NEAR FIELD SEISMIC SITE RESPONSE ANALYSIS OF ALLUVIAL BASIN: A CASE STUDY FOR THE GÖLYAKA, DÜZCE, TURKEY

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ABSTRACT:

Seismic events in the last few decades have demonstrated that local site conditions particular near 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, etc.) plays an important role in increasing seismic damage. The study area is located in the Gölyaka basin that is located within the Eastern Marmara Region and that uniquely falls within the bifurcated near field 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. Considering the concept given above, the local site conditions and 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. To identify the local site effects, the site response analysis (SRA) has been widely used to quantify the local site conditions on propagated ground motions in research and practice. Hence, 1-D site response analyses have been performed considering the nonlinear behavior of the soil deposits using an equivalent linear approach. Then, these results have been correlated with the developed basin model determined by Vs profiles. In general, the site response analyses conducted in the lower Vs prone areas (<180 m/s) demonstrated higher de-amplification levels even in strong motion due to nonlinear behavior in near field (i.e., topographic effect, basin geometry). Similarly, this effect was also unexpectedly observed at some places in the center of the basin for Vs ranges between 180-360 m/s. Although, the sites near the fault rupture show higher amplification, due to topographic effects some exhibit lower amplification for strong motion. Furthermore, apart from the reliable results, the 1-D site response analyses results could not be accurately verified at some places because of the local site effects that could have generated spatial variations in the near field site depending on the dimensional basin geometry and topographical effects.

KEYWORDS: Site Characterization, Site Response Analysis (SRA), Local Site Effects In Near Field, Vs Model For Alluvial Basin, Gölyaka, Düzce

1. INTRODUCTION

Seismic events in the last few decades have demonstrated that local site conditions particular near 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, etc.) plays an important role in increasing seismic damage (e.g., Rodriguez-Marek et al., 2001, Koçkar and Akgün, 2012, 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, 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 Göltyaka and the other areas of Düzce that have been affected by the earthquake are to be rebuilt with the awareness of 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).

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 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 Göltyaka basin that is within the Eastern Marmara Region and that uniquely falls within the bifurcated near field 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 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. To identify the local site effects, 1-D site response analyses have been performed considering the nonlinear behavior of the soil deposits using an equivalent linear approach. Then, these results have been correlated with the developed dimensional basin model determined by Vs profiles discussing the consequences of seismic hazards.

In general, the site response analyses conducted in the lower Vs prone areas (<180 m/s) demonstrated higher de-amplification levels even in strong motion due to nonlinear behavior in near field (i.e., topographic effect, basin geometry). Similarly, this effect was also unexpectedly observed at some places in the center of the basin for Vs ranges between 180- 360 m/s. Although, the sites near the fault rupture show higher amplification, due to topographic effects some exhibit lower amplification for strong motion. Furthermore, apart from the reliable results, the 1-D site response analyses results could not be accurately verified at some places because of the local site effects that could have generated spatial variations in the near field site depending on the dimensional basin geometry and topographical effects.

2. 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. The NAFS 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 NAFS (~10 mm/yr). The Düzce fault separates the Paleozoic–Eocene formations of the Almacık block from the Pliocene–Quaternary continental deposits of the Düzce pull-apart basin. The 1999 Düzce surface rupture is adjacent to the Karadere segment of the 1999 Kocaeli surface rupture from the west. 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 NAFS 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).

The study area is located in the Gölyaka basin that is located within the Eastern Marmara Region and that uniquely falls within the bifurcated near field 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. Considering the concept given above, the local site conditions and dynamic characteristics of sediments have been evaluated in the study area.

3. GEOLOGY AND SUBSURFACE SEDIMENT CHARACTERISTICS

The Precambrian Yedigöller Formation, which is mainly composed of jointed and fractured metagranites, amphibolites and gneiss (Aydın 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 Yiğılca 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). The shallow geotechnical boring data (<20 m) and deep groundwater survey boring (168.5 m) illustrate the Clay, gravel, silt and sand in shallow surface while thick layer of clay (61 m thick) in depth of 64-125 m and sand with 43 m thickness below the clay layer up to 168 m depth (Figure 1 and Figure 2).

4. METHODOLOGY

The local site conditions and 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. To identify the local site effects, the site response analysis (SRA) has been widely used to quantify the local site conditions on propagated ground motions in research and practice. Hence, 1-D site response analyses have been performed considering the nonlinear behavior of the soil deposits using an equivalent linear approach.
5. RESULTS AND DISCUSSION

The results have been correlated with the developed basin model determined by Vs profiles (Figure 5). 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 strength characteristics and bedrock, strong site amplification of ground shaking could be expected. In the following paragraphs, the $V_{S30}$ and SRA results are presented.

5.1. $V_{S30}$ results
Evaluation 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 E and D, 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 results and information obtained through boreholes (i.e., geotechnical parameters, the subsurface layer, groundwater levels) 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 2. As can be seen in Figure 3, the shear wave velocity values vary significantly as expected depending on the thickness of the alluvial layer. As the alluvium thickness increases towards the east, the Vs decreases accordingly (V_{S30} <180m/s; IBC-E class) in Figure 4. 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 Vs 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. Due to Dreger et al., (2007), seismic velocity model complexity 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 Vs results have proved this agreement.

Figure 3. Examples of Vs profile from the two sites, namely, Seis-2 (left) and Seis-20 (right)

Figure 4. Comparison of the Vs profiles (Seis8-Log1 HES) with the adjacent boring logs (Seis13-Log 13 and 14), in left and right respectively
When the west and east side of the plain are compared (Figure 6), 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 properties and thickness may be other reason for observing different $V_{S30}$ values (Figure 6(a)). Figure 6 shows the seismic zonation map of the study area based on shear wave velocity measurements (Figure 5) and the IBC site classes derived from these measurements (Figure 6). 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 detrending 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 6(a). Based on the IBC and TSC site classification, E, D, Z3 and Z4 is the most common class in the study area (Figure 6(b)).

Figure 5. 3-D Vs model of the study area

Figure 6 (a) The local seismic map based on measured mean $V_{S30}$ measurements, (b) The general distribution of the measured shear wave velocity results in different geologic units corresponding IBC 2009 and TSC 2007
5.2.1-D Site Response Analysis (SRA)

In the practice of seismic engineering for current building, a designer considering an alluvial site in a plain with known stratigraphy and geophysical characteristics and almost flat bedrock at approximately 50 m depth may be sufficiently confident in seismic codes and in his/her ability to forecast the seismic response of the site with a simple 1-D model and a plane wave travelling vertically. In this situation, however, surface waves are neglected (Sandron, et. al., 2011). Sometimes, though, near-field conditions are not as simple, and sites with an almost 1-D structure can display unusual behaviors. They documented a case history of this type in which a 1-D deterministic forecast was able to simulate the dynamic behavior of the site only partially. Modern 1-D analyses with vertically propagating SH waves are commonly performed for sites with horizontally layered structures (Kramer, 1996; Hashash and Park, 2001). In SHAKE (Schnabel et al., 1972; see also Idriss and Seed, 1968; Seed and Idriss, 1970; Kramer, 1996), the Kelvin–Voigt model is implemented with strain-dependent curves for the shear modulus and the damping ratio, and the wave propagation equation is solved in the frequency domain (Sandron, et. al., 2011). The results of 1-D SRA selected analysis given in Figure 7 based on 1) the depth of the alluvial, 2) the unusual behavior of the response near the faulting, 3) most common class C and D in the study area, and 4) availability of geotechnical data. The results of the response analysis shows that the study area most excited on period about 1 s. Also by comparing the target response spectra with the average response of seven earthquake scenario in the analysis amplification and peak response shifted to the long periods. There is a good agreement between the geological study and Vs profile of the study area. In the Figure 7 of Seis17, de-amplification can be observed that based on the UBC site class it is E-class. According to Sandron et al. (2011) the response of the alluvial to weak events was more stable than its response to strong ones. This less stability to strong motion can be observed in the SAR results that is due to near field motion excitation. Also unexpectedly, the response of motion is large in the long period compare to the short period even next to the fault zone. This can be observed especially for 1999 Kocaeli and Düzce motions (Figure 7). The response spectra of the site in the middle of the basin (Seis-11 and Seis 13) follows the same shape of target response spectra that can be of deep alluvial sediments with almost no topographic effects (Figure 7).

1. CONCLUSION

This study attempted to obtain a Vs profile and seismic site characterization by using surface wave methods. The seismic survey data was complemented with geotechnical fieldwork to increase the reliability of the study. According to the Vs profile obtained from surface wave 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 Vs and firm ground, namely C and B (IBC 2009) and 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 Gölçay-Düzce that is located on Plio-Quaternary basin and one of Turkey’s major earthquake potential zone near NAFS. In this study, the effect of non-linear behavior of the basin edge has been observed in the $V_{S30}$ map. Furthermore, apart from the reliable results, the 1-D site response analyses results could not be accurately verified at some places because of the local site effects that could have generated spatial variations in the near field site depending on the dimensional basin geometry and topographical effects.
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REFERENCE


