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Site amplification at Avcılar, Istanbul

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Abstract

Avcılar is the suburb of Istanbul that was most heavily damaged during the August 17, 1999 M_w 7.4 Izmit earthquake. Strong ground motion caused fatalities and damage in Avcılar despite being ~90 km from the epicenter. We deployed five portable seismograph stations equipped with Reftek 24-bit recorders and L4C-3D seismometers for 2 months, in order to understand why the local site response was different from elsewhere in Istanbul. A reference station was placed on a hard rock site, and the remaining four stations were placed on other geological units, in areas that had experienced varying levels of damage. We calculated frequency-dependent ground amplification curves by taking the ratios of the spectra at soft and hard rock sites. We obtained similar site response curves for most earthquakes at each site in the frequency range of 0.3–1.6 Hz, and observed no significant site amplification beyond 2.0 Hz at any site. The overall characteristics of the recorded S-waveforms and our modeling of the calculated site amplification curves are consistent with amplification as a result of trapping of seismic energy within a 100–150 m thick, low-velocity subsurface layer. We also review the applicability of microtremor measurements to estimate local site effects at Avcılar. For these data, we used ratios of spectra of horizontal to vertical components to obtain each site response. These results are compared with standard spectral ratios. These microtremor measurements provide consistent estimates of the amplification at most sites at the higher end of the frequency band, namely above 1 Hz. The results from both methods indeed agree well in this part of the frequency band. However, the microtremor method fails to detect amplification at lower frequencies, namely <1.0 Hz.

Keywords: Site effect; Ground amplification; Microtremor; H/V ratios; Frequency of resonance

1. Introduction

During the 17 August 1999 M_w 7.4 Izmit earthquake Avcılar, a suburb of Istanbul (Fig. 1a), suffered much greater damage than neighboring districts located at similar distances and azimuths from the epicenter. Although situated more than 90 km from the fault rupture, strong ground motion killed about 1000 residents and caused severe building damage. A critical question, which prompted this study, is why this severe building damage was concentrated in

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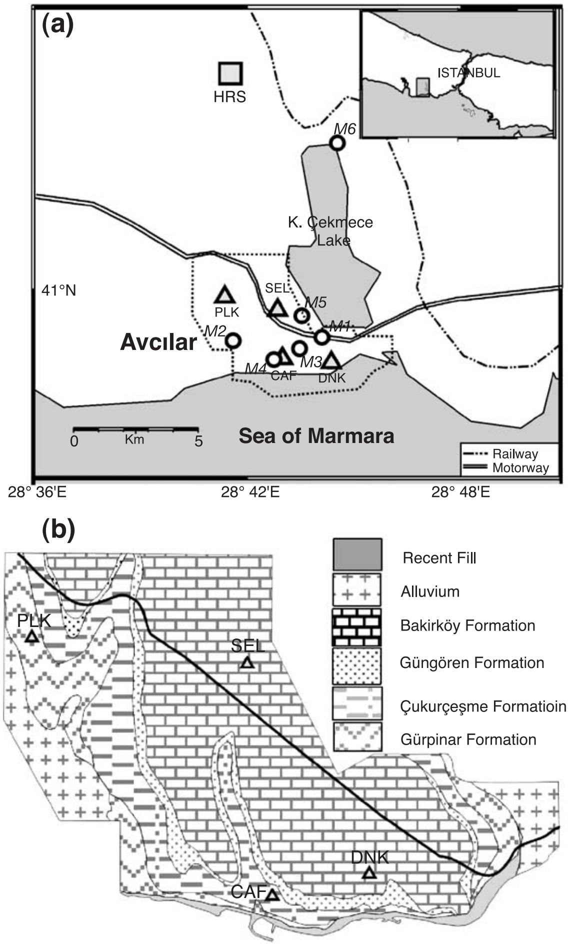

Fig. 1. (a) Map of Avcılar, showing the distribution of temporary seismograph stations used in this study. (b) More detailed map of Avcılar, also showing seismograph stations and generalized geology of the sites, modified after Sen et al. (2001). Distribution of seismic stations for this study. Triangles show short-period L4C sensors; circles show broadband Guralp CMG40T sensors, respectively.

Avcılar and did not affect other districts in the vicinity (Cranswick et al., 2000). There is no clear evidence that the construction techniques used in this part of Istanbul are different from elsewhere, to make the buildings more prone to earthquake hazard. Another potential explanation for such severe damage is the well-known phenomenon of seismic wave amplification. The main purpose of this study is to estimate the site response and understand the role played by the physical properties of the local ground conditions, which may have been be responsible for the observed damage at Avcılar.

It has long been known that each soil type responds differently to ground motions from earthquakes. These observations can be made by comparing earth-

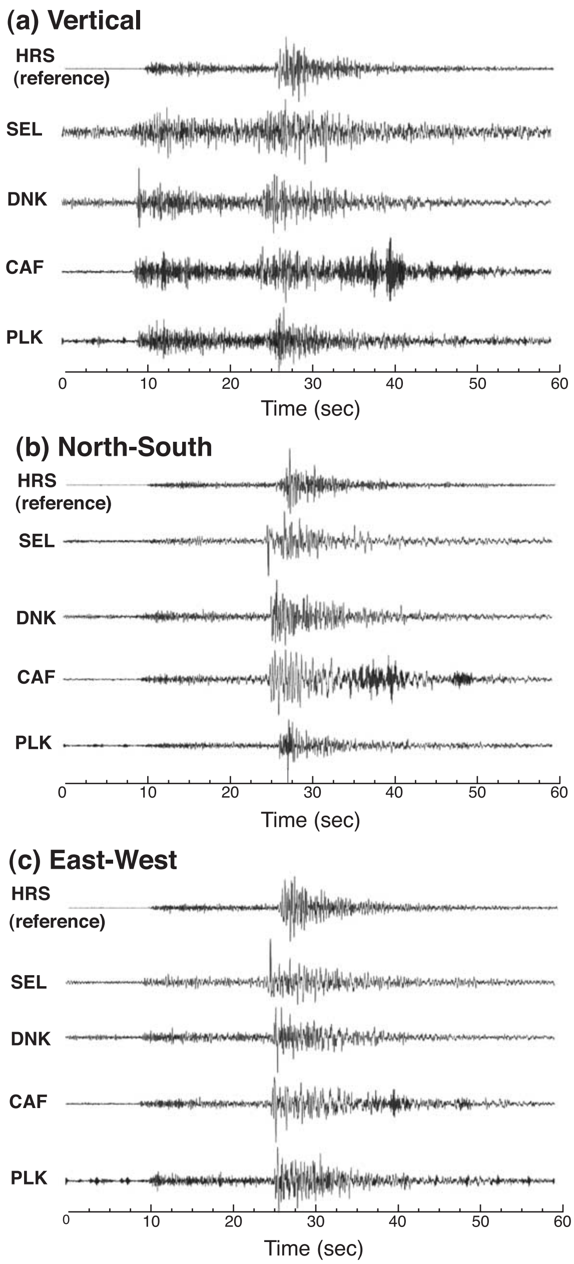

Fig. 2. Comparison of three-component velocity seismograms recorded at all sites for earthquake no. 2 (Table 1). (a) Vertical components. (b) N–S components. (c) E–W components. All seismograms are shown to the same scale.

Table 1
List of earthquakes used

No.	Region	Date	Origin time	Lat. (°N)	Long. (°E)	Depth (km)	Magnitude
1	Sapanca	2 April 2000	18:57:38.1	40.79	30.23	11.4	5.7
2	Sapanca	2 April 2000	23:37:18	40.88	30.18	8.5	3.3
3	Gölcük	3 April 2000	10:17:17.8	40.77	29.74	12.8	3.2
4	Romania	6 April 2000	00:10:38.7	45.74	26.58	133.0	5.4
5	Düzce	9 April 2000	02:32:34.1	40.79	31.15	8.7	3.2
6	Bandırma	15 April 2000	11:03:29.5	40.53	28.23	9.1	3.6
7	Honaz, Denizli	21 April 2000	12:23:08.8	37.85	29.27	14.7	5.2
8	Gemlik	28 April 2000	00:07:24.5	40.45	29.06	7.9	3.3
9	Sea of Marmara	30 April 2000	00:51:32.3	40.79	28.10	8.0	3.1
10	Karamürsel	13 May 2000	23:46:51.6	40.75	29.65	11.1	3.0

These earthquake source parameters are taken from Kandilli Observatory and International Seismological Centre catalogues.

quake records taken from sites with different underlying soil types. Aki (1993) summarized the results obtained both in Japan and in the United States, showing that site amplification depends on the frequency of the ground motion and that younger softer soils generally amplify ground motion more than older and more competent soil. Some observations with moderate-sized earthquakes have also shown that local topography can significantly affect ground motion (e.g. Spudich et al., 1996; Çelebi et al., 1987; Seed et al., 1988; Borcherdt and Glassmoyer, 1992).

Several studies have documented that near-surface unconsolidated sedimentary deposits can significantly amplify seismic waves and thereby increase the damage experienced during an earthquake (Singh et al., 1988; Borcherdt, 1970). It is therefore desirable to develop methods for identifying and characterizing regions prone to this type of site amplification. Ground motion generated by an earthquake is controlled by several factors, such as source characteristics, propagation path, surface geology, and local topography. Boatwright et al. (1991) found a correlation between site amplification estimated from the weak motion records of the 1989 Loma Prieta aftershocks and the observed damage from the mainshock in the Marina District of San Francisco. The calculation of spectral ratios from weak motion records is one of the most frequently applied techniques for the estimation of site response (Borcherdt, 1970; Borcherdt and Gibbs, 1976). In practice, this method consists of taking the spectral ratio between the site of interest and a nearby hard-rock side, these ratios being known as ESRR ratios (Earthquake-based Spectra Ratio relative to Reference site). This method assumes that the hard-rock site is effectively transparent, with no site complexity of its own, so it thus provides a reference site to which ground motion spectra at the other site can be compared. In some cases, a suitable hard-rock reference site may not be found in the vicinity of the site of interest. In this situation, the vertical component is assumed to provide the reference point and the site amplification is regarded as obtainable using the receiver function approach, introduced by Lengston (1979), to obtain crustal shear wave velocity structures, by

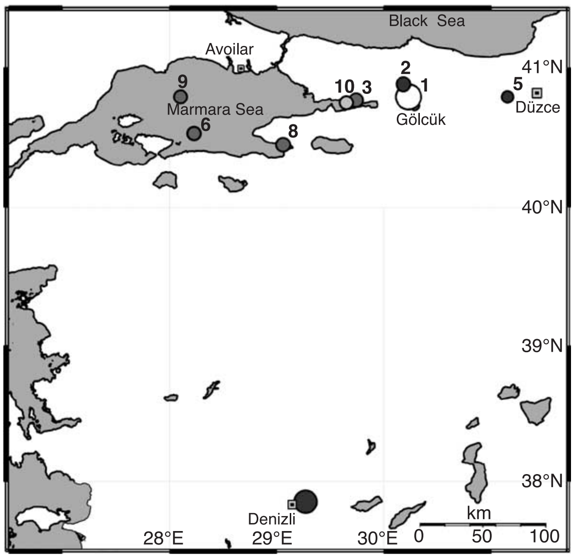

Fig. 3. Map of epicenters of earthquake used from within Turkey.

dividing the spectra of the horizontal component by the vertical one. This is known as the EHV method (from Earthquake-based spectral ratio of Horizontal to Vertical component). Use of this method has been extended to evaluate S-wave amplification using earthquake records (Lermo and Chavez-Garcia, 1993; Field and Jacob, 1995; Castro et al., 1996).

Both these methods require the recording of real events with adequate energy, which can only be captured by long observations campaigns. An economically more attractive method, first introduced by Kanai (1957), involves using ambient seismic noise to evaluate sediment-amplification potential. Several studies (e.g. Ohta et al., 1978; Çelebi et al., 1987; Lermo et al., 1988) have shown that ambient seismic noise observations can reveal the fundamental resonant frequency of surface sediments. Nogoshi and Igarashi (1970) and Nakamura (1989) initially proposed a method of inferring site amplification factors to incident seismic shear waves using ratio of Horizontal to Vertical Noise (NHV) recordings at a single site. This method is easily applied and used to provide direct estimates of the site amplification without requiring a reference site. Much research has been done to investigate the validity of this method (e.g., Borcherdt, 1970; Singh et al., 1988).

Following the 17 August 1999 Izmit earthquake, detailed studies have been carried out on the ground motion in urban Istanbul and its suburbs. By utilizing the data from the post-mainshock instrument deployment, site effect studies have used various methods (Ergin et al., 2000; Meremonte et al., 2000; Özel et al., 2002; Kudo et al., 2002). In this article, we investigate the site response at localities in Avcılar district by applying both the event-based (ESRR) and the microtremor (NHV) methods, respectively, described below. For this purpose, we deployed temporary seismograph stations and recorded weak ground motions from aftershocks of the Izmit and Düzce earthquakes as well as other regional earthquakes. We explored the common characteristics of the various amplification features observed at different sites from different events. We have tried to isolate the individual effects of local topography, soil type variation and azimuthal dependency. We have also made a systematic comparison of the ESRR and NHV methods and tested if, in the case of Avcılar, the more economic microtremor approach may provide an adequate alternative.

2. Geology

In the study area, the so-called cover units of the Istanbul region are present. They are Cenozoic in age and rest on the Carboniferous Trakya Formation, which can be considered as basement for these cover beds but does not itself crop out in the Avcılar area (Sen et al., 2001). Its nearest outcrop is 23 km outside the northern boundary of the study area (Fig. 1b). This unit is overlain uncomfortably by white and beige limestone, clayey limestone, marl and siltstone of the Kırklareli and Sazlıdere Formations of Eocene age. The nearest hard rock

Table 2
Distances and azimuths of earthquakes from each site

Event	Region	HRS		SEL		PLK		CAF		DNK	
		D (km)	A (°)	*D* (km)	A (°)	*D* (km)	A (°)	*D* (km)	A (°)	*D* (km)	A (°)
1	Sapanca	133	103	130	99	132	99	129	99	128	99
2	Sapanca	127	99	124	95	126	95	124	94	122	95
3	Gölcük	95	111	90	106	92	106	89	104	88	105
4	Romania	546	342	555	342	555	343	557	342	558	342
5	Düzce	210	98	206	95	209	96	206	95	205	95
6	Bandırma	72	212	66	249	65	217	64	220	66	221
7	Honaz, Denizli	362	171	352	172	353	172	351	172	350	172
8	Gemlik	76	156	67	154	68	153	65	153	64	155
9	Sea of Marmara	60	237	56	246	55	245	56	249	58	249
10	Karamürsel	89	114	83	108	86	107	83	107	81	108

These data were calculated from the site coordinates and the source parameters listed in Table 1.

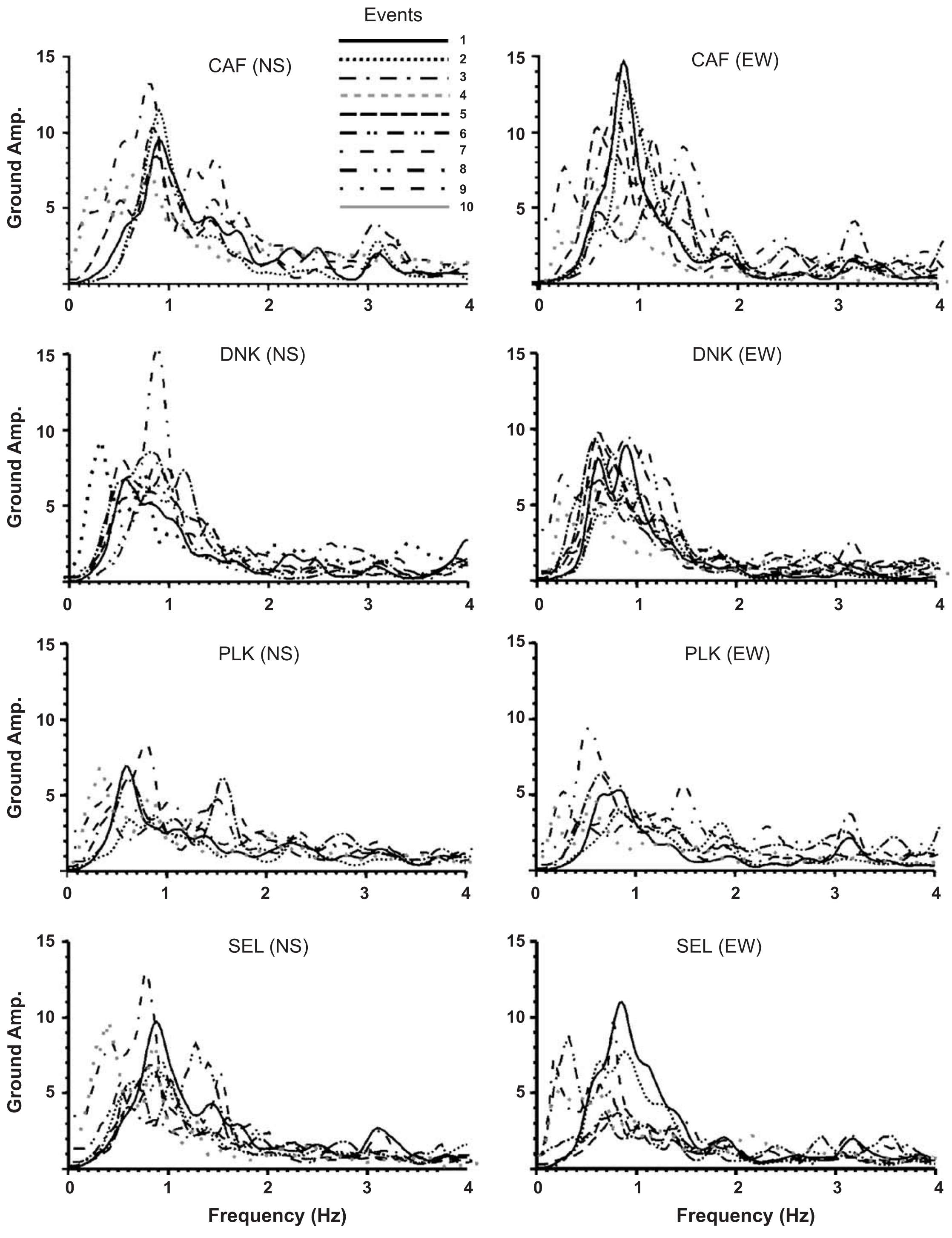

Fig. 4. Comparison of S-wave spectral ratios relative to the reference site, using the ESSR method, for events from the east and south (events 1–3 and 5–10).

site to Avcılar is found on the Sazlıdere formation, where the reference station HRS was installed (Fig. 1a). The Gürpınar formation (Fig. 1b), which consists of greenish-gray, over-consolidated clay and siltstone, overlies the Sazlıdere formation. This Upper Oligocene unit is ~200–220 m thick and is often highly disturbed by landsliding. Seismograph station PLK was located on this unit (Fig. 1b). The Çukurçeşme Formation, a thin (~20–40 m thick) but widespread unit, consists of weakly consolidated or unconsolidated sand and gravel with localised clay or silt lenses, of Miocene age. Seismograph station CAF was located at the contact of this unit with the underlying Gürpınar Formation. The Bakırköy Formation, which is also Miocene but younger than the Çukurçeşme Formation, consists of an alternation of green claystone and white clayey limestone in its lower parts, passing upward into white fossiliferous limestone. Its thickness in the study area ranges between 0 and 30 m, as it has been locally eroded, being the uppermost unit of the sedimentary sequence. Seismograph stations SEL and DNK were located on this unit.

No active faults are reported in the study area. These Cenozoic units are either horizontal or very gently folded. From the soil mechanical point of view, almost all of the cover units, except the Eocene Sazlidere Formation, can be considered as weak to very weak rocks. The Sazlidere Formation can be classified as moderately strong to strong rock Therefore, seismograph station HRS on this unit has been taken as the reference station.

3. ESRR method: data acquisition and analysis

A network of five seismographs was deployed to record Izmit/Düzce aftershocks and regional earthquakes, within a circular area of 10 km diameter, surrounding the Avcılar region. Each of these observation sites (CAF, DNK, PLK and SEL), denoted by triangles in Fig. 1, is located on a different sedimentary unit, as explained in Section 2; the reference rock site (HRS) is indicated by the solid square. Observation was carried out for two months, starting on April 1, 2000. All stations were equipped with three-component Mark Product L4-C velocity seismometers, with 1 Hz natural frequency, and Reftek digital recorders. Continuous recording at 100 samples per second was used, the length of the each seismogram being fixed to 600 s.

The success of the standard spectral ratio technique relies on the availability of a good reference station. Site effect may affect ground motion even on hard rock, as Tucker et al. (1984) discussed in detail. As already noted, the HRS reference site chosen in this study was located on hard Eocene limestone outcrop. Fig. 2 shows examples of velocity seismograms for earthquake no. 2 (Table 1), which was observed at all sites. Amplitudes are much higher and durations longer at other sites compared to the reference station, as was also typically observed for other earthquakes.

During the observation period, earthquakes occurred in different regions of Turkey. Gölcük and Düzce aftershocks, which constitute the majority, were located ~100–150 km east of Avcılar. Although, the number of events recorded at the hard rock site was

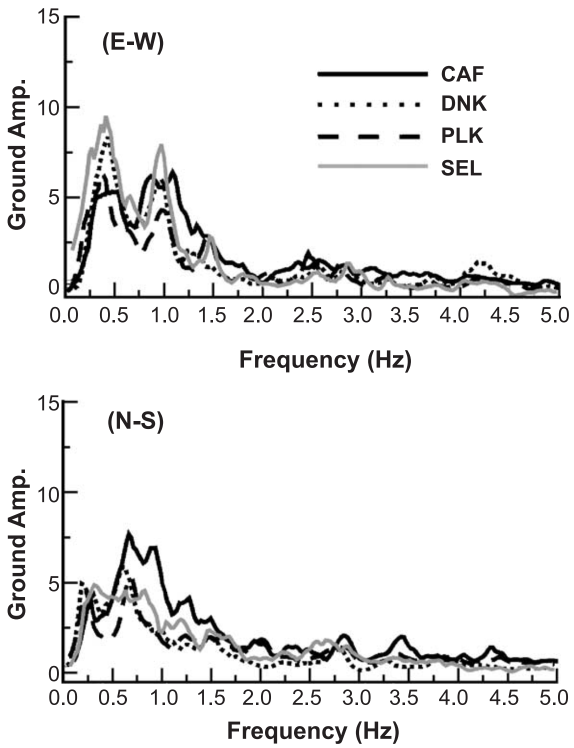

Fig. 5. Comparison of S-wave spectral ratios relative to the reference site, using the ESSR method, for the events from the north (event 4).

much higher, the signal-to-noise ratio of these events was often too low. We have used 10 regional earthquakes, selected on the basis of good recording at all sites and wide azimuthal coverage. Their epicenters are shown in Fig. 3 and source parameters are listed in Table 1. The distances and azimuths of these earthquakes from each station are given in Table 2. These epicentral distances range from 15 to 450 km.

These earthquakes have been partitioned into three groups according to their azimuth: east (events 1, 2, 3, 5 and 10), south (events 6, 7, 8 and 9) and north (event 4). The eastern group consists only of aftershocks, and event 1 in this group provided the best records in terms of signal-to-noise ratio, magnitude and distance. Events in the southern group are particularly useful for testing the azimuthal dependence of site amplification. The Honaz (Denizli) earthquake (event 7) was the largest event to be recorded from this direction. Only one event occurred north of the network (event 7, in Romania; M=5.4) and was clearly recorded by all stations. We recorded no earthquakes from the western direction.

We have used spectral analysis of the S-wave to estimate relative site responses at the four stations. Seismograms of the selected events were first corrected for the system response. Spectral amplitudes were then computed for all available events and stations. We used a constant time window to calculate all spectral ratios, of 40 s length, starting 5 s before and ending 35 s after the S arrival. This ensured that only S-wave and its coda were included, and not surface waves. This duration also ensured that the major part of the S-wave energy was taken into account. A cosine taper was applied over the 5% of each record at each end, before taking the Fourier transform. The resulting spectra were then smoothed using an averaging filter with a bandwidth of 1/3 octave. We derived spectral ratios by dividing the

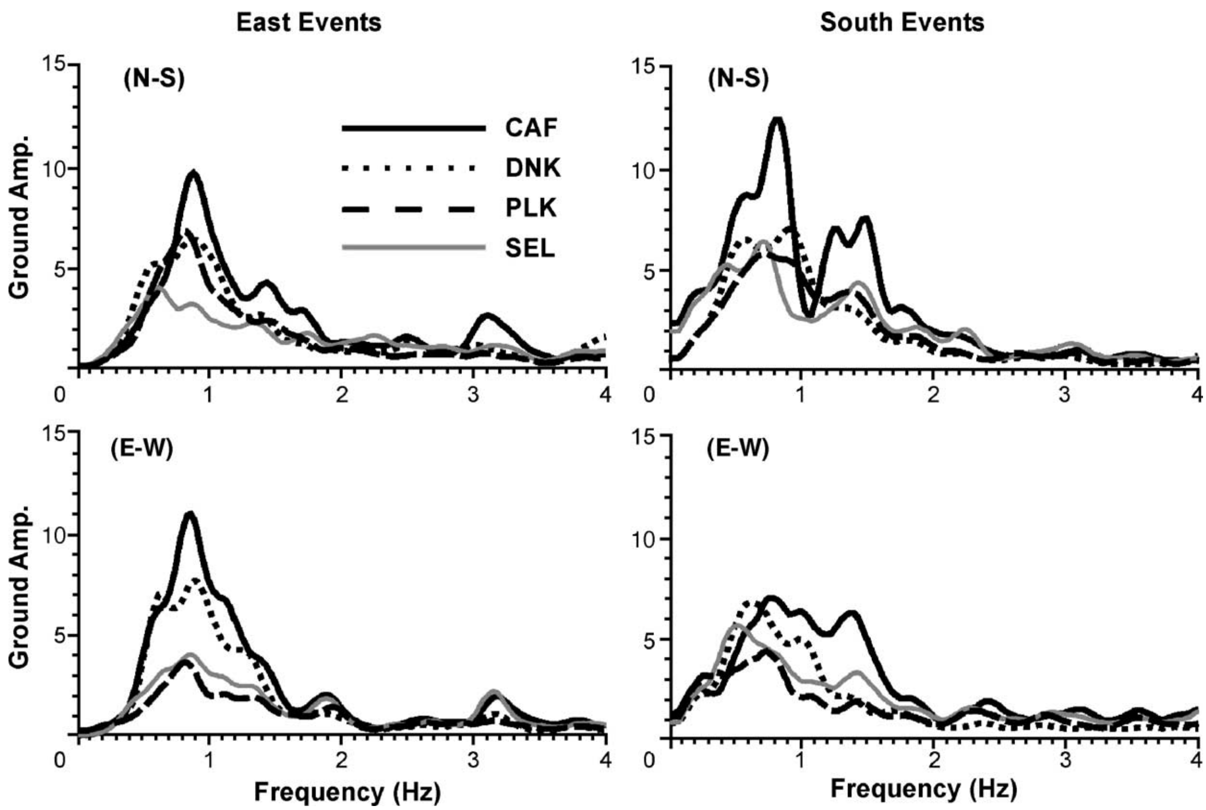

Fig. 6. Stacked spectral ratios for all sites, for events grouped by east or south azimuth, using the ESSR method.

spectrum observed at each site by that at the reference site located on bedrock. Only the frequency band from 0.1 to 5 Hz was included in this study. These operations were repeated for every horizontal component at each station, and for each recorded earthquake.

Fig. 4 illustrates the spectral ratios obtained at four sites relative to HRS, for each earthquake. Inspection reveals that the peaks for each station are generally consistent and show no significant variation between events. All spectra have significant peaks between 0.3 and 1.2 Hz. Several sites have another significant secondary peak at 1.5 Hz. A maximum spectral amplification of 10 or more is typically observed at all sites. The largest amplification is observed at CAF, reaching ~15 at 1.0 Hz.

The Romanian earthquake (event 4) was a strong event that occurred at a distance of ~450 km NNW of the study area. Considering the uniqueness of its azimuth and its size, spectral ratios for this event have been investigated separately (Fig. 5). Like for the other events, amplification by a factor of ~6–8 was observed at all stations between 0.6 and 1.0 Hz.

Integrated amplification curves have been obtained for each station, by separately stacking all spectra from eastern and southern events (Fig. 6). A common spectral peak at 0.3–1.2 Hz is observed for both azimuths, although the eastern events seem to cause slightly higher amplification. The peaks are clustered around 0.7 Hz, with amplification reaching a factor of 8. This factor is higher at CAF, reaching 10. Significant but smaller amplification can be observed, especially for the southern events, at a secondary peak at 1.5 Hz.

4. NHV method: data acquisition and analysis

The microtremor method (NHV method) was first proposed by Nakamura (1989). It computes the spectral ratio of the horizontal to vertical components for background seismic noise. In this analysis, both of the horizontal components are combined, by taking the square root of the sum of the squared spectral amplitudes, to obtain the vector amplitude. In all cases, prior to taking their ratios, spectra were smoothed. We have used two different network configurations for the application of this method. The first configuration is the one described in Section 3, which was primarily intended for recording regional events. Since, for that study, a continuous recording mode was used throughout the observation period, we have selected portions of data, which include background noise suitable for NHV analysis. We have thus eliminated parts that correspond to non-stationary noise bursts.

Fig. 7 shows examples of 100 s portions of stationary and transient noise from the raw records at station SEL. Fig. 8 shows spectral ratios at this site inferred from spectra of these stationary and transient noise records using the NHV method. These were calculated separately for two types of noise conditions: day time/high-traffic (09:00–19:00) and night time/low-traffic (23:00–05:00), for all sites (Fig. 9). Surprisingly, we have not detected any significant scatter between spectra obtained from data portions or between day- and nighttime recordings. This suggests

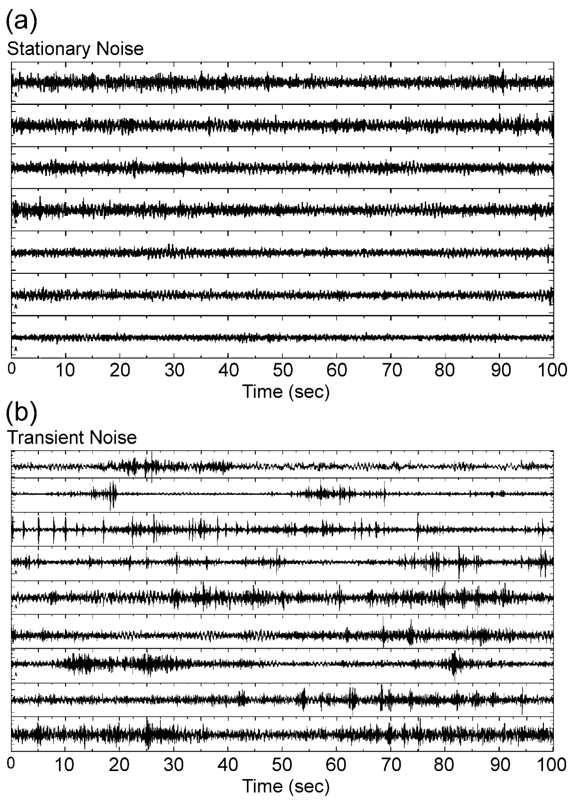

Fig. 7. Example records, of length 100 s, showing stationary (a) and transient (b) noise, on raw records at station SEL.

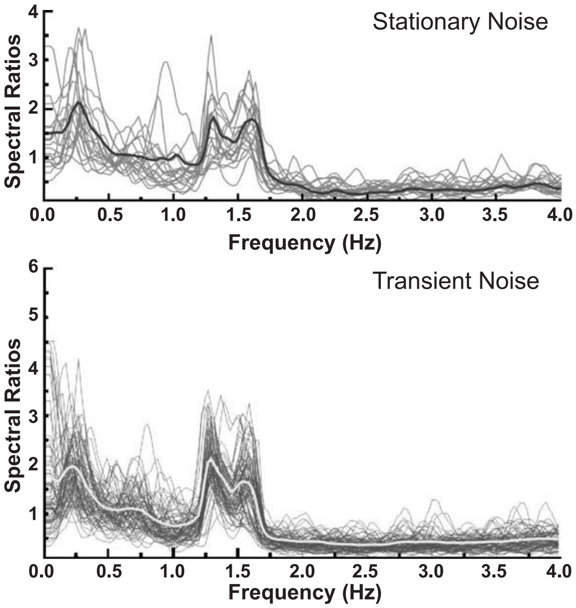

Fig. 8. Spectral ratios at station SEL inferred from noise (microtremor) spectra (using the NHV method), for stationary and transient noise records.

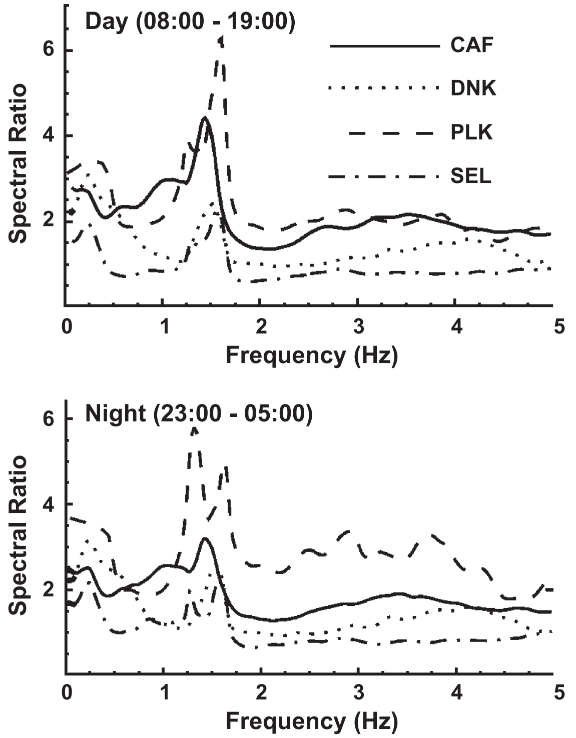

Fig. 9. Spectral ratios at all L4C-type stations inferred from noise (microtremor) spectra (using the NHV method) for daytime (08:00–19:00) and nighttime (23:00–05:00) noise records.

that the background seismic noise at Avcılar is mostly non-anthropogenic. We also note that microseisms do not include much energy at low frequencies (<1.0 Hz) as seen in the mean spectral ratios (Fig. 8). This NHV analysis revealed small amplification factors, generally less than 3.5. More importantly, it completely missed the peaks between 0.3 and 0.9 Hz, previously observed using the ESRR method. However, the secondary spectral peaks near 1.5 Hz are clearly detected at all sites.

Our second configuration of the NHV study has used a different observation system, including six stations with sensors of wider frequency coverage. We used Guralp CMG40T broadband velocity transducers paired with Reftek recorders, which allowed a more appropriate observation of the 0.2–1.0 Hz frequency band. In this new configuration, the location of the stations was slightly different from before, as shown in Fig. 1a, except for station CAF. In order to guarantee that human generated noise is kept to a minimum we took only 1-h recordings very early on Sunday mornings. In all cases, prior to taking their ratios, spectra were smoothed.

We present the results of this second NHV experiment in Fig. 10. The NHV spectrum has a similar shape to the previous NHV results, with generally similar peaks around 1.5 Hz with a low amplification factor of 3–4. Station M6 has the largest amplification factor of 6 in a wide frequency range, of 0.8–3.0 Hz.

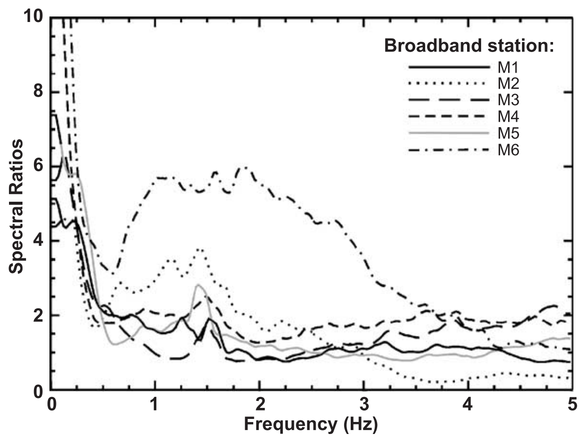

Fig. 10. Spectral ratios at all broadband stations inferred from noise (microtremor) spectra (using the NHV method).

This site is located on the shores of the nearby Küçük Çekmece Lake and is thus expected to reflect the effect of thick layers of soft sediments.

Figs. 9 and 10 thus show clear similarities between the spectra obtained by different applications of the NHV method.

5. Results and discussions

The systematic survey of the site response at the district of Avcılar, using both the ESRR and NHV methods, has shown that significant ground amplification exists. The ESRR method provided more elaborate details about the nature of this ground amplification. In particular, spectral ratios at four different sedimentary sites with respect to a hard rock site, computed from earthquake records using this method, have shown that amplification occurs in the frequency range of 0.3–1.6 Hz, more or less equally at all sites. In addition to its frequency characteristics, we investigated the dependence of amplification on epicentral distance, azimuth and magnitude of the earthquakes that were recorded.

Generally speaking, the frequency dependence of the site amplification has shown common properties at all sites for all events. The analysis has shown clearly that effective amplification by a factor above 5–10 occurs in the low frequency band (0.5–0.9 Hz). A secondary amplification is observed around the frequency of 1.5 Hz, especially at the southern sites, where it reaches a factor of 4–5. However, no significant amplification is observed in the higher frequency band (>3 Hz). Similar results were obtained by Özel et al. (2002), who showed that the amplification factor at Avcılar is ~5–10 and located in the frequency band below 4 Hz.

It is clear that the amplification does not depend on the azimuth of the seismic source. In other words, waves coming from any direction cause similar amplification at all sites, which contradicts the focusing effects suggested by Özel et al. (2002).

We did not observe any significant variation of amplification with the magnitude and distance of each seismic source. As typical example to illustrate this point concerns the two events (1 and 2), of different magnitudes (5.7 and 3.3; Table 1), which occurred in the same epicentral area, caused very similar amplification at all sites (Fig. 4). The same arguments are supported by the Romania (no. 4) and Denizli (no. 7) earthquakes, which had similar magnitudes but different epicentral distances, that show similar amplification at the same frequency range (Fig. 4). We thus conclude that site amplification at Avcılar shows linear behavior in the dynamic range that we have studied.

Although the observational sites were located on different sedimentary units, we have not detected any significant variation in the amplification characteristics. The resonant frequency f observed at all sites was ~0.7 Hz. A first-order estimate of the thickness H of the resonating layer can be calculated as

$$H = \beta/(4f)$$

(Igor et al., 1998) where β is the S-wave velocity. Taking β as within the range 291–434 m/s (Kudo et al., 2002), the thickness for the resonating layer can thus be estimated as 100–150 m. We thus conclude that thick layers of unconsolidated low-velocity sediment overlying rock basement play the primary role in the local site response. The localized large amplification factors and the resulting heavy damage at Avcılar from the Izmit mainshock are thus attributed to a deep-seated velocity contrast. Reverberations are clearly seen following the arrival of the S-wave train, on all seismograms (Fig. 2). Therefore, we suggest that trapping of body waves and subsequent resonance was the primary cause of the observed amplification (Fig. 11).

Comparing the results obtained by the NHV method with the ESRR method, we found that the

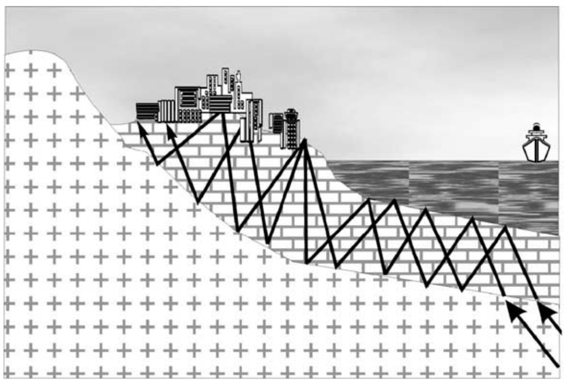

Fig. 11. Schematic diagram of trapping of seismic energy, leading to a resonant effect.

microtremor-based approaches revealed only a limited amount of useful information regarding the site response. We observed that the NHV method provided consistent estimates of the amplification at most sites at the higher end of the frequency band, above 1 Hz. In fact, the results from both the NHV and ESRR methods agree well in this part of the frequency band. However, the NHV method fails to detect amplification at lower frequencies, below 1.0 Hz. This failure of the NHV method at low frequencies suggests that, in this frequency band, the energy of the microtremors is insufficient to induce any oscillatory modes at the local site. The microtremor (NHV) method is thus suitable for revealing peak frequencies related to shallow structures, but is incapable of describing the site effects of deeper structures, as illustrated by the case of Avcılar. We also note that, even constrained to the high frequency band, the amplification factors inferred from the NHV method often do not coincide with those from the ESRR method. We thus suggest that NHV method should only be used as part of a preliminary survey, and its results should be assumed to provide only a partial description of the complete site response. Additional methods from other geophysical techniques need to be applied to determine this.

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