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USE OF AMBIENT NOISE FOR MICROZONATION STUDIES IN URBAN ENVIRONMENT: THE CITY OF THESSALONIKI (N. GREECE)

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ABSTRACT

The horizontal-to-vertical spectral ratio (HVSR) technique applied on ambient noise (Nogoshi & Igarashi, 1971; Nakamura, 1989, 2000) has been recently used increasingly in microzonation studies in urban environments. However, the reliability of the HVSR results is still in debate. Ambient noise measurements were conducted in the city of Thessaloniki (Northern Greece) for examining the limitations of the HVSR technique for cities of similar location and geological setting. Initially, the HVSR of ambient noise are compared with HVSR of earthquake recordings in several locations, in terms of the shape of the curve, the fundamental frequency (fo) and the corresponding HVSR amplitude level (Ao), in order to evaluate the efficiency of the ambient noise HVSR in predicting ground motion properties. The contour maps of fo, Ao and Kg (Nakamura, 1996) are compared to the damage distribution (Leventakis, 2003) for the 20/6/1978, (M6.5) earthquake. This analysis suggests that heavy damage is correlated with Ao and Kg-value, and inversely with fo. Finally, as the subsurface structure varies within the city, ambient noise was simulated for a number of different 1-D and 2-D soil profiles (Anastasiadis et al., 2001). Comparison between the actual and simulated HVSR outlines the reliability of fo in mapping the sediment variation thickness. The aforementioned results are encouraging for the use of the ambient noise HVSR as an inexpensive, fast and efficient tool in microzonation studies in urban environments, comparable to the city of Thessaloniki.

Keywords: Ambient noise, H/V spectral ratio, site effects, noise modeling.

INTRODUCTION

In the last several decades, destructive earthquakes occurring close to populated areas showed that site effects can play an important role to the resulting damages. The evaluation of site effects is then one of the key parameters in microzonation studies. Local site effects may be evaluated by empirical (based on earthquakes or explosions recordings) or theoretical methods (numerical simulation of the site response based on detailed geotechnical and geophysical parameters). The main disadvantage of these

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methods is the high cost and the time consumed for obtaining the earthquake recordings or geophysical and geotechnical prospecting.

The horizontal-to-vertical spectral ratio technique applied on ambient seismic noise measurements (Nogoshi & Igarashi, 1971; Nakamura, 1989, 2000) (which hereafter is referred as ANHVSR technique) has been used as an alternative method to characterize the site response in urban environment. Ambient noise is composed of low amplitude vibrations generated by natural disturbances such as wind, sea tides or of manmade origin as traffic, industrial machinery, household appliances etc (for a complete review for the nature of noise wavefield see Bonnefoy-Claudet et al., 2006a). The seismological community generally agrees that ANHVSR technique gives reliable results in terms of the fundamental frequency of the site (see Bard (1999) and Mucciarelli & Gallipoli, (2001) for a complete review). Several authors (among which Field and Jacob, 1993; Lachet & Bard, 1994; Konno & Ohmachi 1998; Fäh et al., 2001; Uebayashi 2003; Bonnefoy-Claudet et al., 2004; Cornou et al., 2004; Cornou, 2005; Bonnefoy-Claudet et al., 2006b; Guillier et al. 2006) gave theoretical support to the ANHVSR technique. Assuming that ambient noise is due to surface sources randomly distributed in space and time, they computed ambient noise synthetics and almost all confirm the coincidence between the fundamental frequency of ambient noise H/V spectral ratio and the soil column of the site, whatever the structure (1D, 2D or 3D). However, the applicability of the ANHVSR technique to evaluate the site amplification level, its reliability to properly detect lateral discontinuities in urban environments and its limitations are debatable.

In order to better understand the use of the ANHVSR technique in microzonation studies, ambient noise measurements were conducted in the city of Thessaloniki (Northern Greece). The motivation to select Thessaloniki (Figure 1) as a study site was the earthquake of June 20, 1978, (M6.5) that caused severe damages in the city and demonstrated the vulnerability of modern cities. An eight–storey reinforced-concrete building collapsed in the city center, 4000 buildings suffered serious damages and 47 people lost their lives. Although many studies have been conducted since this earthquake, detailed investigation of the damage potential is still needed for an effective preparedness and seismic risk mitigation against future earthquakes. An extended list of relevant publications about the 1978 earthquake can be found in the works of Papazachos and Carydis (1983), Tranos et al. (2003) and Theodulidis et al. (2006).

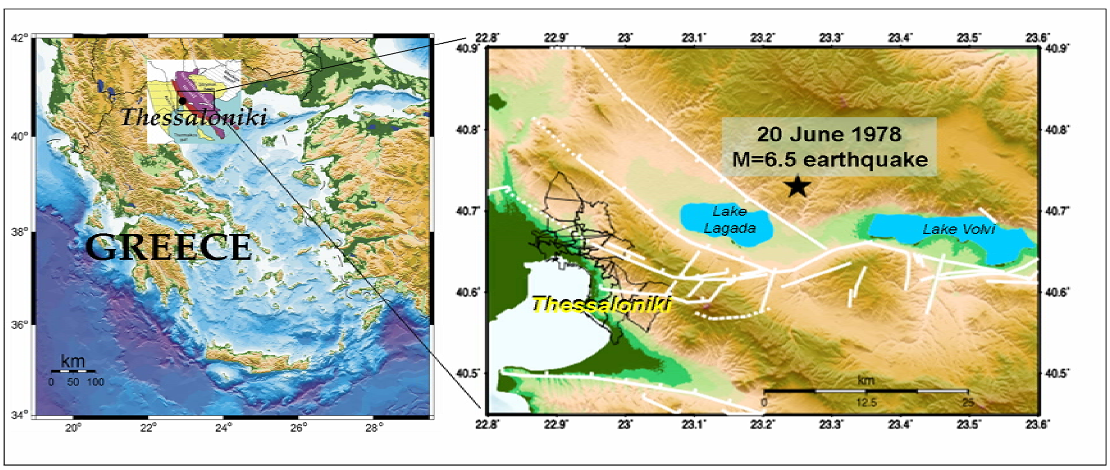

Figure 1. ***Left part:*** **Geographical position of the city of Thessaloniki.**
Right part: **Regional map showing the faults (white lines) along the southern margin of the Mygdonian graben (Tranos et al. 2003; Paradeisopoulou et al. 2006). The epicenter of the 1978 earthquake (Papazachos et al., 1979) is also shown with a star.**

COMPARISON OF THE ANHVSR TECHNIQUE WITH RECEIVER FUNCTIONS

In order to evaluate the efficiency of the ambient noise HVSR in predicting ground motion properties, ambient noise measurements were carried out at ten sites where seismological experiment had been performed in the past (Lachet et al., 1996 [**La**]; Triantafyllidis et al., 1999 [**Tr**]). Two types of sensors were used : an accelerometer Guralp CMG5 [**Tr**] and a broadband velocimeter Guralp CMG40 (T = 20 sec) [**La**] at eight sites (rectangulars in Fig. 2, right lower part) or a short-period Mark Product L22 (T = 0.5 sec) at two other sites (triangles in Fig. 2, right lower part).

The frequency variation of the ambient noise HVSR in comparison with the corresponding mean value from [**La**] and [**Tr**] receiver functions using earthquake recordings, is shown in Figure 2 (left part). In general, the results show that there is a similarity in fundamental frequency (fo) and overall shape of the H/V spectral ratios in all examined sites between noise H/V spectral ratios and earthquake receiver functions. Figure 2 (right upper part) shows for each examined site the comparison between the fundamental frequencies estimated from: the ANHVSR technique and earthquake receiver functions ([**La**] and [**Tr**]). A good agreement between them is observed for almost all sites. The differences and similarities between the ANHVSR technique and the corresponding receiver functions of [**Tr**] and [**La**] as well as the corresponding fundamental frequencies, are discussed thoroughly in Panou et al. (2005a). Thus, 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.

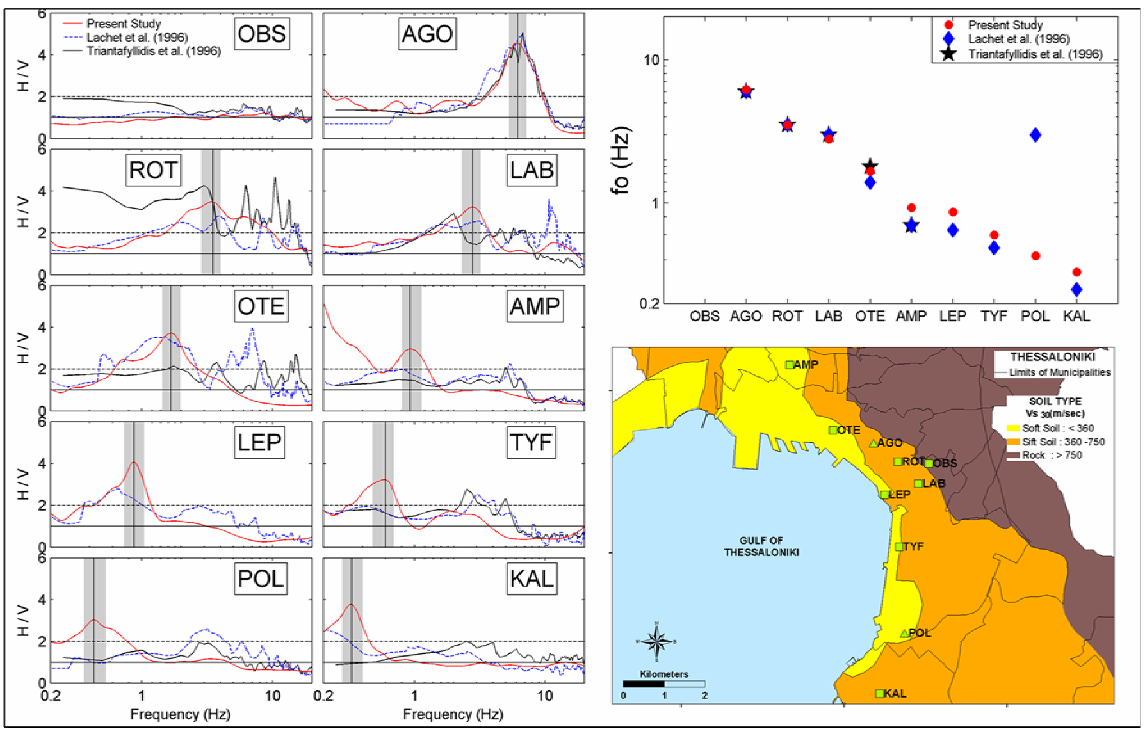

Figure 2. ***Left part:*** **Comparison of the ANHVSR technique (present study, red lines) with earthquake receiver functions (Lachet et al. 1996, blue dashed line; Triantafyllidis et al. 1999, black line) at the same sites.** ***Right upper part:*** **Comparison between the fundamental frequencies derived in the present study (red solid circles) and those from Lachet et al. (1996) (blue solid diamonds) and Triantafyllidis et al. (1999) (black stars) at each site.** ***Right lower part:*** **Locations of ambient noise recordings for which earthquake ground recordings were available in the city of Thessaloniki. The distribution of the shear wave velocities, Vs_{30}, is also shown (Anastasiadis et al., 2001; Theodulidis et al., 2006).**

COMPARISON OF THE ANHVSR TECHNIQUE WITH EARTHQUAKE DAMAGE

In the framework of the “SEISIMPACT-THES” project a Geographic Information System (GIS) database has been designed to combining topographical, geological, seismological and geophysical data, as well as detailed information about damages caused to the buildings by the 1978 earthquake within a broad area of the prefecture of Thessaloniki. Intensity observations from the 1978 earthquake (Leventakis, 2003) were added to the database. This was done by selecting the data points which corresponded to R/C buildings located in the area covered by Leventakis (2003) and assigning the intensity value at the specific location according to that study. This is shown on the map of Figure 3 (left panel) only for the historical center of the city of Thessaloniki.

Ambient noise measurements were performed at the same area (Panou et al., 2005a; Panou et al., 2005b). Sampling intervals between measurement points were approximately 150 m. Then, the ambient noise HVSR for each site was calculated with the J-SESAME and SESARRAY programs (Atakan et al. 2004, Wathelet et al., 2005, http://www.geopsy.org) and the fundamental frequency (fo) and corresponding HVSR amplitude level (Ao) were estimated. Based on the values of the fo and the corresponding HVSR amplitude level, the ground vulnerability index Kg-value ($Kg=Ao^2/fo$; Nakamura, 1996) was also calculated. By spatial interpolation of the fundamental frequency (fo), the corresponding HVSR amplitude level (Ao) and the Kg-value of all the points contour maps were produced (Panou et al., 2005b; Panou et al., 2006). Then, the contour maps were compared with the observed detailed damages distribution induced by the 1978 earthquake and the quantitative assessment of these comparisons is shown in Figure 3 (right panel). It was found that in areas where heavy damages were observed, the fundamental frequency (fo) of the sites was generally lower, while the corresponding HVSR amplitude level (Ao) and the Kg-value was higher than in those exhibiting light damage. Furthermore, Kg-values exhibit a better correlation with the damage distribution compared to that of the HVSR amplitude level (the coefficient of determination, R^2, of Kg is 0.94 while for Ao is 0.92). The aforementioned results indicate that the ANHVSR technique and its product, namely, ground vulnerability index Kg-value, can satisfactorily point out areas of higher seismic risk potential in the city of Thessaloniki.

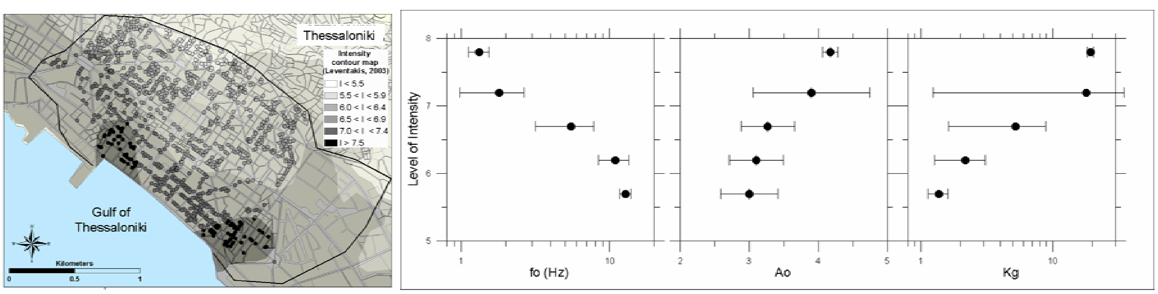

Figure 3. ***Left panel:*** **Corresponding values of macroseismic intensities from the 1978 earthquake (Leventakis 2003) on buildings (SEISIMPACT-THES, Final Report, 2005) within the examined area (black line).** ***Right panel:*** **Correlation between the average ± one standard deviation fundamental frequency, fo (*left part*), the corresponding HVSR amplitude level, Ao (*middle part*), and the ground vulnerability index, Kg (*right part*), with macroseismic intensities I.**

AMBIENT NOISE SYNTHETICS

For modeling the ambient noise originated by human activity for sites with heterogeneous subsurface structures, we used the two-step numerical code that has been developed within the European SESAME project (Moczo & Kristek, 2002). In the first step, the noise sources are represented by surface or subsurface point forces that are randomly distributed in space, direction (vertical or horizontal), amplitude and time. The source time function is either delta-like signal (impulsive sources) or a pseudo-monochromatic signal (“machine” sources, harmonic carriers with the Gaussian envelope). In the second step according to the structure (1D, 2D or 3D) the computation of the associated wave field is performed with different patterns. For 1D horizontally layered media Green’s functions are computed by using the wavenumber method proposed by Hisada (1994, 1995), while for 3D structures the computation is performed by using an explicit heterogeneous finite-difference scheme solving equations of motion in the heterogeneous visco-elastic medium with material discontinuities (Moczo et al., 2002).

Synthetic spectral ratios HVSR were calculated using the SESARRAY software (Wathelet et al. 2005, http://www.geopsy.org) following the recommendations of the SESAME project (SESAME Deliverable 23.12, 2004). As the duration of the synthetics is limited (1.5 to 6 minutes) no automatic window selection was applied and the whole recording was used instead. For calculating the spectral ratios, each recording was divided into time intervals of 20 seconds duration each. It has to be pointed out that the maximum computed frequency in case of 1D simulation was 14.28 Hz, while in case of 2D simulation the upper frequency was 3 Hz. The HVSR of the ambient noise synthetics were calculated after the following steps were applied: (a) application of a cosine taper, (b) computation of Fourier spectra in all three components (E–W, N–S, UP), (c) smoothing of the Fourier amplitude spectra by a Konno-Ohmachi algorithm (Konno & Ohmachi, 1998) with parameter b set equals to 40. For each site the H/V spectral ratio was plotted versus frequency and the fundamental frequency (fo) and the corresponding HVSR amplitude level (Ao) were obtained.

1D SIMULATION AND COMPARISON WITH EXPERIMENTAL RESULTS OF ANHVSR

The locations for which synthetic recordings of ambient noise were calculated are shown in Figure 4. These specific locations were chosen as they lie along certain lines, most of which are parallel to the main geological structures of the area (NW-SE direction), which means that the 1D structure assumption is quite reliable, while two others are perpendicular to these structures (NE-SW direction), in order to be compared with 2D model simulations along the same two lines.

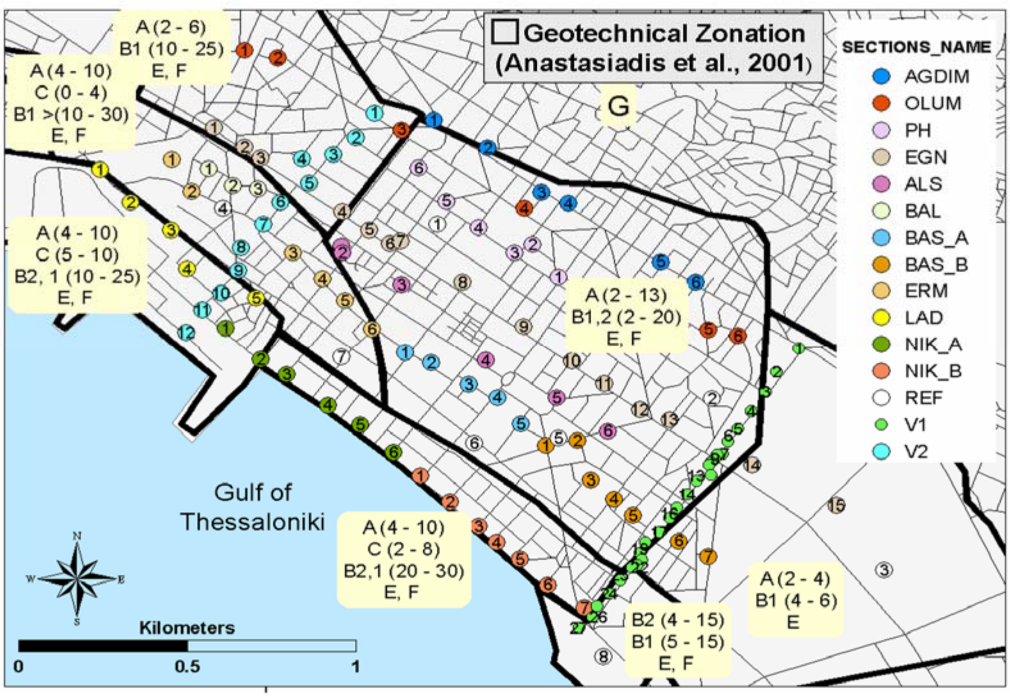

Figure 4. Locations for which ambient noise was computed. In the right panel the names of the profiles along which the synthetic recordings were computed are listed. The numbering of the locations along each profile is the one used in the presentation of the results. The geotechnical division of the area according to Anastasiadis at al. (2001) is also shown. The main sedimentary formations are denoted by capital letters and their thickness is written in parentheses.

Two examples of results obtained by using these simulations are shown in Figures 5 and 6. In each figure we plotted at each location the spectral ratios HVSR computed by using actual ambient noise (black continuous line for the average HVSR and dotted lines for the average +/- standard deviation) and synthetic ambient noises (blue dotted line). The horizontal black continuous line corresponds to a HVSR ratio of 1, while the dotted line corresponds to a HVSR ratio of 2. Also, the actual HVSR peak frequency (black vertical line) and its standard deviation (gray shaded area) are plotted. In the bottom part of Figure 5 the 1D geological structure of each site is shown. The distances between the sites are also written. The geological structure is visualized by color-coding the formations and using the same symbols as Anastasiadis et al. (2001). When the sites of the sections had almost the same geotechnical profile, like as it is shown in the lower left panel in Figure 6, then the average 1D structure was used in the simulation (Figure 6, lower right part). In this case, the location of each measurement is shown on the profile and distances between locations are written.

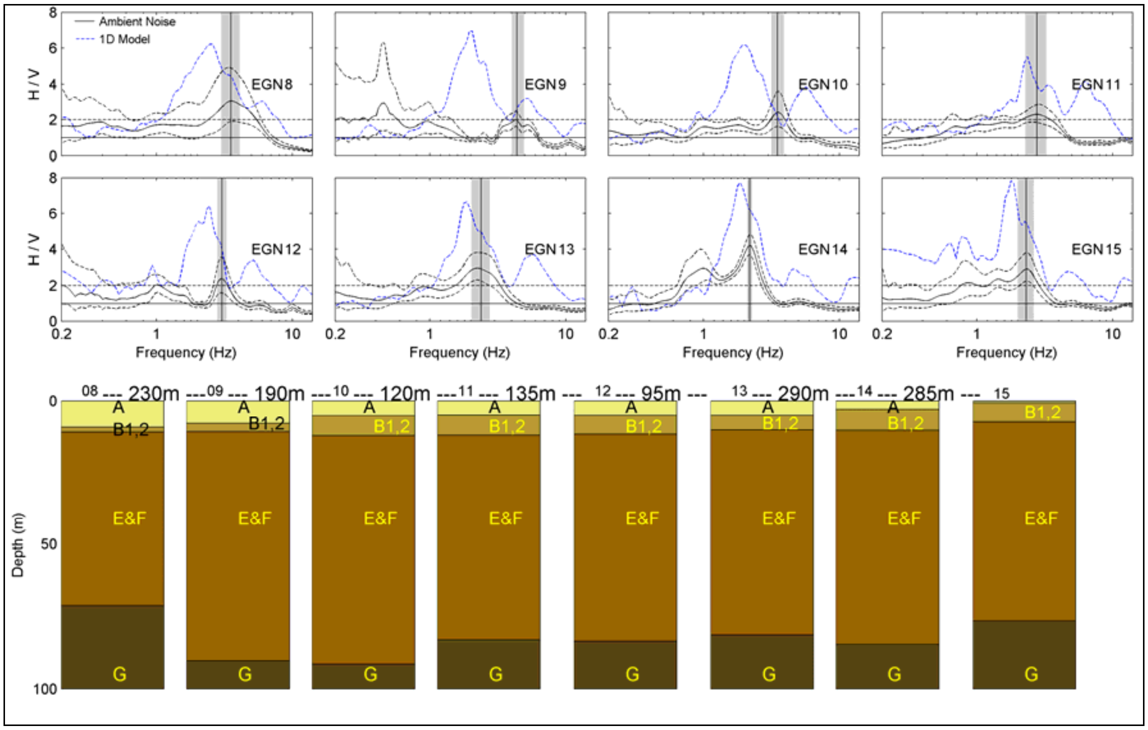

Figure 5. Results obtained along the EGN section. *Upper part:* Spectral ratios HVSR of ambient noise measurements (black continuous line for the average value and dotted lines for the average +/- standard deviation) and spectral ratios computed by using ambient noise synthetics (blue dotted line). The horizontal black continuous line corresponds to a ratio of 1, while the dotted line corresponds to a ratio of 2. The fundamental frequency (black vertical line) and its standard deviation (gray shaded area) are also plotted. *Lower part:* 1D geological structure of each site that was used for the simulation is shown (from Anastasiadis et al., 2001).

Figure 7 summarizes the results obtained at all sites displayed in Figure 4 by using 1D simulations. More specifically the fundamental frequencies and amplifications calculated by using synthetic recordings are compared to the corresponding experimental results. The correlation of the fundamental frequencies is satisfactory although there are several locations where the theoretical values deviate from the corresponding experimental values. On the contrary, in amplifications, there is no correlation whatsoever.

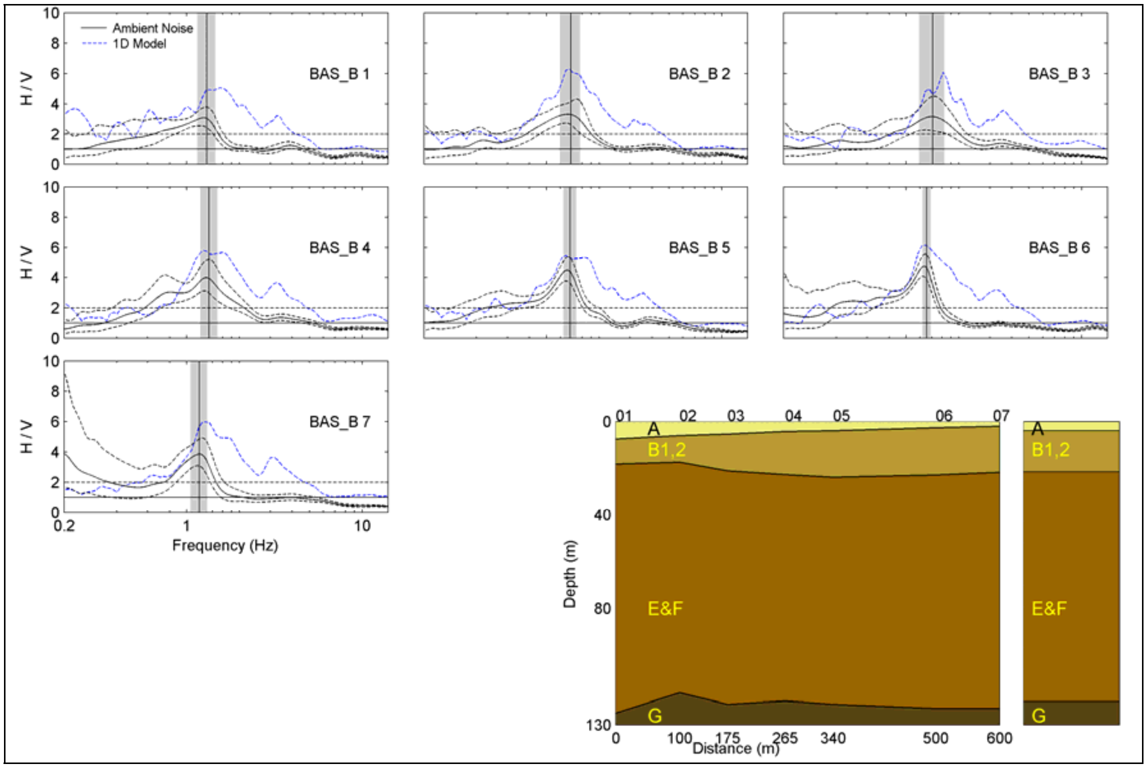

Figure 6. Results obtained along the BAS_B profile. ***Upper part:*** **See legend of Figure 5.** ***Lower part:*** **1D geological structure that was used for the simulation is shown (from Anastasiadis et al., 2001).**

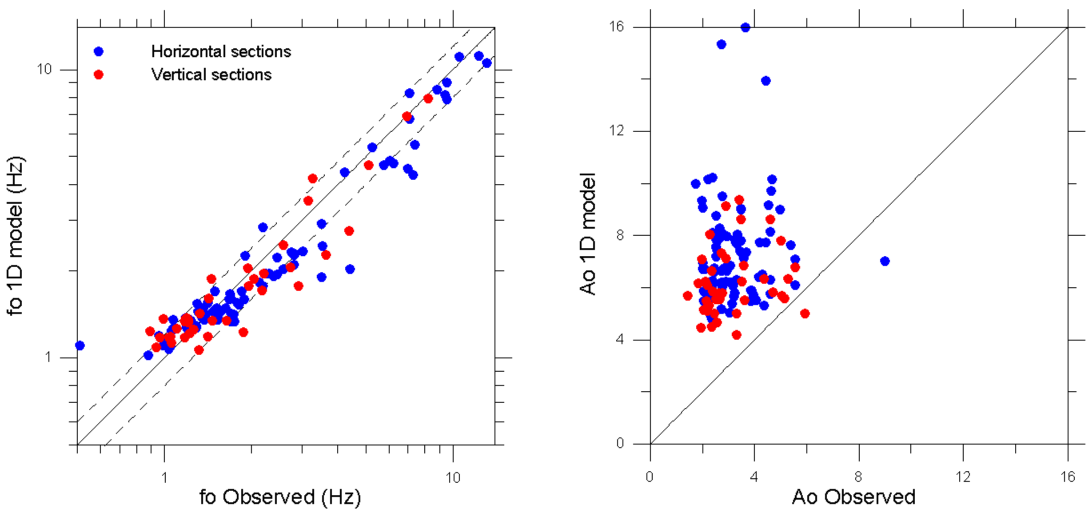

Figure 7. Comparison between HVSR fundamental frequencies and amplitudes computed by using synthetic recordings and the experimental values. Blue points indicate values observed at sites lying on profiles parallel to the structure (NW-SE direction), while red points indicate values observed at sites lying along profiles perpendicular to the structure (NE-SW direction). The continuous line is the bisector and the dotted lines a deviation of 10% from the bisector.

2D SIMULATION AND COMPARISON WITH EXPERIMENTAL RESULTS OF HVSR

For the two-dimensional ambient noise simulation, the two profiles shown in Figure 4 were selected. These profiles are perpendicular to the main geological structures of the area, which makes them especially appropriate for 2D simulation. Along the V1 (Vertical 1) section the mean spacing between measurements is about 40 meters, that is the highest measurements density throughout the area of study. In Figure 4 the sites 5 to 24 for the V1 (Vertical 1) profile and 4 to 11 for the V2 (Vertical 2 profile are those for which 2D simulation was performed. Figure 8 presents the 3D structure of the two profiles with respect the underlying formations adopted.

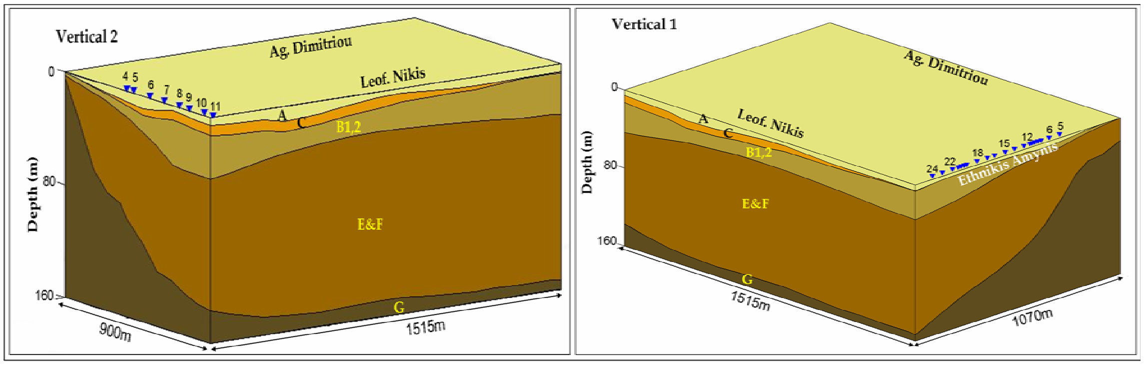

Figure 8. Three-dimensional presentation of the geotechnical model (Anastasiadis et al., 2001) which was used for the 2D noise simulation along the V1 (right part) and V2 (left part) profiles. Blue triangles denote the locations of the receivers.

Figures 9 and 10 show for each site the spectral ratios computed by using 2D noise synthetics (red line), the spectral ratios calculated by using 1D noise synthetics (blue dashed line) and those experimentally determined (black continuous line for the average value and dotted lines for the standard deviation). The horizontal black continuous line corresponds to a spectral ratio equals to 1, while the dotted line corresponds to a ratio equals to 2. Also, the fundamental frequency (black vertical line) and its standard deviation (gray shaded area) are shown. The comparison was performed for the frequency band from 0.5 to 3Hz. From these figures there is a rather good correlation between the shapes of the measured spectral ratios with the shapes of the spectral ratios which were computed by using 2D noise synthetics.

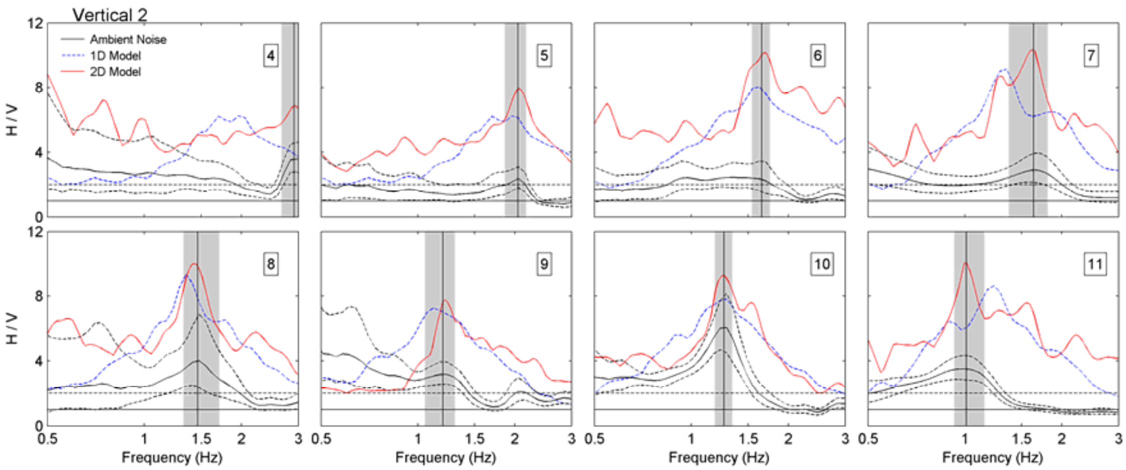

Figure 9. Same as in Figure 10 for profile Vertical 2.

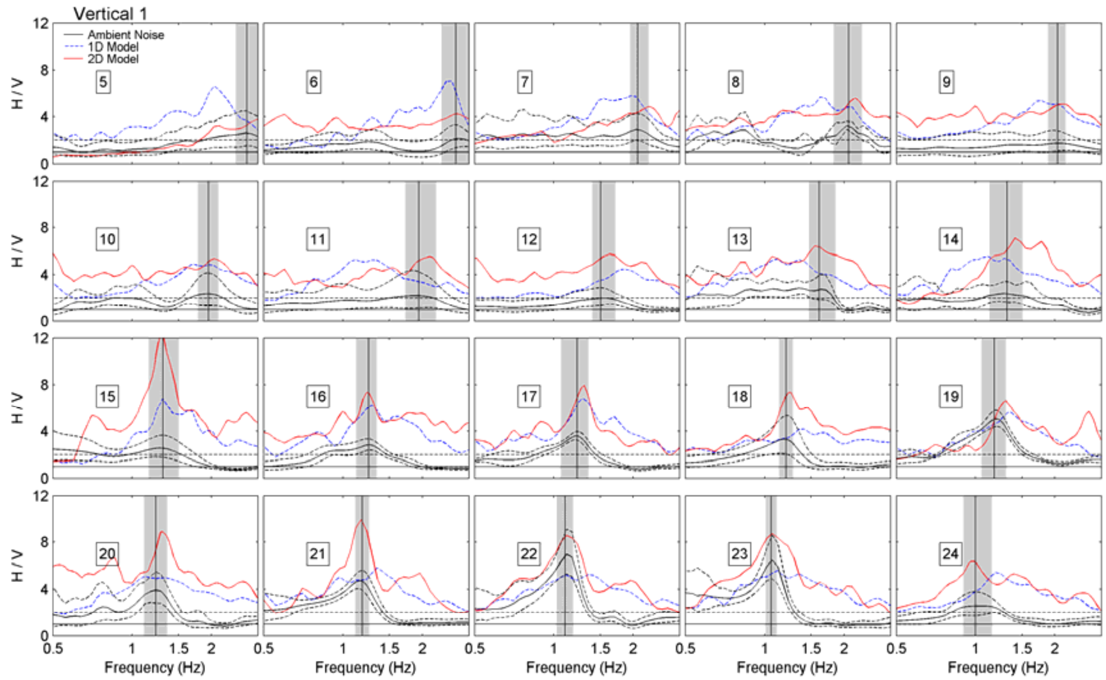

Figure 10. Spectral ratios computed by using 2D noise synthetics (red line), spectral ratios calculated by using 1D noise synthetics (blue dashed line) and experimental spectral ratios (black continuous line for the average value and dotted lines for the standard deviation) for each location, for profile Vertical 1. The horizontal black continuous line corresponds to a ratio equals to 1, while the dotted line corresponds to a ratio equals to 2. Also, the fundamental frequency (black vertical line) and its standard deviation (gray shaded area) are shown.

Figure 11 shows the comparison between fundamental frequencies and their corresponding amplitudes derived from actual ambient noise measurements and from ambient noise synthetics.

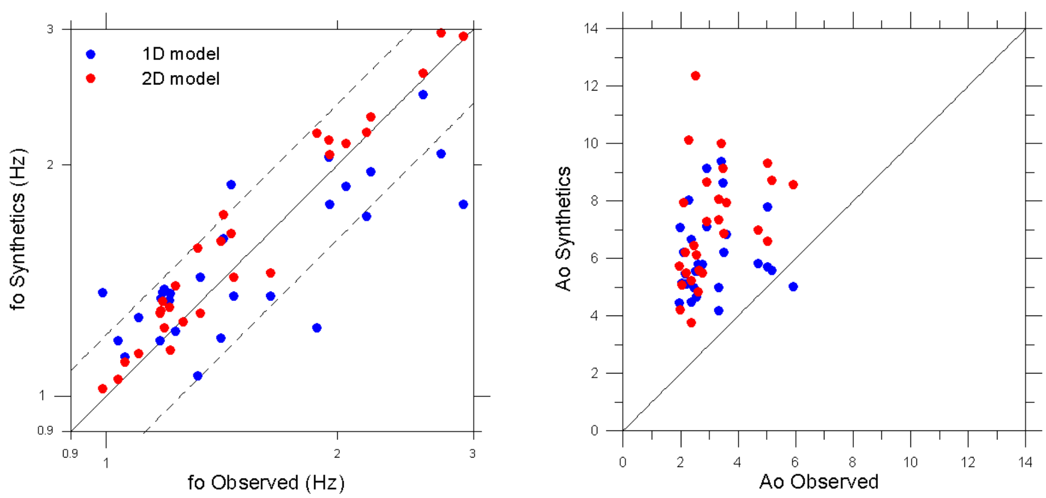

Figure 11. Comparison between HVSR peak frequencies and corresponding amplitudes derived from real ambient noise recordings and from noise synthetics. Blue points indicate results obtained by using 1D noise synthetics, while red points indicate results derived from 2D noise synthetics. The continuous line is the bisector, while the dotted lines correspond to a deviation of 10% from the bisector.

As far as the fundamental frequencies are concerned, the correlation is satisfactory, while for the amplitude no correlation can be found, amplitude derived from noise synthetics systematically overestimating the actual amplitude. It also has to be pointed out, that 2D noise synthetics provide fundamental frequencies in better agreement with the actual ones, especially at lowest frequencies.

CONCLUSIONS

The objective of this study was to examine the validity of the ANHVSR technique in site characterization in urban environment, taking as a test area the city of Thessaloniki. For this purpose we performed reliability tests that led us to the following conclusions:

1. The HVSR of ambient noise recordings at selected sites within the city of Thessaloniki were found to be in good agreement with corresponding results from previous studies using the H/V receiver function technique.
2. The fundamental frequency, fo, the corresponding HVSR spectral ratio, Ao, and the ground vulnerability index, Kg, are well correlated with the macroseismic intensity data (MSK scale) of the 20/6/1978 earthquake.
3. The ANHVSR technique can reliably detect lateral discontinuities in urban environments, such as the city of Thessaloniki.

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