



SIMULATED GROUND MOTIONS WITH SITE EFFECTS POTENTIAL EVALUATED THROUGH TRANSFER FUNCTIONS AND H/V MEASUREMENTS: CASE STUDY FOR İZMİR, TURKEY

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ABSTRACT

İzmir is the third largest city in Turkey, situated in a complex tectonic region with several destructive earthquakes in the history. The latest one of these occurred in 1778 and has caused significant damage in the city. In addition to the complex tectonics young and soft sediments are wide-spread in the metropolitan area, especially in the northern part of the city north of the İzmir Bay. This area is covered by the Quaternary sediments originating from the large Gediz river delta system and poses important challenges in the built environment with respect to the earthquake loads.

In order to assess the fundamental frequencies of the soft sedimentary layers in the area, H/V spectral ratio method is adopted on ambient vibrations. The entire city is examined through a coarse grid points where H/V measurements were conducted systematically following the SESAME guidelines (Bard et al., 2004; Chatelain et al., 2008; Guillier et al., 2008). In addition, H/V measurements were performed on a denser grid for three locations in both northern and central parts of the city. Variation of the resulting fundamental frequencies correlates well with the expected distribution and the thickness of the soft sediments. Furthermore an analytical assessment based on equivalent linear approach is used. An iterative process is applied for developing representable soil profiles based on the results of the analytical approach combined with the H/V measurements. Obtained results give important indications that can be used for further analysis of site response on simulated ground motions based on earthquake scenarios (Bjerrum et al., 2013).

INTRODUCTION

İzmir, the third largest city in Turkey, is located on the west coast of Turkey surrounded and underlain by several active faults (Emre et al. 2005). Previous GPS studies have confirmed a westward migration of the Anatolian microplate, with rotation of western Anatolia in the area around İzmir (e.g. McClusky et al. 2000; Nyst and Thatcher 2004). This migration and rotation result in reactivation of faults along the west coast of Turkey and İzmir is of this reason exposed to significant seismic hazard. The city has historically experienced strong ground shaking due to earthquakes. The latest large earthquake in the area was in 1778, following two events separated in time by approximately 50 years. Macroseismic intensities in İzmir have been estimated to up to MMI = X for these events (Ambraseys

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and Finkel 1995; Papazachos and Papazachou 1997; Papazachos et al. 1997). Low seismic activity in the last 240 years, and the results of a local GPS study focusing on the local tectonic deformation around İzmir (Aktuğ and Kılıçoğlu 2006) indicate that stresses are building up across the faults in the area (Figure 1).

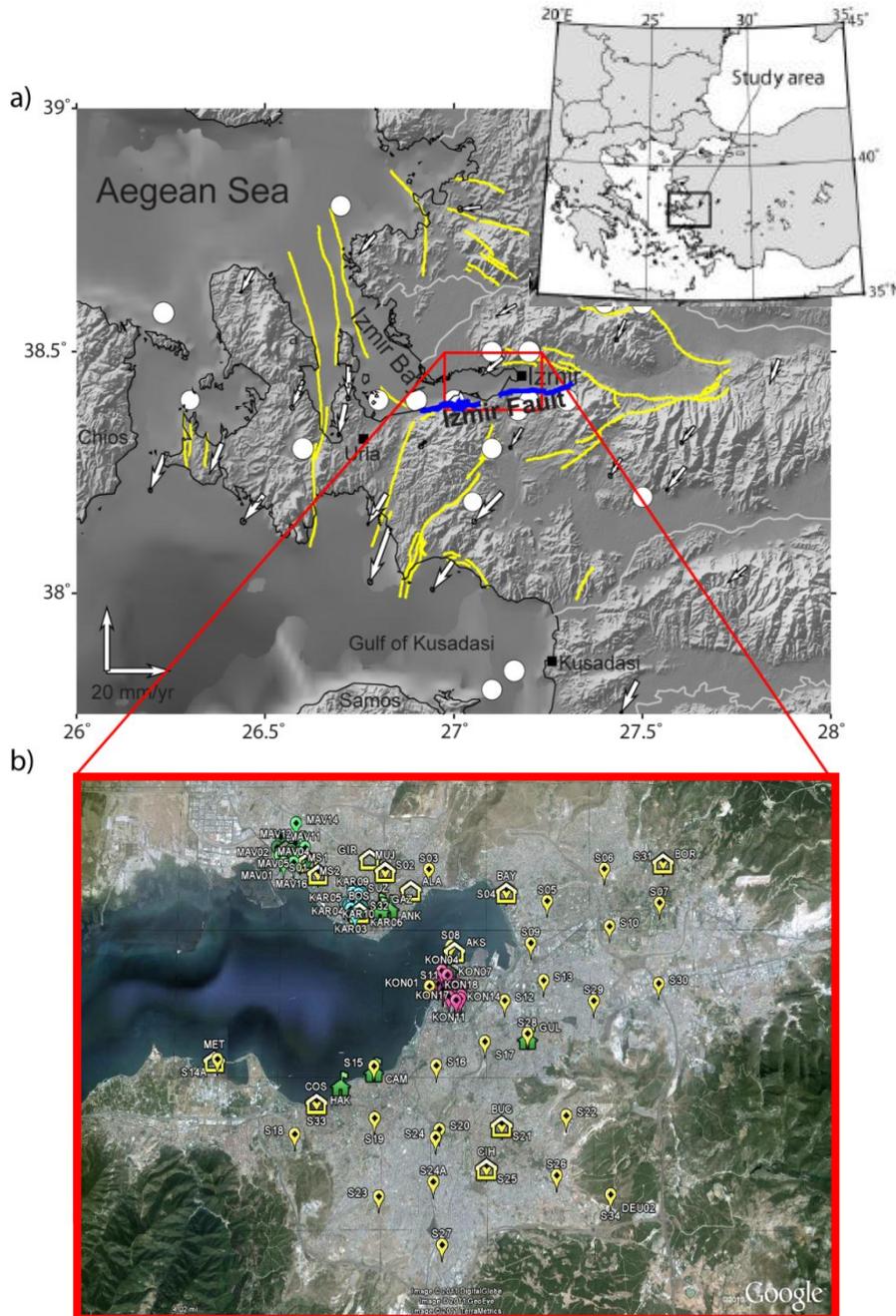


Figure 1. a) Map of the İzmir and surroundings. The faults mapped by MTA (Emre et al., 2005) are shown as yellow lines, İzmir fault is marked with blue. The historic events in the area are indicated as white circles (Ambraseys and Finkel, 1995; Papazachos and Papazachou, 1997; Papazachos et al., 1997) and the GPS velocity field from Aktuğ and Kılıçoğlu (2006) is shown as white arrows. b) Location of sites for H/V measurements. (Yellow: Large grid points; Pink: dense grid in Konak; Blue: dense grid in Karşıyaka; Green: dense grid in Mavişehir). Map prepared in Google Earth © .

İzmir is located directly above a normal fault of approximately 40 km length, potentially capable of generating a $M_w=6.9$ earthquake (Wells and Coppersmith 1997). In addition, large parts of the metropolitan area are underlain by soft sedimentary deposits, especially on the northern (Karşıyaka) and eastern (Bornova) parts of the İzmir Bay. In the north the deltaic deposits from the

Gediz river poses significant challenges to the built environment with settlement problems in buildings, high liquefaction potential due to high water saturation etc. The sediment thickness is highly variable within the city of İzmir, where also topographic high areas of bedrock outcrops are present. It is therefore important and timely to address the local site effects in İzmir, especially taking into account the possible large ground motions that are expected from future earthquakes. Site amplification in İzmir has previously been estimated by the Metropolitan Municipality of İzmir (MMI) (2000). The reported amplification factors are in the range of 3-4 in the central and northern parts of the city. More recently, Altun et al. (2012) used borehole data from MMI (2000) to perform a 1D dynamic site response analysis. They found that most of the area along the northern coast of İzmir Bay is prone to large ground shaking potential due to the soft sedimentary deposits, the deep bedrock level, the shallow underground water table and the proximity to the active İzmir fault.

Previously both probabilistic and deterministic (based on ground motion simulations) seismic hazard analyses have been conducted for the area around İzmir. Expected ground motions of 0.4 g for a 475 year return period were predicted, while earthquake rupture scenarios predicted ground motions on bedrock level exceeding 750 cm/s^2 in the center of the city (MMI, 2000; Bjerrum 2007; Bjerrum and Atakan 2008; Deniz et al. 2010; Bjerrum et al., 2013). Figure 2 shows the average peak ground motions (in PGA and PGV) from the study of Bjerrum et al. (2013).

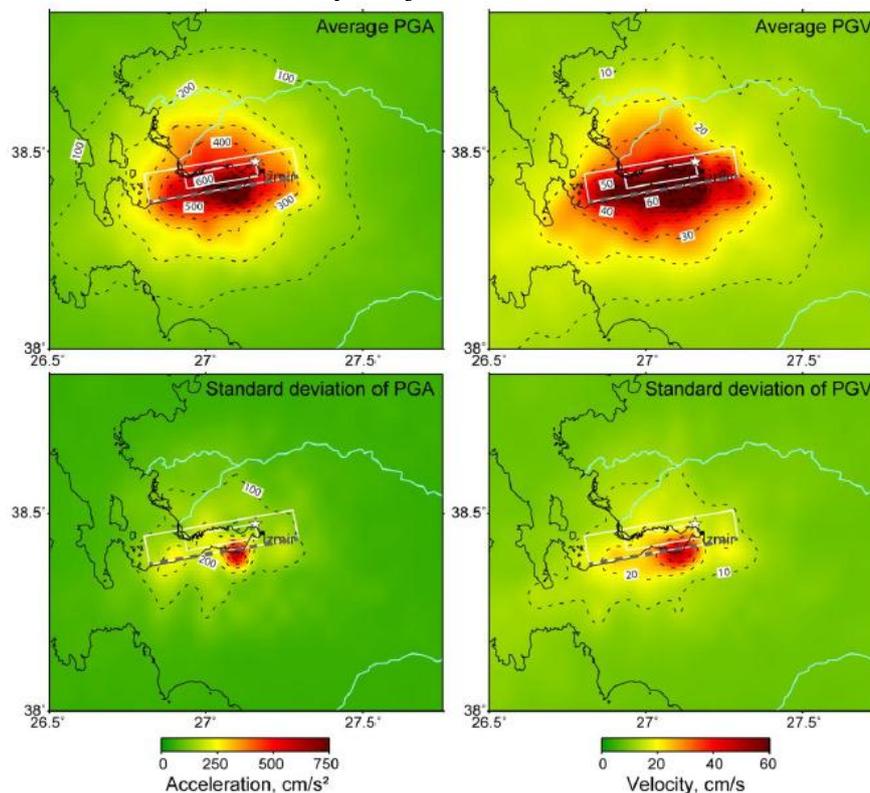


Figure 2. Spatial distribution of average ground motion and standard deviation of PGA (left) and PGV (right) from ground motion simulations (from Bjerrum et al., 2013). The surface projection of the ruptured fault plane and asperity are shown as white rectangles, the surface trace is marked with a thick stippled line. The nucleation point is shown as a white star.

The objective of this study is to highlight the local site effects potential in İzmir due to a future large earthquake, using H/V measurements across the metropolitan area of İzmir. Measurements were conducted in both a coarse grid points covering the entire city (approximately $2 \times 2 \text{ km}$) as well as at denser grid points (max 300 m spacing) on three selected areas (Figure 1b). Fundamental frequencies obtained from the H/V measurements are then used in an iterative process to obtain representative 1D soil columns for Karşıyaka on the northern coast of İzmir bay.

METHODOLOGY AND DATA

Nakamura's H/V technique (Nakamura, 1989) is based on the assumptions that the horizontal and vertical components on hard ground (bedrock) have similar characteristics and that the vertical component of ground motion on the ground surface is similar to the horizontal component at the bedrock. The spectral ratio between the horizontal and vertical components of ambient noise recorded at the surface is assumed to capture the fundamental frequency of the soil column as well as the related amplification. Nakamura (2010) further claims that this is caused by multiple reflections of SH-waves in sedimentary layers overlying the bedrock. Many studies have validated the benefits of the method e.g. for Japan (Nakamura 1989), Oakland, California (Field and Jacob 1995), Israel (Gitterman et al. 1996), Thessaloniki, Greece (Lanchet et al. 1996), Lisbon, Portugal (Teves-Costa and Matias 1996) and the Rhone Delta, France (Bour et al. 1998). It is generally believed that reliable estimates of the fundamental frequency can be obtained, whereas there is still uncertainty regarding the amplification factors (Atakan, 2009). The empirical H/V technique uses recordings of ambient noise from a three-component seismograph and as such it is a cheap and practical method to apply in urban environments like İzmir.

We collected ambient noise data in spring 2010, covering a large part of the metropolitan area of İzmir in a coarse grid of approximately 2x2 km, and for three smaller and denser grids in the areas Mavişehir, Karşıyaka and Konak/Alsancak. In total we investigated 87 sites. The smaller and denser grids were chosen for areas where the site classification study by MMI (2000) yields the largest expected amplification. The data were collected using three SARA SR04 digitizers with 4.5 Hz geophones, and recording on laptops. Each recording was approximately 30 minutes long and a sampling frequency of 100 Hz was used. This set up is found valid to investigate fundamental frequencies down to 0.3 Hz (Bard et al. 2004). For the data acquisition we used SEISLOG (Utheim and Havskov 1998) and for organizing and checking the data we used SEISAN (Ottemöller et al. 2011). Processing of the collected data was done with the software GEOPSY (Wathelet 2011). H/V spectral ratios were calculated using a window length of 25 s with no overlap and tapered with a 5% cosine function. A Konno and Ohmachi smoothing with a smoothing constant of 40 was used without filtering (Konno and Ohmachi 1995). Anti-triggering was set with a minimum STA/LTA of 0.2 and maximum STA/LTA of 2.5, where the time windows of the STA and LTA were set to 1 s and 30 s, respectively.

Soil response can be calculated theoretically from known soil structures using linear response analysis. In such a case the theoretical transfer function is calculated for a site where the layered soil column is known. In the case of İzmir detailed information on the soil velocity structure is not known, and we therefore model a simplified soil structures for the district of Karşıyaka in İzmir. In the modeling we tested different soil column models and calculated the corresponding theoretical transfer functions. These functions are then compared to the average H/V spectral ratios we obtained from the recorded ambient noise data. In an iterative process we have obtained two representative 1D soil columns for Karşıyaka, one for a 60 m thick soil column and another for a 100 m thickness. The modeling is conducted with first obtaining the approximate average shear-wave velocity of the soil column from

$$f_0 = \frac{V_{s,ave}}{4 \cdot H}, \quad (1)$$

where f_0 is the fundamental frequency (obtained from the H/V spectral ratio) and H is the thickness of the assumed sediment column (Kramer, 1996). The average shear wave velocity found from this equation is then used as an initial average velocity of the soil column for analytical computations. The results are then compared to the H/V spectral ratios. The entire process is repeated until a satisfactory match is found and the corresponding soil structure is obtained.

The calculation of soil response is based on the assumption of horizontal layer boundaries for the soil layers and the bedrock, as well as infinite extent of the layers in the horizontal direction. Furthermore, the response of the soil layers is assumed to be mainly caused by vertically propagating SH-waves (Kramer, 1996). In the software SHAKE2000 (Ordóñez, 2011), used for calculation of soil response, the layers in the soil profile are assumed to be homogenous and have the properties of visco-elastic materials. The equivalent linear approach has been used successfully for several ground

response analyses e.g. for the Rhone Delta, France (Bour et al. 1998), Armenia, Columbia (Slob et al. 2002) and Bangalore, India (Sitharam and Anbazhagan 2008).

The soil structure is constructed and modified until the fundamental frequency of the transfer function for the soil response, matches the fundamental frequency found from the average H/V spectral ratio curve, when ambient noise is used as input motion in SHAKE2000. When a satisfactory soil column is obtained, we calculate the soil response due to the ground shaking from the simulated ground motions obtained by Bjerrum et al. (2013). The soil response is calculated based on two levels of the ground motions; first one, the simulated ground motions that are scaled to have a maximum acceleration of 0.3g (scaled) and the second, the full amplitudes from the simulated spectral accelerations (unscaled). The scaled waveform is introduced, since ground motions of more than 0.3-0.4 g may induce non-linearity in the soil response, and the linear approach therefore may no longer be valid.

Sedimentary deposits are usually classified according to properties like grain size, matrix type, cementation, water content, cohesion forces and porosity (Atakan, 1995). In geotechnical applications other layer specific properties like density, viscosity, confining pressure, degree of consolidation, stiffness, shear strength, shear wave velocity, damping, Poisson ratio, Young's modulus, bulk modulus and Lamé's constants are also important (NDT-Resource Center 2011; Pluijm and Marshak 2004). When describing the behavior of soils in an analytical process, it is assumed that all these parameters are reduced to stiffness and damping (Atakan 1995; Kramer 1996; Ordóñez 2011). Damping, unit weight, G/G_{max} curves and damping curves for damping and stiffness for clay, sand and rock used in the modeling are chosen as average values (Amir M. Kaynia, personal communication).

ANALYSIS RESULTS

From the field experiment we obtained H/V spectral ratios for sites across İzmir, and we have determined the fundamental frequency distribution in the metropolitan area of İzmir. These are shown in Figure 3. The distribution of the fundamental frequency found from the H/V curves shows low values of less than 1 Hz along most of the coast. The topographic high areas, with bedrock outcrops, are clearly visible in the distribution with higher fundamental frequencies.

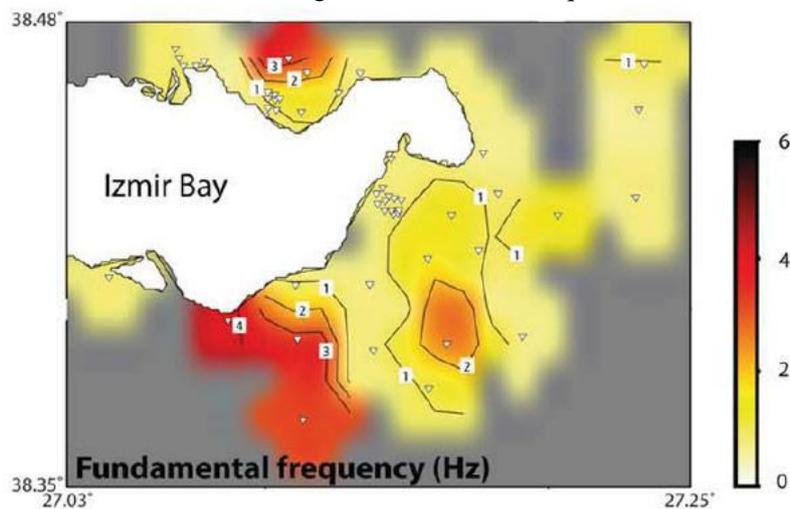


Figure 3. Distribution of the fundamental frequency found from the H/V measurements. Lower frequencies correspond to the soft sediment layers in the city (yellow), while the high frequencies correspond to the stiffer soils or topographic highs where bedrock is outcropped (orange-red). The grey colored areas are with no measurement points. Measurement sites are marked by triangles.

In the analysis of the H/V spectral ratios obtained from the dense field measurements we focus on the three areas Karşıyaka, Konak and Mavişehir, for which we have measurements of ambient noise from 15-20 sites, with station spacing of no more than 300 m. After processing the data and excluding data from points which showed no clear peak in the H/V spectral curve, measurements from 9, 12 and 5 sites from the Karşıyaka, Konak and Mavişehir grid, respectively, were used to calculate

representative averages of the H/V curves (Figure 4). The average H/V curves found for Karşıyaka and Konak both give a clear peak for frequencies of 0.6- 0.9 Hz. For larger frequencies low ratios are found for Karşıyaka, while a second peak around 3-5 Hz is observed for Konak. In case of Mavişehir, amplification levels above 2 are found for the lower frequencies. However, the peak is not as clear as found for Karşıyaka and Konak and at 2 Hz, there is a sharp decrease in amplification. The curve obtained from Mavişehir is quite similar to the curve obtained from Karşıyaka, except for the missing clear peak, and a shoulder at frequencies higher than the peak frequency. This shape arises from one of the measurement points with predicted large amplification around 1-2 Hz (shown in grey in Figure 4, upper right plot).

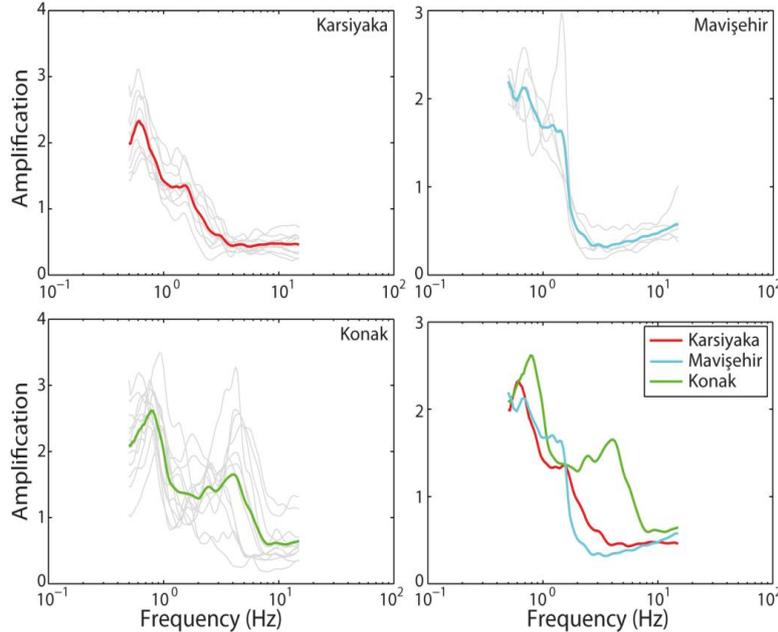


Figure 4. H/V curves as measured in the field (gray lines), the colored bold lines show the averages for the three areas of special interest, Karşıyaka, Konak and Mavişehir. The lower right panel gives a comparison of the average H/V curves from the three areas.

We model two soil columns of different thickness for the Karşıyaka district (60 m and 100 m depth). We use two different input bedrock ground motions throughout our analysis based on the ground motion simulations of Bjerrum et al. (2013), with $PGA = 0.53g$ (unscaled), and one case where the simulated ground motion has been scaled to $0.3g$. In addition we use ambient noise as input when defining the best-fitting soil structure. In the soil columns, the upper 10 m are assumed to be sand, while the rest of the soil column is assumed to consist of clay with increasing velocity with depth (Kuruoglu, 2004; Yalcin, 2008). The best fitting velocity structures to the average H/V curves are shown in Figure 5. We propagate the ambient noise, scaled ground motion and unscaled ground motion through the soil columns using an analytical approach. It is clear, that when the ambient noise is used as input, the largest amplification is expected, and the fundamental frequency corresponds to the fundamental frequency obtained from the H/V spectral ratio. When the bedrock ground motions are used as input in SHAKE2000, both amplification and fundamental frequency decrease. This corresponds to what is expected from the relations between shear modulus/rigidity and the shear wave velocity and frequency given in equation 1:

$$v_s = \sqrt{\frac{G_{max}}{\rho}}, \quad (2)$$

where G_{max} is the maximum shear modulus and ρ is the density (Kramer, 1996). According to equations (1) and (2) if the input ground motion is large, the strain is large, which implies that the rigidity is low, following the G/G_{max} curves. This corresponds to lower shear wave velocity, giving a low fundamental frequency.

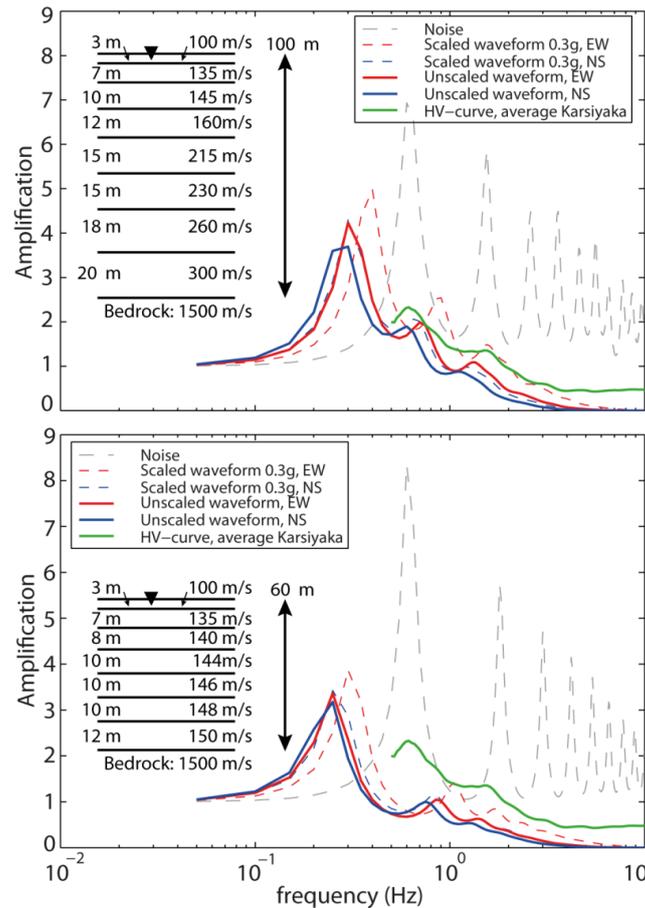


Figure 5. Transfer functions obtained from SHAKE2000. Legend describes type of input ground motion. Soil structures for the two modeled soil columns are shown with corresponding layer thicknesses and velocities, 100 m thickness (top) and 60 m thickness (bottom). The H/V-curve is the average curve for Karşıyaka, also shown in Figure 4.

The soil columns modeled for Karşıyaka both contain low shear wave velocities, which gradually increase with depth. The average shear wave velocities in the two models are 143 m/s and 137 m/s for the 100 m and 60 m soil columns, respectively. The amplification level, when the simulated ground motion is propagated through the soil columns, is largest for the soil column which is 100m thick.

DISCUSSION AND CONCLUSIONS

Nakamura's technique is widely accepted to identify the fundamental frequency. From the H/V spectral ratios, based on field measurements of ambient noise, very low fundamental frequencies were found for the coastal area. In this study, a very good correlation of topography with the fundamental frequency is found. The topographic high areas, such as north of Karşıyaka and southeast of Konak, are easily identified from the map showing the distribution of the fundamental frequencies from the H/V spectral ratios (Figure 3). Oppositely, very low fundamental frequencies are found for low lying areas along the coast, where thick sediment deposits are expected.

In the second part of this study we modeled the response of two soil columns for the Karşıyaka district in İzmir. The thicknesses of the soil columns are based on generalized assumptions of very thick soil columns for the Mavişehir district, located on top of the old delta from the Gediz River, west of Karşıyaka and thinner soil columns in the innermost part of İzmir Bay (Kuruoglu, 2004). In our models we assumed thicknesses of 60 m and 100 m. We were able to model soil structures resulting in a soil response with a fundamental frequency corresponding to what was obtained from the H/V spectral ratios, based on ambient noise measurements.

We have interpreted the H/V curves by modelling simple generalized soil structures for Karşıyaka with soil response similar to what was found from the H/V spectral ratios. The H/V spectral ratios obtained from ambient noise measurements yield low fundamental frequencies for the coastal area in İzmir, and the topographic high areas are clearly identified from the high fundamental frequencies. The two soil columns, with soil response of fundamental frequency corresponding to the H/V spectral ratios modeled for the Karşıyaka district, imply an increase in the low frequency content of the ground motions when accounting for the soil columns, as compared to the ground motion at bedrock level. However, PGA is found to be lower. Increased thickness (model of 100 m) results in larger amplification of the ground motion.

The results presented are meant as a preliminary study of the site effect potential for İzmir, and future studies are needed for better estimation of the transfer functions representing the response of the soil layers. A detailed microzonation study is recommended including the classification of soil structures and seismic velocities systematically determined for several soil profiles together with the depth of the soft sediment layers across the city.

ACKNOWLEDGEMENTS

We have during our field work and visits to İzmir been assisted by several people from Dokuz Eylül University in İzmir. We would especially like to thank Elif Balkan, Çağrı Çaylak, Ezgi Çınar, İlknur Kaftan, and Emre Timur for assistance in the field, together with Åse Oliv Bjørge from University of Bergen. We are grateful to Ersan Özsoy, who assisted during the fieldwork in İzmir. We would also like to thank Amir M. Kaynia from Norwegian Geotechnical Institute, regarding the analytical computations.

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