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Evaluation of Local Site Conditions Using Ambient Seismic Noise Recordings: A Case Study from Ankara, Turkey

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EVALUATION OF LOCAL SITE CONDITIONS USING AMBIENT SEISMIC NOISE RECORDINGS: A CASE STUDY FROM ANKARA, TURKEY

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ABSTRACT

This paper aims to investigate the site response of the sediment characteristics and to perform seismic hazard studies in Ankara, Turkey through conducting short-period noise recordings of microtremor measurements at 352 project site locations on the Upper Pliocene to Pleistocene fluvial and particularly Quaternary alluvial and terrace sediments in the Ankara basin. The spectral ratios relative to a firm site reference station (SSR) and the spectral ratio between the horizontal and vertical components (HVSR) of the microtremor measurements at the ground surface have been used to estimate the fundamental periods and the amplification factors of the site. The results of this study identified three main factors that influence site response, namely, the age of the near-surface deposits, the sediment thickness and the non-linear soil behavior. In particular, the HVSR results showed that the variation of the fundamental period map agreed well with the maximum value of the amplification as well as with the seismic sediment characteristics that provided satisfactory estimates of the site response of soft deposits.

INTRODUCTION

The effect of local site conditions is directly related to significant damage and loss of life. During the past decades, the effect of local soil conditions is known to have caused serious damage during several earthquakes. While there are several other potential factors contributing to damage (such as topography, basin effects, liquefaction, structural deficiencies, etc.), the amplification of ground motion due to local site conditions (such as ground motion resonance and amplification) plays an important role in increasing seismic damage. These observations, as well as numerous others, indicate that the quantification of site effects is a necessary component of a comprehensive assessment of seismic hazard (Rodriquez-Marek, 2001).

Even though Ankara may be considered safe in terms of earthquake hazards owing to its considerable distance to major fault systems (i.e., approximately 75-100 km), the damage that occurred for example through the Michoacan Earthquake (1985) that was located more than 350 km from Mexico City but caused extensive damage due to a large impedance contrast between the very soft material and underlying bedrock that amplified shaking at the ground surface should not be disregarded. Further, the Kocaeli Earthquake (1999) which resulted in significant damage at the Avcılar area that is located about 90 km away from the earthquake source in Gölcük-İzmit. Hence, the impact of local site conditions subsequent to the significant influence of strong ground motions on site amplification carries an important weight in geotechnical earthquake engineering. Due to these reasons, even though Ankara may be considered to be situated distant to major fault systems, the influence of the unconsolidated sediments under earthquake triggered motions need to be investigated. In addition, areas of high seismicity, such as the Marmara region in Turkey present opportunities for determining amplification and resonant frequencies through analysis of strong motion data. The frequency of high magnitude events and the vast array of seismic instruments in operation may provide abundant data for obtaining these site factors. However, in Central Anatolia such as the Ankara region, seismic activity is less frequent and stations are widely spaced or almost absent (Koçkar, 2006). Installing a temporary network to record the events for a reliable estimation of site conditions may be much more costly in such a region. Recording ambient noise, in contrast, is easy, fast and economical to estimate the local site conditions. The use of ambient short-period noise measurements to obtain ground motion response has been successful in several studies in constraining resonance using the Reference Site of the SSR method (Borcherdt, 1970; Kagami et al., 1982 and 1986; Steidl et al., 1996; Ibs-von Seth and Wohlenberg, 1999; Hruby and Beresnev, 2003). Spectral ratios provide a good estimate of local amplification provided that the reference site is effectively free of site effects and is located near the soft soil profile. However, the HVSR method has also proven to be a more reliable method in some cases that produces more correlative results (Lermo and Chavez-Garcia, 1993 and 1994; Field et al., 1995; Duval et al., 1995; Bard, 1999; Horike at al., 2001; Chavez-Garcia et al., 2007). It was originally proposed by Nakamura (1989) in order to satisfy the source and path effect problem particularly in highly urbanized cities which is thought to be the main source of error in the spectral ratio methods. This technique has been successful in overcoming the source and path effect problem, and thus provides reliable estimates of local amplification. It offers an alternative when there is no reference station, or when the reference station fails to record the same events as the soft soil stations (Chavez-Garcia, 2007). Hence, it appears that the HVSR techniques are useful in seismic zonation in such cases, but a thorough understanding of subsurface heterogeneities and non-linear effects at the study site is essential for a reliable interpretation of the data (Finn, 1991; Bour et al., 1998; Lecave et al., 1999; Koçkar, 2006; Chatelain et al., 2008).

This paper presents regional information regarding the site response of the sediment characteristics and to perform seismic hazard studies within the Ankara basin. Evaluation of the site conditions within the Ankara basin started with an assessment of the local geologic formations and mapping of surface geology based on available sources of information. The data from the geologic map was correlated with data from detailed site investigations and short-period noise recordings of microtremor measurements performed. Specifically, the average spectral ratios relative to a firm site reference station (SSR) and the spectral ratio between the horizontal and vertical components (HVSR) of the microtremor measurements at the ground surface has been used to estimate the fundamental periods and the amplification factors of the site. Specifically, the HVSR results indicated that the variation of the fundamental period map agreed well with the maximum value of the amplification as well as with the local site conditions that provided satisfactory estimates of the site response of soft deposits, particularly in the Quaternary alluvial sediments of the Ankara basin. These results appeared to complement and to correlate well with the seismic site characterization studies used to characterize the depositional setting of the geologic units for reliably determining the local site character (Koçkar, 2006). The conducted data and relationships were used to develop hazard assessment maps (i.e., site period and site amplification maps) of Ankara that may be used in zonation studies along with discussing the consequences of the seismic hazards.

GENERAL SETTING, SEISMICITY AND SEDIMENT CHARACTERISTICS

Ankara, the capital city of Turkey with a population of about 4 million, is located at an intersection point of highways connecting east to west and north to south of Anatolia. The study area is located in the Ankara basin towards the west of the center of the city in an approximately ENE-WSW-trending, 25-30 km long, and 10-15 km wide fault-bounded depression that drains from the east to the west direction through the Ankara River. The study area lies within the major growth potential for Ankara and has been moderately to densely populated with mostly residential structures and small to large industrial buildings (Fig. 1).

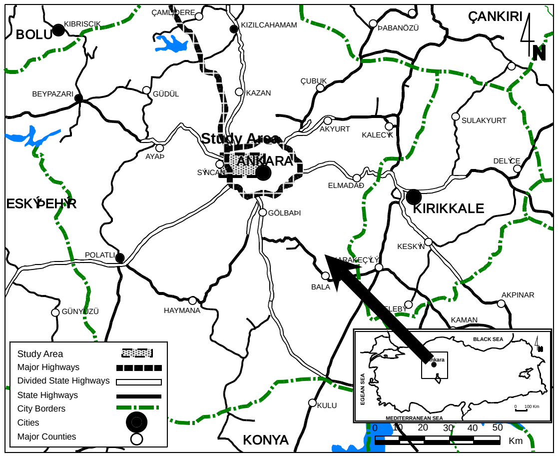

Fig. 1. Location map of the research area that is situated towards the western part of the city center of Ankara.

The faults in the Ankara basin are seismically active but are only capable of producing smaller earthquakes (M < 5). Recent seismic activity within about 50 to 75 km of Ankara includes the June 6, 2000 Orta earthquake and its aftershocks (M_D=5.9, 5.2 and 5.0; Kandilli Observatory and Earthquake Research Institute, KOERI, 2007), the July 31-August 9, 2005 Bala earthquake series (M_L=5.3, 4.8 and 4.6; KOERI, 2007) and the December 12-27, 2007 Bala earthquake series (M_L=5.7 and 5.5; KOERI, 2007). These local earthquakes are relatively moderate seismic events that may affect Ankara. On a regional scale, the Ankara region may be affected by the surrounding large-scale fault systems, particularly the North Anatolian Fault System (NAFS), the Salt Lake Fault Zone (SLFZ) and the Seyfe Fault Zone (SFZ), which are capable of producing large destructive earthquakes (M > 7.0; Koçyiğit, 1991; Koçkar, 2006). Some of the prominent examples of the major events that have occurred along these systems are the November 26, 1943 Kastamonu earthquake (M_L=7.3), the February 1, 1944 Gerede earthquake (M_L=7.3) and the August 13, 1951 Çankırı earthquake (M_L=6.9) along the NAFS, and the March 19, 1938 Taşkovan-Akpınar earthquake (M_L=6.6, KOERI, 2007) along the SFZ. Hence, significant seismic events that might take place along these large-scale Fault Systems and Fault Zones might affect Ankara and its surroundings and thus have to be considered seriously in regards to seismic hazard assessment.

In the research area, the geologic units outcropping in the region range from Pre-Upper Miocene to Quaternary in age. The 1:25,000 scale geologic map subdivides the surface geology into four main units: (1) Pre-Upper Miocene to Lower Pliocene basement rocks, (2) Upper Pliocene to Pleistocene fluvial deposits (Plio-Pleistocene fluvial), (3) Quaternary terrace deposits, and (4) Quaternary alluvial deposits (Fig. 2). This study focuses on the characteristics of the three younger sedimentary units, collectively known as “Ankara clay” (Ordemir et al. 1965).

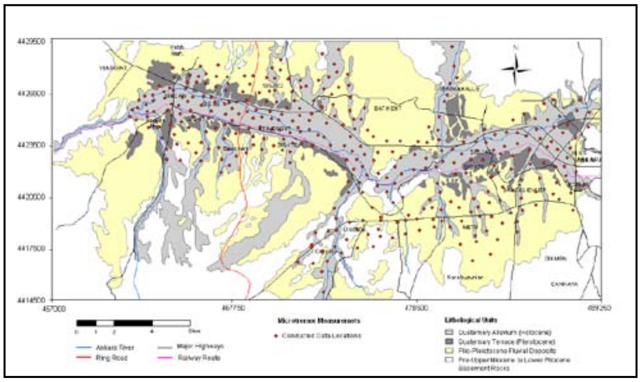

Fig. 2. Map depicting the major geologic units and microtremor measurement locations in the study area (geological features modified from Akyürek et al., 1997 and Erol et al., 1980 by field studies performed and reported in Koçkar, 2006).

The Plio-Pleistocene fluvial deposits are widely exposed and cover the major part of the study area. These fluvial sediments show a continental origin and have accumulated in and near the fault-bounded basins of the study area (Fig. 2). These deposits possess highly heterogeneous structures and appearance in terms of their mineral composition, particle size and color. The geologic unit appears to be preconsolidated in the upper layers due to desiccation (Ordemir et al., 1977) and is observed to be mixed with Quaternary sediments at the outlets of the basin. They refer to it as preconsolidated, stiff, fissured “Ankara clay” (Ordemir et al. 1965). Their thicknesses range from a few meters to 200 m based on their stratigraphic position (DSİ, 1975; Erol et al., 1980). Water-bearing strata are not encountered in the unit most probably due to the considerable clay content of the sediments.

The Quaternary alluvial and terrace sediments were deposited by flood waters on the flat flood plains of the Ankara River in the fault-bounded Ankara basin (Fig. 2). The Quaternary deposits are differentiated as terrace deposits (Upper Pleistocene) present at the margins, and alluvium (Holocene) present at the stream beds (Erol, 1993). It is difficult to differentiate the terraces from the Plio-Pleistocene fluvial sediments, especially at higher terrace elevations which show similar sediment characteristics. However, these sediments are relatively less stiff. Therefore, step-like terraces are differentiated geomorphologically based on their elevations relative to the surrounding younger alluvium deposits (Erol et al., 1980). The estimated thicknesses of these sediments generally vary from 5 to 10 m (DSİ, 1975; Koçkar, 2006). The Quaternary alluvial sediments are relatively thick and were deposited by flood waters along the recent river beds (Fig. 2). These are normally consolidated, soft deposits that are relatively more homogeneous than the other geologic units (Lohnes, 1974; Sürgel, 1976). The groundwater level ranges between 2 to 6 m (DSİ, 1975). The thickness of the alluvial deposits generally ranges from 5 m to 30 m (Erol, 1973; Ordemir et al., 1977; Kasapoğlu, 1980; Koçkar, 2006).

FIELD TESTING AND DATA ANALYSIS

The short-period noise recordings of the microtremor measurements were carried out at 355 project site locations on the Plio-Pleistocene Fluvial and Quaternary Alluvial and Terrace sediments to study the seismic response in the western part of the Ankara basin (Fig. 2). The average spectral ratios relative to a firm site reference station (SSR) and the spectral ratio between the horizontal and vertical components (HVSR) of the microtremor measurements at the ground surface have been used to estimate the fundamental periods and the amplification factors of the site. Of the 352 measured data points, about 207 (58.81%) and 132 (37.50%) of the data fell within the units of the Quaternary alluvial and terrace sediments and Plio-Pleistocene Fluvial sediments, respectively. Additionally, 13 (3.69%) of the data were taken from rock sites surrounding the Ankara basin to be used as reference stations for the construction of a “reference site spectra” (sediment-to-bedrock). The field measurements were conducted by adopting a grid system where the microtremor recording points were attempted to be spaced at about 500 m. A Geographic Information System (GIS) software was used to merge the various data, to assess the spatial extent of site characteristics and to classify the sites for the preparation of a seismic zonation map and for the evaluation of site-conditions for seismic hazard assessment.

The microtremor field equipment comprised of a DATAMARK LS-8000 WD type measuring instrument as a data recorder and an Akashi JEP-6A3, three component, built-in acceleration seismometer. During the recording of the measurements, the sampling interval rate was 100 Hz and the duration of each sample recording was 300 s. For further processing, only the quiet sections of the noise recordings were used. At least three 20 s quiet time intervals were chosen to process microtremor data after filtering the noise. The mean values of the amplitude spectra of these intervals were calculated for all sites and components. During processing of the data for each of the measurement points that were recorded in the field study, a Fast Fourier Transform (FTT) procedure was applied on each selected windows to waveform data after period or frequency analysis, and then the obtained Fourier spectrum were smoothened with a Parzen window by applying appropriate low and high pass filters and band width. Finally, the processed Fast Fourier spectrums for three components of the ambient noise (Fourier spectra) were developed to calculate the HVSR and the SSR spectra. After applying these procedures to the other selected windows of the same record, the mean values of them were taken as the final HVSR and SSR spectrum. Finally, these processed FFT results were evaluated to check the accuracy and hence the reliability of the results and to validate the experimental techniques in the study area. During the evaluation of the records, the recording files have been processed and analyzed by using SPECTRATIO (Version 5.3, Rosset, 2002) that runs under the Matlab programming software (Rosset, 2005) and MicPlot (Version 1.1, Motoki, 2002) which runs under UNIX (Mirzaoğlu, 2005). SPECTRATIO (Rosset, 2002) is a quite useful Matlab routine that has been partially modified and used herein to process and analyze the ambient noise records.

It should be noted that the microtremor study was also complemented by the available site investigation study in the project area for the purpose of reliability assessment. This way, the site investigation technique measurement locations (i.e., standard penetration, shear wave velocity, etc.) were attempted to be in close proximity as much as possible for a sound data correlation, and thus the quality of the information gathered from the microtremor measurements was evaluated. Therefore, regarding the site characterization studies that were used to complement the local site characteristics, the seismic data obtained from the average shear wave velocities and boring data obtained from standard penetration test results in the upper 30 m of near-surface geologic units were utilized to characterize the geological units according to the design code of the IBC 2006 (International Code Council; ICC, 2006). Recent seismic code provisions have adopted site classification using average shear wave velocity and their correlated index measurements of standard penetration results in the upper 30 m of a site as the sole parameter for site classification (Borcherdt, 2002; Dobry et al., 2000). Shear wave velocity is a critical factor to identify the stiffness of the sediment and might be a useful parameter to characterize local geologic conditions quantitatively for calculating site response (Park and Elrick 1998; Wills et al. 2000; Holzer et al., 2005). Hence, local site conditions were characterized to develop a regional $V_s(30)$ model for the site classes (Koçkar, 2006; Koçkar and Akgün, 2008).

The site conditions specified by IBC 2006 practically distinguish soil profiles in five main categories (Table 1). Each category is assigned factors appropriate for the site conditions.

The average shear wave velocity measurements and correlated index measurements of the average standard penetration resistance to 30 m [$V_s(30)$ and N(30)] have been calculated in accordance with Eqs. (1) and (2) below, and then used to develop categories for local site conditions.

$$V_s(30) = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \qquad (1)$$

$$N(30) = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{N_i}} \qquad (2)$$

where, V_{si} is the shear wave velocity (m/s), N_i is the standard penetration resistance (ASTM D 1586-84) not exceeding 100 blows/0.3 m, directly measured in the field without corrections, and d_i is the thickness of any layer between 0 and 30 m.

Table 1. IBC 2006 site class definitions using the mean shear wave velocity and the mean standard penetration resistance to 30 m (ICC, 2006)

Site class	**Soil profile name**	**Average properties in the upper 30 m**	
		Soil shear wave velocity, V_s (m/s)	**Standard penetration resistance, N (blows/0.3 m)**
A	Hard rock	$V_s > 1,500$	N/A
B	Rock	$760 < V_s \leq 1,500$	N/A
C	Very dense soil and soft rock	$360 < V_s \leq 760$	$N > 50$
D	Stiff soil profile	$180 \leq V_s \leq 360$	$15 \leq N \leq 50$
E	Soft soil profile	$V_s < 180$	$N < 15$

Near-surface seismic measurements of shear waves were performed at 204 locations and compiled with existing data from 55 locations by previous studies in Quaternary alluvial and terrace, and Plio-Pleistocene fluvial sediments. The standard penetration test results of near-surface geologic units were compiled from 911 previous studies in Quaternary alluvial and terrace, and Plio-Pleistocene fluvial sediments (Koçkar, 2006). The average shear wave velocity in the upper 30 m of near surface geologic units were calculated for a total of 215 testing locations in the Quaternary deposits. These results showed two units with different $V_s(30)$ characteristics, Quaternary Alluvium of E-Site, Quaternary alluvium and terrace deposits of D-Site. Plio-Pleistocene Fluvial sediments were described as an undifferentiated single unit on the geologic map. $V_s(30)$ results were calculated at 42 test points. These results led to a decision to classify them as relatively less dense fluvial deposits of D-Site and denser fluvial deposits of C-Site based on the environment of deposition. In the

Quaternary deposits, the N(30) results were calculated for 429 test points. They were classified within two different units showing similar depositional characteristics with shear velocity results, and then characterized with respect to these three units, Quaternary Alluvium of E-Site, Quaternary alluvium and terrace deposits of D-Site. The Plio-Pleistocene Fluvial sediments which are generally intercalated with Quaternary older terrace deposits were investigated at a total of 482 test locations. Since they are particularly cemented, deformed and uplifted compared to the surrounding environment of Quaternary alluvial and sometimes terrace deposits, their N(30) results gave relatively stiffer results. These site categories were classified as the fluvial deposits of D-Site and the fluvial deposits of C-Site based on the depositional environment.

Regression relations were developed between shear wave velocity and correlated index measurements of penetration resistance and depositional setting. Available data from 123 sets of $V_s(30)$ and N(30) results at the same locations were studied for correlation (Koçkar, 2006). These results assembled from correlating the shear wave velocity with the standard penetration resistance of the sediments through regression equations to construct the site classification map of $V_s(30)$ are given in Fig. 3 (Koçkar, 2006; Koçkar and Akgün, 2008). These correlations can be applied to the areal distribution, physical properties and thickness of the geologic units to estimate and map shear wave velocity potential for the entire study area. Note that some geologic units may not be directly assigned to site classes (i.e., Quaternary deposits and Plio-Pleistocene Fluvial deposits may not be easily assigned to D-Sites). Quaternary terrace deposits were classified along with fluvial deposits of D-Site having similar site characterization results, as well as depositional characteristics. Hence, areas which are classified as E-Site will be the most adversely affected during a seismic event, and additional site-specific studies may be required. Areas classified as D-Site will be moderately affected, and areas classified as C-Site are least likely to be affected during seismic events. Hence, it can be pointed out that site characterizations depending on the shear wave velocity results are an appropriate quantitative measure of sediment conditions and may give valuable evidences to define the local site conditions, which might be helpful in correlating the characteristics of the generalized sedimentary mapping units with other site characterization results (i.e., site effect studies).

EVALUATION OF THE RESULTS ON SITE EFFECTS

In the study area, relatively more competent Plio-Pleistocene Fluvial sediments and particularly competent rock sites possess a relatively flat response curve, while alluvial soft soil sites generally exhibit a peak of maximum amplitude defining their fundamental frequency or period. In particular, the boundary between component material units and soft sediments can be clearly inferred from the change in the spectral shape of records for various sites. Hence, a conclusion might be obtained from the processed Fourier spectrum results, where the conducted microtremor measurements indicate that a impedance contrast exist between the Quaternary Alluvial sediments (particularly Holocene age deposits) and the more competent Plio-Pleistocene Fluvial sediments and rock units.

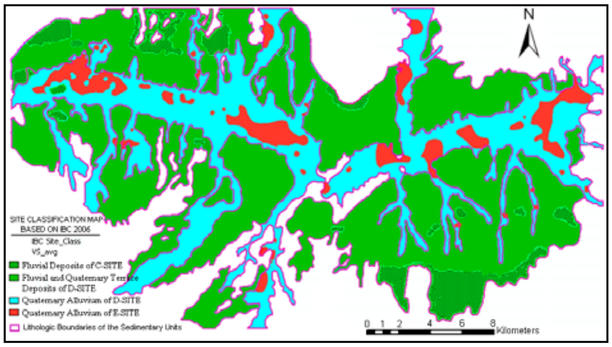

Fig. 3. Regional site classification zonation map of the Ankara Basin in regards to the site classes as specified by IBC 2006 based on measured and estimated $V_s(30)$ measurements (Koçkar and Akgün, 2008).

Figures 4 through 5 given below present examples of calculated SSR spectra as compared to the HVSR spectra for various sites (i.e., MOB-36, -79, -226 and -353). The plots show clear similarities between the different types of spectra. The spectral ratios always have dominant maxima at higher periods for both spectral ratios of acceleration spectrums (Fig. 4). Although, relatively small differences along the spectral shapes and amplitudes exist, these figures reveal good overall patterns and agreements between the transfer functions obtained by the two methodologies. In the research area, however, some of the mobile stations, for instance MOB-55 and -206; and MOB-273 and -342 are exceptions. In case of these mobile stations, neither the period nor the amplitude of the main peak of the SSR showed similarities with the HVSR (Fig. 5). The stations MOB-55 and -206 were situated in the vicinity of a high-density traffic, where high-noise amplitudes have spoiled the shape of the SSR spectrum. The lack of hard-rock sites in or around the research area presented obstacles in using the SSR method around the Ankara basin. MOB-273 and -342 are sites where the alluvial sedimentary unit thickness is relatively high, which appears to be the reason why the information reflected through the SSR spectrum is low. In contrast, these factors seem to have little or no effect on the HVSR spectra. The HVSR peak period increases with increased amplitude accelerations due to non-linearities in the behavior of the loose alluvial soils. When the thicknesses of the surficial soil deposits decrease, the amplitudes obtained by the two methods become similar. These results were also proved by Field and Jacob (1993) and Bour et al. (1998). However, it may be interesting to note that at few locations (i.e., MOB-345 and MOB-3), there might have been some ground motion resonance possibly in the form of earthquake shaking even though the surficial soils comprise a relatively small layer of sediment over the competent material of bedrock. This may probably be due to the sharp impedance contrast between these two layers related with the non-uniform configurations of surface topography (Fig. 6). The mobile microtremor measurements at points MOB-345 and MOB-3 were conducted on the side of a very narrow river valley that comprises a thin layer of loose alluvial sediment over the fractured limestone and andesitic bedrock unit, respectively. It should be emphasized that patterns of surface motion may be influenced in a major way by surface topography and by non-uniform subsurface configurations (Boore, 1972).

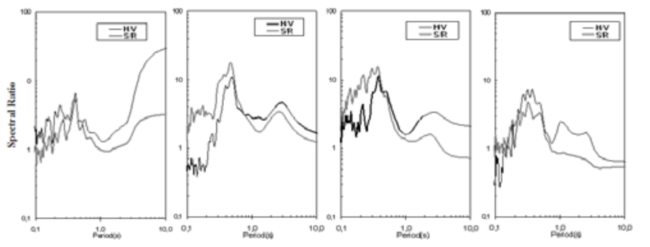

Fig. 4. Examples of calculated SSR spectra as compared with HVSR spectra at four different sites that show clear similarities between the different types of spectra at mobile stations MOB-36, -79, -226 and -353, respectively.

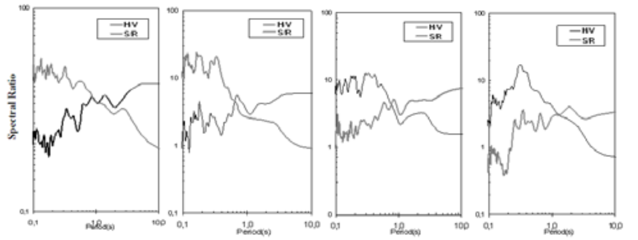

Fig. 5. Examples of calculated SSR spectra as compared with HVSR spectra at four different sites that show dissimilarities in the period and in the amplitude of the main peak of the SSR at mobile stations MOB-55, -206, -273 and -342, respectively.

As a consequence of these results, it needs to be emphasized that the frequencies of the main peaks in the SSR spectra are being influenced by local noise sources in the urban regions of the Ankara basin, where they are not controlled by the thickness of the cover layer. The observed sensitivity of the SSR spectra to local noise sources can be explained as follows. As the thicknesses measured at the base are relatively small, the frequencies obtained are high. This corresponds to the fact that smaller distances to noise sources cause increasing noise amplitudes, while the portion of high frequencies in the signal spectrum grows. As a consequence, high-frequency peaks occur. The spectrum provided by the reference site is not normally influenced by the same local noise source. Therefore, the high-frequency part of the spectrum is not eliminated during the formation of the SSR giving rise to the high-frequency main peaks in the SSR spectra. Unfortunately, reference sites situated at relatively quiet locations without local noise sources in order to compare the noise amplitude of the sediments particularly in highly urbanized cities such as Ankara that might adversely affect some of the SSR results have to be considered during the determination of the fundamental frequencies. In the case of the HVSR spectra, both numerator and denominator spectra are taken at the same site. It is thus possible that influences of local noise sources are eliminated when forming the spectral ratio. The result for MOB- 55 and -206 in Fig. 5 indicate that the noise amplitudes do not significantly affect the reliability of cover thickness values calculated from HVSR main frequencies. These observations strongly suggest that the HVSR ratio actually is not affected by the presence of local noise sources.

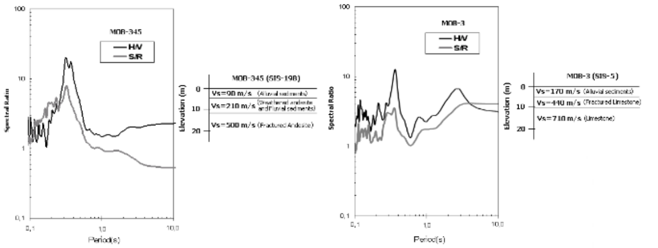

Fig. 6. The sharp impedance contrast between the thin layer of loose alluvial sediments and the fractured limestone and andesitic bedrock unit in relation to the non-uniform configuration of the surface topography, respectively (MOB-345 and MOB-3).

On the basis of these results, it would appear that it is possible to use the HVSR spectral ratio to determine the fundamental resonant frequency and establish the seismic zonation in terms of a predominant period map of the Ankara basin. Even though it is generally accepted that HVSR ratios obtained from microtremor measurements would at times lead to very reliable spectral amplification values, they can be well adapted to the urban environments to be of great value for site effects and thus can be taken into consideration when finalizing the seismic hazard assessment in the study area with respect to site amplification.

SEISMIC HAZARD ASSESSMENT

In the Ankara basin, different lithologies associated with typical amplification factors have been identified in the field. Preliminary results showed a good correlation between thickness and/or the type of soft soil and the fundamental frequency obtained with the HVSR method. The results obtained from the microtremor study were utilized to map the variation of spectral amplifications for the Ankara basin where each microtremor measurement point provided a spectral ratio and enabled an estimation of the fundamental period and the maximum value of the amplification at the site studied. Through performing spatial interpolation between these microtremor measurement points, a map of the resonance periods over the Ankara basin (Fig. 7) and a map of the maximum amplifications observed at these fundamental periods (Fig. 8) were prepared (Koçkar, 2006). It is important to note the qualitative character of the maximum amplification values. The Nakamura method does not presently enable the level reached by the peak of the HVSR to be related to the amplification of a signal at the surface relative to that in the bedrock during a strong tremor. Only the relative amplifications between two measurement points are assumed to be significant (Lachet and Bard, 1994; Bard, 1999).

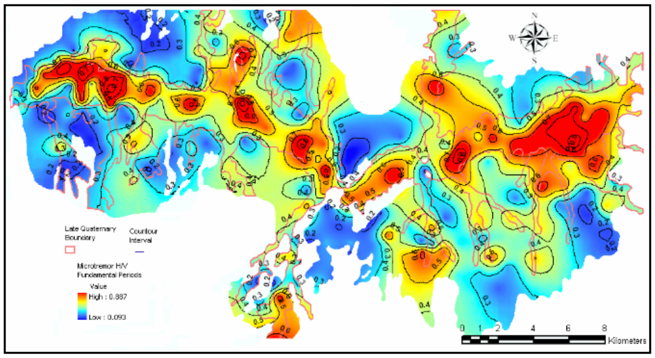

Fig. 7. Map of fundamental frequencies (resonance periods) obtained with the HVSR method over the Quaternary alluvial and Plio-Pleistocene fluvial sediments of the Ankara basin

Regarding the map presented in Fig. 7, it can be clearly observed that the fundamental periods are consistent with the geological setting of the research site. Regarding the general distribution of the fundamental periods, they are ranging from about 0.1 to 0.9 s that appear to be relatively variable due to the presence of different units ranging from sedimentary units to competent rock in the Ankara basin. The fundamental periods relatively increase to a range from about 0.4 to 0.9 s along the Quaternary deposits (particularly Holocene sediments) of the Ankara basin that comprise the flood water plains trending in the east-west direction of the Ankara river and its main tributaries. These ranges of the fundamental periods also appear to be variable within this range for this unconsolidated deposit. The possible reasons for this variability of the fundamental periods which are also thought to be connected with the variability of the shear wave velocities of the sediments (Fig. 3), may be most likely due to the variability of the material properties including thickness of the alluvial sediment and density.

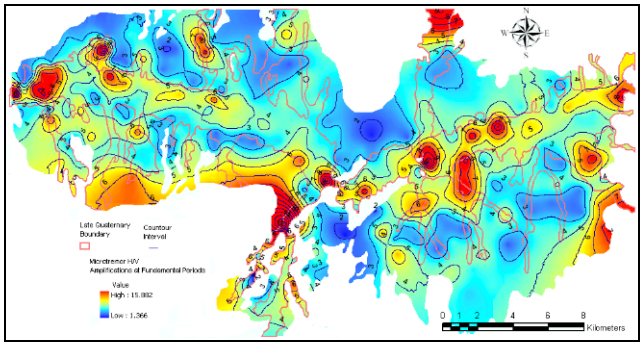

Fig. 8. Map of amplifications at resonance periods obtained with the HVSR method over the Quaternary alluvial and Plio-Pleistocene fluvial sediments of the Ankara basin

Regarding the map presented by Fig. 8, it can be interpreted that the maximum amplifications observed at these fundamental periods are also relatively consistent with the geological setting of the research site in the Ankara basin. Considering the general distribution, relative site amplifications generally range from about 2.0 to 11.0 [HVSR is 16.0 at only one mobile station (MOB-345) in the Quaternary deposit] that appear to be relatively variable due to the depositional character and topographical conditions of the geologic environment of the various lithologies in the Ankara basin. The Quaternary sediments amplify the ground motion higher than the surrounding older geologic units by generally two to four folds. This confirms the thickening of the unconsolidated alluvial sediments covering the seismic substratum which appears to increase at some locations in the Quaternary sediments of the Ankara basin.

Regarding the comparison of the geotechnical seismic data with the HVSR method in the Ankara basin, it was observed that the fundamental period map agreed well with the seismic characterization results conducted in the project area (Fig. 3). The higher amplification results at fundamental periods were observed along the Quaternary sediments in the studied region which generally corresponded to the thicker unconsolidated materials that had low shear wave velocity characteristics. The comparison of these results indicated that the HVSR peak period increased with increased amplitude accelerations due to non-linearities in the behavior of the soils. The amount by which the period shifted at each site depended on the resonant period of the site. A lower peak period, corresponding to a shallower bedrock surface, generally resulted in a greater shift in the period than a higher peak period associated with a deeper bedrock surface.

CONCLUSIONS

Methods and procedures that were used in the course of this study included seismic hazard evaluations to enable the assessment of site effects. The study area lies within the major growing potential, present and future settlement province of Ankara. The sources of the recent examples showed that the significant seismic events that have taken place in and around the Ankara basin might affect Ankara and its surroundings. Therefore, the earthquake hazard assessment performed in this study proved to be very important for the second largest and also the capital city of Turkey for preliminary site evaluations, general land-use and urban planning, and delineation of special zones where additional site-specific studies may be required before major development is approved.

Regarding the site effects in seismic hazard assessment according to the processed Fourier spectrum results, the relatively more competent Plio-Pleistocene Fluvial sediments and particularly rock sites had a relatively flat response curve, while alluvial soft soil sites generally exhibited a peak of maximum amplitude defining their fundamental frequency or period. From the seismic zonation studies, the HVSR fundamental periods and the maximum amplifications observed at these fundamental periods were determined to be consistent with the geological setting of the research site in the Ankara basin. In particular, the boundary between component material units and soft sediments could be clearly inferred from the change in the spectral shape of records for various sites. Hence, the conducted microtremor measurements indicated that an impedance contrast existed between the Quaternary Alluvial sediments (particularly Holocene age deposits), and the more competent Plio-Pleistocene Fluvial sediments and rock units.

The results of this study identified three main factors that influenced site response, namely, the age of the near-surface deposits, the thickness of the Quaternary sediment deposits and the non-linear soil behavior. Quaternary sediments amplified ground motions at longer periods larger than the older Plio-Pleistocene Fluvial sediments due to the presence of the low-velocity deposits in the near-surface. Regarding the comparison of the geotechnical seismic data with the HVSR measurements in the Ankara Basin, variation of the fundamental period map agreed with the maximum value of the amplification as well as with the seismic characterization results. 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. These results also indicated that the HVSR peak period increased with increased amplitude accelerations most probably due to the non-linearities in the behavior of the soils. The amount by which the period shifted at each site depended on the resonant period of the site. A lower peak period, corresponding to shallower bedrock surface, generally resulted in a greater shift in the period than a higher peak period associated with a deeper bedrock surface.

This study has shown that the method of HVSR, based on the recording of background noise, might provide reliable data on the seismic behavior of gently dipping alluvial soft soil layers that generally showed maximum amplitude defining their resonance periods. It is recommended that the various experimental approaches should be combined so as to a more thorough microzonation of a given region, in particular those located in weak seismic activity areas and/or in high levels of ambient noise.

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