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Local site effects in Ataköy, Istanbul, Turkey, due to a future large earthquake in the Marmara Sea

Mathilde B. Sørensen,[1]* Ivo Oprsal,[2]† Sylvette Bonnefoy-Claudet,[3]‡ Kuvvet Atakan,[1]
P. Martin Mai,[2] Nelson Pulido[4] and Caglar Yalciner[5]§

[1] *Department of Earth Science, University of Bergen, Allegt.* 41, 5007 *Bergen, Norway. E-mail: sorensen@gfz-potsdam.de*
[2] *Institute of Geophysics, Swiss Federal Institute of Technology ETH, Zurich, Switzerland*
[3] *LGIT, Université Joseph Fourier, Grenoble, France*
[4] *Earthquake Disaster Mitigation Research Center EDM, NIED, Kobe, Japan*
[5] *Osmangazi University, Eskisehir, Turkey*

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SUMMARY

Since the 1999 Izmit and Düzce earthquakes in northwest Turkey, many seismic hazard studies have focused on the city of Istanbul. An important issue in this respect is local site effects: strong amplifications are expected at a number of locations due to the local geological conditions. In this study we estimate the local site effects in the Ataköy area (southwestern Istanbul) by applying several techniques using synthetic data (hybrid 3-D modelling and 1-D modelling) and comparing to empirical data. We apply a hybrid 3-D finite-difference method that combines a complex source and wave propagation for a regional 1-D velocity model with site effects calculated for a local 3-D velocity structure. The local velocity model is built from geological, geotechnical and geomorphological data. The results indicate that strongest spectral amplifications (SA) in the Ataköy area occur around 1 Hz and that amplification levels are largest for alluvial sites where SA reaching a factor of 1.5–2 can be expected in the case of a large earthquake. We also compare our results to H/V (horizontal to vertical component of the recorded signal) spectral ratios calculated for microtremor data recorded at 30 sites as well as to ambient noise synthetics simulated using a 1-D approach. Because the applied methods complement each other, they provide comprehensive and reliable information about the local site effects in Ataköy. Added to that, our results have significant implications for the southwestern parts of Istanbul built on similar geological formations, for which, therefore, similar SA levels are expected.

Key words: earthquakes, fault model, finite-difference methods, hybrid method, Istanbul, strong ground motion.

INTRODUCTION

Istanbul, with a population exceeding 12 million, is considered one of the world's megacities exposed to a large earthquake hazard. The catastrophic consequences of the two large earthquakes in Izmit and Düzce in 1999 have highlighted the need for careful analysis of seismic hazard including local site effects, although the earthquake hazard in this region has been a topic of considerable interest for a long time. Recent results from several studies (e.g. Atakan *et al.* 2002; Erdik *et al.* 2003, 2004; Pulido *et al.* 2004) emphasize the importance of earthquake preparedness and risk mitigation in the Istanbul metropolitan area and its rapidly growing surroundings. The present study addresses the issue of local site effects in this area.

Previous studies of local site effects, following the 1999 Izmit and Düzce earthquakes, have focused mainly on the Avcilar district of western Istanbul (e.g. Özel *et al.* 2002; Tezcan *et al.* 2002), and on the city of Adapazari in the east (e.g. Bakir *et al.* 2002; Komazawa *et al.* 2002; Sancio *et al.* 2002; Beyen & Erdik 2004; Ansal *et al.* 2004), which experienced significant damage mainly due to site effects. In both areas, the presence of soft sediments in basin structures has caused strong amplification of earthquake ground motion during past earthquakes.

As for the city of Istanbul, less attention has been paid to the possible effects of local geological variations. In a recent study, Birgören *et al.* (2004) found amplification levels up to a factor of 7 for some geological formations at 1 and 3 Hz

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*Now at: GeoForschungsZentrum Potsdam, Section 5.3, Potsdam, Germany.
†Now at: Charles University, Faculty of Mathematics and Physics, Department of Geophysics, Prague, Czech Republic.
‡Now at: Department of Astronomy, Physics of the Earth and Meteorology, Comenius University, Bratislava, Slovak Republic.
§Now at: EOST-IPG, Strasbourg, France.

frequencies, based on spectral ratios of records from a $M = 4.2$ earthquake.

The main objective of this study is to estimate the local site effects in the Ataköy district of the Bakirköy Municipality which lies to the east of the Atatürk international airport in southwestern Istanbul. In general, the area is geologically representative of the southwestern part of Istanbul (Fig. 1a)—and the results, therefore, give an insight into the site conditions in this larger-scale area. An important argument for focusing on this area stems from recent results of ground motion modelling (Pulido *et al.* 2004) where the highest ground motions due to a scenario earthquake in the Marmara Sea are expected in the southwestern part of Istanbul (Fig. 1b). This trend is also supported by probabilistic seismic hazard results for this area, predicting the highest seismic hazard in the southern parts of the city due to the close vicinity to the North Anatolian fault (Atakan *et al.* 2002). In addition to that, the area is densely populated, including critical facilities such as the Atatürk international airport and several industrial installations.

In this study, we apply three parallel approaches for assessing the local site effects in the Ataköy region. We express the site effects in terms of amplification describing the ratio of the ground motion at the free surface to that at bedrock level. Since our final goal is to understand the site effects in three dimensions, we use a hybrid finite-difference (FD) procedure to calculate spectral amplification due to a 3-D velocity–density model representing the Ataköy area. In order to improve this model and obtain further insight into the local variations of site effects, H/V (horizontal to vertical component of the recorded signal) spectral ratios are calculated for recorded microtremor data and compared to H/V spectral ratios for synthetic ambient noise data based on a 1-D geological model.

The applied hybrid 3-D FD procedure for calculating spectral amplifications (SA; Oprsal & Zahradnik 2002; Oprsal *et al.* 2002) combines source, path and site effects in two consecutive steps. In the first step, input ground motions for bedrock conditions are modelled for a target scenario earthquake and a regional 1-D crustal structure (Pulido *et al.* 2004). In the second step, a 3-D FD scheme is used for calculating the SA within the study area for a local 3-D velocity structure. The procedure is capable of computing the full 3-D wavefield propagation. The resulting ground motion and corresponding SA factors (related to a bedrock site) cover the local area through surface receivers placed on a fine square grid. This kind of modelling and comparison provides a comprehensive picture of the site effects, although uncertainties in the input geological model may limit the final result.

The H/V spectral ratio method (or 'Nakamura method') (Nakamura 1989, 2000) is a well-established method for fast and cost-efficient estimation of site effects. The limitations of the methodology are studied in detail in previous review papers (e.g. Lachet & Bard 1994; Atakan 1995; Kudo 1995; Mucciarelli 1998; Mucciarelli *et al.* 2003; Atakan *et al.* 2004a). General consensus is that when the method is applied under careful experimental conditions (i.e. type of the instruments used, measurement details with regard to the sensor coupling, surface conditions, external factors such as wind, rain, etc. and the processing techniques used for analysis), fundamental frequencies on which the amplifications occur can be reliably assessed. However, the method is less reliable for the absolute amplification factors.

Synthetic noise data based on a 1-D model representative of an alluvial site in the Ataköy area provide additional information about the effect of local geology on the site amplification, and thus helps in interpreting the microtremor results. The method used to model the synthetic noise has recently been developed for more systematic investigation of the H/V spectral ratio method (Bonnefoy-Claudet *et al.* 2004), however, the simulated noise also provides an input for studies of the effect of different velocity structures on the H/V ratio. As opposed to other analytical methods for estimating the ground response such as with 1-D layered damped soil on elastic bedrock using earthquake records (e.g. SHAKE, Schnabel *et al.* 1972), the method used in this study takes advantage of the noise wavefield and, therefore, provides a more appropriate basis for correlating the empirical results from the H/V spectral ratios.

Due to the differences in their uncertainties, the applied methods complement each other well, and in combination give a reliable estimate of the local site effects in the Ataköy area.

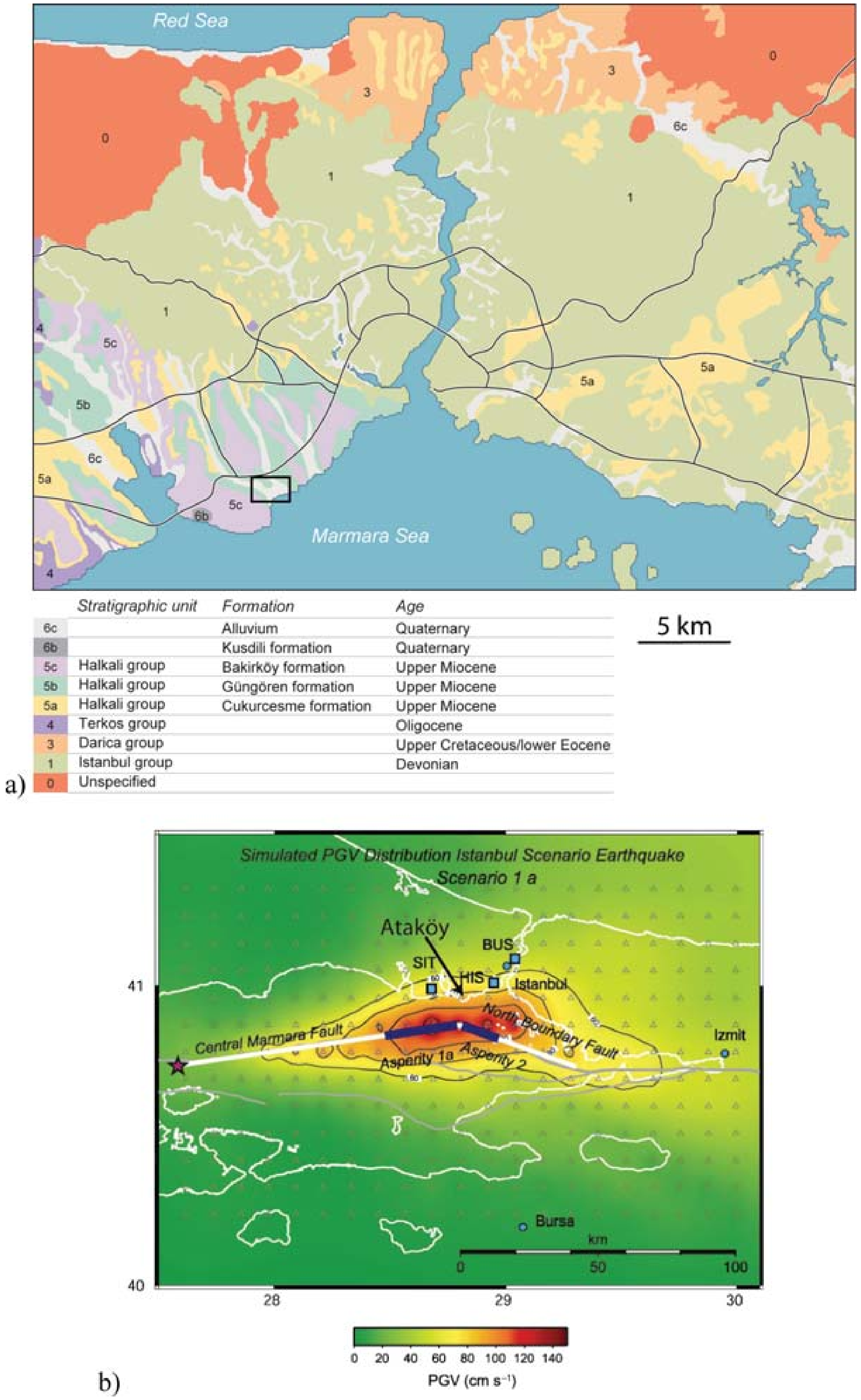
GEOLOGICAL SETTING AND SITE SELECTION

The metropolitan area of Istanbul is underlain by Palaeozoic bedrock outcropping in the northern part of the city (north of Golden Horn) with alluvial systems of Quaternary age dissecting into the bedrock (Fig. 1a). In the southwestern part of the city, on the other hand, weaker geological formations are dominating such as the Bakirköy and Güngören formations, with significant interplay of alluvial and delta systems. Taking into account this broad perspective, our attention is focused on the southwestern part of Istanbul, where the strongest local site effects are expected.

In general, dominating geological formations in southwestern Istanbul are the Bakirköy and Güngören formations, which are both of upper Miocene age. The Bakirköy formation is composed of alternating layers of limestone, marl and clay, whereas the Güngören formation consists of green coloured plastic clay, marl and clayey siltstone. These are also the dominating formations in the target area for this study, the Ataköy district. Fig. 2 shows a detailed geological map of the Ataköy area. In addition to the Bakirköy and Güngören formations, the Kusdili formation of Quaternary age outcrops in a limited area and is composed of clay with molluscs, silt and mud. The overlying alluvial deposits (Quaternary) are the result of fluvial activity and consist of unconsolidated sediments composed of gravel, sand, silt and clay. In some parts of the area, construction material is dumped over the alluvium, overlain by a thin layer of gravel (20–30 cm) and filled with soil on top (40–50 cm). The total thickness of these deposits is approximately 2–3 m. Our study focuses on the Bakirköy and Güngören formations because of their large spatial extent, as well as on the alluvium where strong site amplifications are expected to occur.

3-D MODELLING OF LOCAL SITE EFFECTS

The frequency-dependent ground response in the Ataköy area, due to a finite-extent source, regional-model path effects, and detailed local structure, is calculated using the hybrid FD procedure of Oprsal & Zahradnik (2002) and Oprsal *et al.* (2002). We use the hybrid formulation to model the complete wavefield because direct FD computations for a frequency range of engineering interest are too demanding in terms of computer memory and time. As for the methods used for the wave propagation modelling in complex 3-D media, an FD method is considered one of the most appropriate means for complete wavefield simulation because of its simplicity, stability and relatively simple implementation. To decrease the time and memory demands, our hybrid method computes the wavefield by FD in a local model containing complex 3-D structure embedded in a



	Stratigraphic unit	Formation	Age
6c		Alluvium	Quaternary
6b		Kusdili formation	Quaternary
5c	Halkali group	Bakirköy formation	Upper Miocene
5b	Halkali group	Güngören formation	Upper Miocene
5a	Halkali group	Cukurcesme formation	Upper Miocene
4	Terkos group		Oligocene
3	Darica group		Upper Cretaceous/lower Eocene
1	Istanbul group		Devonian
0	Unspecified		

Figure 1. (a) Geological map of Istanbul. The black square indicates the location of Ataköy. Redrawn from Oktay & Eren (Istanbul Metropolitan Municipality, Site Survey and Earthquake Department). (b) Peak ground velocities (PGV) predicted by Pulido *et al.* (2004) for a $M = 7.5$ scenario earthquake in the Marmara Sea. The star indicates the rupture initiation point, the thick white lines the extent of the rupturing fault and the blue lines the asperity locations (modified from Pulido *et al.* 2004).

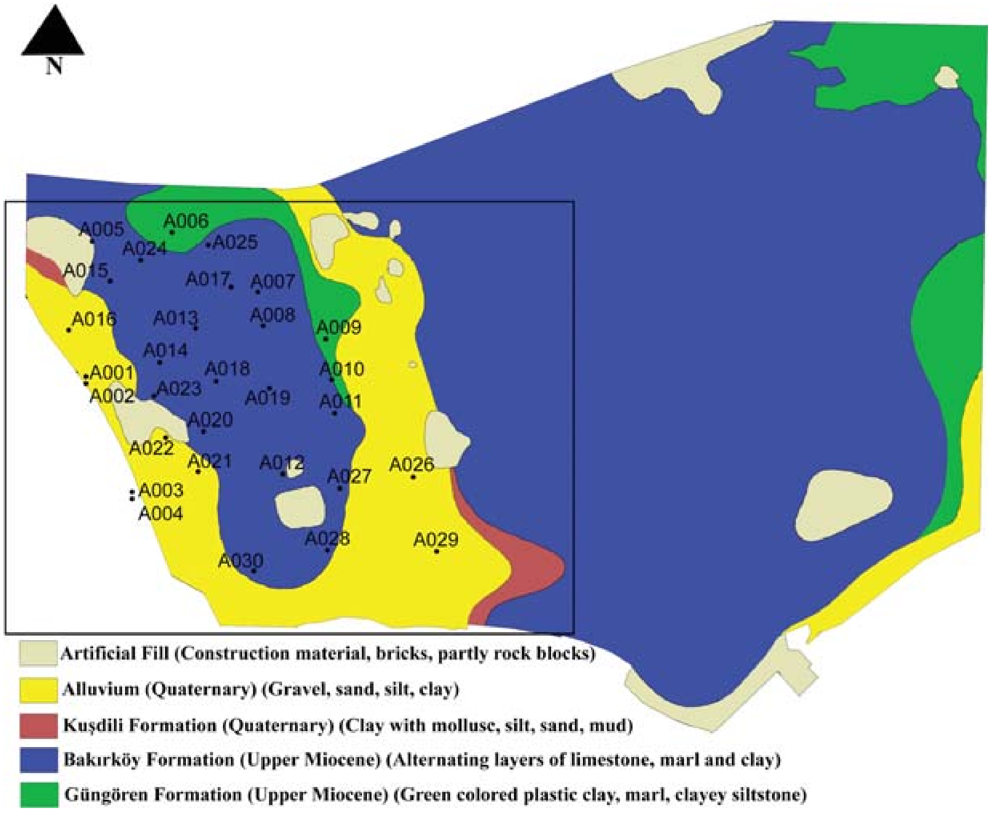


Figure 2. Geological map of Ataköy and Bakirköy districts, western Istanbul. The study area is outlined by the black box. Colours represent different geological formations. Numbered dots represent the microtremor recording sites used for calculating H/V spectral ratios. The dimensions of the study area are approximately 2.2 × 3.3 km. The map is provided by Istanbul Technical University.

(usually simpler and smoother) regional-structure medium. Combination of the source, path and local site effects in a two-step procedure (Fig. 3), was first introduced by Alterman & Karal (1968) for representation of a seismic source in 2-D simulation. The present method is a 3-D/3-D FD version, which is described in detail in Oprsal & Zahradnik (2002), Oprsal *et al.* (2002) and Oprsal *et al.* (2005). Here we only give a short summary.

In the first step, ground motion time-series are calculated for receivers covering the surface of a double-planed box [called excitation box (EB)] surrounding the local site of interest. These calculations, for a seismic source placed outside the EB, are performed for a regional crustal velocity model with an outcrop V_s of 2.0 km s^{-1}, using the methodology of Pulido *et al.* (2004). This is based on a procedure combining a deterministic simulation at low frequencies (0.1–1 Hz) with a semi-stochastic simulation at high frequencies (1–10 Hz). A finite-extent scenario earthquake source embedded in a flat-layered 1-D velocity structure is assumed. The source consists of a number of asperities, which are divided into subfaults assumed to be point sources. The total ground motion at a given site is obtained by summing the contributions from the different subfaults. For the low frequencies, subfault contributions are calculated using discrete wavenumber theory (Bouchon 1981) and summed assuming a given rupture velocity. At high frequencies, the subfault contributions are calculated using the stochastic method of Boore (1983) and summed using the empirical Greens function method of Irikura (1986). The radiation pattern is changed from a theoretical double-couple radiation pattern at low frequencies to a uniform radiation pattern at high frequencies following Pulido & Kubo (2004). The resulting wavefield for receivers on the EB is saved on disk.

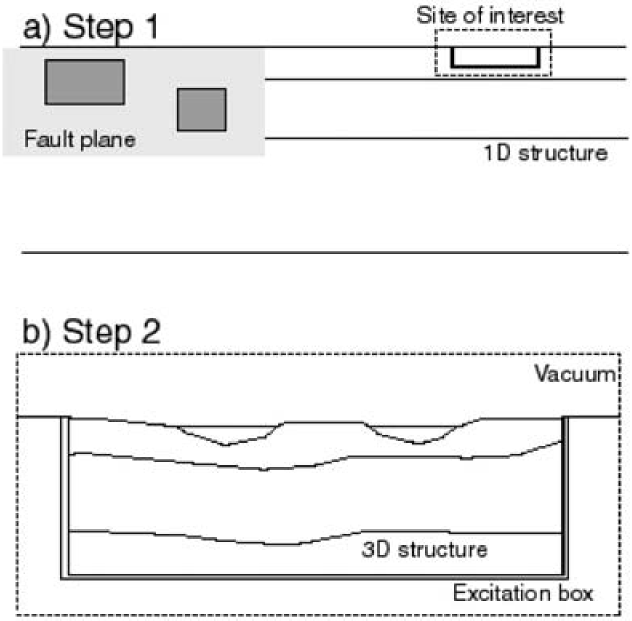


Figure 3. Schematic illustration of the hybrid procedure used for modelling spectral amplification for a dense grid in Ataköy. (a) In the first step, ground motions are calculated on the excitation box using a regional 1-D velocity model. Dark grey fields within the fault plane are asperities. (b) In the second step, surface ground motions are calculated using a 3-D finite difference scheme and a local velocity model. Fig. 3(b) corresponds to the stippled box in 3(a).

In the second step, we perform a hybrid wavefield injection of the excitation computed in the first step into the second step 3-D FD method. The 3-D FD modelling now comprises detailed local structure and occupies only a small fraction of the model size considered in the first step. This approach benefits from the efficiency of the less demanding source-and-path-effects methods while exploiting the wavefield completeness of the FD method. Thus final response contains the combined effects of source, path, and site effects while the memory and time requirements are still in realistic bounds.

The hybrid coupling keeps the excitation boundary fully transparent in the second step. The scattered wavefield penetrates freely out of the EB and, if reflected by an inhomogeneity, it freely propagates through the EB back into the local structure. The same applies for possible new sources added in the second (FD) step (Oprsal & Zahradnik 2002; Oprsal *et al.* 2002, 2005).

The scenario earthquake used in the first step of the calculations is a slight modification of the worst-case scenario for the city of Istanbul defined by Pulido *et al.* (2004), which assumes a combined rupture of the two segments of the North Anatolian Fault in the Marmara Sea (total fault length 130 km) in a $M = 7.5$ earthquake with rupture initiation in the westernmost end. Fault asperities are located in the central part of the rupturing fault, close to the boundary between the two fault segments, considering the seismicity in the area. Stress drop is calculated using the results of Das & Kostrov (1986) to 50 bar (background) and 100 bar (asperity), whereas rise time (3 s) and rupture velocity (varying randomly between 2.8 and 3.2 km s^{-1}) are based on the values for the 1999 Izmit earthquake. We use the 1-D regional crustal velocity model, which is used for routine earthquake location in the Marmara Sea region (Serif Baris, personal communication, 2003). From this scenario earthquake, the ground motions were calculated on a coarse regular grid covering the Marmara Sea area.

As input for the second step of the computations, a densely sampled wavefield on the EB is needed. This was obtained by interpolating the above described coarse-grid regional simulation result. In order to avoid aliasing effects when creating the densely sampled wavefield (spacing 0.25 m) from the coarsely gridded input data (spacing 10 km) we used a Fourier-domain resampling approach. Waveforms were first aligned with respect to propagation direction

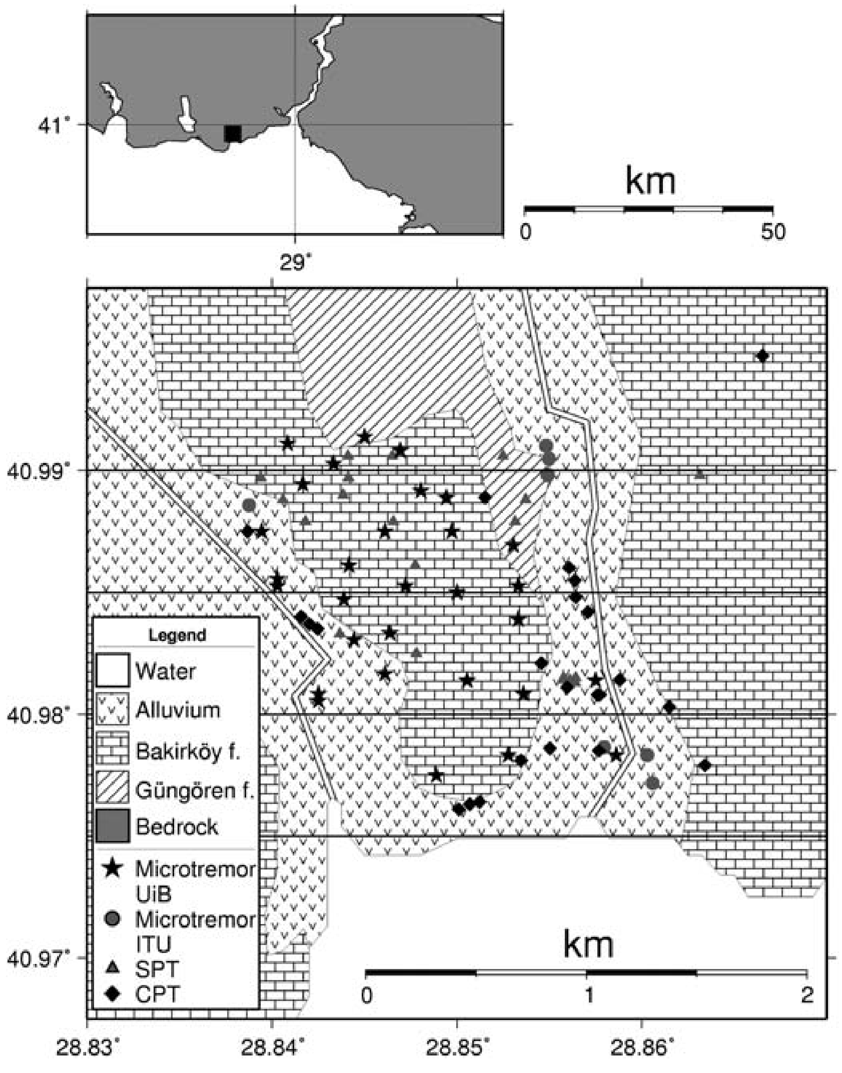


Figure 4. Surface geometry of geological model of Ataköy, used in 3-D FD modelling. The black square in the uppermost map shows the extent and location of the lowermost map. Symbols indicate borehole locations for standard penetration test and cone penetration test data and microtremor recording sites used by Istanbul Technical University (ITU, Eyidogan *et al.* 2000) and University of Bergen (UiB, this study). The four horizontal lines show the locations of the profiles in Fig. 5.

using a cross-correlation approach, and then spatially interpolated on to the fine grid. The time-shifts for the input waveforms were interpolated to the fine grid as well, and then used to undo the waveform alignment.

The local 3-D geological model is based on available geological, geotechnical and geomorphological data. The data sources are microtremor measurements, standard penetration test data, cone penetration test data, geological and geomorphological maps and empirical relations for rock characteristics (Schön 1996). The geometry of the model is determined from the geological and geomorphological maps of the area, and a number of assumptions have been made. The surface geometry is shown in Fig. 4 together with the locations of recording sites and boreholes. The alluvial layer in the model is maximum 5 m thick in all places except under the sea where it reaches 10 m. The alluvium is assumed to be deposited in the depression caused by erosion of the Bakirköy formation due to fluvial activity (i.e. there is no change of the Bakirköy formation base under the alluvium). The Bakirköy formation is 20 m thick, thinning northwards as it erodes at the surface. In the eastern part of the model, the formation is slightly thicker in order to incorporate the increased elevation. The Güngören formation is 80 m thick, thinning in places where erosion occurs. A number of EW cross-sections of the resulting model are shown in Fig. 5, and in Fig. 6 is shown elevation maps of the different layers in the model.

The velocity model of the area is built on the geological model and gives Vp, Vs and density as a function of depth. Quantification of the velocities for the 3-D grid is based on the formulae given in Table 1. For the alluvium, a low surface velocity and a low depth gradient is used. The chosen *S*-wave velocity is consistent with a NEHRP class E soil (soft soil) at the surface compacting to a class D soil (stiff soil) at 10 m depth. Due to heavy exploitation of water through boreholes in the Ataköy area, the present ground water level is at 100 m below ground level (ITU Gelistirme Vakfi 2000). In general, in the larger Ataköy–Bakirköy region, ground water level varies between 60 and 160 m. This implies that we can assume dry soil conditions for the alluvial layer, and for simplicity we assume a V_p/V_s ratio of 1.732. For the Bakirköy and Güngören formations, low surface velocities are chosen. For the upper 5 m there is a large velocity gradient for these formations, whereas the gradient is much lower for depths

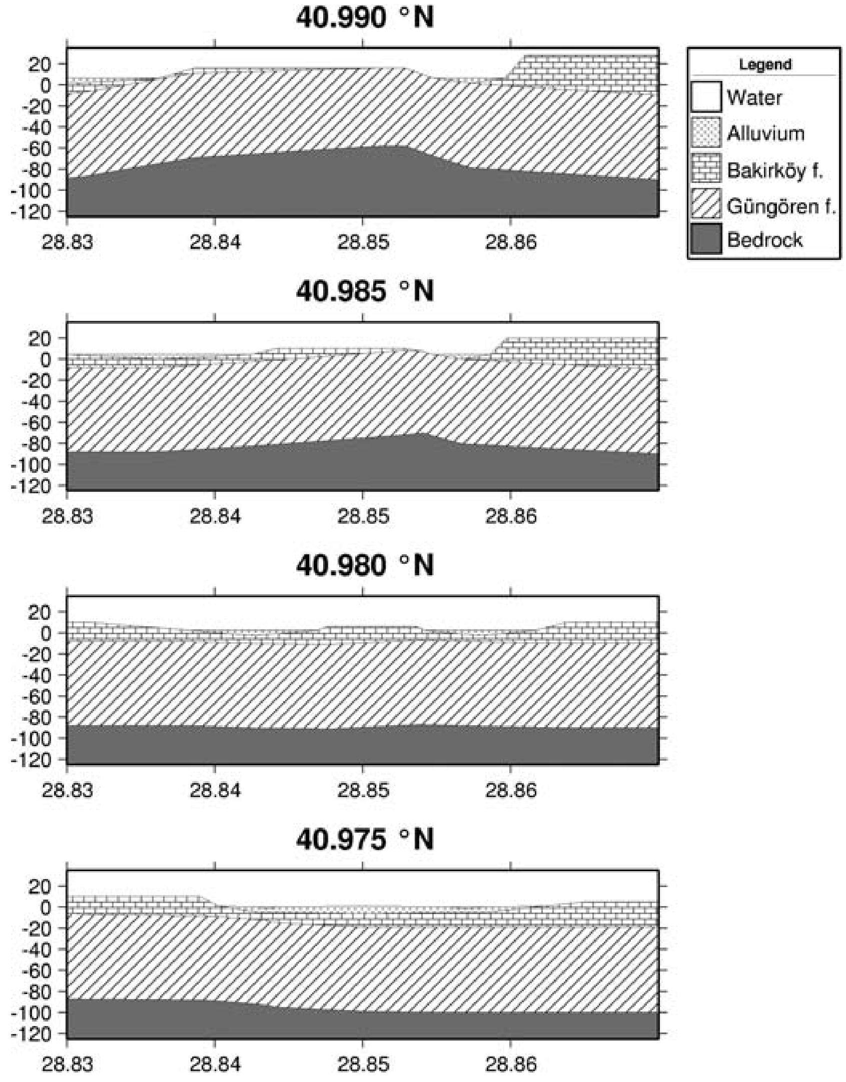


Figure 5. EW cross-sections of the geological model of the Ataköy area, used in the 3-D FD modelling. The locations of the profiles are shown in Fig. 4. The lowermost plot is in the southernmost part of the model, going northwards. Note the thinning of the Bakirköy formation towards north in most of the model due to erosion.

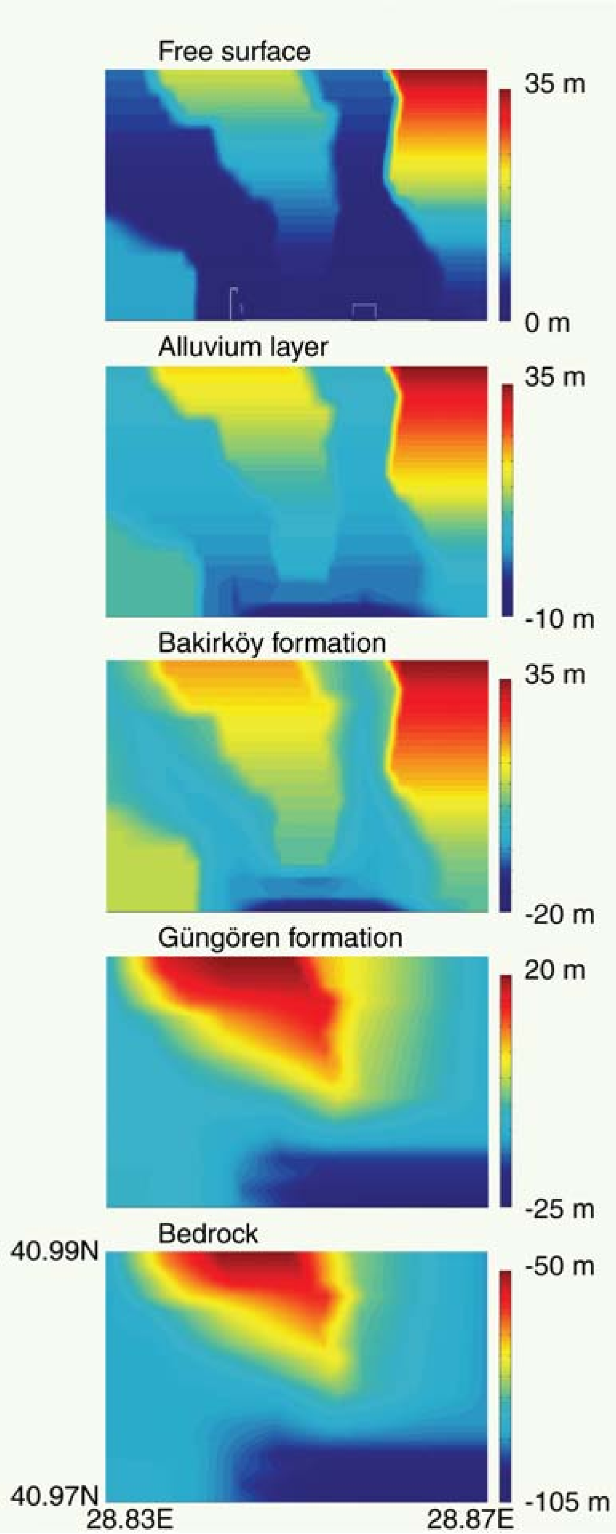


Figure 6. Elevation plots of top of the layers of the geological model of Ataköy, used in the 3-D FD modelling.

larger than 5 m. The low surface velocities and high gradients for the uppermost meters are included to take into account the strong weathering taking place at the surface. For the bedrock, the velocity structure is chosen in order to be consistent with the velocity model used in step 1 of the modelling (Pulido *et al.* 2004) at depths larger than 150 m. In the formulae of Table 1, input depths are relative to the free surface, implying that the velocity i.e. at the top of the Bakirköy formation is dependent upon the depth of the overlying alluvium. This is to take into account the increased pressure arising from increased overburden.

The dimensions of the site of interest, given by the geological model, are 3360 and 2219 m in the EW and NS directions, respectively, and approximately 180 m in depth. The *S*-wave velocities V_s are between 260 and 2100 m s^{-1}, and maximum *P*-wave velocity $V_p = 3600$ m s^{-1}. These high variations in material parameters impose strong demands on the computational part of the FD problem. The influence of the water layer is neglected, which is supposed not to be playing a major role in the resulting wavefield since it is only present in the very southernmost part of the model. Therefore, FD computation of the site effects was performed on a vertically irregular grid with grid steps being 1.5 m in the vicinity of the free surface and 21 m in deeper parts of the model. The horizontal spacing of the grid is 2.5 m and remains unchanged through the whole visualized part of the model because of the spatial distribution of low-velocity riverbeds. However, to minimize the spurious reflections, the model was extended to each side and depth by 70 grid points where the grid step increases towards the edges of the computational model. At this part, where the known model is extended, we gradually decrease the depth of the interfaces and increase the grid step. To decrease spurious reflections, we apply tapers (Cerjan *et al.* 1985) at the strip of 50 grid points breadth around the edges, and non-reflecting boundaries at the edges of the computational model (Emerman & Stephen 1983). The PML technique was taken into consideration in place of non-reflecting boundaries, however, these are too computationally demanding in our formulation. The frequency band is 0–8 Hz and the time step determined from the minimum ratio of $DX(x, y, z)/(1.6^{*}\, Vp(x, y, z))$ is $DT = 4.0 \times 10^{-4}$ s. The computational model dimensions, further extended by the taper zones, are then 4600 and 3500 m in the EW and NS directions, respectively, and approximately 1500 m in depth. The total number of the grid points is 1.5×10^{8}, occupying approximately 5.9 GB of core memory, which is on the edge of reasonable time demand for a two-processor PC. Because of very modest topography, the model in the computations has a flattened free surface. The flattening shifts the vertical structural profile under each point on the free surface so that such a profile remains unchanged.

To provide a more complete picture of the site ground motions on potential buildings, we give the results in the spectral amplification. The spectral amplification factors for pseudo-acceleration response (PSA) depending on the frequency are shown in Fig. 7(a). Shown PSA factors cover the whole area and they are computed as ratio of 5 per cent damping spectral responses computed for the 3- and 1-D (bedrock) models, respectively. The maximum PSA amplifications for the alluvial sites are well above 1.5, especially at frequencies above 3 Hz. Lower amplification levels, less than 1.5, are uniformly distributed over the entire area at all frequencies (Fig. 7a). A more pronounced amplification can be expected for frequencies between 10 and 20 Hz due to the shallow low-velocity deposits.

To compare the 3-D FD modelling with a possibly more sophisticated 1-D linear method, we performed a series of approximately 3×10^{5} 1-D-structure-response computations (Mueller 1985) for points regularly distributed on the free surface. The 1-D structure for each point was exactly the same as the vertical profile under such a point in the 3-D model, hence pseudo-3-D modelling. The code for 1-D response computation in layered media was adopted after Bartak & Zahradnik (1991). The PSA factors are shown in Fig. 7(b). The

Table 1. Formulae used for quantification of the velocities for the 3-D model used for 3-D FD modelling. V_s is S-wave velocity, V_p is P-wave velocity and ρ is density. $Z' = Z - Z_{\text{free surface}}$ is the depth relative to the free surface.

Formation	V_s (m s^{-1})	V_p/V_s	ρ ($\cdot$1000 kg m^{-3})
Alluvium	$150 + 5 \cdot Z'$	1.732	$1.7–1.224 \cdot \exp(-0.846 \cdot Z')$
Bakirköy	$260 + 96 \cdot Z'$ for $Z' < 5$ m $685 + 11 \cdot Z'$ for $Z' > 5$ m	1.8	$2.2–1.224 \cdot \exp(-0.846 \cdot Z')$
Güngören	$200 + 60 \cdot Z'$ for $Z' < 5$ m $445 + 11 \cdot Z'$ for $Z' > 5$ m	1.8	$2.0–1.224 \cdot \exp(-0.846 \cdot Z')$
Bedrock	$450 + 11 \cdot Z'$	1.8	$2.3–1.224 \cdot \exp(-0.846 \cdot Z')$

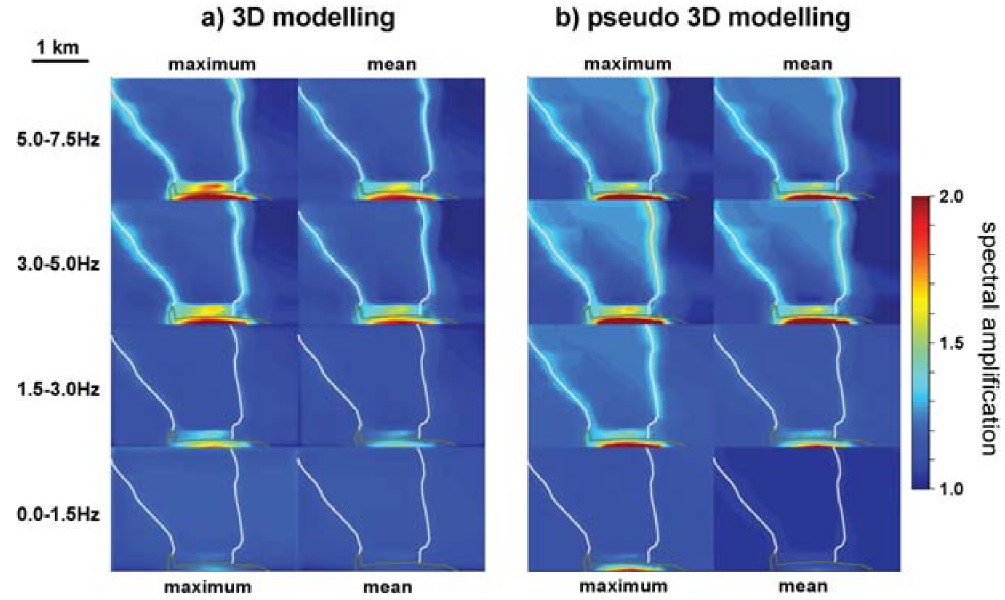


Figure 7. (a) Spectral amplification (pseudo-acceleration response PSA, damping 5 per cent) with respect to a bedrock site for 3-D FD modelling. The results are shown for a set of frequency bands; the left and right sides of the panel correspond to the maximum and mean PSA amplification. The amplified response of the southern part and of the two alluvial systems is apparent. (b) Spectral amplification (pseudo-acceleration response PSA, damping 5 per cent) with respect to a bedrock site for the pseudo-3-D (1-D) modelling. The results are shown for a set of frequency bands; the left and right sides of the panel correspond to the maximum and mean PSA amplification. The amplified response of the southern part and of the two alluvial systems is apparent. The geographical extent of the results shown corresponds to the area shown in Fig. 6. The central parts of the alluvial systems are marked as white lines.

maximum amplification for the alluvial systems is approximately 1.5. The significant amplification at these sites is well visible for all frequency bands, which is the main difference between the 1-D and 3-D response computation.

H/V SPECTRAL RATIOS OF MICROTREMOR DATA

Recorded microtremor data give the opportunity of assessing the fundamental frequency at a given site based on the H/V spectral ratio technique (also known as 'Nakamura method') (Nakamura 1989, 2000; Lermo & Chávez-García 1993). This method is extensively used in microtremor studies throughout the world. The method is discussed in detail in previous studies and the reader is referred to the literature on this topic. Some recent discussions are given in Atakan *et al.* (2004a,b), Guillier *et al.* (2006) and Chatelain *et al.* (2006).

The H/V spectral ratio method is based on the assumption that amplification of microtremor ground motion, mainly consisting of Rayleigh wave energy, due to the presence of a soft surface soil layer, only occurs for the horizontal component of ground motion. Under this assumption, the vertical component of ground motion can be used to remove source and path effects from the signal and isolate the effect of the site (Lermo & Chávez-García 1993). The microtremor recordings are transformed into the frequency domain and the horizontal spectrum is divided by the vertical spectrum. The resulting spectral ratio gives frequency-dependent amplification for the site.

In spite of the known limitations of the method, various sets of experimental data (e.g. Field & Jacob 1993; Duval *et al.* 1994, 1995; Field *et al.* 1995; Lachet *et al.* 1996; Gitterman *et al.* 1996; Fäh *et al.* 1997; Lebrun *et al.* 1997; Riepl *et al.* 1998) confirm that the spectral ratios are much more stable than the raw noise spectra and exhibit a clear peak at soft soil sites, which is well correlated with the fundamental resonance frequency. These observations are supported by several theoretical investigations (Field & Jacob 1993; Lachet & Bard 1994; Lermo & Chávez-García 1994; Bonnefoy-Claudet *et al.* 2004), showing that synthetics obtained with randomly distributed, near surface sources lead to H/V ratios sharply peaked around the fundamental S-wave frequency, whenever the surface layers exhibit a sharp impedance contrast with the underlying stiffer formations.

During a field campaign in the Ataköy area, microtremor data were collected at 30 sites (Fig. 2). The sites were located mainly on the alluvium and the Bakirköy formation. Site selection was based on avoiding too much man-made noise and at the same time obtaining good coupling of the sensor to the ground. At each site, a minimum of 3 × 10 min of seismic noise was collected continuously using the GBV-316 (GeoSIG) portable digital seismographs. Each seismograph contains a 16-bit digitizer and a 4.5 Hz three-component built-in sensor. The technical specifications of the instruments used were tested extensively through previous studies (Atakan *et al.* 2004a) and have a resolution down to 0.5 Hz (also down to 0.3 Hz under specific conditions). Communication was done using the Seislog data acquisition software developed for Pocket PC (Ojeda *et al.* 2004).

Data were processed using the recently available software J-SESAME (Atakan *et al.* 2004b), developed for calculation of H/V spectral ratios. An automatic window selection module is included, which filters out noisy time windows by applying an antitrigger algorithm based on the STA/LTA ratio (short term average divided by the long term average of the signal amplitudes). The data are organized according to the recording sites and average H/V spectral ratios are computed using standard processing techniques (Atakan *et al.* 2004b).

The H/V spectral ratios calculated for sites on the alluvium and Bakirköy formation are presented in Figs 8 and 9, respectively. For the alluvial sites (Fig. 8), a strong peak is observed around 1 Hz. An additional, more diffuse peak is indicated around 3–6 Hz. For the Bakirköy formation (Fig. 9), there is again a clear peak around 1 Hz whereas no peaks are observed for higher frequencies. This indicates that the 3–6 Hz peak observed for the alluvium is an effect of the alluvial layer, whereas the 1 Hz peak is probably caused by deeper lying formations.

In a previous study by Eyidogan *et al.* (2000), microtremor recordings were collected at a few sites in the Ataköy area (Fig. 4). H/V ratios for these data, recorded mainly on alluvial deposits, are in agreement with the results obtained in the present study.

1-D MODELLING OF AMBIENT NOISE

In order to check the H/V spectral ratio results for the recorded microtremors, ambient noise was simulated using a 1-D model representative of a site in Ataköy. The H/V spectral ratio for the simulated noise was then calculated for comparison with the H/V spectral ratios of the recorded microtremors. The noise simulations were performed as described by Bonnefoy-Claudet *et al.* (2004), simulating noise originated by human activity for sites with heterogeneous subsurface structure. In this study, the site is considered as a 1-D structure, and the Green's functions for the medium are calculated using the method of Hisada (1994). The H/V spectral ratio for the synthetic noise was calculated using the J-SESAME software as described for the recorded microtremors.

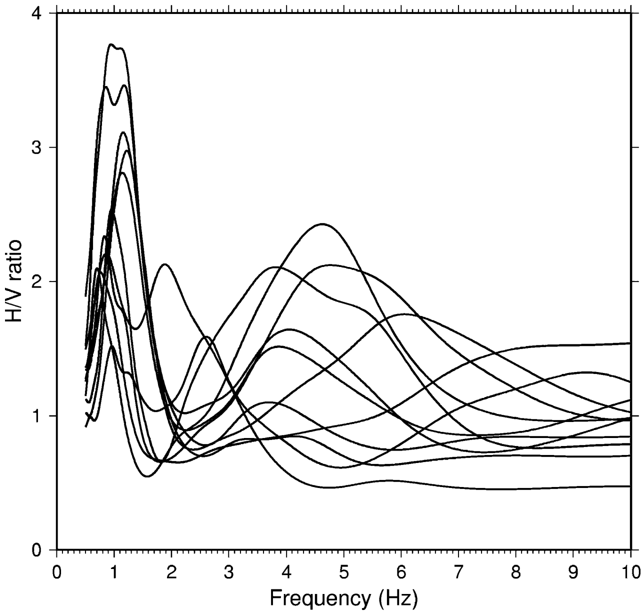


Figure 8. Average H/V spectral ratios for sites located on alluvium.

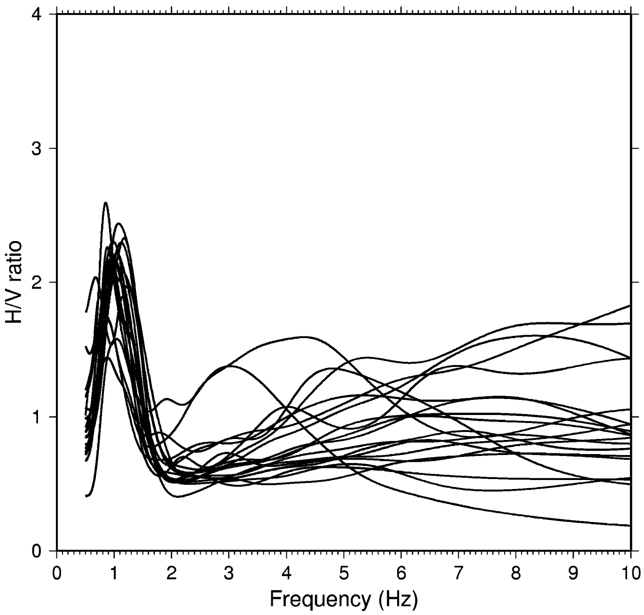


Figure 9. Average H/V spectral ratios for sites located at Bakirköy formation.

Ambient noise was simulated for a site representative of an alluvial site. The 1-D structure of the site is taken from the 3-D model used for 3-D FD simulations. The 1-D model was defined as a large number of layers with a layer thickness of 5 m to be consistent with the grid spacing in the 3-D modelling. The composition of the site is illustrated in Fig. 10 and the velocities are given in Table 2.

Noise sources were modelled as point forces with delta-like source time functions located at fixed depths (4 and 8 m) and distributed randomly in space, direction, amplitude and time. Convolving Green's functions calculated by the method of Hisada (1994) gave synthetic noise representative of the site.

The resulting H/V spectral ratio curve is shown in Fig. 11. The significant peak around 1 Hz observed for the recorded microtremors is present but less clear and shifted towards lower frequencies for the model results. There is a weak peak around 5–7 Hz which is probably associated with the 3–6 Hz peak observed for the recorded microtremors. The reduced H/V amplitudes and the shifted peak frequencies indicate uncertainties in the layer thicknesses or impedance contrasts in the model.

COMPARISON AND DISCUSSION

Individual results obtained from the empirical data and their comparison to 1-D and 3-D synthetic modelling show the following features:

(i) 3-D synthetic results give an insight to the complexity of the site response, especially for higher frequencies where lateral varia-

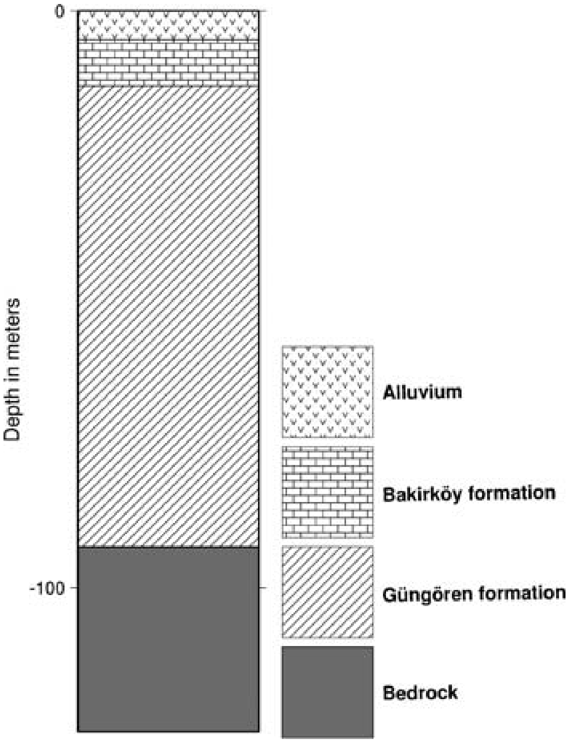


Figure 10. 1-D model used for simulating ambient noise at an alluvial site: 5 m alluvial layer, 8 m Bakirköy formation, 80 m Güngören formation and bedrock (half space). Velocities of the different layers are given in Table 2.

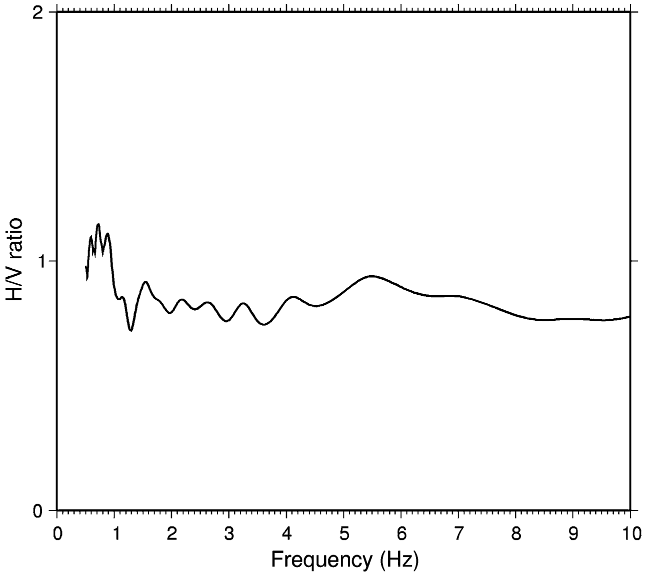


Figure 11. H/V spectral ratios calculated for simulated ambient noise at 1-D alluvial site.

tions become more visible. In this respect the response of the alluvium is clearly visible at frequencies higher than 2 Hz.

(ii) Regarding the frequency content of the site effects, the clear peaks observed in the microtremor data around 1 Hz are comparable to 3-D synthetic results. However, some differences are observed due to uncertainties in the velocity model, which is based on very limited available data. The 1 Hz peak is in good agreement with what might be expected from the soil thickness using the relation $f_{\text{peak}} = v_{s,\text{ave}}/4H$ where $v_{s,\text{ave}}$ is average S-wave velocity and H is thickness of the soil layer.

(iii) The different methodologies predict different values for the amplification factors. The recorded microtremors have significantly higher amplification levels when compared to the synthetic 3-D data.

(iv) Our results from the 3-D modelling, based on a simulated strong ground motion (scenario earthquake of magnitude 7.5 in the Marmara Sea) predict maximum amplification factors in the range 1.5–2. This is significantly lower than our results from microtremor data and previous results on weak motion data (Birgören *et al.* 2004).

(v) One explanation for the lower amplification factors for the synthetic 3-D data relative to the microtremor measurements is that the real structure is definitely more complicated than our models, resulting in a poorer wavefield in terms of scattering for the modelling.

(vi) The discrepancies between the site effect estimates of the various methodologies reflect the lack of good geotechnical data in the area. With the availability of S-wave velocity profiles, the input models can be improved significantly, which is expected to lead to more consistent results. In this respect, our model could be used as a starting model for refinement in future studies.

(vii) Based on the above, it is recommended that site effects in the Ataköy area should be taken into account in any future application towards earthquake risk mitigation. Our results indicate that for a target earthquake of magnitude 7.5 in the Marmara Sea, a minimum amplification factor of 1.5 within the frequency band of 0.5–1.5 Hz is expected.

The study area is covered mainly by the Bakirköy formation, which consists of alternating layers of limestone, marl and clay of Upper Miocene age. This formation is quite fragmented and altered at the surface. The underlying Güngören formation has similar characteristics with respect to the lithology. The alluvium, on the other hand, represents the most critical unit in terms of site amplifications and is limited to the fluvial depositional centres. The proximity to the coast of the area influences the lithological characteristics of both the sediments and sedimentary rocks. The gentle topography of the area, with shallow synclines and anticlines plunging towards the Marmara Sea in the south, represents an environment, which is significantly different from classical alluvial valleys or closed sedimentary basins. In this respect, the expected site effects also differ

Table 2. Velocity model used for 1-D modelling for alluvial site. The site is taken from the model used for 3-D FD modelling, and minimum and maximum velocities are reported for each layer.

Thickness (m)	Vs (m s^{-1})	Vp (m s^{-1})	Density ($\cdot$1000 kg m^{-3})	Formation
Alluvial site				
5	157–173	272–300	1.4–1.7	Alluvium
8	751–834	1352–1500	2.2	Bakirköy
80	610–1468	1098–2642	2.0	Güngören
Half-space	1490–2100	2681–3780	2.3	Bedrock

significantly. Modelling such an environment in 3-D presents several challenges with respect to the seismic velocities and their lateral variations. The 3-D model outlined in this paper, therefore, introduces significant constraints in seismic wave propagation. In many respects the model resembles to a simplified 2-D approximation due to the 'open-ended architecture' of the system where the lateral extent of the sedimentary units are continuous over large distances. The 3-D FD computation of PSA amplification shows a remarkable resemblance to the 1-D pseudo-3-D method.

In the present study, non-linear soil behaviour has not been taken into account. At the modelled ground shaking levels, there is a chance that non-linearity will affect the amplification levels. Currently, we do not have enough information available on the dynamic soil properties to estimate the degree of non-linearity. However, damage observed from previous earthquakes, for example, during the 1999 Izmit earthquake, indicates that amplifications may persist even at damaging ground-shaking levels as is observed, for example, for La Molina, Peru (e.g. Bernites *et al.* 1985; EERI Reconnaissance Team 1975).

Despite the uncertainties in the input 3-D velocity model for the FD simulations, results are in reasonable agreement with the H/V spectral ratio results based on recorded microtremor data. The fact that independent studies based on completely different data and methodologies give results in agreement supports the validity of conclusions drawn from these results.

IMPLICATIONS AND CONCLUSIONS

In this study, local site effects in the Ataköy district of western Istanbul have been studied using three different approaches. A hybrid FD method was applied to calculate amplification levels on a fine grid covering the entire Ataköy area based on a local geological model. This modelling indicates that amplification levels are highest for the alluvial sites, where amplification up to a factor of two is predicted. H/V spectral ratios of recorded microtremors were determined, and revealed a dominating peak of amplification around 1 Hz for the whole area. For the alluvial sites a more diffuse secondary peak was observed at 3–6 Hz frequencies. These ratios were compared to H/V ratios calculated for synthetic noise at three sites representative of Ataköy. The synthetic data generally indicated peaks at higher frequencies due to uncertainties related to the highly simplified input models. This underlines the importance of good geotechnical data in site effect assessment.

Based on the above discussions it is clear that site effects in the Ataköy area will have significant consequences in case of future large earthquakes in the Marmara Sea. However, other factors such as construction practices, density of building stock and proximity to alluvial sediments will play an important role, especially when taking into account the frequency variations of the site effects. Our results are naturally valid only for the Ataköy area, however the similarity of the geological formations in the neighbouring Bakirköy and Zeytinburnu districts may give an insight to possible consequences in these highly populated areas in Istanbul. The similarity of the studied region to the surrounding areas makes it possible to use the present results in a broader context, concerning the importance of local site effects in southwestern Istanbul.

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