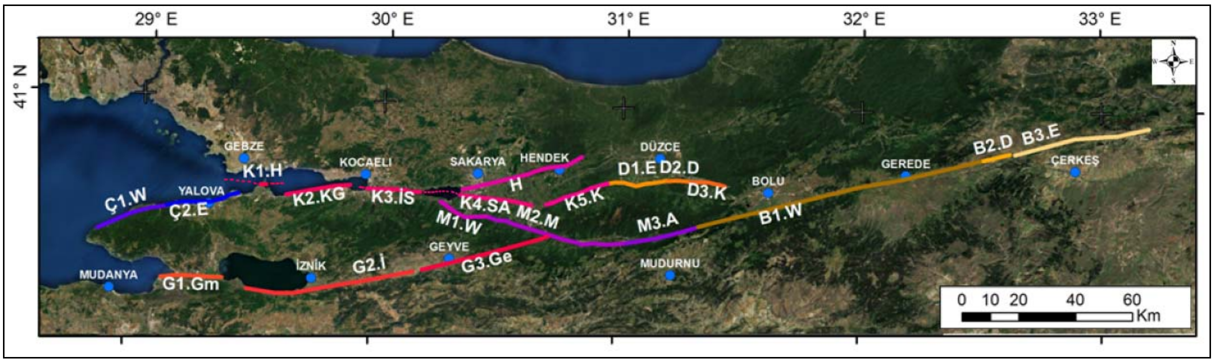

Figure 3.1. Final seismic source model of the study area.

4. PROBABILISTIC SEISMIC HAZARD ASSESSMENT PARAMETERS

The parameters required for adaptation of the source model into a probabilistic seismic hazard assessment are rupture length, rupture width and slip rates for each individual segment in order to be able to calculate characteristic magnitude from Wells and Coppersmith (1994) (Eq. 4.1) and utilize Youngs and Coppersmith (1985) characteristic model. Rupture area, magnitude relationship proposed by Wells and Coppersmith (1994) is:

$$M_w = 3.98 + 1.02 \log (RA) \qquad \text{(Eq. 2.1)}$$

where, RA is the rupture area acquired from multiplication of surface rupture length and rupture width. Surface rupture lengths of each segment is given in Table 4.1. The surface rupture lengths of each segment was determined during seismic source modeling and rupture width values were acquired from literature (Ayhan et al., 1999; Burgmann et al., 2002a; Burgmann et al., 2002b; Meade et al. 2002; ; Özalaybey et al., 2002; Utkucu et al., 2003; Reilinger et al. 2006; Ayhan and Koçyigit, 2010).

In order to develop recurrence models, it is necessary to calculate seismic moment accumulated on each fault segment, and seismic moment accumulated on each segment is calculated by utilizing the equation given below (Aki, 1966):

$$M_0^T = \mu A D \qquad \text{(Eq. 2.2)}$$

where, M_0^T is total seismic moment, μ is rigidity (dyne/cm^2), A is rupture area (km^2) and D is annual slip rate (mm). The rigidity value is taken as 3.0 x 10^{11} dyne/cm^2 (Youngs and Coppersmith, 1985; Ambraseys, 2002). The slip rates of each segment was determined either from literature (Okumura et al., 1993; Ayhan et al., 2000; McClusky et al., 2000; Meade et al., 2000; Kondo et al., 2005; Koçyiğit et al., 2006; Reilinger et al., 2006; Ayhan and Koçyiğit, 2010) or extracting the known values from the total regional slip rate. It is known that the regional slip rate, i.e., slip rate in the study area, varies between 16 – 25 mm/yr (strike slip) according to geologic data (McClusky et al., 2000; Reilinger et al., 2006) and 25 ± 5 mm/yr (strike slip) according to GPS data (Straub et al., 1997; McClusky et al., 2000; Kahle et al., 1999 and 2000; Reilinger et al., 2006). The most problematic section is where the Geyve segment of the Geyve-İznik fault, the western continuation and Mudurnu segments of the Mudurnu-Abant source, and the Sapanca-Akyazi, Karadere and Hendek segments of the Kocaeli source run sub-parallel to each other. In order not to exceed the maximum slip rate of 30 mm/year, an approach where only either the Sapanca-Akyazi and Karadere segments or the Hendek fault is allowed to be ruptured for each scenario was developed for the probabilistic seismic hazard assessment. Thus neither the total slip rates exceeded the regional maximum at a N-S section, nor the representation of the actual event where the Hendek fault was not ruptured during the 1999 earthquake but ruptured during after-shocks, was neglected.

Table 4.1. Total Surface Rupture lengths of each seismic source

Seismic Source	Number of Segments	Length (km)
Kocaeli Earthquake	5	131.78
Düzce Earthquake	3	41.25
Mudurnu – Abant Earthquakes	3	93.82
Bolu Earthquake	3	160.69
Hendek Fault*	1	43.93
Geyve – İznik Fault	3	127.13
Çınarcık Fault	2	51.28

* Hendek fault is included as a parallel segment to Kocaeli earthquake seismic source.

4.1. EARTHQUAKE CATALOGUE

The earthquake catalogue prepared by KOERI (2007) was utilized due to its definition of being homogeneous, i.e., including different magnitude scales. The catalogue includes earthquakes having a magnitude larger than 4 between 1900 and 2005. The secondary event analysis (de-clustering) analysis was performed on the catalogue due to its mutually exclusiveness of the events as well as to guarantee that the catalogue can be represented by a Poisson process which is utilized to describe earthquake phenomena in time domain (Gardner and Knopoff, 1974). For this purpose, a catalogue having 337 earthquakes falling within the study area was primarily processed in accordance with the previously stated main earthquake events both in terms of time and space via utilizing the temporal-spatial bounds proposed by Deniz (2006). Following the primary de-clustering analysis, the remaining earthquakes were secondarily checked manually for further related events. Therefore the final catalogue having 120 events was utilized in further analyses.

Another catalogue correction, namely catalogue completeness analysis was performed in order to ensure that the catalogue fits earthquake recurrence relation which is considered to represent true long-term relations (Stepp, 1973). Stepp (1973) states that all earthquake catalogues are biased due to less dense deployment of seismograms and lack of settlement in the earlier earthquake records. Therefore, the de-clustered catalogue (having minimum and maximum event dates for 1905 and 2005, respectively) was checked for the distribution of magnitudes in time (Figure 4.1) and for completeness as proposed by Stepp (1973).

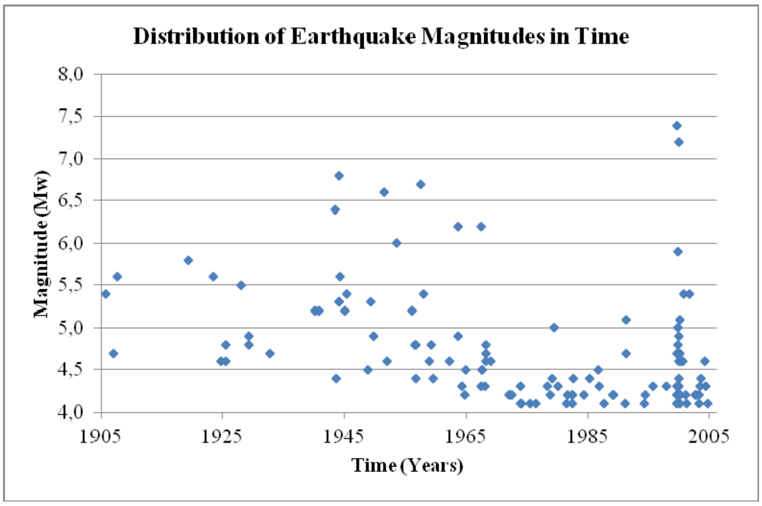

Figure 4.1. Distribution of earthquakes in time

The catalogue was observed to be biased for small magnitude events having $M_w<4.6$ before 1964. This observation was also mentioned in the study of Atakan et al. (2002) where the records for the modern instrumental period were stated to have begun from 1964, and the same observation was also made by Kalkan et al. (2009). Thus the catalogue was investigated in accordance with two time intervals for small ($M_w<4.6$), and intermediate - large events ($M_w\geq4.6$), namely 41 years and 100 years of completeness, respectively. In light of these findings, the regression coefficients '*a*' and especially '*b*' were determined according to these final catalogue parameters via utilizing the equation given below that is proposed by Gutenberg-Richter:

$$log(N) = a - b(M) \qquad \text{(Eq. 5.1)}$$

where, N is the number of earthquakes with magnitude equal or greater than M. Therefore, the Gutenberg-Richter '*b*' value for log_{10} mean annual exceedence rate was acquired according to both the least squares method and maximum likelihood method for the entire region, i.e., individual *b* values for each seismic source was not considered as it was observed during de-clustering analysis that each large magnitude earthquake has an effect on individual seismic sources, therefore triggering different seismic sources. The average '*b*' value of 0.71 is compatible with the range of 0.9 ± 0.2 for shallow (>70 km) earthquakes proposed by Gutenberg and Richter (1949). Along with this general identification, the *b*-value acquired in this study is highly compatible with the previous studies (Atakan et al., 2002; Erdik et al., 2004; Deniz, 2006; Crowley and Bommer, 2006; Kalkan et al., 2009).

4.3. Ground Motion Prediction Equations and Segmentation Relationship

In this study, four different Next Generation Attenuation (NGA) Ground Motion Prediction Equations (GMPEs) were utilized during probabilistic seismic hazard assessment, these are: Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) (from now on referred as AS08, BA08, CB08 and CY08, respectively) as all four of these GMPE's found applications for worldwide shallow crustal (<70 km) data and for Europe and Middle East (Stafford et al., 2008, Douglas, 2011).

The segment, source and scenario relationship defined by USGS Workgroup on California Earthquake Probabilities San Francisco (SF Bay WG Report, 2003) was used in this study. Therefore, each different rupture scenario regarding rupture of single segments as well as adjacent segments could be modeled. However, in order to incorporate different scenarios into the model, weights of these scenarios should be determined. In order to determine these weights, recurrence models of the seismic sources were developed based on the seismicity of the sources (Figure 4.2) and Youngs and

Coppersmith characteristic model. Details on source-segment-scenario and weights can be found in Cambazoğlu (2012) and Özkan et al. (2011).

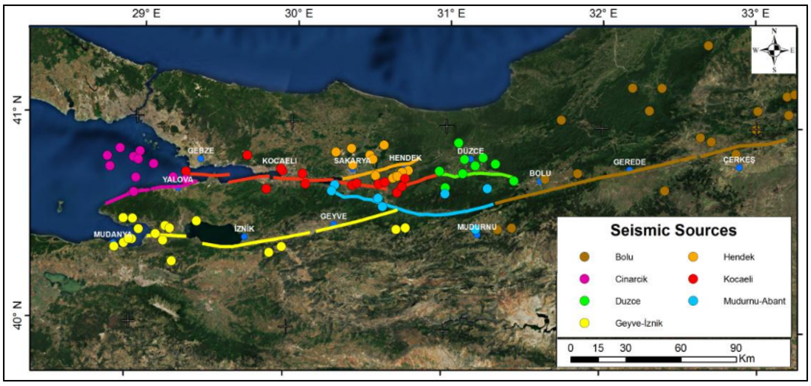

Figure 4.2. Seismicity of each seismic source

5. RESULTS AND DISCUSSION

As previously mentioned, the probabilistic seismic hazard assessment was performed for Düzce city center with 31.16N 40.84E coordinates. Three different standard deviations were utilized for the GMPEs and two different site conditions (namely Vs_{30} = 360 and 760 m/s) were considered for 10% probability of exceedence for 50 years. These parameters were incorporated into Haz43 computer code developed by Norman Abrahamson as an upgrade to Haz38 (Abrahamson, 2006, unpublished) which is validated by Pacific Earthquake Engineering Research (PEER) Center (Thomas et al., 2010). The code computes seismic hazard by utilizing the methodology for probabilistic seismic hazard assessment developed by Cornell (1968) and with the fundamental assumption that earthquakes within a given source zone are completely random in terms of spatial location and these events occur independently in time which means the events occur as a Poisson process. It is known that standard deviations play an important part consistent with the statistical basis for standard deviation value for normally distributed data where ±1 standard deviation covers 84% of the total data and ±3 standard deviation covers 99% of the data in a normal distribution. The equally weighted average of the GMPEs for 3 standard deviations yielded 0.621g and 0.561g for Vs_{30}=360 m/s and Vs_{30}=760 m/s site conditions, respectively. A recent study conducted by Kalkan et al. (2009) by utilizing NGA (Next Generation Attenuation) GMPEs indicates that the area of interest of this study falls within 0.4 – 0.6 g for 10% probability of exceedence in 50 years for Vs_{30}=760 m/s rock site and between 0.44 and 0.72g for Vs_{30}=360 m/s soil site. As these values from the literature are to be considered, the previous observation regarding the standard deviation is further supported.

Finally, two different sensitivity analyses, in terms of seismicity (G-R *'b'* value) and model geometry were conducted. The seismicity sensitivity was performed for 0.6, 0.71 and 0.8 *'b'* values for equally weighted results of GMPEs, and it was observed from the results that G-R 'b' parameter does not play a significant role for these values and varies only by about 0.001g. The second sensitivity in terms of model geometry was performed by changing segmentation of two seismic sources, namely Düzce and Bolu-Gerede sources. The Düzce seismic source which was modeled as three segments according to Duman et al. (2005) was changed into two segments according to the segmentation definition of Pucci et al. (2006), and Bolu-Gerede seismic source which was modeled as three segments according to Barka and Kadinsky-Cade (1988) was divided into five segments according to segmentation of Kondo et al. (2005). The segment-scenario-source and weights were re-defined (Cambazoğlu, 2012) and probabilistic seismic hazard assessment was performed by taking the remaining parameters constant.

Changing the model with regards to segmentation of the Bolu seismic source does not affect the results; however the change in the segmentation of the Düzce seismic source from three segments to two segments affects the results with a 5% decrease in the final PGA values. The reason for this decrease may be due to inability of the model to include normal and thrust components of the two segments as discussed by Pucci et al. (2007), and modeling purely strike slip with vertical dip, thus neglecting the hanging wall or footwall effect which might have contributed to the results.

This study was conducted in order to generate a generalized seismic source model through comprehensive literature survey and utilization of lineament extraction techniques to ensure the spatial locations, segmentation and length of the seismic sources in the Eastern Marmara region, and to check the applicability of the model via a probabilistic seismic hazard assessment for the Düzce city center. It was observed from the PSHA results that the model can be even further improved by including different fault mechanisms (normal or reverse components) into the analysis. It can be discussed that inclusion of 3-D subsurface geometry of faults, i.e. dip directions and dip amounts, can further improve the model by reflecting the natural conditions as well as hanging wall effect when strike-slip fault with normal components are considered.

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