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Integration of Surface Wave Seismic Survey Testing Results and Segmented Seismic Source Model of NAFS for PSHA of the Gölyaka-Düzce Tectonic Basin, Turkey

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ABSTRACT

This study mainly focuses on the determination of site effects for the Plio-Quaternary sediments of Gölyaka-Düzce, Turkey by characterizing local soil conditions. Probabilistic seismic hazard assessment (PSHA) analysis was performed to observe the effect and importance of local site conditions. The study area is located within the Eastern Marmara Region and uniquely falls within the bifurcated section of the North Anatolian Fault System (NAFS). This tectonic basin is bounded by the surface rupture of the 1999 Düzce and 1999 Kocaeli Earthquakes respectively from south and northwest. The local site conditions and dynamic sediment characteristics of the study area were evaluated by active and passive surface seismic surveys that were performed at 29 sites. By combining these, dispersion curves were obtained and high-resolution Vs profiles were successfully constructed. In the PSHA study, four different ground motion prediction equations were selected. Local site conditions and non-linear effects have a significant role in the damage pattern of the 1999 Kocaeli and Düzce Earthquakes and the PSHA analyses based on earthquake magnitude, proximity of the source and local site conditions as reflected from the results of the field surface wave measurements.

Introduction

Nearly all destructive earthquakes that occurred during the last three decades have clearly shown that local soil conditions can have a remarkable influence on the ground motion and on the damage pattern (e.g., Rodriguez-Marek et al., 2001, Koçkar and Akgün, 2012). Almost all recent destructive earthquakes (Spitak, Armenia 1988, Iran 1990, Philippines 1990, Northridge 1994, Kobe 1995, Armenia, Columbia 1999, Kocaeli and Düzce 1999, New Zealand 2010, Van 2011, Sichuan 2015). These have brought additional evidence of the dramatic importance of site effects. Therefore, to understand spatial variations of the ground motion, gathering elaborative information from soft soil is crucial. It is widely recognized that site classification based exclusively on V_{S30} is overly simplified in many circumstances due to factors such as topographic and basin effects, site resonances, sharp impedance contrasts, and deeper structure that influence local ground shaking (Assimaki et al., 2008). While several other site classification schemes have been proposed to address these issues (e.g., Rodriguez- Marek et al., 2001; Cadet et al., 2008), they have not been adopted up to date by the current standard code-based design that relies on seismic site classification via V_{S30} (Cox et al., 2011). If Gölyaka and the other areas of Düzce that have been affected by the earthquake are to be rebuilt with the awareness of

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seismic hazard, the new construction must be based on seismic standards such as those found in the International Building Code (IBC; ICC 2009) or Turkish Seismic Code (TSC 2007). One key step required by seismic provisions in modern building codes is the determination of seismic site classification, which is necessary to determine the expected seismic design forces for the structure. Code-based seismic site classification is based on the subsurface characteristics (e.g., soil-rock stiffness, layering, etc.) of the site within the top 30 m (Dobry et al., 2000). The study area is located within the Eastern Marmara Region where the North Anatolian Fault System (NAFS), one of the major active fault systems in Turkey with a significant earthquake potential is situated. The area uniquely falls within the bifurcated section of the NAFS and this tectonic basin is bounded by the surface rupture of the 1999 Düzce Earthquake from the south and the 1999 Kocaeli Earthquake from the northwest. On 12 November 1999, a Mw 7.2 earthquake struck the Düzce region of Turkey. The earthquake was devastating, resulting in 763 casualties and 4,493 wounded citizens (Özmen and Bağcı, 2000).

In this study local site conditions and dynamic sediment characteristics of the study area were evaluated by passive (Microtremor Array Measurement, MAM) and active (Multichannel Analysis of Surface Wave, MASW) surface seismic methods performed at 29 sites. By combining the dispersion curves, high-resolution V_s profiles were successfully constructed. Four different ground motion prediction equations were applied for a Probabilistic Seismic Hazard Assessment (PSHA) of the study area with 10% probability of exceedance for 50 years. PSHA analyses indicate that based on the earthquake magnitudes, proximity of the source and local site conditions, non-linear effects, having a significant role in the damage pattern observed after the 1999 Kocaeli event, especially the 1999 Düzce event, are apparent.

Seismicity

The November 12, 1999 Düzce earthquake is the second of the devastating 1999 Marmara earthquakes which resulted in a 45 km rupture surface. Horizontal and vertical displacements of 3.0 m and 5.0 m have occurred along the rupture, respectively (Taymaz, 1999). The west end of the rupture line is located close to the point of the east end of the rupture line of the August 17 Kocaeli earthquake (Barka, 1999b). The NAFS, which is an active right-lateral fault bounds to the westward-extruding Anatolian block towards the north. It represents a transform margin that generally follows a pre-existing zone of crustal weakness: a suture zone inherited from an earlier N–S collisional phase. GPS networks have measured current strain-rates of 20–30 mm/yr (i.e., Reilinger et al., 2000; Kahle et al., 2000) in the northern part of the Anatolian block, with vectors oriented towards WNW in the easternmost region, E–W in the center, and S–W in the Aegean. The North Anatolian Fault splays into two main strands from the west of the Bolu district: the Düzce fault to the north and the Mudurnu fault to the south. According to Ayhan et al. (2001), the Düzce fault accommodates up to 33% to 50% of the current GPS strain across the NAFZ (~10 mm/yr). The Düzce fault separates the Paleozoic–Eocene formations of the Almacik block from the Pliocene– Quaternary continental deposits of the Düzce pull-apart basin. The Düzce fault is adjacent to the Karadere segment of the Kocaeli surface rupture from the east. The latter and the Düzce fault form two diverging strike–slip strands linked by a fault junction with no step-over. This geometrical array configures a releasing fault-wedge whose long-term morphological expression is represented by the wedge shaped basin of the Gölyaka area (Pucci et al., 2007). The Düzce fault appears in the east to join the single trace of the NAFZ via a right-releasing step-over formed by the WNW–ESE trending Bakacak and Elmalık faults. Conversely, the western part of the fault splays out from the WSW–ENE trending Karadere section that restrains the İzmit Fault. According to Lettis et al. (2002), this western boundary of the Düzce fault segment forms a complex right releasing step-over with the Karadere section that presumably has barred the August rupture propagation. As a result, this releasing zone controls the present-day Düzce Basin depocentre Lake Eften (Pucci et al., 2007).

Geology and Subsurface sediment characteristics

The Precambrian Yedigöller Formation, which is mainly composed of jointed and fractured metagranites, amphibolites and gneiss (Aydin et al., 1987), constitutes the local geologic basement. The Upper Cretaceous Akveren Formation contains intercalated clayey limestones and marls. The Cretaceous units are overthrusted onto the Eocene Yiğilca Unit (andesites, basalts) and the Çaycuma Formation (sandstones, mudstones and limestones). The unconsolidated Plio-Quaternary Karapürçek Formation and the Quaternary alluvium lie unconformably over the older units. The main geologic structure in the study area is the E–W trending northern segment (Düzce Fault) of the NAFS that crosses almost all of northern Turkey. The Düzce Fault plays an important role in the deformation and morphological evolution of the area. Its right lateral strike-slip motion forms the Düzce Plain, which is an extensional sedimentary basin filled with a column of sediments up to 260 m thick. The Alluvial deposits of Quaternary age, consisting of unconsolidated sediments composed of gravel, sand, silt and clay which overlay the other formations are the result of fluvial activity (Şimşek and Dalgıç, 1997).

Field measurements and data analysis

In this study, MASW records with 1.5 m geophone spacing (5 m offset) and 16.5 m spreading, and MAM records with 10 m geophone spacing (10 m offset) and 110 m in length have been employed. A combination of the dispersion curves obtained by these two different methods led to an achievement of a high resolution soil profile for seismic characterization. An analysis of the surface wave method led to the determination of a 1D shear wave profile which was used to obtain the velocity of the underlying strata. From the surface wave method conducted in the study area, a 3D V_s model was created (Figure 1). As expected in shallow bedrock, in the west of Gölyaka, the Vs velocity increases rapidly due to the fine alluvium cover. Towards the middle of the valley, the deeper the layers, the lower are the V_s values (Figure 1). In Figure 1, the 3D V_s model shown at Seis-27- 29- 30 measurement points are located on the Düzce fault according to the active faults proposed by MTA (2012) that have been measured in the proximity of the 1999 Düzce earthquake rupture. In addition, the measurements located in the southern edge of the Melen (Eften) lake and within the deformation zones that have been created by the Düzce fault, as well the thickness of the current Eften's unconsolidated soft lacustrine deposits are the other important factors that led to the observation of low V_s values. Furthermore, in the southeastern and eastern part of the area, low V_s values have been observed. During processing of the raw data received from the surface wave measurements, the phase velocity-frequency (VF) according to the scope of the initial velocity field conditions (zero) and the maximum expected end phase velocity have been determined. To achieve more reliable results with the use of these input parameters, the ending phase velocities need to be set according to site characteristics. VF values have usually been considered in the range of 2-15 Hz for MASW records and 5-30 Hz for MAM records for this study as proposed by Park et al. (1999) and Eker et al. (2012). The Phase shift Method has been selected for the MASW records while the Spatial Auto Correlation 2D conversion method has been selected for the MAM records. Finally, the obtained dispersion curve, using a nonlinear least squares method was used with the reverse process in the creation of the final V_s profile. In this step, phase velocity-frequency graphs (dispersion curve), the relative signal-noise ratio and the quality of the data points were checked. Examples of the processed velocity profile and the related dispersion curves obtained from the measurements in the basin at different sites are given in Figure 2 and Figure 3. The spatial distributions of V_{S30} and site classes for site effect assessment and microzonation have been determined. Vertical changes in sediment properties in the geological units, the relationship between the mean shear wave velocity of the upper 30 m of the soil profile and horizontal non-linearity in material properties and thickness of the layer and the site classes were investigated. The collected data was used to create the V_{S30} microzonation and site class map.

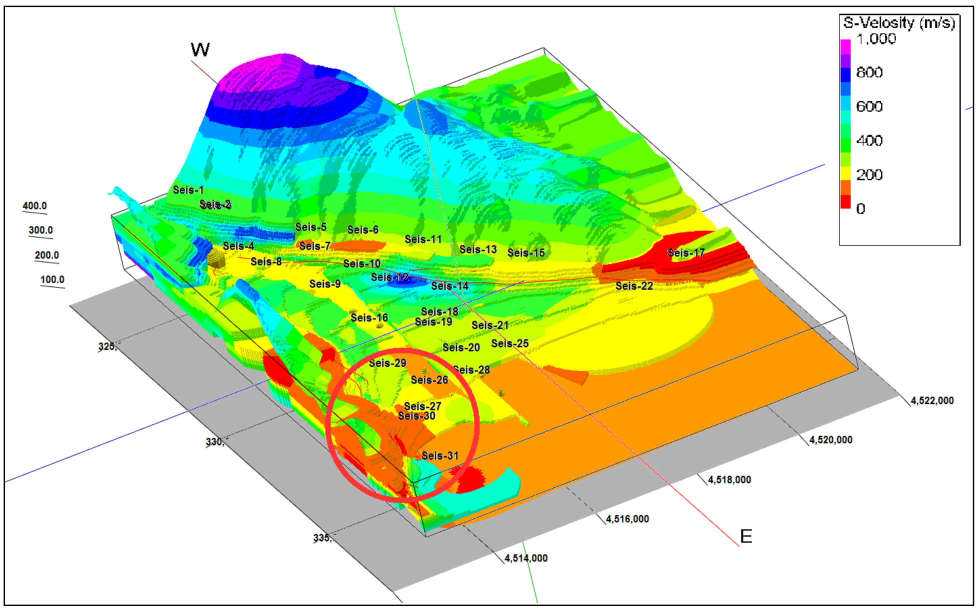

Figure 1. The 3-D V_s profile constructed for the study area from the seismic survey data and measurement points located on 1999 Düzce fault rupture illustrated in the red circle

Discussion

The alluvial deposits and other sediments and softer sedimentary rocks represent the most important geological units from the site effect point of view. In fact, due to the contrast between their generally poor mechanical characteristics and bedrock, strong site amplification of ground shaking could be expected. In the following paragraphs, the V_{S30} and PSHA results are presented.

V_{S30} results

Examination of the seismic survey method results reveals that the shear wave velocity varies from 98 to 197 m/s within the upper 10-15 m of the alluvial deposits. These values observed in alluvium (Holocene) or in the relatively high altitudes around the basin-ridge which contains thicker alluvium or the terrace deposits could be classified according to the IBC 2009 code as classes D and E, and as classes Z4-C and Z4-D according to TSC 2007. Considering the heterogeneity of the site, for the site class determination surface wave method by its own is not deemed sufficient. Hence, along the seismic data information and information obtained through boreholes (i.e., geotechnical parameters, the subsurface layer, groundwater levels, etc.) were combined and compared. The analysis results of combined active and passive surface wave method in Quaternary and Pliocene sediments, classified as IBC-E, IBC-D class, and soil profiles are given in Figure 3. As can be seen in Figure 3, depending on the thickness of the alluvial layer shear wave velocity varies significantly as expected. As the alluvium thickness increases towards the east the V_s decreases accordingly (V_{S30} <180m/s; IBC-E class) in Figure 4.

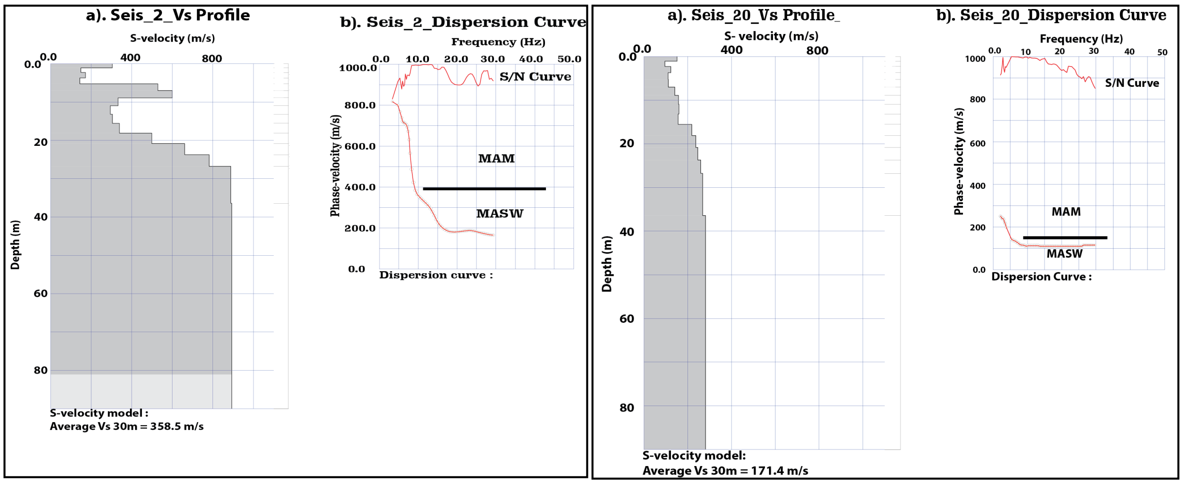

Figure 2. Examples of V_s profile from the two sites, namely, Seis-2 (left) and Seis-20 (right)

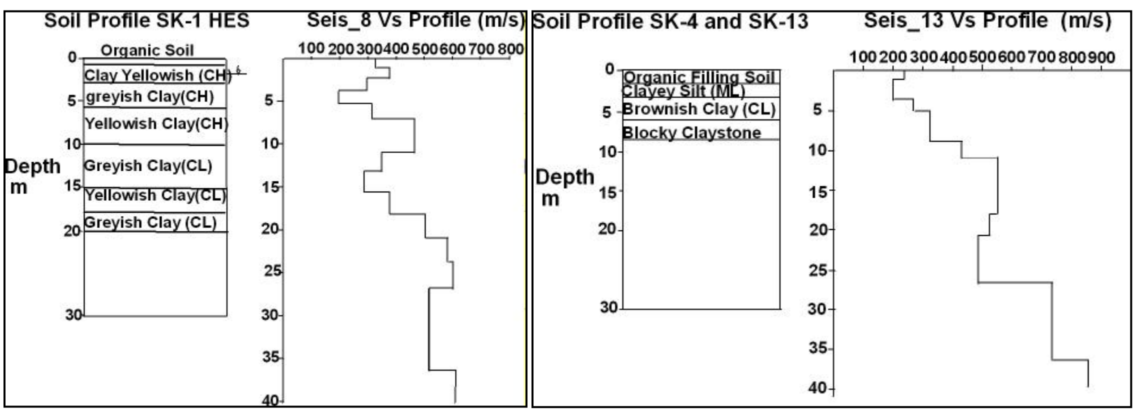

Figure 3. Comparison of the V_s profiles (Seis8-Log1 HES) with the adjacent boring logs (Seis13-Log 13 and 14), in left and right respectively

However, low shear wave velocity values in the thicker areas increases toward the west of the valley (i.e., towards the Upper-mid Eocene sedimentary deposits) as the bedrock depth decreases rapidly and in 30-40 m depth engineering bedrock of shear wave velocity values greater than 1100 m/s was observed. When examining the measurement results in the basin where the valley spreads, the engineering bedrock in the V_s profile has not been revealed up to 30-40 meters. In addition, not only the engineering bedrock was not observed at 55 m but deeper sediment layers with lower shear wave velocity values were observed. When the west and east side of the plain are compared (Figure 4), it is clearly observed that the relatively lower V_{S30} values are concentrated towards the east and southeast side of the plain. A possible reason is that the Efteni Lake has moved its course from the east and north toward southeast where the present lake and Düzce faults are located. Existence of unconsolidated lacustrine with different thickness and horizontal variation in material

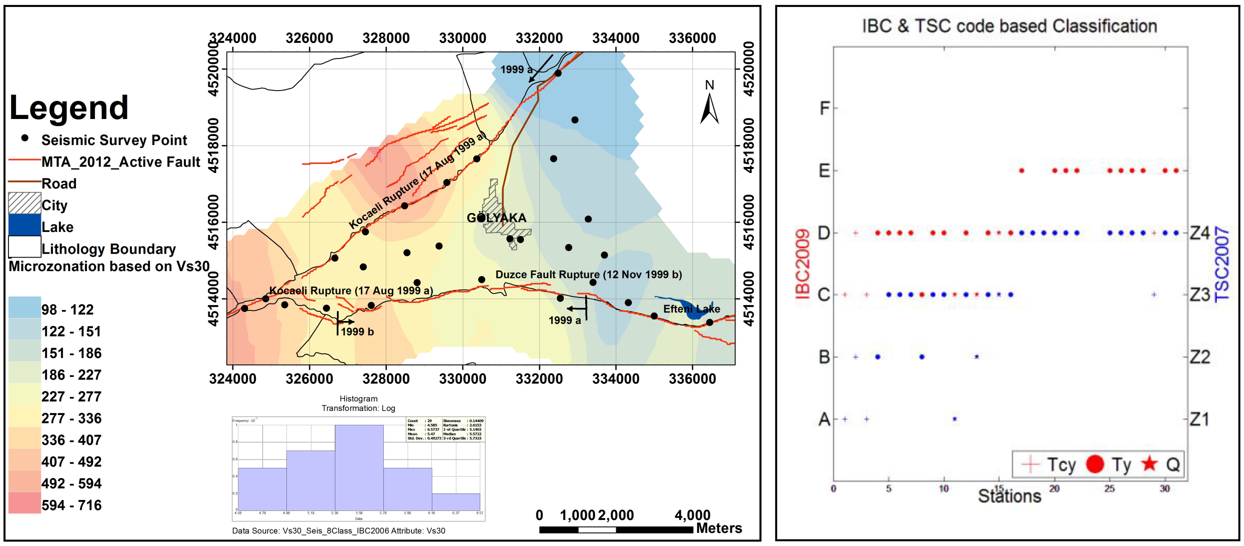

Figure 4. Left: The local seismic map based on measured mean V_{S30} measurements, right: The general distribution of the measured shear wave velocity results in different geologic units corresponding IBC 2009 and TSC 2007

properties and thickness may be other reason for observing different V_{S30} values (Figure 4-left). Figure 4 shows the seismic zonation map of the study area based on shear wave velocity measurements and the IBC site classes derived from these measurements. In the generation of the V_{S30} interpolation map, ordinary kriging method with constant semivariogram model type was performed to quantify the spatial structure of the data and to produce a prediction map in terms of the V_{S30} values by considering the anisotropy. In this technique, logarithmic transformation was applied in accordance with the distribution of the acquired data. By utilizing the trend analysis, the presence of the normal trend was determined and the Gaussian interpolation was used in the de-trending stage. Although some parts of the study area were not covered by the conducted seismic survey in terms of V_{S30} data, these were included in the regional seismic map presented by Figure 4 (left-hand side of the figure).

PSHA analyses and results

The PSHA analysis was conducted for each of the V_{S30} survey point. The PSHA is based on the methodology followed by Cambazoğlu et al. (2012) where seismic source model (segment lengths, widths and slip rates) is formed based on satellite image analysis (lineament extraction) and extensive literature survey (Figure 5). This is a generalized model encompassing the surface ruptures of the 1999 Kocaeli Earthquake, 1999 Düzce Earthquake, 1957 Abant and 1967 Mudurnu Earthquakes, 1944 Bolu-Gerede Earhquakes as well as the Geyve-İznik and Çınarcık

Fault Zones and Hendek Fault which is the eastern continuation of the Kocaeli surface rupture. Therefore, the effects of both near field and far field sources were included in the model for the analysis of the study area. The earthquake catalogue used in this PSHA (KRDAE, 2011) was declustered and the completeness of the catalogue was checked based on approach proposed by Stepp (1973) where catalogue was determined to be incomplete for earthquakes <4.6 starting from 1964 (Cambazoğlu, 2012). The Gutenberg-Richter 'b' value was determined as 0.68 which is concordant with the literature (Erdik et al., 2004; Deniz, 2006; Crowley and Bommer, 2006; Kalkan et al., 2009). The analysis was performed for four different GMPEs, namely Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) with equally weighted averages. The PSHA analyses was conducted for PGA including 3 standard deviations in order to encompass 99%, in other words the worst case scenario. The analyses was performed for 10% probability of exceedance for 50 years, corresponding to a 475 years return period. The results for the PSHA analysis are presented in Figure 6.

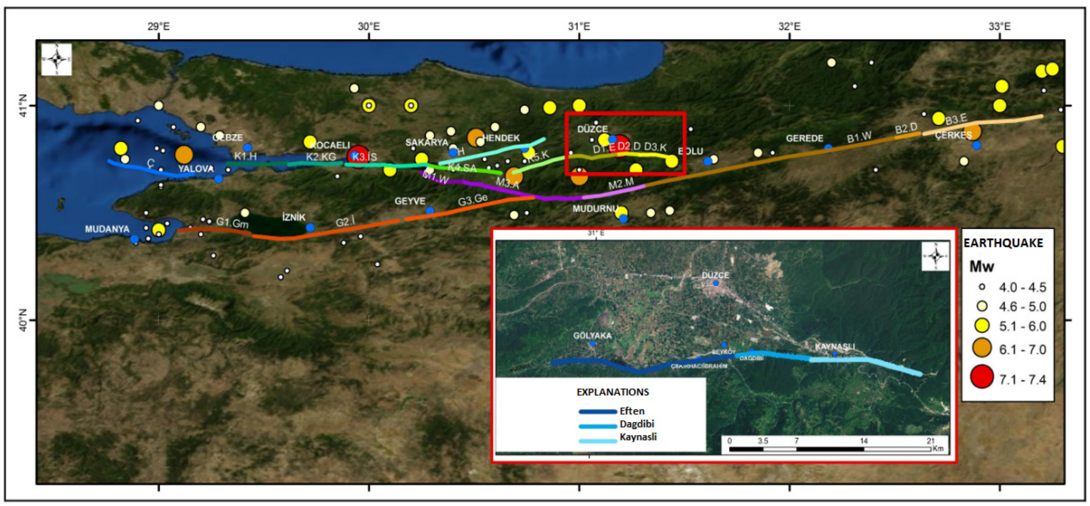

Figure 5. Seismic source model used in the PSHA analysis

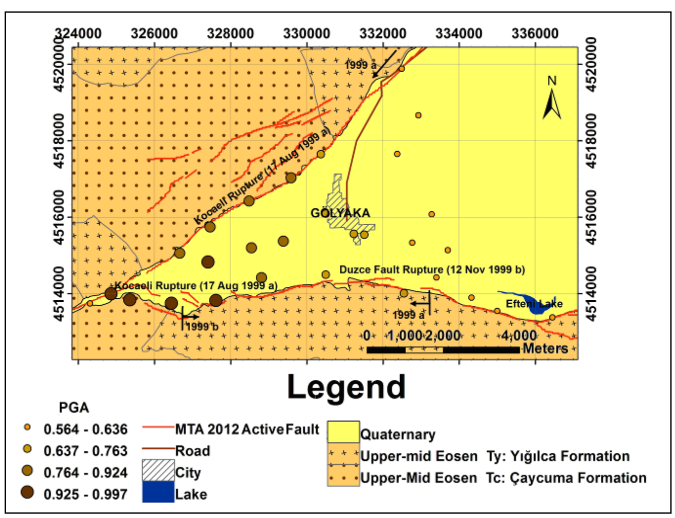

Figure 6. The PSHA results overlain on geology and active faults proposed by MTA, 2012.

Conclusions

This study attempted to obtain a V_s profile and seismic site characterization by using active and passive surface wave methods. The seismic survey data was complemented with geotechnical fieldwork to increase the reliability of the study. According to the V_s profile obtained from MASW and MAM measuring data, shear wave velocity of engineering bedrock was determined to be about 1100 m/s at shallow depths where the valley is narrower towards the west while in center of the basin, with increased alluvium thickness, the V_{S30} values have decreased significantly leading to IBC 2009 and 2007 TSC building codes of E and Z4-D and Z4-E, respectively. Soil classification by the IBC 2009 code in the older geological units in the investigated area (Yığılca and Çaycuma formation) and on the border between young with old units in the upper 30 m (30 m profile) shows higher V_s and firm ground, namely C and B (IBC 2009) and Z2-Z2-C (TSC 2007) due to soil material non-linearity effects. Results of this study by utilizing microzonation is important in terms of seismic hazard and site-specific studies for the developing district of Gölyaka-Düzce that is located on Plio-Quaternary basin and one of Turkey's major earthquake potential zone near NAFS. In this study, sites with shear wave velocity lower than 180 m/s are prone to high seismic hazard and should be paid special attention. At the same time, the effect of non-linear behavior of the basin edge has been observed in the V_{S30} map. Furthermore, based on the PSHA results; considering the seismic source model used in this study, it can be observed that the PGA values are strongly dependent on the distance to source parameter while non-linear behaviour of the PGA values due to variation in V_{S30} data could also be observed.

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