DEVELOPMENT OF A 3-D TOPOGRAPHICAL BASIN STRUCTURE BASED ON SEISMIC AND GEOTECHNICAL DATA: CASE STUDY AT A HIGH SEISMICITY AREA OF GÖLYAKA, DÜZCE, TURKEY

Karim YOUSEFI-BAVIL¹, Mustafa K. KOÇKAR², Haluk AKGÜN³

ABSTRACT

The near-fault situation and high seismicity of an area makes the determination of the bedrock geometry more complex, and in return, it makes this area much more critical and important for the studies of site response analysis in account of seismic hazard assessment. Without a good model of topography and basin structure, any powerful calculation method would be in lack of a well-developed basin response. The study has been conducted in the Gölyaka basin that uniquely falls within the bifurcated section of the North Anatolian Fault System. The surface rupture of the 1999 Earthquakes of Kocaeli (Mw=7.4) and Düzce (Mw=7.2) bound this tectonically formed basin, respectively.

In the study area, a 3-D basin structure of the model has been developed based on the geophysical and geotechnical data along with the geology. In particular, combined active and passive surface wave methods along with the H/V microtremor measurements at 29 locations, the vertical electrical sounding at 14 locations, the geotechnical boring data at about 30 locations and one deep boring data have been used to develop the structure of the sediment basin. The high-resolution 1-D shear wave velocity profile has been obtained through surface wave methods by using active Multichannel Analysis of Surface Waves (MASW) and passive Microtremor Array Method (MAM), respectively. The Schlumberger Vertical electrical sounding (VES) method has been applied to evaluate the bedrock of the basin depth. Furthermore, the H/V measurements have been carried out to be correlated with the fundamental period of the deepest point of the constructed basin. Finally, geotechnical and deep boring data have also been used along with the basin geology to be cross-referenced with the 1-D V profile. The result of this comprehensive survey led to a well-developed 3-D geometry model of the Gölyaka basin.

The 3-D basin geometry model has been developed from the seismic surface wave results and later correlated with the results of the VES, deep Gölyaka basin fundamental periods and geotechnical boring data. Based on the surface wave results and the 2-D velocity profiles obtained, a bedrock level with an average velocity of 1100 m/s was accepted as the bedrock depth limit in the region. The implemented deep and geotechnical boring data with seismic results suggested that Gölyaka basin is composed of about five to seven sedimentary layers. It was concluded that the thicknesses of the alluvial sediments within the Gölyaka basin were estimated to be about 200-350 m, with irregular basin geometry and heterogeneity due to over-step faulting near the basin boundary. Furthermore, this in return, has resulted in inclined layering and nonlinearity in the velocity profile. The constructed model can successfully be used for site effects characterization and response studies in the region.

Keywords: Basin Topography; H/V Methods; VES; 3D-V; Basin Geometry Model; Gölyaka-Düzce

1. INTRODUCTION

Seismic events in the last few decades have demonstrated that local site conditions, particularly near

¹M.Sc., Geotechnology Unit, Geological Engineering Department, Middle East Technical University, Ankara, Turkey, kyousefibavil@gmail.com
²Ph.D., Earthquake Engineering Implementation & Research Center, Gazi University, Ankara, Turkey, mkockar@gazi.edu.tr
³Prof. Dr., Geotechnology Unit, Geological Engineering Department, Middle East Technical University, Ankara, Turkey, hakgun@metu.edu.tr
earthquake prone areas that can generate significant amplifications and spatial variations of earthquake ground motion, play a major role in the level of ground shaking. Hence, the amplification of ground motion due to local site effects (i.e., topographical conditions, ground motion resonance and basin geometry) plays an important role in increasing seismic damage (e.g., Rodriguez-Marek et al., 2001; Koçkar et al., 2012; Eker et al., 2015; Koçkar, 2016). 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 and Sichuan 2015) have brought additional evidence of the dramatic importance of site effects. In the near-source region ground motions may exhibit forward directivity effects due to the rupture front and direction of slip being aligned with the direction toward the site of interest (Brendon et al., 2011). Furthermore, seismic velocity model complexity in the form of velocity contrast with a low velocity are expected to be important in site-specific ground motions at sites located close to the fault or within the low velocity fault zone (Dreger et al., 2007). Also, according to Sandron et al. (2011), the response of the alluvial to weak events was more stable than its response to strong ones. In addition, modeling weak events was easier than strong ones in the near field. The study area is located in the Gölyaka basin that is within the Eastern Marmara Region and that uniquely falls within the bifurcated section of the North Anatolian Fault System (NAFS). The surface rupture of the 1999 Düzce and 1999 Kocaeli Earthquakes bound this tectonically formed basin respectively, from south to 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 (Afet İşleri Genel Müdürlüğü, Deprem Araştırma Dairesi, 2000).

In this study, considering the concept given above, the local site conditions and the dynamic characteristics of sediments have been evaluated in the study area. Then, the basin geometry has been developed to characterize the sediment conditions based on the Vₛ profiles that has successfully developed through the surface seismic surveys at 29 sites. Then, these results have been correlated with the topographical, vertical electrical sounding, geological, geotechnical data along with H/V results to discuss the heterogeneity and basin effects on the consequences of seismic hazards. In general, according to the Vₛ profile obtained from surface wave measuring data, shear wave velocity of the engineering bedrock was determined to be about 1100 m/s. The deepest estimated alluvial thickness was about 200-350 m in the center of the basin. Evidence on the existence of faulting can be obtained from the deep boring and vertical electrical sounding survey results along with the geology and topography. This study shows that the higher fundamental period values are not always accompanied with the higher H/V amplitudes in the area because of impedance contrast resulting from the velocity contrast in the sites. The constructed model in this study can be reliably used for local site effects and site response studies in near field.

2. GEOLOGY AND SEISMICITY OF THE STUDY AREA

2.1 Geology

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 (Figure 1). 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).
2.2 Seismicity of the study area

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, namely 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 Elmalk 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).
2. METHODS

Basin geometry modelling of the study area was carried out by means of all geological, geotechnical and geophysical studies. In the following subsection, the methods and the tools that were used for this purpose are briefly explained.

2.1 Geological and Geotechnical Engineering Data

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). A total of 30 shallow geotechnical boring data along with one deep groundwater survey boring data have been used in this site investigation study.

2.2 Seismic Surface Wave Methods

In this study, Multichannel Analysis of Surface Wave (MASW) active methods, records with 1.5 m geophone spacing (5 m offset) and 16.5 m spreading, and Microtremor Array methods (MAM), passive methods, records with 10 m geophone spacing (10 m offset) and 110 m in length have been employed at 29 sites for each testing study. A combination of the dispersion curves obtained by these two different methods (i.e., active and passive) led to an achievement of a high resolution deep soil profile for seismic characterization. An analysis of the surface wave method led to the determination of a shear wave soil profile that was used to obtain the velocity results of the underlying strata. From the surface wave method conducted in the study area, a 3-D Vs model was created.

2.3 Vertical Electrical Sounding (VES)

The Vertical Electrical Sounding (VES) has proved very popular with engineering investigations due to the simplicity of the techniques. The electrical geophysical survey method is the detection of the surface effects produced by the flow of electric current inside the earth. Vertical Electrical Soundings (VES) using Schlumberger array were carried out at 14 stations. Overburden in the basement area is thick and warrant large current electrode spacing for deeper penetration, therefore the largest current electrode spacing AB/2 used was 1250-600 m.

2.4 H/V Method

The H/V technique is based on the spectral ratio of horizontal to that of the vertical recording of ambient noise at a single site (Nakamura, 1989). The method was intended to achieve the amplification of the S-waves due to soft sediments by microtremor measurements. It is claimed that the spectral ratio of the horizontal to vertical components of the recorded ambient noise is equivalent to the ratio of the S-waves from an earthquake recorded on the surface of the sediments to that of the sediment–bedrock interface at the bottom of the sediment layer (Atakan, 2009).

The 29 microtremor measurements were recorded at the seismic survey locations by using single mobile velocimeter and analyses of these records were processed by the H/V technique (Nakamura, 1989). The majority of the records were taken from the Quaternary sites. The spectral ratio between the horizontal and vertical components (H/V) of the microtremor measurements at the ground surface has been used to estimate the fundamental periods and the H/V amplitudes of the site. Experimental data obtained by microtremor measurements were used in correlation with the available geological, geotechnical and surface seismic tests results to obtain much more reliable and comprehensive information on the Plio-Quaternary sediments, and thus to identify and characterize the site amplification and fundamental frequency in urban areas.

3. RESULTS
3.1 Geological and Geotechnical Results

The shallow geotechnical (<20 m) along with the deep boring data (168.5 m) indicate clay, gravel, silt and sand in shallow surfaces while a thick layer of clay (61 m thick) at a depth of 64-125 m and sand with 43 m thickness below the clay layer up to a 168 m depth exists (Figure 1 and Figure 2). The Plasticity Index ranges between 10-25% up to depth of 15 m as revealed from the samples obtained from the geotechnical tests.

![Figure 2. Geotechnical and groundwater boring soil profile survey of the study area.](image)

3.2 Seismic Surface Wave Results

A 3-D V_s model of the study area was developed through combined passive (MAM) and active (MASW) surface wave methods. The evaluation of the surface seismic results reveals that the shear wave velocity results are less than 180 m/s within the upper 10-15 m of the alluvial deposits. These values are observed in alluvium (Holocene) or in the relatively high altitudes around the basin-ridge which contains thicker alluvium or the terrace deposits. In both case, the V_s results are less than 150 m/s which implies the presence of groundwater. Considering the heterogeneity of the site, the surface wave method by its own is not deemed sufficient. Hence, the seismic results and information obtained through the boreholes (i.e., geotechnical results, the subsurface layer thickness, groundwater levels) were combined and compared. The analysis results of combined active and passive surface wave method in Plio-Quaternary sediments were determined and presented as a whole in developing the 3-D basin model. As can be seen in Figure 3, the shear wave velocity results vary significantly as expected depending on the thickness of the alluvial layer. As the alluvium thicknesses increase towards the east, the V_s results decrease accordingly. However, the shear wave velocity results increase toward the west of the valley (i.e., towards the Upper-mid Eocene sedimentary deposits) where the bedrock depths decrease rapidly at about 30-40 m and in the engineering bedrock shear wave velocity values greater than 1100 m/s were observed. When examining the measurement of these results in the basin where the valley spreads, the thickness of the engineering bedrock in the V_s profile has not been revealed approximately up to 200-250 meters. Hence, the engineering bedrock was not observed in the middle of the basin depth (i.e., 50-100 m) due to penetration of these sediments having lower shear wave velocity results to this depth. According to Dreger et al. (2007), complexity of the seismic velocity model in the form of velocity contrast with a low velocity are expected at sites located close to the fault or within the low velocity fault zone. The V_s results have proved this agreement in the study area, especially near the faulting area in the south edge of the basin and to the south east of the basin.
Furthermore, these complexities in the velocity contrast observed in the center of the basin where the layers having lower shear wave velocity results observed at middle of the depth as stated before. When the west and east side of the plain are compared (Figure 3), it is clearly observed that the relatively lower $V_s$ results 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 the north towards the southeast where the present lake and Düzce faults are located. Existence of unconsolidated lacustrine sediments with various thicknesses and horizontal variation in material properties, their thicknesses and different consolidation degrees might be the other reason for observing different $V_s$ results or velocity contrast in the basin center and the edges.

![Figure 3. A 3-D $V_s$ model of the study area](image)

### 3.2 Vertical Electrical Sounding (VES) Results

The VES results provide additional information to estimate the thickness of the alluvial deposit and the depth of the engineering bedrock along with the faulting zone based on the geology and topography in the study area. The thickness of the alluvial deposit varies in the basin. The deepest estimated alluvial thickness is about 200-350 m in the center of the basin. From the center to the edge of the basin as the resistivity increases, the thickness of the alluvium decreases. The resistivity of the surface soil is less than about 20 Ohm.m while the resistivity values increase with depth (~200 Ohm.m) for bedrock of fractured sandstone/andesite in the study area. The existence of the faulting along with the geological observation can be estimated from the resistivity diagram in Figure 4 and Figure 5.
Figure 4. Three parallel VES profiles (Apparent resistivity decrease due to faulting zone)
3.2 H/V Results of Microtremor Study

Fundamental periods and the maximum values for the H/V amplitudes were estimated from the microtremor measurements at 29 sites in the study area. When the distribution of the fundamental periods is examined (Figure 6), higher fundamental periods were generally observed along the sites located within the alluvial basin of thick Quaternary sediments. As can be seen in Figure 6, the periods range in between 0.26 and 1.67 s. The relatively larger thickness of the soft soil deposits is a possible explanation for the dominancy of the periods greater than 0.6 s. Towards the northern part of the region, predominant site periods for the Quaternary deposits decrease with a decrease in soil thickness as expected. Analyses of the period peaks with subsurface geology reveal the presence of relative thickness of the soft sediments in the Gölyaka basin. The same soil behavior was observed by several researchers (i.e., Bour et al., 1998; Gueguen et al., 1998; Bodin et al., 2001; Duval et al., 2001; Nguyen et al, 2004; D'Amico et al., 2008; Rosenblad and Goetz, 2010, Eker, et al., 2015). This manifests itself more clearly when the impedance contrast ratio between the relatively stiff and soft sediments is high. The amplification of ground motions at a site is significantly affected by the natural period of a site by considering both shear wave velocity and soil depth. Since, the velocity contrast is observed in the shear wave velocity profile, we know that the shear velocity has its own effects on the natural periods of the sites. On the other hand, the microtremor results are highly dependent on the impedance contrast differences between the layers as a result of velocity and material density. So, naturally, this contrast can be observed in the H/V amplification. However, when the distribution of the fundamental periods at the north and the south sides of the plain is to be examined, it is being explicitly seen that the fundamental periods of the deposit at these parts of the plain are generally lower than that of the center. That might be the reason for the lower periods in the edges due to shallow bedrock depth.
4. CONCLUSIONS

This study attempted to obtain a $V_s$ profile and develop a 3-D basin model by using surface wave methods. The seismic survey results were complemented with electrical sounding, geotechnical and H/V results to increase the reliability of the study. According to the $V_s$ profile obtained from surface wave measuring data, shear wave velocity of engineering bedrock was determined to be about 1100 m/s.

Seismic velocity contrast with a low velocity was observed at sites located close to the fault or within the low velocity fault zone due to near field effects. These effects can be observed especially near the faulting area in the south edge of the basin and towards the southeast of the basin. Furthermore, these complexities in the velocity contrast are observed in the center of the basin where the sediment layers having lower shear wave velocity results are observed at the middle of the basin depth (i.e., 50-100 m).

The estimated maximum thickness of the alluvial sediments is about 200-350 m in the center of the basin. As the resistivity results increase, the thickness of the alluvium decreases from the center to the edge of the basin. The existence of the faulting zone along with the geological and topographical observation can be estimated by using the resistivity results.

The amplification of ground motions at a site is significantly affected by the natural period of a site considering both shear wave velocity results and soil depth. However, this study shows that the higher fundamental period values are not always accompanied with higher H/V amplitudes in the area because of impedance contrast resulting from velocity contrast in near field sites. The microtremor results are highly dependent on the impedance contrast differences between the layers. Therefore, at locations where the bedrock is close to the surface, the H/V technique gives higher amplitudes corresponding to their relatively lower periods. The higher amplification results at fundamental periods were observed along the Quaternary sediments of the studied region which generally
corresponded to the thicker unconsolidated materials that possessed low shear wave velocity characteristics within this unit.

The over-step nature of the Düzce fault that has resulted in differential sediment thickness and heterogeneity in basin geometry has in return provided nonlinear behavior in the velocity and in the dynamic parameters of the basin sediments. Thicker sediment deposits has led to higher fundamental periods. This especially could be observed more clearly when the H/V measurements on the center of the plain are compared with those at the edge of the basin. Evolution of these sediments might have been associated with the tectonic faulting activities in the study area. The constructed model in this study can be reliably used for site effects and response studies in near field sites of the studied region.

5. ACKNOWLEDGMENTS

The authors would like to thank the Middle East Technical University (METU) Scientific Research Project (BAP-03-09-2012-002) for providing financial support to this study.

7. REFERENCES


