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Reliability of Ambient Noise Horizontal-to-Vertical Spectral Ratio in Urban Environments: The Case of Thessaloniki City (Northern Greece)

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Abstract—In the framework of an ambient noise measurement project in the downtown district of the City of Thessaloniki (Northern Greece), several tests and evaluation of noise recordings were performed in selected sites. This data set was processed and compared with previous results for the same sites in terms of horizontal-to-vertical (H/V) spectral ratio obtained from weak and strong motion earthquake data. The recording system used was tested against a reference one. Finally, systematic ambient noise measurements were performed at eight sites in the city's downtown area, to evaluate diurnal and seasonal variations. It was concluded that the recording system used was reliable and the ambient noise H/V spectral ratios were in good agreement with relevant results previously obtained. Diurnal variation of the ambient noise H/V spectral ratio showed that it is preferable to perform measurements during the calm hours of the day, when man-made noise is relatively low. However, no systematic seasonal fluctuation effect on the ambient noise H/V spectral ratio was identified.

Key words: Ambient noise, H/V spectral ratio, site effects, urban environment.

1. Introduction

Site response is largely identified as significant information which needs to be considered in many studies, such as microzonation, source parameters, etc. Sites where the seismic motion is amplified are generally those where significant damage enhancement occurs during strong earthquakes. The best procedure for determining the site response of a particular sedimentary location is to record ground motion during an earthquake and calculate the spectral ratio of the sediment site recording to a nearby reference site located on rock (e.g., Borcherdt, 1970). However, to achieve site response surveys using this technique in a reasonable period of time may be difficult, especially in regions of low seismicity. On the other hand, the numerical

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prediction of site effects with a reasonable confidence level requires detailed knowledge of key geotechnical and geophysical parameters which is also a difficult task.

An alternative approach of characterizing site response in an urban environment involves the use of the H/V spectral ratio of ambient noise recordings. Ambient noise is low amplitude vibrations of soil generated by natural disturbances such as wind, sea tides or of man-made origin such as traffic, industrial machinery, household appliances, etc. The spectral ratio of horizontal to vertical component of ambient noise usually shows a peak which indicates the fundamental frequency of the investigated site (NOGOSHI and IGARASHI, 1971; NAKAMURA, 1989). Recently, several researchers (among which FIELD and JACOB, 1993; LACHET and BARD, 1994; LERMO and CHÁVEZ-GARCÍA, 1994a) have theoretically supported the H/V spectral ratio technique through numerical simulations showing that synthetics obtained by randomly distributed near-surface sources lead to H/V spectral ratios sharply peaked around the fundamental *S*-wave frequency, whenever the surface layers exhibit a sharp impedance contrast with the underlying stiffer formations.

In experimental studies, the applicability of the method has also been demonstrated at several areas. OHTA *et al.* (1978) showed that predominant ground period (~2.5 sec) of the spectra in both ambient noise and strong motion records of the 1968 Tokachi-oki earthquake was due to the presence of deep alluvial deposits. KAGAMI *et al.* (1982, 1986) and FIELD *et al.* (1990) demonstrated also that simultaneous observation of the spectra of ambient noise was appropriate to identify the fundamental frequency in surface layers. The comparison between the fundamental frequency obtained of the ambient noise H/V spectral ratios and receiver functions of earthquake recording (strong or weak motion data) allowed researchers (LERMO *et al.* 1988; LERMO and CHÁVEZ-GARCÍA, 1994b; FIELD and JACOB, 1995; CHÁVEZ-GARCÍA and CUENCA, 1996; TOSHINAWA *et al.* 1997; OJEDA and ESCALLON, 2000; DUVAL *et al.* 2001; SATOH *et al.* 2001; HORIKE *et al.* 2001) to report that the fundamental frequencies of ambient noise spectral ratios agree with the fundamental frequencies observed in earthquake motions and give a good estimation of the fundamental frequency of the site. YAMANAKA *et al.* (1993) found a very good agreement between the sediment-to-bedrock spectral ratios (hereafter refered to as SSR ratios) from strong motion data and ambient noise at periods more than 5 sec in Los Angeles, California. SEEKINS *et al.* (1996) comparing the SSR ratios of ambient noise, *S*-waves weak motion data and codas in San Francisco, California, found good agreement both in the fundamental frequency and in the amplitude level. On the other hand, DIAGOURTAS *et al.* (2001) performed ambient noise measurements in the City of Heraklion (Crete, Greece) and observed that the amplitude levels of ambient noise H/V spectral ratios were generally lower than those resulting from the SSR ratios. However, they also found remarkable similarity and consistency in the amplification frequency band between ambient noise H/V spectral ratios, the SSR ratios and 1-D modelling based on geotechnical data.

While it is true that in some cases the ambient noise results agree reasonably well with those obtained from earthquakes recordings, in other cases such an agreement is not satisfactory. In southern California, UDWADIA and TRIFUNAC (1973) compared directly spectral characteristics of strong motion and ambient noise and found that the effects of local site conditions appeared to be overshadowed by source mechanism and propagation path. ROVELLI *et al.* (1991) reported significant differences in the value of fundamental frequencies and in the spectral width of the corresponding spectral peaks between SSR ratios of ambient noise measurements and strong motion records of various sites of Italy. GUTIERREZ and SINGH (1992) obtained a quantitative mismatch between SSR ratios of strong motion and ambient noise data in the Acapulco area.

MUCCIARELLI *et al.* (1996) and MUCCIARELLI (1998) filled the gap from the methodological and experimental point of view by performing several experiments under controlled conditions. They suggested that for *in situ* measurements in a town, accelerometers should be avoided and seismometers should be used instead. The measurements should be performed when weather conditions are not discouraging (e.g., rain, strong winds). Finally, by performing measurements during different seasonal and daily times reasonably stable results were obtained. A complete review of modern applications of ambient noise measurements for site effect estimation can be found in BARD (1999). Recently, a European project called SESAME (**S**ite **E**ffect**S** assessment using **AM**bient **E**xcitations) aims to study site effects assessment techniques using ambient vibrations. One of the main tasks of the SESAME project is to search the experimental aspects that influence the stability of ambient noise measurements (ATAKAN *et al.* 2004; DUVAL *et al.* 2004).

The ambient noise H/V spectral ratio technique is less time consuming and considerably less costly than other classical geophysical site investigations. Although the seismological community generally agrees that the H/V spectral ratio of ambient noise gives reliable results in terms of fundamental frequency, the method has been developed mainly empirically. Therefore, before applying the H/V spectral ratio on ambient noise recordings in an urban environment, there is a need to thoroughly check and evaluate the method. In this paper several critical reliability tests have been performed including instrument evaluation, comparison of the noise H/V spectral ratios with earthquake receiver functions. Diurnal and seasonal variations of the noise H/V spectral ratios at selected sites in the City of Thessaloniki (Greece) were also examined.

2. Method Used

In order to investigate stability and reliability of the ambient noise H/V spectral ratio in the City of Thessaloniki, the following tests were performed: (i) Instrument evaluation, (ii) comparison of ambient noise H/V spectral ratios with earthquake receiver functions at the same locations, (iii) diurnal variation of the H/V spectral ratios of ambient noise and, (iv) seasonal variation of the H/V spectral ratios of ambient noise.

The software used to analyze noise recordings was SEISAN_7.2 (Havskov and Ottemöller, 2000). A visual inspection of the ambient noise recordings was made in order to exclude portions with unusually large amplitudes or spikes. No instrumental correction was carried out for the ambient noise measurements, as the sensor components employed (Lennartz 3-D/5 sec) have the same response characteristics in the frequency range of 0.2–20 Hz. Therefore, the analysis was focused only on this frequency range.

The following processing steps were performed to our data: (a) Computation of Fourier amplitude spectra in all three components (E–W, N–S, vertical) over all windows with 1 min duration each, (b) smoothing of the Fourier amplitude spectra (hereafter FAS) using a moving average window (1/4, 1/2, 1/4) with 50 iterations, (c) computation of the noise H/V spectral ratio by dividing each horizontal component to the vertical one, (d) averaging the noise H/V spectral ratio separately for the two horizontal components of the recording, to detect any significant difference between them.

2.1. Instrument Evaluation

The objective of this initial test was to compare the H/V spectral ratio obtained by the recording system to be used for massive ambient noise measurements [Cityshark 24-bits recorder (Chatelain *et al.* 2000) coupled with a Lennartz 3-D/5 s velocimeter sensor] and a "reference" system (Reftek 72A coupled with a Guralp CMG40 velocimeter broadband sensor). Furthermore, local seismic experiments performed in the City of Thessaloniki used mainly this type of recording system. The sensors were chosen to be both velocimeters and accelerometers. According to the work of Atakan *et al.* (2004), who tested fifteen different types of sensors, velocimeters were all usable for recording ambient noise, whereas accelerometers are not appropriate due to their insensitivity in low frequency band.

The two seismic systems have been tested at the Central Seismological Station (OBS) of the Geophysical Laboratory of the Aristotle University of Thessaloniki (Fig. 1), which is located on hard rock (gneiss). Both sensors were installed on a concrete pier isolated from the basement of a two-story building and two time series of five minutes were recorded simultaneously, at a sampling of 100 Hz.

Figure 2 (left part) displays the comparison between the average noise H/V spectral ratios obtained from the two recording systems. Examining the amplitudes and shapes of the H/V spectral ratios it can be realized that these are in good agreement with in the entire frequency range. To better quantify this comparison, the spectral ratio abstraction *d*[H/V] between the two recording systems was accomplished (Fig. 2, right part). It is apparent that for most of the frequency range there is

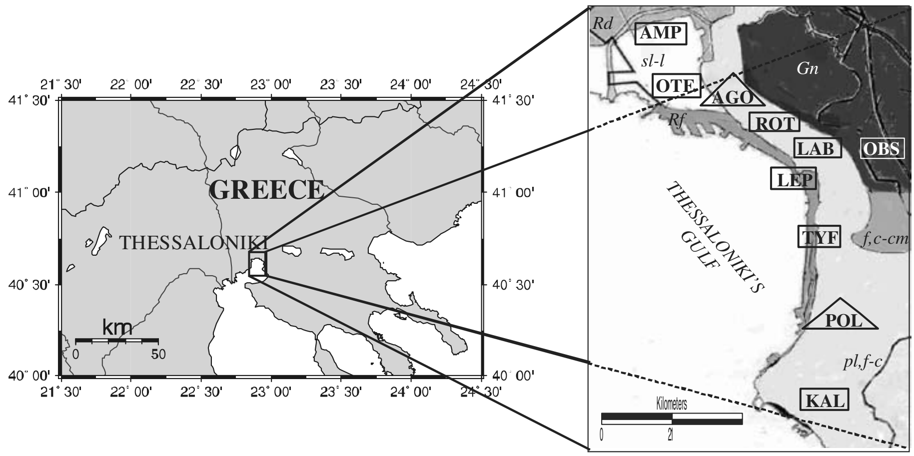


Figure 1
Left: Location of the City of Thessaloniki, Northern Greece. *Right:* Map of the region of Thessaloniki with the main geological units (Rf: Debris; Rd: River-torrential deposits with thickness up to 10 m; sl-l: Quaternary silty layers; f,c-cm: Pleistocene undivided layers with thickness up to 40 m; pl,f-c: Neogene deposits; Gn: Gneiss) and the location of the sites for which weak and strong motion earthquake data were available (IGME, 1978).

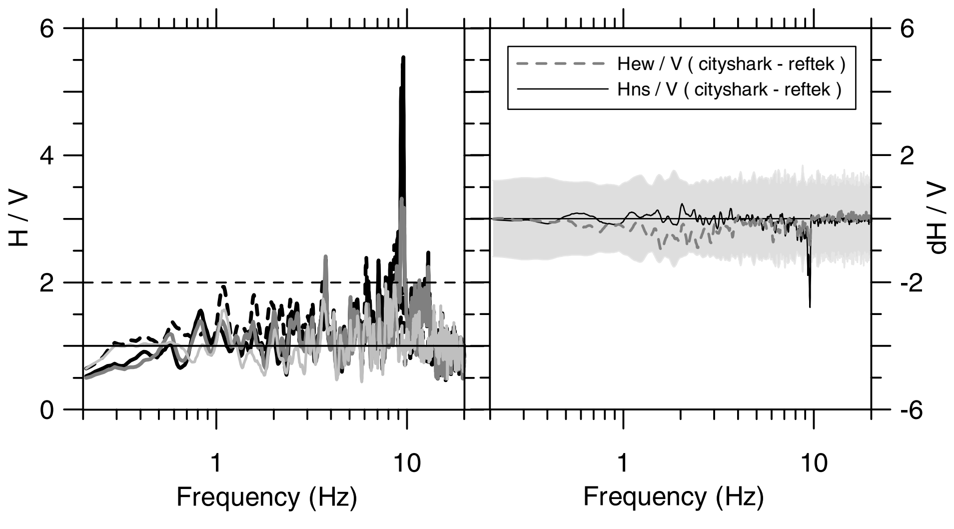


Figure 2
Left: Average H/V spectral ratio for the two recording systems: Cityshark–Lennartz (Hns/V: grey dark line; Hew/V: grey light line) and Reftek – Guralp (Hns/V: black dashed line; Hew/V: black line). *Right:* Difference between the spectral ratios of the two recording systems: dHew/V = Hew/V (Cityshark – Lennartz) - Hew/V (Reftek–Guralp): grey dashed dark line; dHns/V = Hns/V (Cityshark–Lennartz) - Hns/V (Reftek–Guralp): black solid line. Shaded area represents the ±1 standard deviation of the H/V spectral ratio from the CityShark-Lennartz system.

no significant difference between the recording systems, given that d[H/V] falls in between the ± 1 standard deviation of the H/V spectral ratio coming from the CityShark-Lennartz system. Our results are further supported by DUVAL *et al.* (2004), who made a detailed study of the influence of the acquisition system on noise H/V spectral ratio, using different recorder types and velocimeter sensors. They have also shown that the H/V spectral ratio of ambient noise was not dependent on the tested equipment.

2.2. Comparison of Ambient Noise H/V Spectral Ratios with Receiver Functions

In order to compare H/V spectral ratios of ambient noise recordings with results from other techniques traditionally used for site effect studies, ambient noise measurements were carried out at ten sites within the City of Thessaloniki (Fig. 1). At each site ambient noise data were continuously recorded for at least 10 min and as long as 40 min. The coupling between the sensors and the ground was: Tile of pavement at sites KAL (10 m distance from 5-story buildings), AMP (10 m distance from 6-story buildings), LEP (next to the Royal Theatre of Thessaloniki), asphalt at sites AGO (free field), LAB (5 m distance from 4-story buildings), OTE (next to 2-story buildings), POL (free field) and ground at sites TYF (15 m distance from 8-story buildings), ROT (free field). The data were sampled at 100 Hz and the average noise H/V spectral ratios of each recording were calculated with the same procedure described above.

At the same ten sites, Reftek stations had been installed between 25 November 1993 and 19 February 1994 (LACHET *et al.* 1996 [**La**]; TRIANTAFYLLIDIS *et al.* 1999 [**Tr**]) and recorded several local and regional events. Two types of sensors were used at each site: An accelerometer Guralp CMG5 [**Tr**] and a broadband velocimeter Guralp CMG40 ($T = 20$ sec) [**La**] at eight sites (rectangulars in Fig. 1) or alternatively a short-period Mark Product L22 ($T = 0.5$ sec) at two other sites (triangles in Fig. 1). [**La**] compared the SSR ratio and the H/V spectral ratios of weak motion data with the H/V spectral ratios of ambient noise. They found that although the three methods are equally able to reveal the site fundamental frequency, the amplitude of the noise H/V spectral ratios is lower than that of the other two ratios. In [**Tr**] SSR ratio and H/V spectral ratios of accelerometer data is compared. They found that the fundamental frequency is identified by all methods, while the amplification level is generally underestimated when the H/V spectral ratio is used. Moreover, they compared the spectral ratios of 1-D synthetics seismograms with those derived from experimental data, and the two sets were found to be consistent at most sites.

Due to the fact that both EW and NS horizontal components give similar H/V spectral ratios, hereafter only results for the EW component are presented. In the upper part of Fig. 3 the variation with frequency of the average noise H/V spectral ratio for the EW component is shown compared with the corresponding mean value

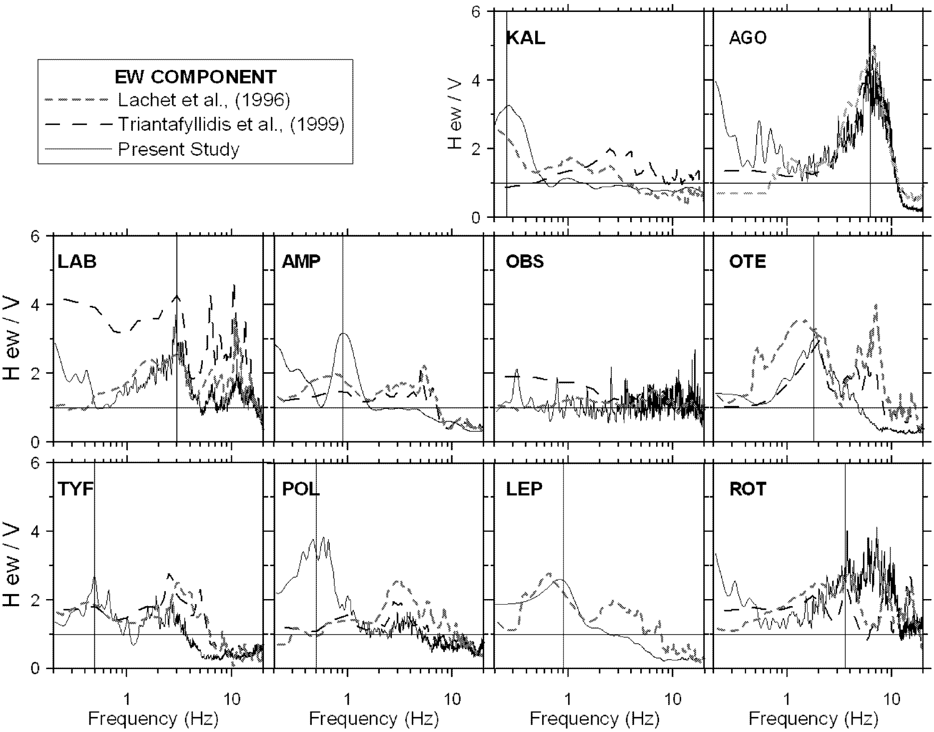


Figure 3
Comparison of the H/V spectral ratio from ambient noise data obtained in the present study (EW component: black solid line) with earthquake receiver functions at the same sites. Vertical solid line indicates the fundamental frequency.

from [**La**] and [**Tr**] receiver functions using earthquake recordings. In general, the results indicate a similarity in fundamental frequency and overall shape of the H/V spectral ratios at all examined sites between noise H/V spectral ratio and earthquake receiver functions. More importantly, there is good agreement on the determination of the fundamental frequency for most of the sites.

A systematic difference between the noise H/V spectral ratios and the corresponding receiver functions of [**Tr**] in the low frequency band (f < 1 Hz) was observed, while good agreement is found in the higher frequency band. However, at site LAB a significant difference between the noise H/V spectral ratios and accelerometer data is observed. At the site LEP, [**Tr**] receiver function was not estimated, because the noise level at this site was very high, producing a poor signal-to-noise ratio. Conversely, the very good agreement of noise H/V spectral ratio with [**La**] receiver functions, based on velocimeter data, is evident for most sites for the entire frequency range. Such an agreement also has been noted by CHÁVEZ-GARCÍA and CUENCA (1996), TOSHINAWA *et al.* (1997) and OJEDA and ESCALLON (2000), among others. However, at the site POL differences in low frequencies are most probably due to the L22 sensor (T_o = 0.5 sec), used in [**La**]. Their results are less reliable for frequencies below 2 Hz, due to the relatively poor response of L22 sensor in this frequency range. At the ROT site ambient noise measurement was performed about 30 m to the east of those of [**La**] and [**Tr**], probably explaining the observed difference in a narrow band frequency between 5 Hz to 8 Hz. At the site OTE, although the agreement between the three methods is satisfactory, the second harmonic that clearly could be seen in the H/V receiver functions does not appear in the noise H/V spectral ratio. Nevertheless, the agreement between the three independent estimations may be considered as satisfactory, supporting the idea that ambient noise measurements can be used as a reliable measure of site effects in the City of Thessaloniki.

Finally, based on layer thickness and shear-wave velocity values from ANASTASIADIS *et al.* (2001), we calculated the corresponding fundamental frequencies at each site, using algorithms proposed by KANAI (1962) and HADJIAN (2002). Figure 4 (left part) shows for each examined site a comparison between the fundamental frequencies estimated from: noise H/V spectral ratio, earthquake receiver functions ([**La**] and [**Tr**], selected from the H/V spectral ratios shown in Fig. 3), and theoretical models. Figure 4 (right part) displays the graph that compares the fundamental frequencies estimated from noise H/V spectral ratio with those from theoretical models. A good agreement between them is observed for all sites. It is apparent that the estimated fundamental frequencies by the aforementioned methods are in good agreement at the sites AGO, LAB, ROT, OTE, KAL, TYF, LEP and AMP with those estimated by the noise H/V spectral ratio. The striking disagreement observed

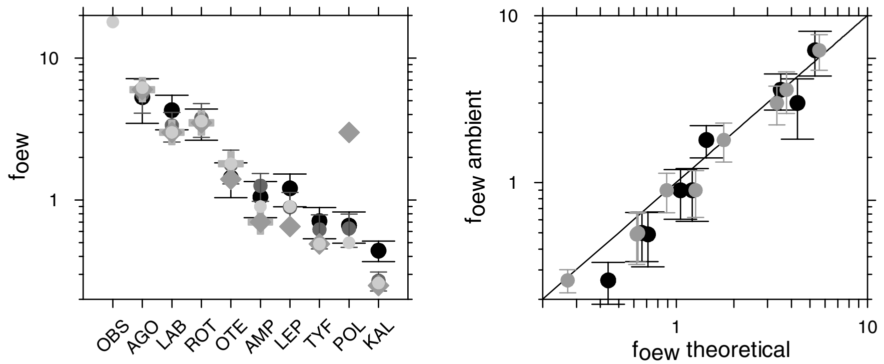


Figure 4
Left: Comparison between the fundamental frequencies derived in the present study (grey light solid circles), and those from KANAI (1962) with ±1 standard deviation (black solid circles), LACHET *et al.* (1996) (grey solid diamonds), TRIANTAFYLLIDIS *et al.* (1999) (grey cross) and HADJAN (2002) with ±1 standard deviation, (grey dark solid circles) at each site. *Right:* Plot of the fundamental frequencies derived in the present study versus the theoretical values estimated from algorithms of KANAI (1962) with ±1 standard deviation, (black solid circles) and HADJAN (2002) with ±1 standard deviation, (grey solid circles).

at the site POL is due to the L22 sensor used by [**La**], as already explained. For the site OBS, as a rock site, no theoretical fundamental frequency was estimated.

2.3. Diurnal Variation of the H/V Spectral Ratio of Ambient Noise

To study the diurnal variation of the noise H/V spectral ratios we recorded five minutes of ambient noise data every one-hour for two consecutive summer days at eight sites (Fig. 5) in the downtown district of the City of Thessaloniki. These sites are spread in the historical center of the city where dense ambient noise measurements are performed and display a variety of geological conditions (ANASTASIADIS *et al.* 2001). The coupling between the sensors and the soil for the sites PLD, CIT, IAS, was cement and the recording system was placed in the basement of 8-story buildings. At the sites FOK, JWB, PHA, ELF the recording system was placed in the ground floor of 8-story buildings and the coupling between sensors and soil was mosaic. The ambient noise recordings are classified into five time categories: morning (05:00 a.m.–9:00 a.m. GMT), midday (10:00 a.m.–13:00 p.m. GMT), afternoon (14:00 p.m.–16:00 p.m. GMT) (with market open and closed), evening (17:00 p.m.–21:00 p.m. GMT) (with market open and closed) and night

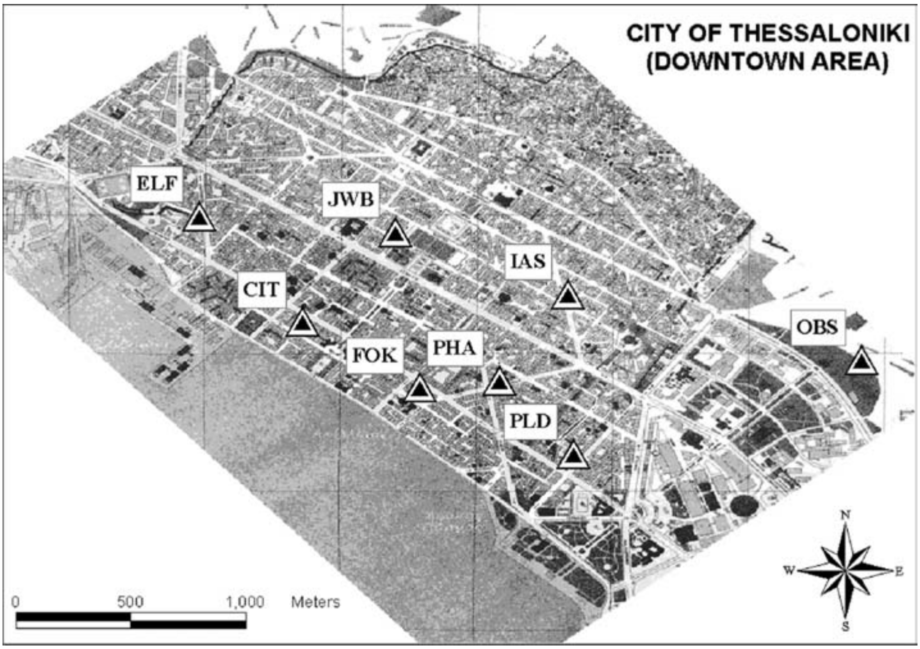


Figure 5
Location of the eight sites of the Thessaloniki downtown area, where diurnal and seasonal ambient noise measurements were performed.

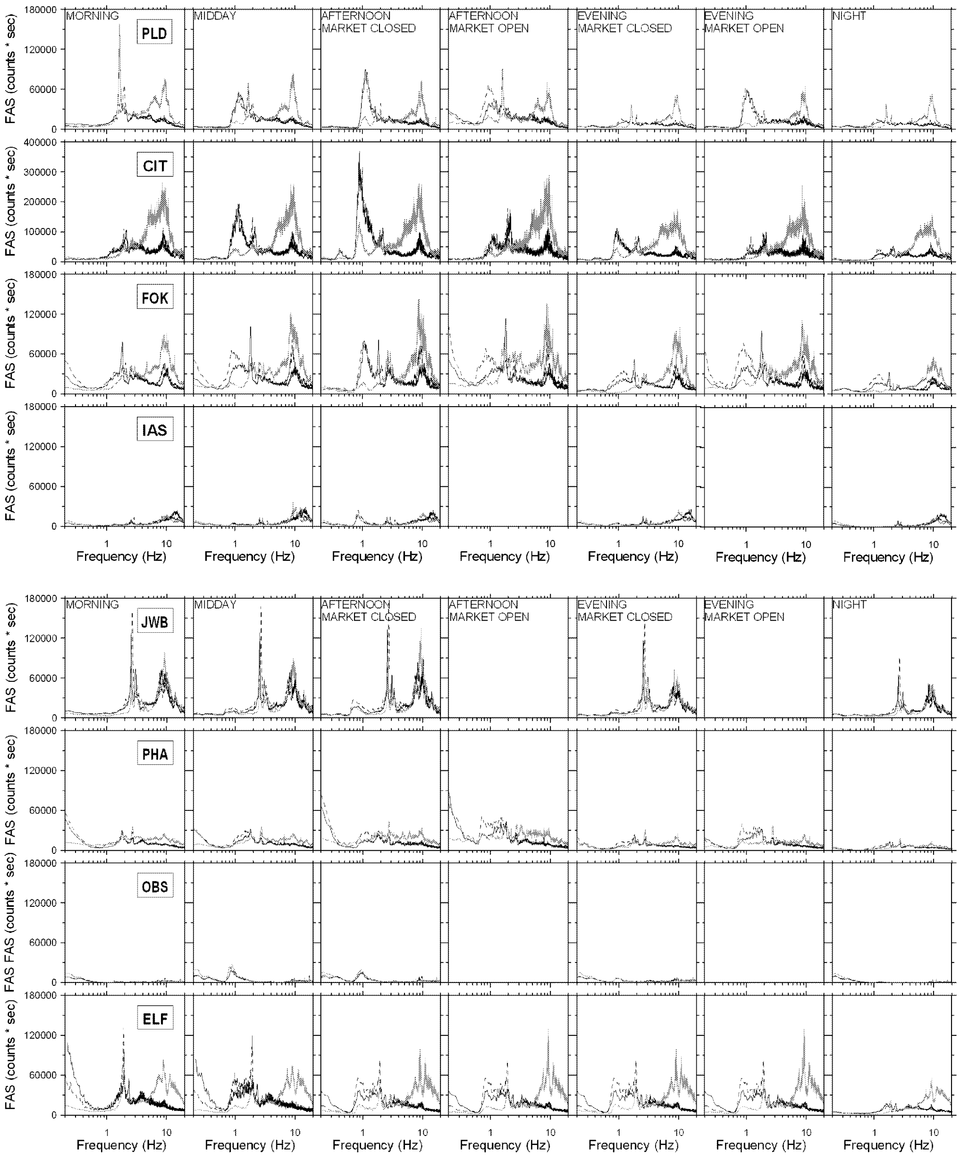


Figure 6
Comparison of the average FAS of ambient noise data for diurnal variation (EW component: black line; NS: dashed line; Vertical component: grey line).

(22:00 p.m.–04:00 a.m. GMT). The average noise H/V spectral ratios of each category were calculated separately for each horizontal component, as described before.

Figure 6 displays the average FAS of each component for all time categories for each site. Looking at this figure, it is clear that spectral amplitudes of each component recorded on sediment sites (PLD, CIT, FOK, JWB, PHA, ELF) are generally higher than those recorded on rock (OBS and IAS). On rock sites Fourier amplitude spectra for all three components show remarkable stability in time while on sediment sites they vary significantly. In general, the FAS shape of the vertical component is stable whereas its amplitude barely decreases during the night period. The only exception is at site PLD, where the FAS of the vertical component during morning measurements is higher than the others. In general, daytime recordings present considerable fluctuations in the FAS shape of the horizontal components, caused mainly by urban man-made noise, whereas their amplitude decreases considerably during night.

Figure 7 illustrates the comparison between the average H/V spectral ratios of ambient noise measurements obtained for all time categories for each site. Regarding the noise H/V spectral ratio results obtained for the five different time periods of a day, several comments can be made. First, at every site variations of the noise H/V spectral ratio in terms of shape are similar in both horizontal components, except for site JWB where a sharp peak appears in NS direction at around 3 Hz. At all sites, variation in amplitude level of the noise H/V spectral ratio is present. Such a variation also has been observed by other researchers (e.g., TEVES-COSTA *et al.* 1996; NAVARRO *et al.* 2001; ALFARO *et al.* 2001). Furthermore, for the majority of the sites the amplitude level of the fundamental frequency during the morning time period is smaller than for the night-time period. This is particularly apparent at sites PLD, FOK, ELF and PHA. These sites are located in buildings close to the main streets of the center of Thessaloniki, where peak traffic occurs between 06:00 a.m.–14:00 a.m. GMT (TSILINGIRIDIS *et al.* 2002). This is a strong indication that the noise H/V spectral ratio is influenced by man-made activities during working hours, as has been noted in a number of relevant studies (e.g., FYEN, 1990; GITTERMAN *et al.* 1996; MILANA *et al.* 1996). In addition, BAHAVAR and NORTH (2002) also observed that high-frequency levels are higher during local daytime than at night-time.

Using as reference H/V spectral ratio that of night measurements, divergence, d[H/V], from the rest time categories are plotted as a function of frequency (Fig. 8). In the same figure the ± 1 standard deviation of night measurements is also given. In most examined sites, values of divergence higher than ± 1 standard deviation are observed on fundamental frequencies pointing out significant diurnal variation of H/V spectral ratio amplitude level. However, at the sites FOK, PHA and ELF, significant divergences also appear in low frequency range ($f < 0.4$ Hz). At these sites a 'bump' of the noise H/V spectral ratio at frequencies lower than 0.4 Hz is observed mainly during daytime. Some studies suggested that long-period ($T > 10$ sec) noise is probably caused by local fluctuation in the atmospheric pressure field. Although atmospheric pressure variation causes both vertical and horizontal displacements, the associated 'bump' may be the principal source of noise for horizontal components. It was found that noise variability in

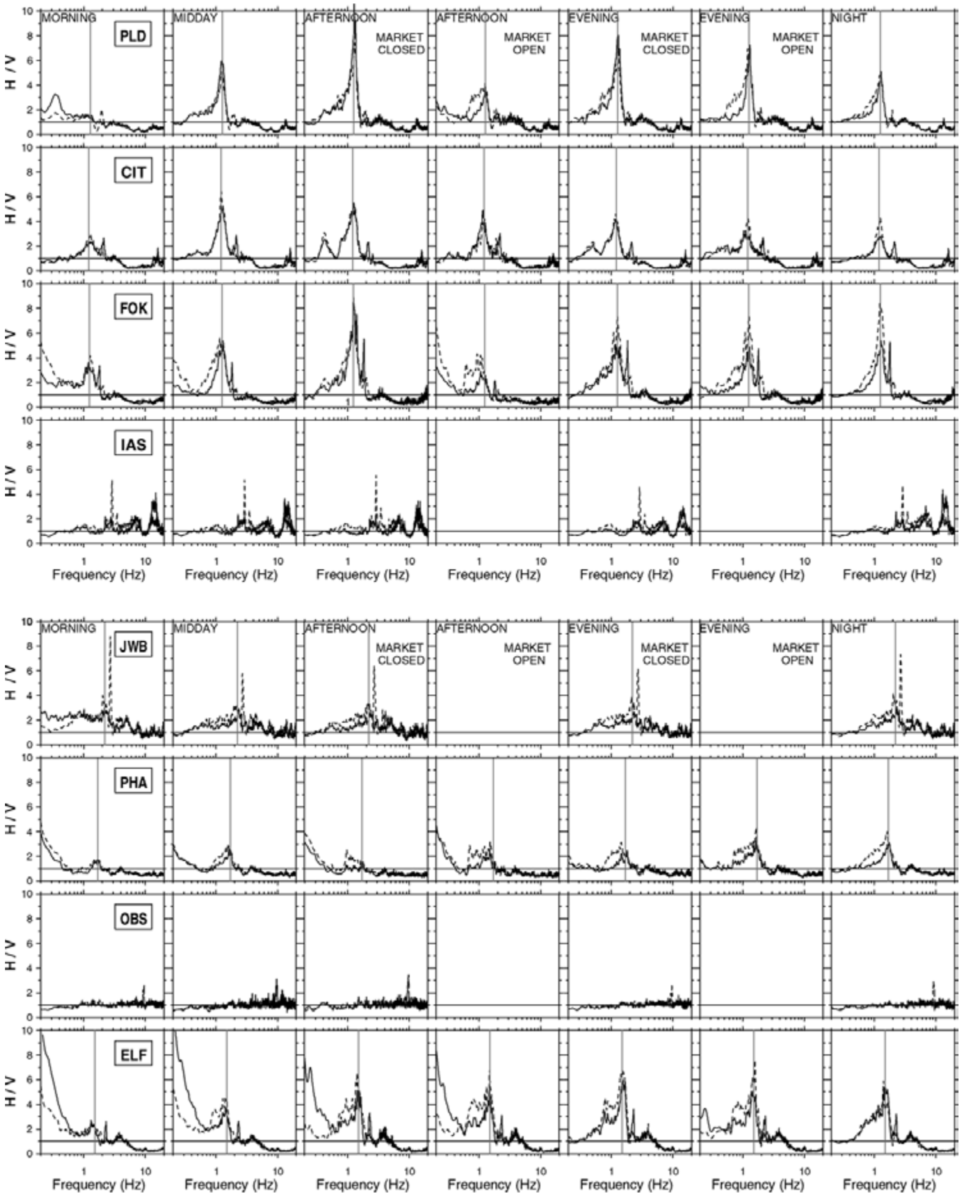


Figure 7
Comparison of ambient noise data for diurnal variation (Hew/V: black line; Hns/V: black dashed line). Fundamental frequencies are indicated by a thin vertical line.

the long-period band appears mostly in the horizontal component whereas the long-period vertical component is relatively stable as a function of time (SORELLS, 1971; SORELLS *et al.* 1971; PETERSON, 1993; GAULL *et al.* 1995; BODIN *et al.* 2001).

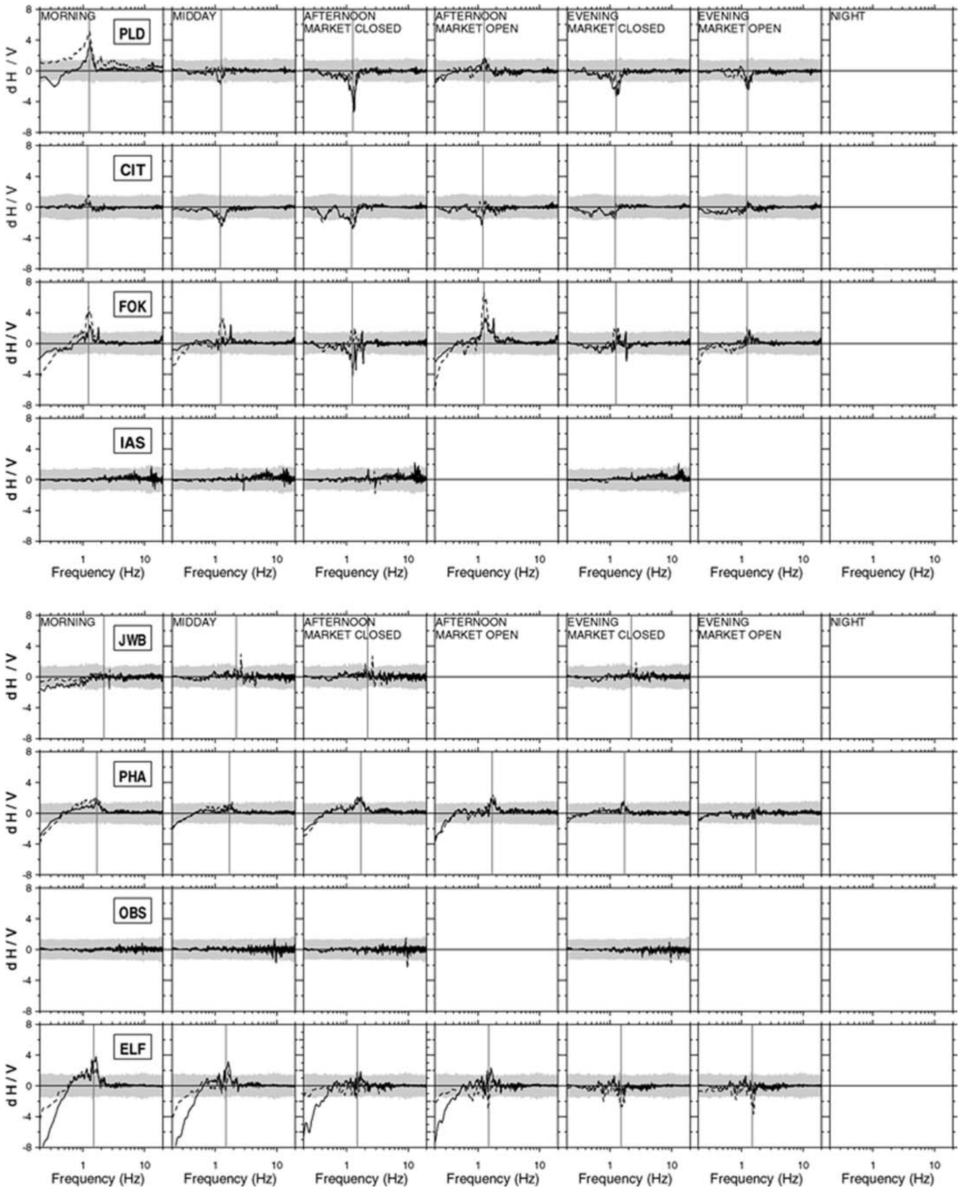


Figure 8
Difference between the diurnal spectral ratios: dH/V = [H/V night – H/V other time category]. The shaded area represents ±1 one standard deviation of night recordings (Hew/V: black line and Hns/V: black dashed line).

To check the stability of the noise H/V spectral ratio, the standard deviation for each time category was estimated (Fig. 9). It is interesting to observe that there is a

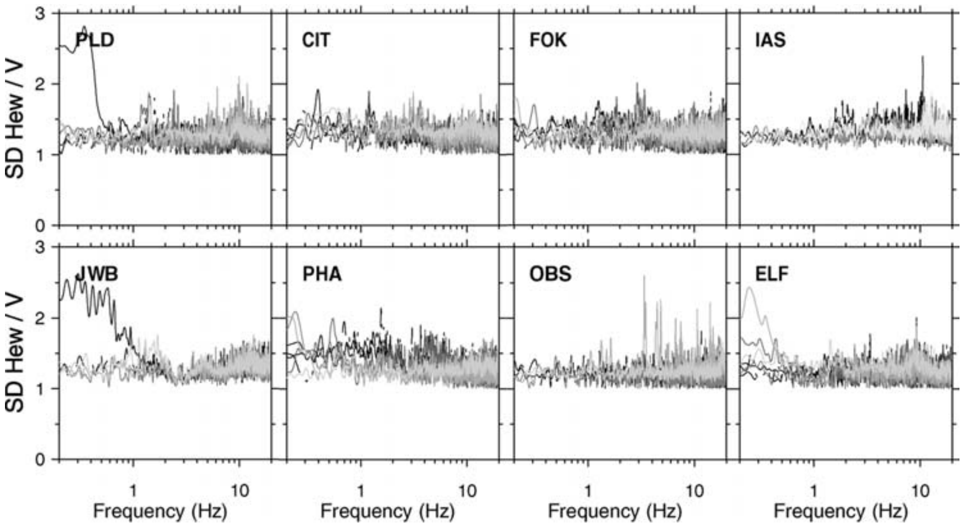


Figure 9
Comparison of the standard deviation of the noise H/V spectral ratio for diurnal variation. Morning (black line), midday (black dashed line), afternoon with market open (grey to dark line) and closed (black dashed/dotted line), evening with market open (grey light line) and closed (grey dark line) and night (grey to light line).

fairly good stability and similarity in the shape of the standard deviation in the whole frequency range for all time categories for the sites CIT, FOK, IAS, PHA and OBS. However, at the sites PLD, JWB and ELF standard deviation values at frequencies lower than 0.5 Hz are quite high.

Finally, we compared the diurnal variation of the atmospheric pressure (provided by the Regional Meteorology Center, Meteorology Station of Macedonia Airport) during the ambient noise measurement period with the diurnal variation of the noise H/V spectral ratio. The variation of the wind speed (provided by the Regional Meteorology Center, Meteorology Station of Aristotle University of Thessaloniki) during our measurements was negligible. As shown in Fig. 10 the local atmospheric pressure field was relatively stable during the days that ambient noise measurements were taken at sites PLD, IAS, ELF, PHA and OBS. Significant atmospheric variation (>5 hPa) is present only at sites CIT, FOK and JWB. In Fig. 11 two striking examples comparing the diurnal variation of the atmospheric pressure with noise H/V spectral ratio, are shown. At site ELF (upper part of Fig. 11) although there is a 'bump' at frequencies lower than 0.4 Hz at the noise H/V spectral ratio of daytime recordings, the corresponding atmospheric pressure is almost invariable. To the contrary, at site CIT (lower part of Fig. 11) although significant fluctuation is observed in the local atmospheric pressure field, no 'bump' at frequencies lower than 0.4 Hz is found at the noise H/V spectral ratio. Similar behavior was observed for the rest of the examined sites suggesting that, at least for the City of Thessaloniki and for

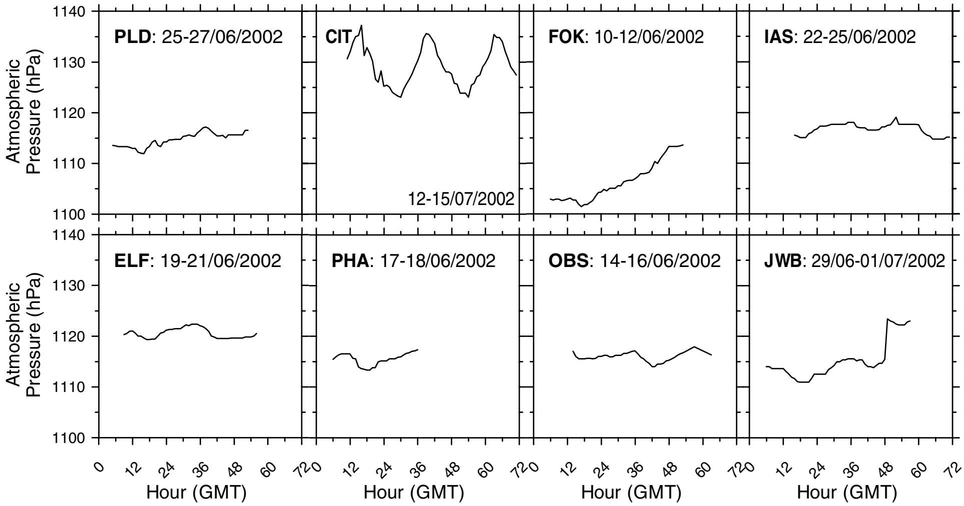


Figure 10
Diurnal variation of the atmospheric pressure field during the ambient noise measurement time period.

the low the frequency band (0.2 Hz < f < 0.5 Hz), the atmospheric variation field did not affect the noise H/V spectral ratio.

2.4. *Seasonal Variation of the H/V Spectral Ratio of Ambient Noise*

In order to examine the seasonal variation of the noise H/V spectral ratio, ambient noise measurements were performed during winter-time at the same eight sites (Fig. 5). The recordings were divided into the same five categories and data were processed in a similar way. The market during winter measurements was closed.

The seasonal variation of the average noise H/V spectral ratio as a function of frequency is llustrated in Fig. 12. As can been seen, the shape of the noise H/V spectral ratio at all sites shows a noticeable stability both in fundamental frequency and amplitude level, especially during the evening and night measurements. At site IAS a sharp peak at approximately 3 Hz appears in the summer-time measurements however it is not apparent in the winter. This may be due to an unknown man-made noise, present only during summer-time measurements. For all of our sites the ‘bump’ at low frequencies (below 0.4 Hz), wherever it was observed during summer-time (e.g., at sites FOK and ELF) disappears during winter period measurements. Using as reference the H/V spectral ratio of summer night measurements, differences from the winter night periods are plotted in Fig. 13, together with the ± 1 standard deviation of summer night recordings. In most examined sites, values of divergence higher than ± 1 standard deviation are observed close to fundamental frequencies, pointing out the significant seasonal variation of the H/V spectral ratio amplitude level.

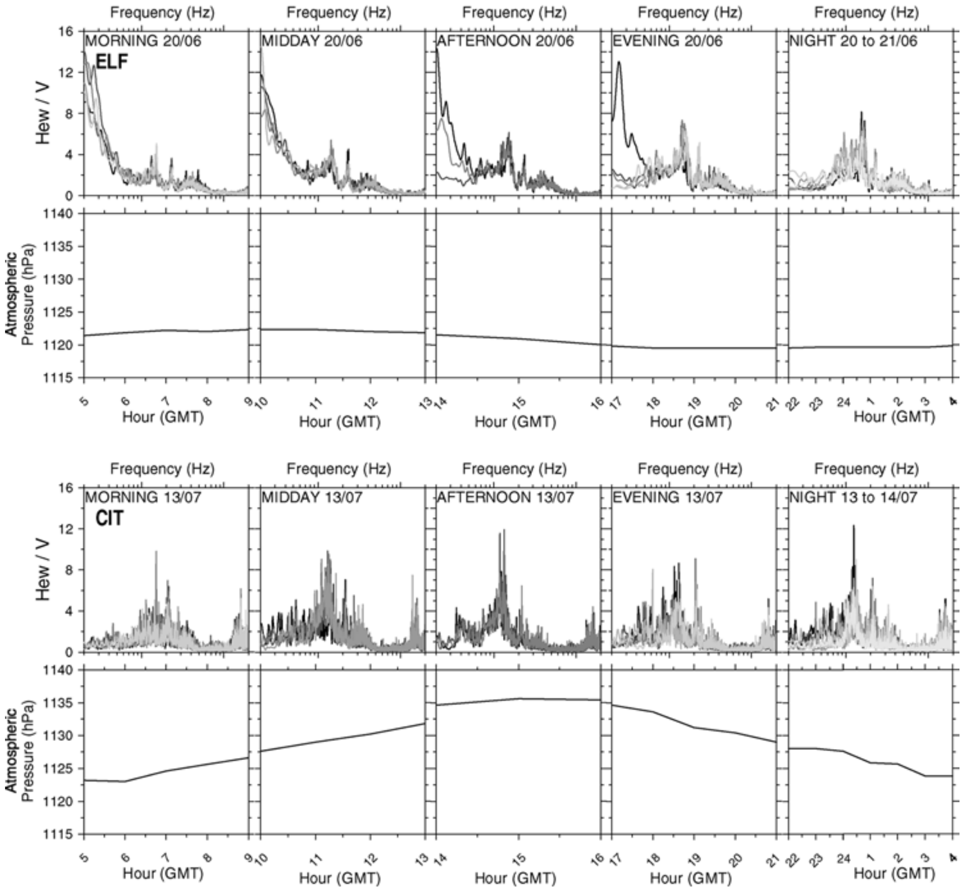
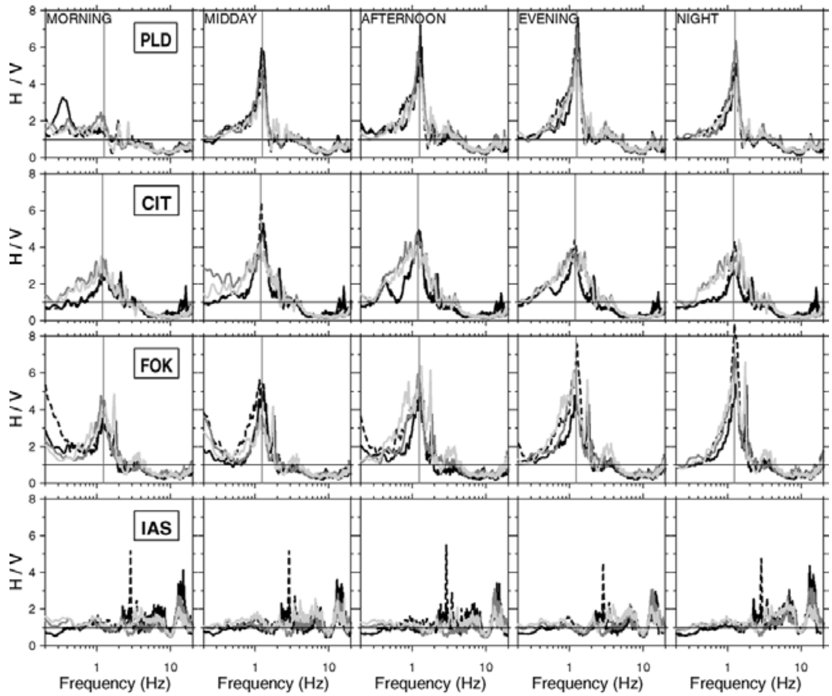


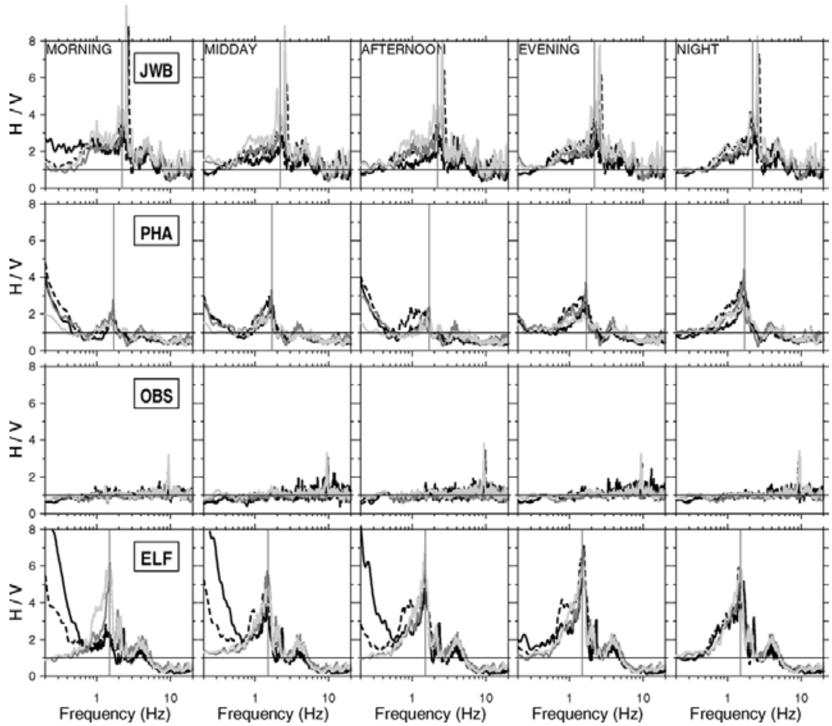
Figure 11
Comparison of the diurnal variation of the atmospheric pressure and the noise H/V spectral ratio at site ELF (upper part) and CIT (lower part). Each H/V spectral ratio line corresponds to a discrete hour with a 5 min measurement.

As shown in Fig. 14 the local atmospheric pressure field was relatively stable during the winter period when ambient noise measurements were taken. Although the variation of hourly traffic is similar for both the summer and winter periods (TSILINGIRIDIS *et al.* 2002), at sites FOK and ELF the installation days were 24–25 December, which are characterized by relatively low traffic. Finally, the fundamental frequency at all sites is practically constant, regardless of the season in which the

►

Figure 12
Comparison of the noise H/V spectral ratios between the summer (Hew/V: black line; Hns/V: black dashed line) and winter period (Hew/V: grey dark line; Hns/V: grey light line).


MORNING
MIDDAY
AFTERNOON
EVENING
NIGHT
PLD
CIT
FOK
IAS
H / V
Frequency (Hz)


MORNING
MIDDAY
AFTERNOON
EVENING
NIGHT
PLD
CIT
FOK
IAS
JWB
PHA
OBS
ELF
H / V
Frequency (Hz)

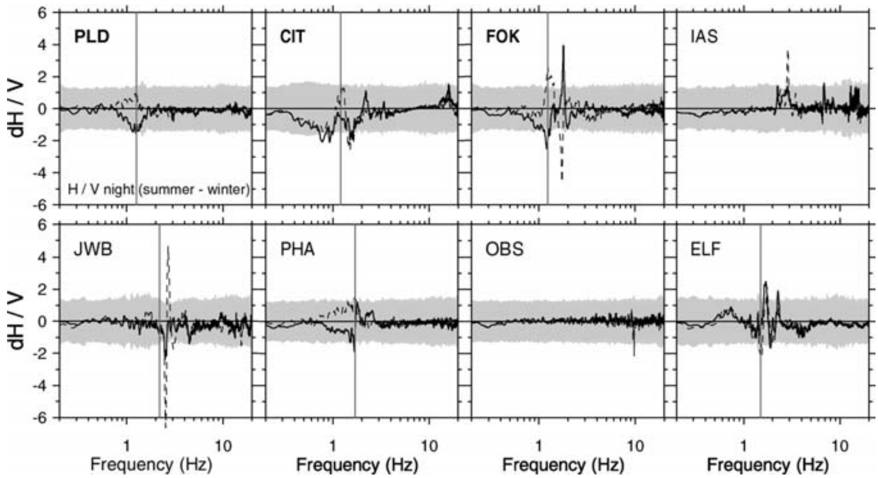


Figure 13
Difference between the seasonal spectral ratios: [dH/V = H/V summer night – H/V winter night]. The shaded area represents ±1 one standard deviation of summer night recordings. (Hew/V: black line and Hns/V: grey dashed line).

measurements were performed, as has also been observed by other researchers (DUVAL *et al.* 1995; SUZUKI *et al.* 1995; BOUR *et al.* 1998; DELGADO *et al.* 2000; LEBRUN *et al.* 2001).

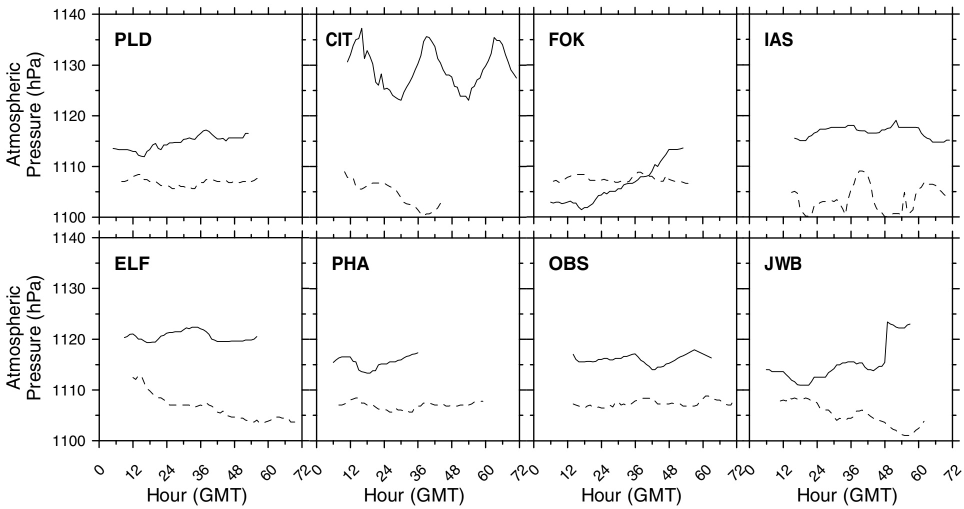


Figure 14
Seasonal variation of the atmospheric pressure field during the summer (black line) and the winter period (13–31/12/2002) (black dashed line).

3. Discussion and Conclusions

The objective of this study is to examine the ability and reliability of the H/V spectral ratio technique using ambient noise measurements in site characterization in an urban environment, taking as a test area the City of Thessaloniki (northern Greece). Reliability tests performed in our study, although focused in certain cases, led us to the following conclusions:

- The recording system that was selected to be used for massive measurements gives reliable results within the frequency range of 0.2 Hz to 20 Hz.
- The H/V spectral ratios of ambient noise recordings at selected sites within the City of Thessaloniki were found to be in good agreement with respective results from previous studies using the H/V receiver function technique.
- The H/V spectral ratios of ambient noise in both horizontal components were found to be similar in terms of amplitude level and shape.
- The study of the diurnal variation of the H/V spectral ratio of ambient noise suggested that it is preferable to perform ambient noise measurements during the calm hours of a day, when man-made noise within the urban environment does not exceed a desirable level.
- It was observed that for the City of Thessaloniki there is no systematic seasonal effect on the H/V spectral ratio of ambient noise.

Additional reliability tests could also have been performed to extensively investigate the influence of many other parameters on the ambient noise H/V spectral ratio (e.g., DUVAL *et al.* 2004). However, such a thorough investigation was far beyond the aim of this study. Nevertheless, the aforementioned limited number of tests may be considered as a minimum prerequisite before one attempts to perform massive ambient noise measurements in urban environments for a site response investigation.

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REFERENCES

ALFARO, A., Pujades, L.G., GOULA, X., SUSAGNA, T., NAVARRO, M., SANCHÉZ, J., and CANAS A. (2001), *Preliminary Map of Soil's Predominant Periods in Barcelona Using Microtremors*, Pure Appl. Geophys. *158*, 2499–2511.

ANASTASIADIS, A., RAPTAKIS, D., and PITILAKIS, K. (2001), *Thessaloniki's Detailed Microzoning: Subsurface Structure Site Response Analysis*, Pure Appl. Geophys. *158*, 2597–2633.

ATAKAN, K., DUVAL, A-M., THEODULIDIS, N., BARD, P-Y., ACERRA, C., ALGUACIL, G., AZZARA, R., BLAREL, F., BONNEFOY-CLAUDET, S., BORGES, A., CARA, F., CORNOU, C., CULTRERA, G., CHATELAIN, J-L., DIMITRIU, P., DUNAND, F., Fäh, D., GRANDISON, M., GUÉGUEN, P., GUILLIER, B., HAGHSHENAS, E., HAVSKOV, J., KIND, F., MORENO, B., OHRNBERGER, M., PANOU, A., RAO, S., RIPPERGER, J., ROQUETTE, P., SAVVAIDIS, A., SØRENSEN, M.B., TENTO, A., TEVES-COSTA, P., VIDAL, S., VOLLMER, D., and ZACHARAPOULOS, S. (2004), *On the Reliability of the H/V Spectral Ratio Technique*, 11th International Conference on *Soil Dynamics and Earthquake Engineering*, 7–9 January, 2004 (Berkeley, USA).

BAHAVAR, M. and NORTH, R. (2002), *Estimation of Background Noise for International Monitoring System Seismic Stations*, Pure Appl. Geophys. *159*, 911–944.

BARD, P.-Y. (1999), *Microtremor Measurements: A tool for site effect estimation?* In *The Effects of Surface Geology on Seismic Motion* (edst. Irikura, Kudo, Okada and Sasatani) (Balkema, Rotterdam, 1999) pp. 1251–1279.

BODIN, P., SMITH, K., HORTON, St., and HWANG, H. (2001), *Microtremor Observations of Deep Sediment Fundamental in Metropolitan Memphis, Tennessee*, Eng. Geol. *62*, 159–168.

BORCHERDT, R. D. (1970), *Effects of Local Geology on Ground Motion near San Francisco Bay*, Bull. Seismol. Soc. Am. *60*, 29–61.

BOUR, M., FOUISSAC, D., DOMINIQUE, P., and MARTIN, C. (1998), *On the Use of Microtremor Recordings in Seismic Microzonation*, Soil Dyn. Earthq. Eng. *17*, 465–474.

CHATELAIN, J.-L., GUEGUEN, Ph., GUILLIER, B., FRÉCHET, J., BONDOUX, F., SARRAULT, J., SULPICE, P., and NEUVILLE, J.-M. (2000), *Cityshark: A User-friendly Instrument Dedicated to Ambient Noise (Microtremor) Recording for Site and Building Response Studies*, Seismol. Res. Lett. *71*, 698–703.

CHÁVEZ-GARCÍA, F.J. and CUENCA, J. (1996), *Site Effects in Mexico City Urban Zone. A Complementary Study*, Soil Dyn. Earthq. Eng. *15*, 141–146.

DELGADO, J., LÓPEZ CASADO, C., GINER, J., ESTÉVEZ, A., CUENCA, A., and MOLINA, S. (2000), *Microtremors as a Geophysical Exploration Tool: Application and Limitations*, Pure Appl. Geophys. *157*, 1445–1462.

DIAGOURTAS, D., TZANIS, A., and MAKROPOULOS, K. (2001), *Comparative Study of Microtremors Analysis Methods*, Pure Appl. Geophys. *158*, 2463–2479.

DUVAL, A.-M., BARD, P.-Y., MÉNEROUD, J.-P., and VIDAL, S. (1995), *Mapping Site Effects with Microtremors*, Proc. of 5th Intern. Confer. on *Seismic Zonation*, 17–19 October, 1995, (Nice, France) vol. *2*, pp. 1522–1529.

DUVAL, A.-M., BARD P.-Y., LEBRUN B., LACAVE-LACHET, C., RIEPL, J., and HATZFELD, D. (2001), *H/V Technique for Site Response Analysis. Synthesis of Data from Various Surveys,* Boll. Goef. Teor. Appl. *42*, 267–281.

DUVAL, A.-M., CHATELAIN, J.-L., GUILLIER. B., and the SESAME WP02 TEAM, *Influence of experimental conditions on H/V determination using ambient vibrations (noise),* 13th World Conf. on Earthquake Engineering, 1–6 August, (Vancouver, British Columbia, Canada 2004).

FIELD, E., HOUGH, S.E., and JACOB, K. (1990), *Using Microtremors to Access Potential Earthquake Response: A Case Study in Flushing Meadows, New York City*, Bull. Seismol. Soc. Am. *80*, 1456–1480.

FIELD, E., and JACOB, K. (1993), *The Theoretical Response of Sedimentary Layers to Ambient Seismic Noise*, Geophys. Res. Lett. *20–24*, 2925–2928.

FIELD, E, and JACOB, K. (1995), *A comparison of Various Site-response Estimation Techniques, Including Three that are not Reference-Site Dependent*, Bull. Seismol. Soc. Am. *85*, 1127–1143.

FYEN J. (1990), *Diurnal and Seasonal Variations in the Microseismic Noise Level Observed at the NORESS Array*, Phys. Earth Plan. Inter. *63*, 252–268.

GAULL, B. A., KAGAMI, H., and TANIGUCHI, H. (1995), *The Microzonation of Perth, Western Australia, Using Microtremor Spectral Ratios*, J. Earthq. Eng. *11*, 173–191.

GITTERMAN, Y., ZASLAVSKY, Y., SHARIPA, A., and SHTIVELMAN, V. (1996), *Empirical Site Response Evaluations: Case Studies in Israel*, Soil Dyn. Earthq. Eng. *15*, 447–463.

GUTIERREZ, C. and SINGH, S.K. (1992), *A Site Effect Study in Acapulco, Guerrero, Mexico: Comparison of Results from Strong-motion and Microtremor Data*, Bull. Seismol. Soc. Am. *82*, 642–659.

HADJIAN, A.H. (2002), *Fundamental Period and Mode Shape of Layered Soil Profiles*, Soil Dyn. Earthq. Eng. *22*, 885–891.

HAVSKOV, J. and OTTEMÖLLER, L., *SEISAN: The Earthquake Analysis Software*, Report of Inst. Solid Earth Physics, Univ. Bergen (Bergen, Norway 2000).

HORIKE, M., ZHAO, B., and KAWASE, H. (2001), *Comparison of Site Response Characteristics Inferred from Microtremor and Earthquake Shear Waves*, Bull. Seismol. Soc. Am. *91*, 1526–1536.

IGME (1978), *Geological Map of Thessaloniki*, Institute of Geology and Mineral Exploration.

KANAI, K. (1962), *On the Spectrum of Strong Earthquake Motions*, Bull. Earthq. Res. Inst. *40*, 71–90.

KAGAMI, H., DUKE, M., LIANG, C., and OHTA, Y. (1982), *Observations of 1–5 Second Microtremor and their Application to Earthquake Engineering. Part II: Evaluation of Site Effect upon Seismic Wave Amplification due to Extremely Deep Soil Deposits*, Bull. Seismol. Soc. Am. *72*, 987–998.

KAGAMI, H., OKADA, S., SHIONO, K., ONER, M., DRAVINSKI, GOTO, N., and KUDO, K. (1986), *Observations of 1–5 Second Microtremor and their Application to Earthquake Engineering. Part III: A Two-dimensional Study of Site Effects in the San Fernando Valley*, Bull. Seismol. Soc. Am. *76*, 1801–1812.

LACHET, C. and BARD, P.-Y. (1994), *Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura's Technique*, J. Phys. Earth. *42*, 377–397.

LACHET, C., HATZFELD, D., BARD, P.-Y., THEODOULIDIS, N., PAPAIOANNOU, Ch., and SAVVAIDIS, A. (1996), *Site Effects and Microzonation in the city of Thessaloniki (Greece): Comparison of Different Approaches*, Bull. Seismol. Soc. Am. *86*, 1692–1703.

LEBRUN, B., HATZFIELD, D., and BARD, P.-Y. (2001), *Site Effect Study in Urban Area: Experimental Results in Grenoble (France)*, Pure Appl. Geophys. *158*, 2543–2557.

LERMO, J., RODRIGUEZ, M., and SINGH, S., K. (1988), *The Mexico Earthquake of September 19, 1985—Natural Periods of Sites in the Valley of Mexico Form Microtremor Measurements and Strong Motion Data*, Earthq. Spect. *4*, 805–814.

LERMO, J. and CHÁVEZ-GARCÍA, F.J. (1994a), *Are Microtremor Useful in Site Response Evaluation?* Bull. Seismol. Soc. Am. *84*, 1350–1364.

LERMO, J. and CHÁVEZ-GARCÍA, F.J., (1994b), *Site Effect Evaluation at Mexico City: Dominant Period and Relative Amplification from Strong Motion and Microtremor Records*, Soil Dyn. Earthq. Eng. *13*, 413–423.

MILANA, G., BARBA, S., DEL PEZZO, E., and ZAMBONELLI, E. (1996), *Site Response from Ambient Noise Measurements: New Perspectives from an Array Study in Central Italy*, Bull. Seismol. Soc. Am. *86*, 320–328.

MUCCIARELLI, M., BETTINALI, F., ZANINETTI A., VANINI, M., MENDEZ, A., and GALLI, P. (1996), *Refining Nakamura's Technique: Processing Techniques and Innovative Instrumentation*, 25th General Assembly of the European Seismol. Com., 9–14 September, 1996 (Reykjavik, Iceland) pp. 1–6.

MUCCIARELLI M. (1998), *Reliability and Applicability of Nakamura's Technique Using Microtremors: An Experimental Approach*, J. Earthq. Eng. *2*, 625–638.

NAKAMURA, Y. (1989), *A Method for Dynamic Characteristics Estimation of Subsurface Using Microtremor on the Ground Surface*, QR Railway Tech. Res. Inst. *30*, 25–33.

NAVARRO, M., ENOMOTO, T., SÁNCHEZ, F.J., MATSUDA, I., IWATATE, T., POSADAS, A.M., LUZÓN, F., and SEO, K. (2001), *Surface Soil Effects Study Using Short-period Microtremors Observations in Almeria City, Southern Spain*, Pure Appl. Geophys. *158*, 2481–2497.

NOGOSHI, M. and IGARASHI, T. (1971), *On the Amplitude Characteristics of Microtremor (Part 2)*, J. Seismol. Soc. Japan *24*, 26–40.

OHTA, Y., KAGAMI, H., GOTO, N., and KUDO, K. (1978), *Observations of 1–5 second Microtremor and their Application to Earthquake engineering. Part I: Comaparison with Long-period Accelerations at the Tokachi-Oki Earthquake of 1968*, Bull. Seismol. Soc. Am. *68*, 767–779.

OJEDA, A. and ESCALLON, J. (2000), *Comparison between Different Techniques for Evaluation of predominant Periods Using Strong Ground Motions Records and Microtremors in Pereira Colombia*, Soil Dyn. Earthq. Eng. *20*, 137–143.

PETERSON, J. (1993), *Observations and Modelling of Seismic Background Noise*, U.S. Department of Interior Geological Survey (Albuquerque, Mexico 1993).

ROVELLI, A., SINGH, S.K., MALAGNINI, L., and AMATO, A. (1991), *Feasibility of the Use of Microtremors in Estimating Site Response during Earthquakes: Some Test Cases in Italy*, Earthq. Spect. *7*, 551–561.

SATOH T., KAWASE H., and MATSUSHIMA S. (2001), *Differences between Site Characteristics Obtained from Microtremors, S-waves, P-waves, and Codas*, Bull. Seismol. Soc. Am. *91*, 313–334.

SEEKINS, L., WENNERBERG, L., MARGHERITI, L., and LIU, H.-P. (1996), *Site Amplification at Five Locations in San Francisco, California: A Comparison of S-waves, Codas, and Microtremors*, Bull. Seismol. Soc. Am. *86*, 627–635.

SESAME PROJECT, 2001–2004, ***S**ite **E**ffect**S** assessment using **AM**bient **E**xcitations*, http://sesame-fp5.obs.ujf-grenoble.fr.

SORELLS, G. G. (1971), *A Preliminary Investigation into the Relationship between Long-period Seismic Noise and Local Fluctuations in the Atmospheric Pressure Field*, Geophys. J. *26*, 71–82.

SORELLS, G. G., MCDONALD, J.A., DER, Z.A., and HERRIN, E. (1971), *Earth Motion Caused by Atmospheric Pressure Changes*, Geophys. J. *26*, 83–98.

SUZUKI, T., ADACHI, Y., TANAKA, M. (1995), *Application of Microtremor Measurements to the Estimation of Earthquake Ground Motions in Kushiro City during the Kushiro-Oki Earthquake of 15 January 1993*, Earthq. Eng. and Struct. Dyn. *24*, 595–613.

TEVES-COSTA, P., MATIAS, L., BARD, P.-Y. (1996), *Seismic Behaviour Estimation of Thin Alluvium Layers Using Microtremor Recordings*, Soil Dyn. Earthq. Eng. *15*, 201–209.

TOSHINAWA, J., TABER, J., and BERRIL, J. (1997), *Distribution of Ground-motion Intensity from Questionnaire Survey, Earthquake Recordings, and Microtremor Measurements - A Case Study in Christchurch, New Zealand, during the1994 Arthus Pass Earthquake*, Bull. Seismol. Soc. Am. *87*, 356–369.

TRIANTAFYLLIDIS, P., HATZIDIMITRIOU, P., THEODOULIDIS, N., SUHADOLC, P., PAPAZACHOS, C., RAPTAKIS, D., and LONTZETIDIS, K. (1999), *Site Effects in the City of Thessaloniki (Greece) Estimated from Acceleration Data and 1-D Local soil Profiles*, Bull. Seismol. Soc. Am. *89*, 521–537.

TSILINGIRIDIS, G., ZACHARIADIS, Th., and SAMARAS, Z. (2002), *Spatial and Temporal Characteristics of Air Pollutant Emissions in Thessaloniki, Greece: Investigation of Emission Abatement Measure*, Sci. Total Environ. *300*, 99–113.

UDWADIA, F. and TRIFUNAC M. (1973), *Comparison of Earthquake and Microtremor Ground Motions in El Centro, California*, Bull. Seismol. Soc. Am. *63*, 1227–1253.

YAMANAKA, H., DRAVINSKI, M., and KAGAMI, H. (1993), *Continuous Measurements of Microtremor on Sediments and Basement in Los Angeles, California*, Bull. Seismol. Soc. Am. *63*, 1227–1253.

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