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ABSTRACT

This study encompasses dynamic soil characterization and seismic hazard mapping of the Plio-Quaternary and especially Quaternary alluvial sediments of the Çubuk district and its close vicinity that is situated towards the north of Ankara. The project site is located at a region which has a potential of being seriously affected by a possible earthquake occurring along the Çubuk Fault Zone that is thought to be a continuation of the Dodurga Fault Zone and a sub-fault belt of the North Anatolian Fault System that is one of the most prominent fault systems in Turkey with significant earthquake potential. Non-invasive seismic methods were used to obtain a 1-D shear wave velocity profile of the subsurface at 41 sites and two measurements were taken at each site for passive and active surface wave methods. The Multichannel Analysis of Surface Wave Method (MASW) and the Microtremor Array Method (MAM) were used as active and passive surface wave methods, respectively. By combining these two techniques, the shear wave velocity profiles of the sites were obtained. Based on the results, site classes were assigned for seismic hazard assessment studies followed by a preparation of a seismic zonation map of the site utilizing GIS software.

INTRODUCTION

The sedimentary deposits that affect wave propagation should be identified by an efficient tool in order to characterize and classify the sites based on the effects of the soil types related with ground motion response. An important element in establishing seismic design criteria for an engineering site is the measurement of seismic shear wave velocity (V_s). At present, site characterization is often reduced to the specification of a single number, i.e., V_{s30}, shear-wave velocity over 30 m from the surface (Borcherdt, 1994). This number is used in some well-known building codes (IBC 2000-2003, UBC97, and NEHRP) to classify the site and to compute the expected site amplification characteristics and fundamental period of the soil profile. Recently, the surface wave method has become the seismic technique most often used to estimate the shear wave velocity of the soil because of its non-invasive nature and greater efficiency in data acquisition and processing, cost as well as time (Stokoe et al., 1994; Miller et al., 1999, Park et al., 1999, and Park Seismic, 2009).

The purpose of this study is to characterize the dynamic soil properties and to develop a seismic map of the Upper Pliocene to Pleistocene fluvial sediments and especially the Quaternary alluvial deposits of the Çubuk district and its close vicinity. The study area covers the Çubuk district and its close vicinity, mainly the north part of the Çubuk Plain which is situated approximately 38 km north of Ankara (Fig. 1). In the content of this study, sediment conditions were determined and soil profiles were characterized by surface geophysical methods at different locations. Non-invasive seismic methods such as the Multichannel Analysis of Surface Wave Method (MASW) and the Microtremor Array Method (MAM) were used to obtain a 1-D shear wave velocity profile of the subsurface at 41 points. These two measurements were taken at each of the 41 points for passive and active surface wave methods. To meet the requirements of preserving high resolution at shallow depths while also extending the shear wave velocity measurement to greater depths, a combined usage of the active and passive surface wave methods was adopted. Dynamic soil characteristics of the study area have been assessed by detailed geotechnical seismic site characterization in the region. Based on the results, site classification systems were utilized for seismic hazard assessment studies followed by a preparation of a seismic zonation map of the site utilizing GIS software.

GEOLOGY AND SEISMOTECTONICS

The Çubuk depression area or tectonic basin is occupied by both lacustrine and fluvial clastics and contains volcanic intercalations (Tabban, 1976; Koçyiğit and Türkmenoğlu, 1991). Based on the tectonic regime and style of deformation, the units exposed in and nearby the study area are classified into two categories, namely, paleotectonic units or basement rocks, and neotectonic units. The rock units cropping out in the region range from Triassic to Quaternary in age. The older rock units in the region are highly deformed pre-Upper Miocene basement rocks, Miocene deposits and Upper Miocene-Lower Pliocene rocks (Fig. 2). The older stratigraphic rock units in this region are overlain uncomfortably by the horizontal or gently dipping Upper Pliocene to Pleistocene fluvial red clastics and Quaternary alluvial deposits (Erol et al., 1980; Koçyiğit and Türkmenoğlu, 1991; Akyürek et al., 1996). In concordance with the scope of this study, the engineering geological and seismic site characteristics of the neotectonic units (the Upper Pliocene to Pleistocene fluvial red clastics and Quaternary alluvial and terrace deposits) were mainly investigated, and site classification of these sediments were performed.

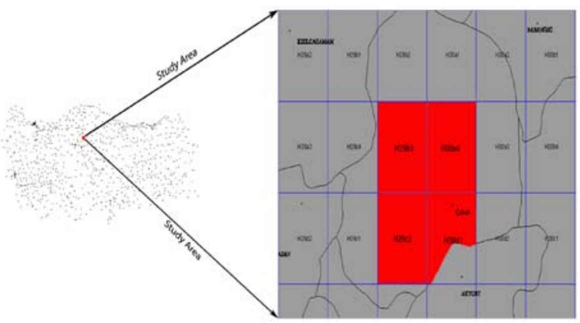


Fig.1 Location map of the study area.

Based on the type and nature of active tectonic regimes and related structures such as faults and basins, an intra-continental tensional neotectonic regime and oblique slip normal faulting characterize the study area (Koçyiğit, 2003). There are many faults having a capability to produce frequently small to moderate seismic events present in the Çubuk Region and the surrounding area. In the area, the main tectonic unit is the Çubuk Fault Zone which is a normal fault with an approximate trend of N20º-30º (Kupan, 1977, Koçyiğit, 1991). It defines the margins of the NE-SW trending Çubuk basin. The tectonic movements are the first sign of the beginning of today's Çubuk Plain formation (Erol, 1980). The basin has taken the form of a graben due to the normal faulting (State Hydraulic Works (DSİ), 1979). Seismic activities that have occurred in this region recently, especially the Orta earthquake (MW=5.9) in June 6th, 2000 and the Çubuk earthquakes (M=4.0) in June 6th, 2000; (Ml = 4.6) in December 29th, 2004 and in January 31st, 2008 (Ml = 4.9) are the most important indicators of this phenomenon. Because of this reason, sediment conditions and soil profiles were characterized in regards to seismic hazard assessment.

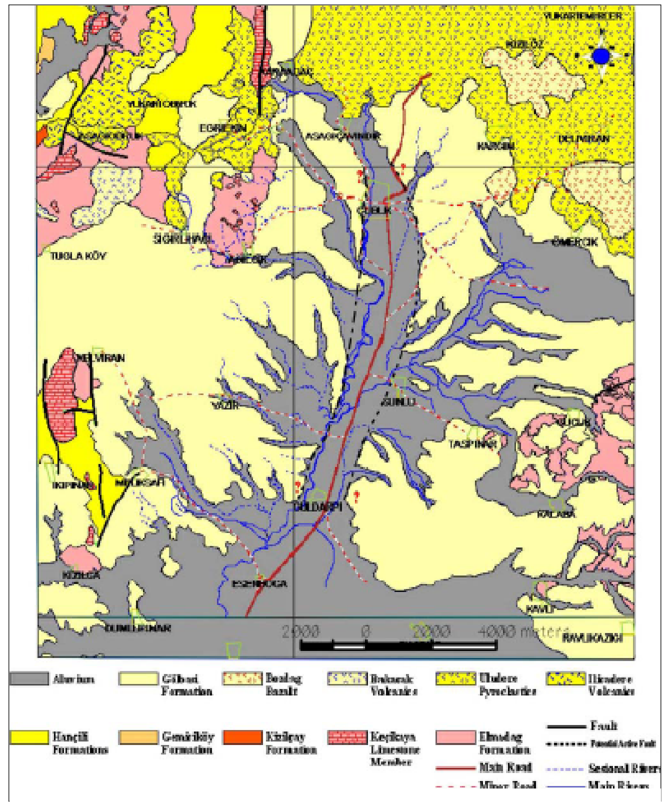


Fig. 2. Geological map of the study area (modified from MTA, 2008 digital database based on the results of the field studies).

SEISMIC SITE CHARACTERIZATION STUDIES

One simple way of determining site condition in seismic hazards estimations is to utilize the characteristic shear wave velocity in shallow depths to classify the stiffness of the geo-materials and to produce a seismic hazard map. The average shear wave velocity for the uppermost 30 m of the soil profile is simply used in the seismic codes (IBC 2003 and 2006, UBC97, and NEHRP, etc) to classify sites into the categories that can be used for assessing the spatial variations of the ground motion in the area. Also, shear wave velocity is an invaluable parameter to distinguish the lithologies quantitatively based on their depositional settings and age. As a result of these, 41 shear wave velocity measurements were taken by active and passive surface wave methods due to the their advantages as mentioned above.

All active and passive measurements were generally recorded in a linear array configuration with twelve 4.5 Hz natural frequency vertical geophones with 5 m spacing. In the MASW method (Park et al., 1999), the offset distance (i.e., the distance between the source and the nearest geophone) was fixed to 5 m. The source was generated by using a 6 kg (13.2 lbf) sledge hammer hitting on a 350 x 350 mm striker plate. The source was placed with a trigger geophone at both ends of the survey line in order to ensure continuity of the lateral homogeneity. In order to eliminate the background noise of the environment, vertical stacking was implemented 3 or 5 times at each shot point of each array to increase the signal-to-noise ratio (i.e., to improve the quality of data). The recording length was selected as 2 s with a 1 ms sampling interval to record the generated surface waves. The phase shift transformation method was used to obtain the experimental dispersion curve as an input parameter for the inversion stage In the MAM survey, the sampling time interval was selected as 2 ms. Ambient noise was recorded with 5 min duration which corresponds to nine times 32 s records. The MAM measurements were taken at the same points where the MASW methods were carried out with the same configuration (linear configuration). The SPAC (Spatial Autocorrelation) analysis (Okada, 2003) was utilized to construct the dispersion curve. According to the theory of the surface wave methods, the measured surface wave records were processed and analyzed by using SeisImager/SW^{TM} V. 2.2 software in the analyses process of the active and passive surface wave measurements. A one-dimensional inversion using a non-linear least square technique was applied to the phase velocity curves for both of the methods and a one dimensional S-wave velocity structure down to a depth of 30 m was obtained.

Shear wave velocities obtained by the MASW and MAM methods at 41 site locations were compared. It was found that the average shear wave velocity variations for the upper 30 m obtained by both methods were within 10% for the 33 measurement points. For the remaining 8 measurement points, the variation between the V_{S30} of two methods varied between 11% and 20%. Considering the error margin of these methods (Xia et al., 1999 and 2002; Chavez-Garcia et al., 2006), it can be inferred that these results are in good agreement with each other. Also, in determining the spatial distribution of V_{S30} and site class processes, V_{S30} parameters acquired by a combination of the two methods were used in this study for all of the 41 data points. Distribution of the mean shear wave velocity for the uppermost 30 m layer can be seen in Fig. 3.

Depending on the result of the implemented surface wave methods, the regional seismic zonation map of V_{S30} was prepared based on the design code of IBC 2006. According to the V_{S30} data, the depositional environment units could not be distinguished by the site classes in the design code of the IBC 2006. The results are within the range of site class D (between 180-360 m/s).

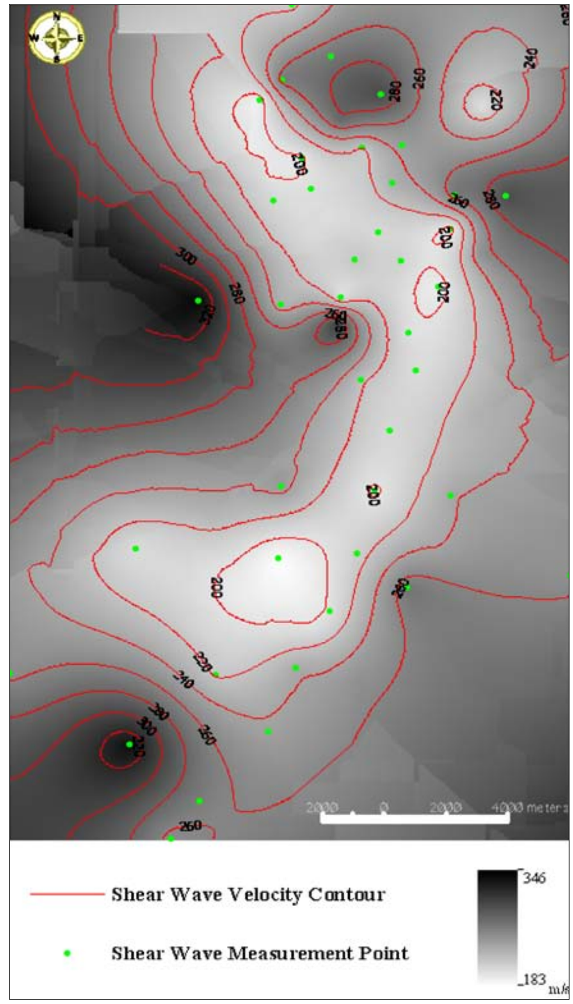
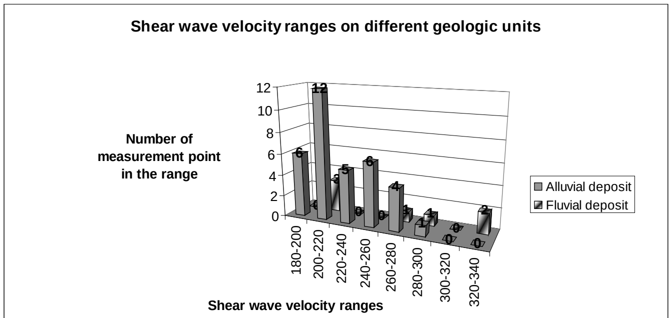


Fig. 3. The regional seismic map based on the measured mean V_{S30} measurements.

A regional seismic map containing the V_{S30} values of the study area can be seen in Fig. 3. As can be seen in the figure, the V_{S30} values around the Quaternary deposit, i.e., towards the center of the basin decreases as expected. Also, a similar trend is followed along the alluvium deposit. At the center of the basin, V_{S30} has a value of 183 m/s which is the boundary between stiff (D site) and soft soil (E site) profile according to IBC 2006. Moreover, V_{S30} has relatively greater values towards the Upper Pliocene to Pleistocene sedimentary deposits at the both sides of the plain. This means that the alluvium is gradually thinner towards the edges of the alluvial basin. Therefore, it is naturally observed that the V_{S30} results gradually increase when the thickness of the alluvium profile decreases within the first 30 m. Although the V_{S30} of the Quaternary geologic units reflects the results of depositional environment settings in the area, some variations of V_{S30} in the unit were observed. The variations may be related to grain size distribution, density, ground water level and cementation in the deposits (Wills et al., 2000; Wills and Clahan, 2006). The V_{S30} measured in two different geologic units described by MTA, show the same characteristics at the interval between 202 and 267 m/s (Fig.4). Hence, in this case, it is very difficult to draw a sharp boundary between these units based on these results.



	180-200	200-220	220-240	240-260	260-280	280-300	300-320	320-340
Alluvial deposit	6	12	5	6	4	1	0	0
Fluvial deposit	0	3	0	0	1	1	0	2

Fig. 4. The measured shear wave velocity range in different geologic deposits.

The depositional setting of the area which took its final form due to the tectonic activities in the area was quantitatively analyzed and the results revealed that the distribution of the unconsolidated, thick sediments spread out in an extensive area in the region. The effects of the presence of the geological structural elements (normal faults), their deformation zones and excessive deposition of the terrace sediments as well as the widespread Upper Pliocene and Pleistocene sedimentary units in the area were analyzed and detected by utilizing in-situ tests. Especially, the shear wave velocity (VS) profiles of the Quaternary sediments follow a low trend to a depth of 55 m. However the same case was also observed for the terrace sediments and the Upper Pliocene and Pleistocene fluvial deposits, due to the presence of the faults and their deformation zones (Fig. 1). Another reason of the presence of the thick soft sediments is that the depositional settings are dominant in the area. Due to the cut and fill process, the sediments are deposited in the area under the control of the depositional (not erosional) setting.

In the classification of the measurement results with respect to lithologies (Fig. 4), two measurement points (Seis-4 and Seis-26) fell within the units of the Quaternary alluvium and terrace deposits but these points are close to the boundary between these deposits and the Upper Pliocene to Pleistocene sedimentary deposits. In addition to this, due to their characteristic shear wave velocity profiles, they were grouped in the Upper Pliocene to Pleistocene sedimentary deposits.

CONCLUSION

Determining the spatial distribution of V_{S30} and site classes have proved that their determination is a useful basis for future zonation studies since site effect studies were defined as a function of this parameter. Shear wave velocity measurements were taken within each of the mapped geologic unit. The relationships between the geologic units, vertical variations in sediment type, average shear wave velocity for the upper 30 m of the soil profile and site classes were investigated. The collected data and relationships were used to develop maps of V_{S30} and site classes were assigned as D according to IBC 2006. Due to the soft thick sediments as a result of the tectonic activities and their deformation zones and also the dominance of the depositional settings in the area, the average shear wave velocity data for the upper 30 m of the soil profile obtained were lower than expected even for the Upper Pliocene to Pleistocene fluvial sediments in the region. Although the amount of the collected data is not sufficient to determine reliable boundary with respect to V_{S30}, it clearly shows that the basin is composed of very thick soft sedimentary deposits. The thickness of the deposits is over 55 m which was determined by this study.

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