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Ambient noise horizontal-to-vertical spectral ratio in site effects estimation and correlation with seismic damage distribution in urban environment: the case of the city of Thessaloniki (Northern Greece)

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Abstract

The validity of the estimation of seismic site response characteristics from ambient noise measurements was investigated in the downtown district of the city of Thessaloniki (Northern Greece), which was strongly affected by the 20/6/1978 ($M=6.5$) damaging earthquake. For this purpose 250 'single site' ambient noise measurements were performed in a dense grid of points covering the center of the city. The ambient noise *H*/*V* spectral ratio for each site was calculated and the fundamental frequency (fo) and corresponding *H*/*V* amplitude level (Ao) were estimated. Contour maps of both, fo and Ao, were compared with results from geological and geotechnical studies as well as with macroseismic data of the 1978 earthquake and were found to be well correlated. These comparisons provide strong evidence that ambient noise measurements properly processed with the (*H*/*V*) spectral ratio technique can be used as an inexpensive and fast tool for microzonation studies in urban environments.

Keywords: Ambient noise; *H*/*V* ratio; Site effects; Seismic damage; Microzonation; Thessaloniki

1. Introduction

After recent earthquakes (e.g. Northridge—USA 1994, Kobe—Japan 1995, Athens—Greece 1999) the a priori estimation of site effects became a major challenge for efficient seismic risk mitigation. Such estimation may come from recordings either from earthquakes, explosions or from theoretical computations. The main disadvantage of these methods is the high cost and the time consumed in conducting field experiments. The spectral analysis of ambient noise is an alternative way to characterize the site response in urban environment. Ambient noise is low amplitude soil vibrations generated by natural disturbances such as wind, sea tides or of manmade 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 site under investigation [1,2].

The reliability of this method has been studied both numerically and experimentally. Several authors computed 'noise synthetics' (among which [3–12]) assuming that ambient noise is due to surface sources randomly distributed in space and time. While almost all of them confirm the coincidence between the fundamental frequency of ambient noise *H*/*V* spectral ratio and the one of soil column of the site, none of them claims a good correlation between the corresponding *H*/*V* amplitude levels.

A large number of observational studies have been performed to experimentally establish the credibility of the method. In the following, some of them are indicatively reported (for a complete review see [13,14]). The comparison between the fundamental frequency obtained from ambient noise *H*/*V* spectral ratios and receiver functions of earthquake recordings or explosion data, allowed researchers (among them, [15–33]) to conclude that ambient noise

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H/*V* spectral ratios do provide reliable estimates of the fundamental frequencies of soil deposits. On the other hand the comparison between the site amplification obtained from ambient noise *H*/*V* spectral ratios and receiver functions of earthquake recordings, led to somewhat less consistent results; some researchers found a good correlation (e.g. [34–40]) while others consider such a comparison not satisfactory (e.g. [31,41–44]).

Many authors (among which, [45–65]) have demonstrated that soil thickness can be determined from the ambient noise *H*/*V* spectral ratio fundamental frequency.

Several papers present comparison between the fundamental frequency and the corresponding *H*/*V* amplitude level with damage distribution or intensity of an earthquake [33,60,66–76]. The agreement is generally quite satisfactory, though only qualitative.

By performing experiments under controlled conditions several authors (e.g. [36,77]) examined parameters that could affect ambient noise measurements such as data acquisition system, processing techniques, etc. Recently, a European project the so-called SESAME (*S*ite *E*ffect*S* assessment using *AM*bient *E*xcitations) aims to examine site effects assessment techniques using ambient vibrations. One of the main tasks of the SESAME project is the research of the experimental aspects that influence the stability of ambient noise measurements [78,79].

In Greece, site effects assessment has been also attempted analysing ambient noise measurements. Kobayashi [80], using Kanai's (1957) method, conducted ambient noise measurements in the city of Thessaloniki and proposed four soil categories with respect to mean predominant period. Diagourtas et al. [81] carried out ambient noise measurements in the city of Heraklion (Crete, Greece) and observed that the amplitude levels of the *H*/*V* spectral ratios were generally lower than those resulting from the standard spectral ratios (SSR). They also found remarkable similarity and consistency in the amplification frequency band between the *H*/*V* spectral ratios, the SSR ratios and 1D modelling based on geotechnical data. Lachet et al. [22] compared the SSR and the *H*/*V* spectral ratios of earthquake recordings with *H*/*V* spectral ratios of ambient noise for the city of Thessaloniki. They found that although the three methods are equally able to reveal the fundamental frequency of a site, there is a general trend between the amplification levels obtained by each technique. Spectral ratios amplification levels obtained at each site exhibit a good correlation with the map of damage intensity. Apostolidis [82] performed ambient noise array measurements in the Euroseistest (Mygdonian graben, Northern Greece) and at 16 different locations within the city of Thessaloniki and estimated shear wave velocity profiles and site specific fundamental frequency. Scherbaum et al. [83] showed that the comparison of shear wave velocity models obtained from inversion of ambient noise array recordings at the island of Lefkas (Western Greece), in the Volvi graben (Northern Greece, Euroseistest site) and at six different locations within the city of Thessaloniki and those obtained by independent geotechnical surveys, ranges from excellent to fair. Leventakis [84] studied the macroseismic effects in the city of Thessaloniki caused by the June 20, 1978 mainshock and proposed contour maps with equal intensities. He also conducted ambient noise measurements in the city of Thessaloniki and data processing was made according to two different methods proposed by Kanai [99]. The city was divided into five zones with respect to soil categorization and for each zone the predominant period was given. Panou et al. [85] comparing *H*/*V* spectral ratios of ambient noise recordings with *H*/*V* receiver functions from weak motion earthquake data at selected sites within the city of Thessaloniki found good agreement. Furthermore, by performing ambient noise measurements in the downtown district of the city of Thessaloniki, during different diurnal and seasonal periods they concluded that: (a) 'single site' measurements within a city should be made during the calm hours of a day when manmade noise is relatively low and (b) there is no systematic seasonal fluctuation effect on the ambient noise *H*/*V* spectral ratio.

The city of Thessaloniki (Northern Greece) is located in an area of moderate to high seismicity and has experienced several destructive earthquakes during 20th century. The most recent earthquake ($M=6.5$, $R\approx 30$ km) occurred in 20/6/1978 and severely damaged many buildings within the city. The ambient noise *H*/*V* spectral ratio has already proved to be an inexpensive and convenient technique to reliably evaluate site effects and contribute to seismic risk mitigation in urban environments. The aim of this paper is to examine the validity and correlation of the ambient noise technique in the downtown district of the city of Thessaloniki by comparing the fundamental frequency, fo, and the corresponding *H*/*V* amplitude level, Ao, obtained from the ambient noise *H*/*V* spectral ratio with available (a) geological data [86], (b) geotechnical [87] data and (c) observed intensities of the 1978 earthquake (EMS_98; [84]).

2. Data acquisition and processing

Ambient noise measurements were performed in the downtown district of the city of Thessaloniki (Northern Greece) (upper part of Fig. 1). The measurement grid (about 1.2 km×2.5 km) covered the historical center of the city and in total 250 measurements were carried out (lower part of Fig. 1). The records were obtained from Monday to Friday either during evening period (18:00–22:00 pm GMT with closed market) or during night period (23:00 pm–05:00 am GMT) as proposed by Panou et al. [85]. The equipment used was the Cityshark 24-bits recorder [88] coupled with a Lennartz 3D/5s velocimeter sensor. The response of the seismometer is flat to velocity between 0.2 and 50 Hz. Data analysis was focused in the frequency range between 0.2 and 20 Hz. Ohta et al. [89] have suggested an observation

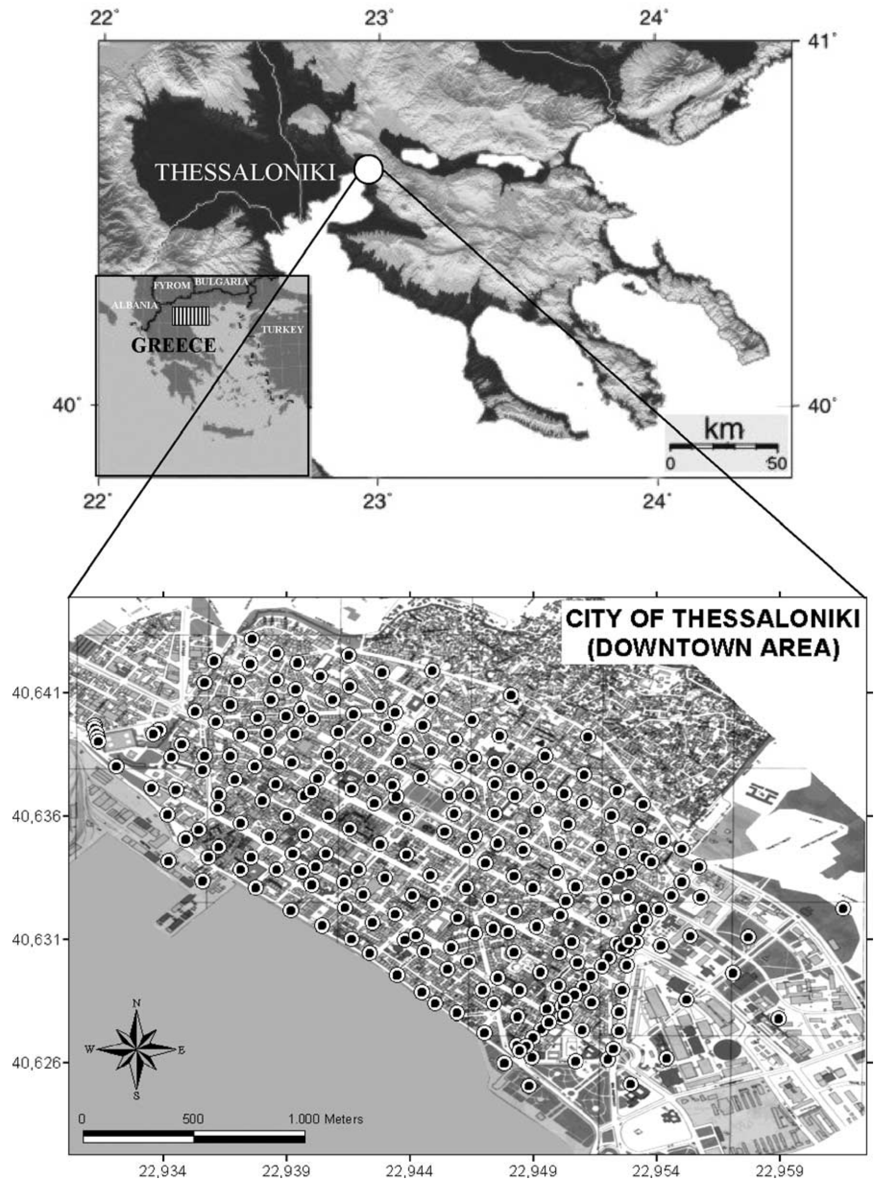

Fig. 1. Upper part: map of the Thessaloniki, Northern Greece. Lower part: location of ambient noise measurements in the downtown district of the city of Thessaloniki.

record at a point at least 10–20 min long in order to get a record good enough for analysis. In this work, for each site the recording system operated continuously for 20 min with a sample rate of 100 Hz.

Ambient noise data were processed in two stages. First, for each ambient noise recording, a number of windows, having a duration of 20 s each, were selected using the 'window selection' module of the JSESAME software [90], in order to exclude portions with unrealistically large amplitudes or spikes, as has been also suggested by Duval et al. [79]. Using the '*H*/*V* processing' module of the JSESAME software, the following steps were applied on the ambient noise data: (a) offset correction, (b) computation of Fourier spectra in all three components (E–W, N–S, UP), (c) application of a cosine taper, (d) smoothing of the Fourier amplitude spectra by a Konno–Ohmachi algorithm [8]. For each frequency point the horizontal recording spectrum was divided by the vertical one, separately for both horizontal components, in order to detect any significant difference between the EW/V and NS/V spectral ratios.

The method of the ambient noise *H*/*V* spectral ratio is based on the existence of a soil (or a rock) layer of low rigidity overlying another more rigid. In the case of sites located on rock, this condition is not met since no contrast exists between materials at the surface and those at depth. Consequently, on outcropping rocks, the *H*/*V* spectral ratio is flat without meaningful peaks. Characteristic equal depth contours along line ETA (Fig. 2, upper part), covering different geological [86] and geotechnical [87] formations of the city, was chosen to evaluate the consistency of

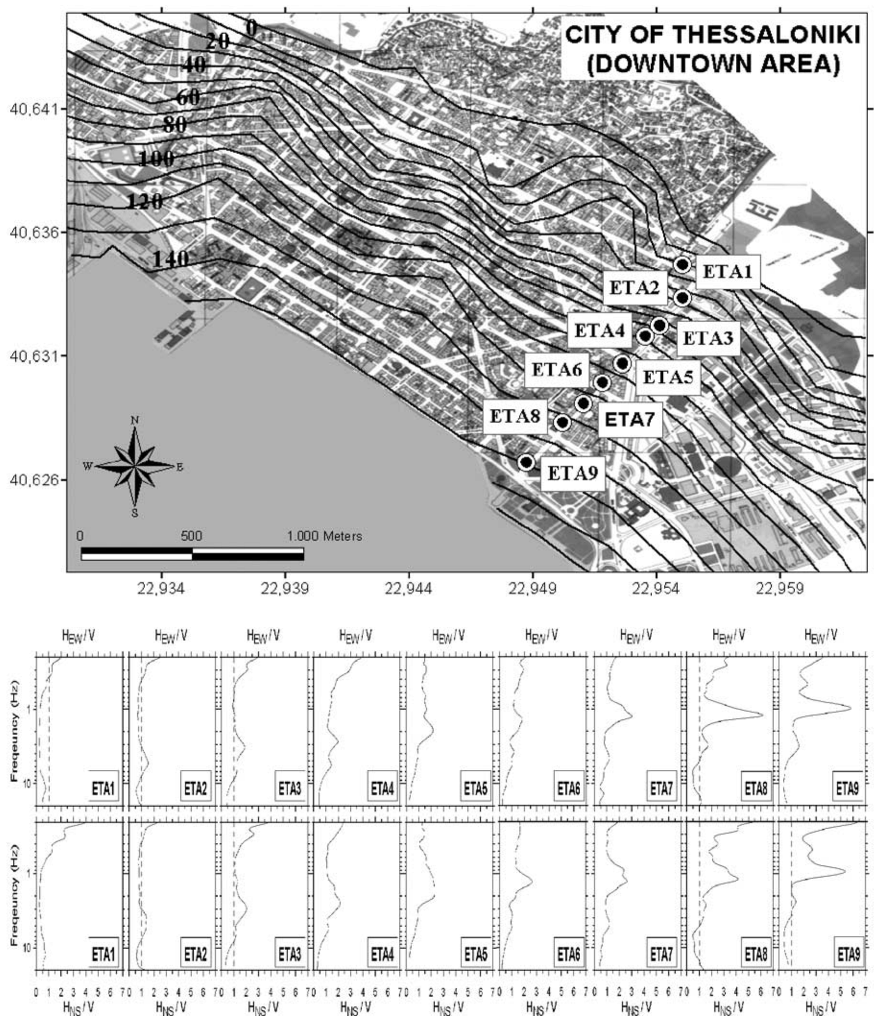

Fig. 2. Upper part: location of ambient noise recording points along the section ETA. Solid lines represent the depth of the bedrock in meters [87]. Lower part: plot of the average *H*/*V* spectral ratio versus frequency for the measurement points located along section ETA.

the ambient noise *H*/*V* spectral ratio. Fig. 2 (lower part) presents the variation of the ambient noise *H*/*V* spectral ratio with frequency for nine ambient noise recordings along this line. Examining the shape of the ambient noise *H*/*V* spectral ratios, it can be realized that the fundamental frequency decreases closer to the shoreline, which is consistent with the increasing thickness of the alluvial deposits in this direction. This is in agreement with relevant studies [55,56, 62,77], among others, who have used *H*/*V* spectral ratio of ambient noise to identify the interface between a basin alluvial filling and the underlying bedrock. The ambient noise *H*/*V* spectral ratios of measurement points ETA8 and ETA9 present a single curve peak with a significant amplification level at frequencies between 0.9 and 1.2 Hz. Measurement points ETA1 and ETA2 are located on bedrock and their *H*/*V* spectral ratios show no amplification.

Each measurement point provides a spectral ratio and enables an estimation of the fundamental frequency for each horizontal component (fo_{ew} and fo_{ns}) and the corresponding *H*/*V* amplitude level (Ao_{ew} and Ao_{ns}), at the site studied. The selection of fo, Ao were made both visually and automatically (JSESAME software; [90]). In Fig. 3, (upper left part) the fundamental frequencies calculated from the EW/V ambient noise spectral ratio (fo_{ew}) versus the ones obtained from NS/V ambient noise spectral ratios (fo_{ns}) are shown. It is clear that there is no significant difference between them for all examined sites. Thus, hereafter in the present study the average value of the fundamental frequency, fo, is used. In Fig. 3 (upper right part) comparison of the corresponding *H*/*V* amplitude level Ao_{ew} and Ao_{ns} is shown. At low amplitude levels ($Ao<3$) the agreement is satisfactory. For higher amplitude levels ($Ao>3$) significant scatter is observed though without any clear trend. For this reason, hereafter in the present study, the average value of the *H*/*V* amplitude level, Ao_{ave}, is also used.

By spatial interpolation of the fundamental frequencies (fo) and of the corresponding (Ao_{eve}) of all the points shown in Fig. 1 (lower part) contour maps were produced, as shown

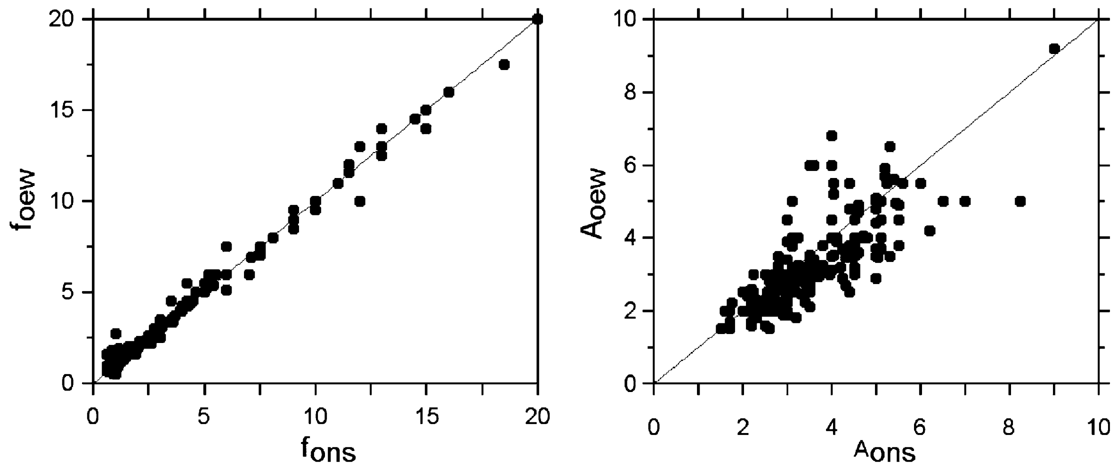

Fig. 3. Left part: comparison between the fundamental frequencies calculated from the ambient noise EW/V spectral ratio (fo_{ew}) and those from NS/V spectral ratio (fo_{ns}). Right part: comparison between the *H*/*V* amplitude level Ao_{ew} and Ao_{ns}.

in Figs. 4 and 5, respectively. As it is illustrated in Fig. 4, low values of the fundamental frequency ($fo < 1.5$ Hz) appear near the coastline, while fundamental frequencies generally decrease from north-east to south-west. This is consistent with the thickening of the alluvial deposits in this direction [87], as is also shown in Fig. 4. Fig. 5 shows the contour map that was calculated from Ao_{ave} of *H*/*V* amplitude level. As it is shown in this figure the zone in the north-east part of the studied region amplifies the ground motion less than that in the south-west part. These results are consistent with the transition of the fundamental frequencies and the thickening of the alluvial deposits in this direction as well. A quantitative presentation of the map of Fig. 4 is shown in Fig. 6 exhibiting good correlation between the thickness of sediments and fundamental frequency in the studied area. Such a correlation has been also observed by other researchers (e.g. [56,64]). However, the dispersion of fundamental frequency as a function of depth, *H*, for $H \geq 100$ m is significantly smaller than those for $H < 50$ m. Large dispersion is mainly observed at high frequency (≥ 10 Hz) peaks that are reported from 4 to about 40 m depth. Such high frequency peak may be due to more superficial strata properties (e.g. colluvium, man-made deposits). Further geophysical and geotechnical investigation is necessary to lighten this issue.

2.1. Comparison with geotechnical data

To check the applicability and reliability of the analysis carried out to estimate site fundamental frequency and corresponding amplitude, ambient noise *H*/*V* spectral ratios results were compared with relevant results based on available geotechnical data for the city of Thessaloniki.

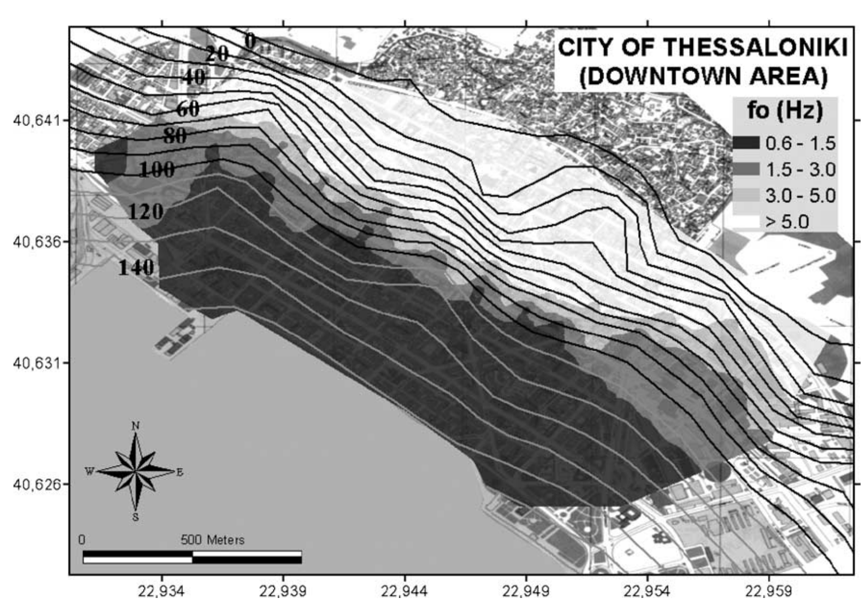

Fig. 4. Contour map of the fundamental frequencies (fo). Continuous lines represent the bedrock depth in meters [87].

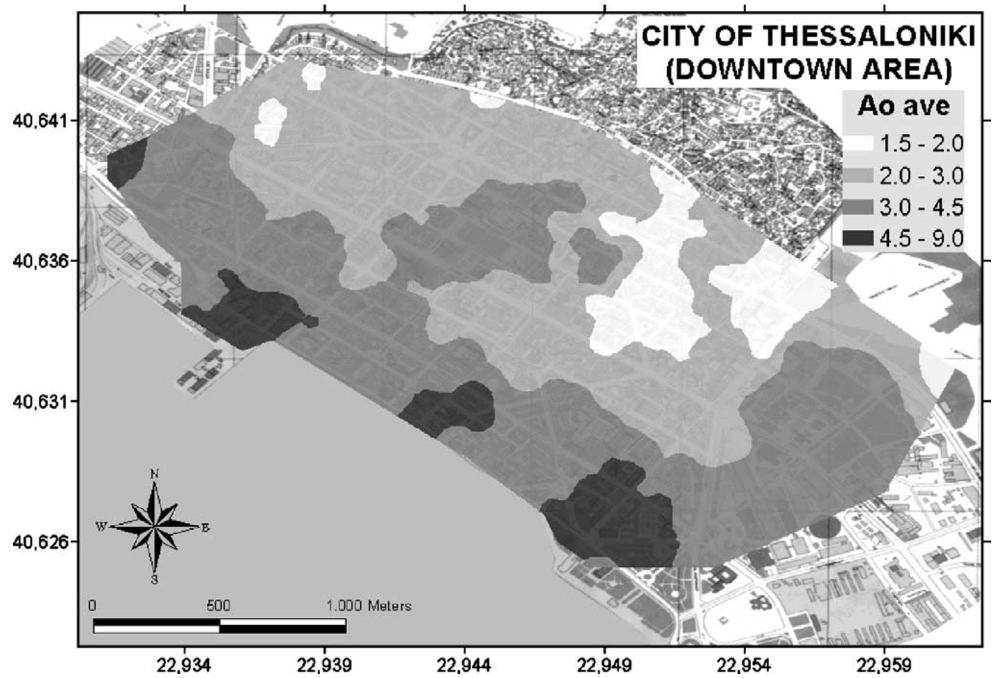

Fig. 5. Contour map of the *H*/*V* amplitude level (Ao_{ave}) at fundamental frequencies.

For this purpose five sections (directions A–E, upper part of Fig. 7) covering different geotechnical conditions of the city [87] were chosen as an example.

Based on the velocity profile and layer thickness values of Anastasiadis et al. [87] and using the algorithms proposed by Kanai and Hadjian [91,92], the corresponding fundamental frequencies were calculated. Fig. 7 (lower part) shows the estimated fundamental frequencies from the ambient noise *H*/*V* spectral ratios and from Kanai–Hadjian relations versus the location of the site for each section (see upper part of Fig. 7 to locate points). As can be seen, the estimated fundamental frequencies by all examined methods are in very good agreement with those estimated by the *H*/*V* spectral ratio from ambient noise measurements.

2.2. Comparison with numerical transfer functions

To further validate the results of the present study, ambient noise *H*/*V* spectral ratios were compared with transfer functions obtained considering one-dimensional (1D) propagation of vertically incident SH waves [93]. Using the geotechnical information from Anastasiadis et al. [87], transfer functions for various angles of incidence (0°, 45°, 60°) were calculated for four sites in the center of the city (Fig. 8 upper part). Fig. 8 (lower right part) compares the *H*/*V* spectral ratios of ambient noise with the 1D transfer functions, revealing a good agreement with respect to fundamental frequency. On the other hand, the peak of the fundamental frequency obtained by the ambient noise *H*/*V* spectral ratio is generally lower than that obtained by numerical modeling, especially for small angles of incidence. Such a difference in amplitude shown by the 1D model could be easily explained by too high Qs values. A lower Qs value could also contribute to also decrease amplitudes of higher harmonics in 1D modeling. However, adopted Qs values of the proposed geophysical and geotechnical model were based on in situ and laboratory data increasing significantly their reliability. Furthermore, except from site CIT, ambient noise *H*/*V* spectral ratio did not give any information on the higher harmonics, although it can be clearly seen in the 1D numerical modeling.

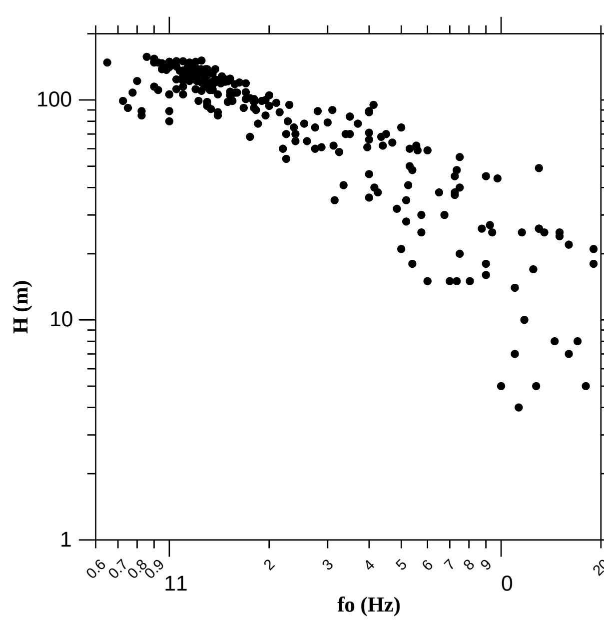

Fig. 6. Bedrock depth as a function of fundamental frequency, fo (see Fig. 4).

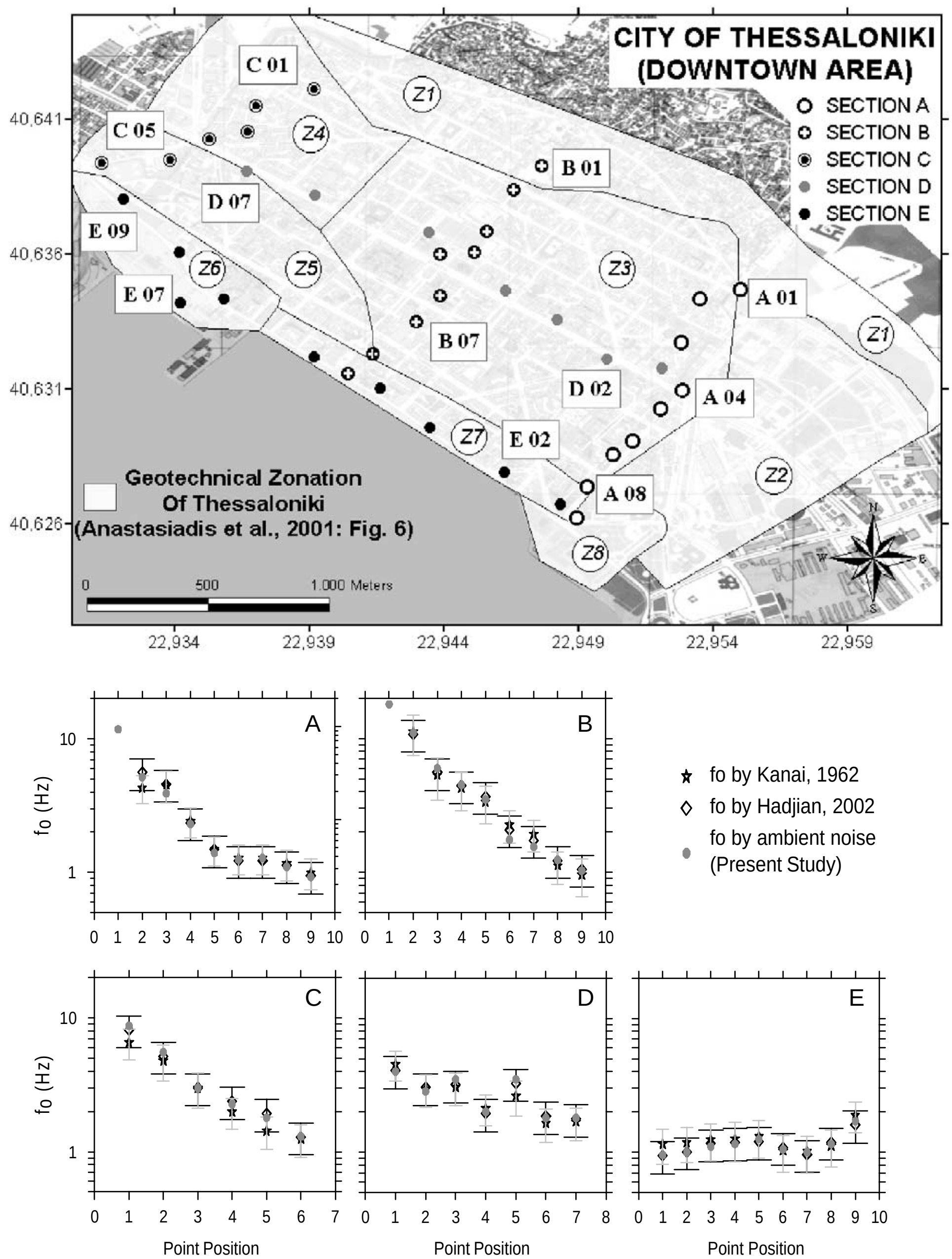

Fig. 7. Upper part: location of ambient noise recording points in sections A, B C, E and D. Lower part: fundamental frequency variation along each cross-section.

For the same sites Triantafyllidis [94] used seven double-couple points sources located at different epicentral distances and azimuths from the city of Thessaloniki to produce 2D synthetics ground acceleration recordings. Fig. 8 (lower left part) shows the comparison between the *H*/*V* spectral ratios of ambient noise with those of 2D synthetics accelerograms in the frequency band 0.5–6 Hz [94]. In general, the results show that there is a similarity for all sites in the general overall shape of the *H*/*V* spectral ratios obtained by the two different techniques. At AGO the fundamental frequency can not be observed because in the 2D simulation maximum cut-off frequency was 6 Hz. However, there is a good agreement in the determination of the fundamental frequency of CIT and LEP.

2.3. Comparison with observed intensities

To check the ability of the applied method in constructing a preliminary fundamental frequency-amplification zonation in the city of Thessaloniki, results of this study were compared with macroseismic data of the 1978 earthquake in terms of MSK intensities. Since the 20/6/1978 earthquake ($M=6.5$) cannot be considered a near field event for the city of Thessaloniki ($R\approx 30$ km), non

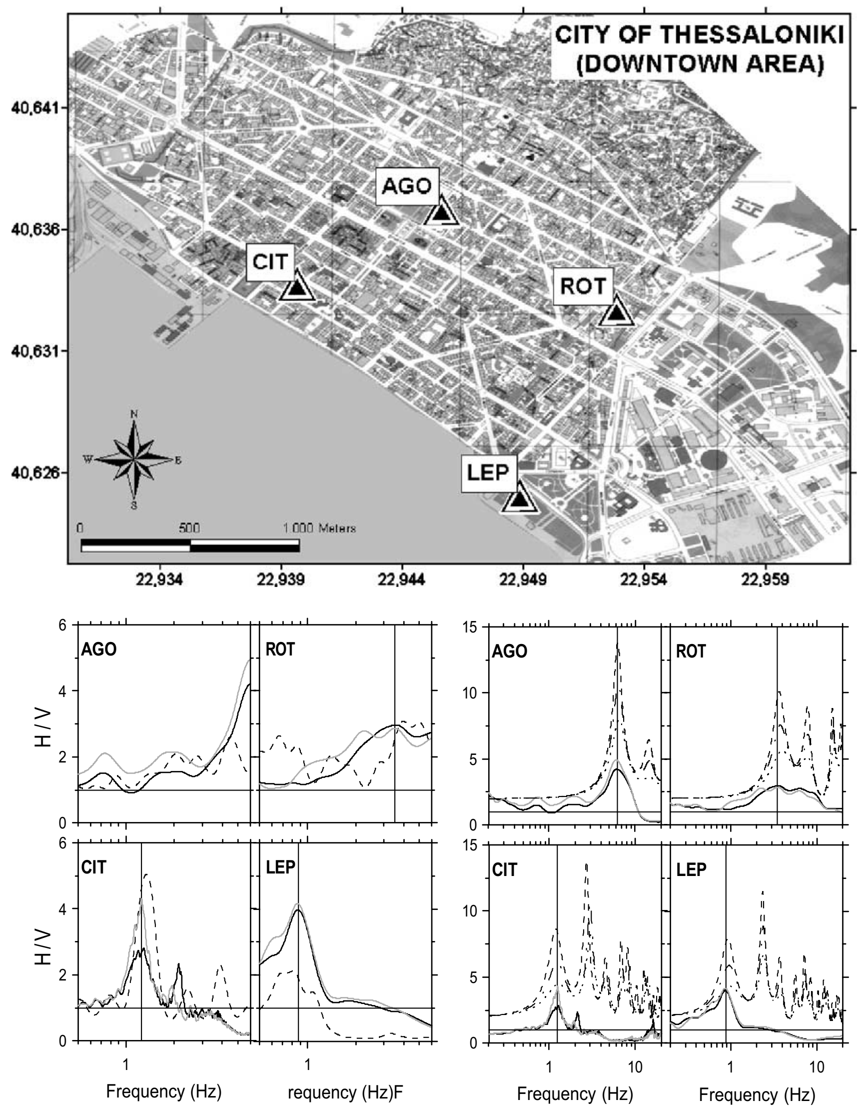

Fig. 8. Upper part: location of the sites for which experimental-synthetic transfer function comparison was performed. Lower left part: comparison of the ambient noise *H*/*V* spectral ratio (present study; black solid line: EW/V, grey solid line: NS/V) with receiver function from 2D modelling weak motion data [94]; black dashed line. Lower right part: comparison of the ambient noise *H*/*V* spectral ratio (present study; black solid line: EW/V, grey solid line: NS/V) with 1D transfer functions for various angles of incidence (0°, dashed line; 45°, dashed dotted line; 60°, dotted line).

uniform damage distribution has been mainly ascribed to site effects as local geology conditions in the city vary significantly.

Fig. 9 shows the contour maps of the fundamental frequency (fo) and of the corresponding maximum amplifications (Ao_{ave}) of the *H*/*V* spectral ratio observed at each site, on which the isoseismal curves for four intensity levels in MSK scale as has been defined by Leventakis [84] are superposed for the whole examined area. A clear correlation is qualitatively observed for both fundamental frequency and the maximum amplification with the damage level. This result supports the idea that the maximum *H*/*V* spectral ratio, Ao, is at least partly indicative of the local site amplification level. On the other hand, although there is no clear physical reason to support a correlation of fundamental frequency with observed damage, this seems to be valid for the city of Thessaloniki, supporting the idea of observed damage enhancement due to soil-building resonance.

These results were further confirmed when using the detailed description of the damage distribution of the 1978 earthquake for the central part of the city, as this was reported by Penelis et al. [95], after converting them to the EMS_98 scale [96]. The historical centre of Thessaloniki at the time of the earthquake consisted mainly of reinforced concrete buildings of 6–9 stories height. Fig. 10 shows the comparison of the contour maps of the fundamental frequency (fo) and the corresponding *H*/*V* amplitude level (Ao_{ave}) versus the EMS_98 damage level.

A quantitative assessment of the previous maps is shown in Fig. 11. The higher levels of intensity (MSK and EMS_98) were observed at sites of low

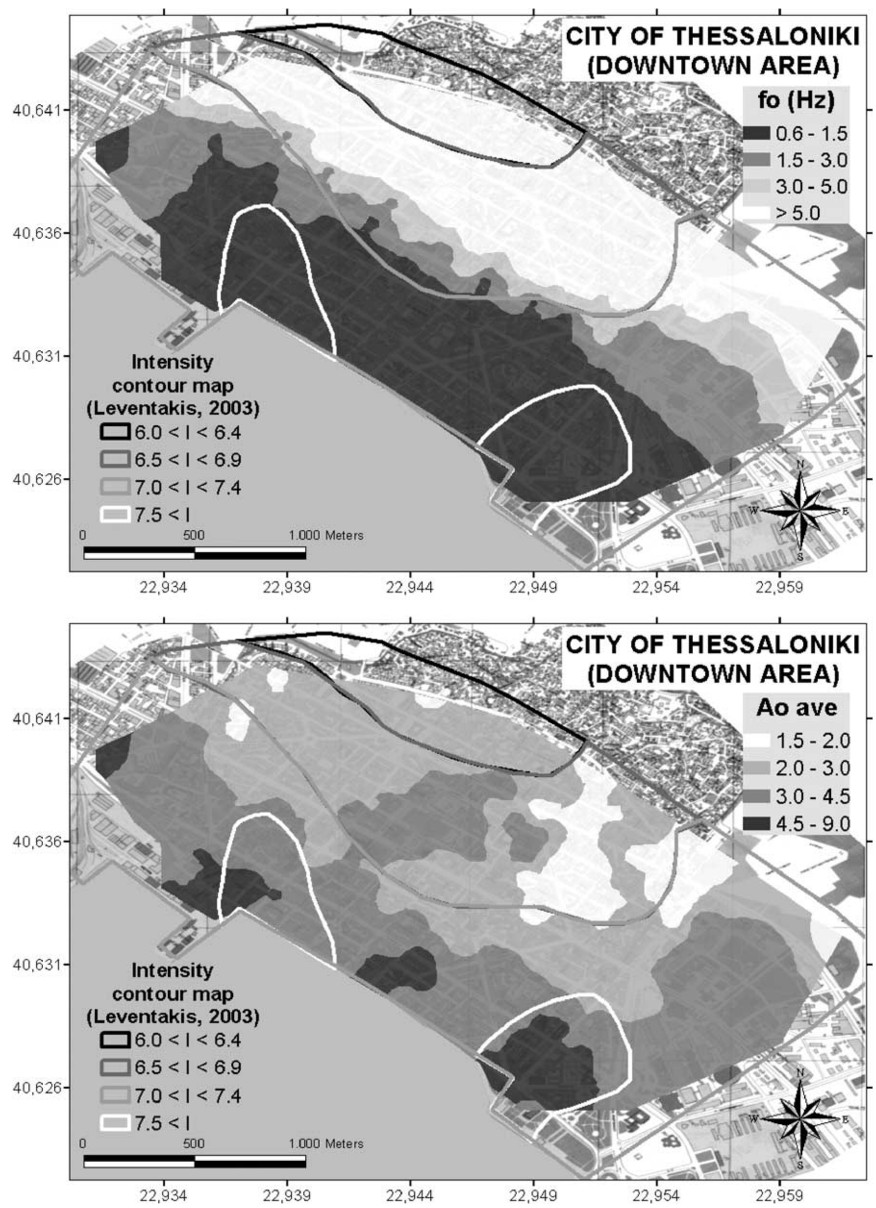

Fig. 9. Comparison of the fundamental frequencies, fo (upper part) and the *H*/*V* amplitude level at fundamental frequencies, Ao_{ave}, (lower part) with the isoseismal intensity curves [84] from the 20/6/1978 ($M=6.5$) Thessaloniki earthquake.

fundamental frequency and correspondingly high *H*/*V* amplitude level, while low levels of intensity were observed at sites with high fundamental frequency and correspondingly low *H*/*V* amplitude level. Despite the observed scatter, the comparison between the observed intensities of the 1978 earthquake, with the fundamental frequency (fo) and the corresponding *H*/*V* amplitude level (Ao_{ave}) of ambient noise *H*/*V* spectral ratio, reveals a satisfactory correlation.

In order to further examine and explain the correlation between the EMS_98 damage grades (hence also the MSK level for the whole examined area) and the *H*/*V* spectral ratio fundamental soil period, the dynamic amplification of the buildings (U_{building}) at the fundamental soil period (To = 1/fo) was calculated, using the formula

$$U(\text{To}) = \frac{1}{\sqrt{\left(1-\frac{T_0^2}{T^2}\right)^2 + \frac{4\zeta^2 T_0^2}{T^2}}} \tag{1}$$

where T is the fundamental period of vibration and can be roughly expressed as $T=$ number of storeys/10 in seconds. As an initial approximation, building response can be described by Eq. (1), based on the assumption that the dynamic response of a linearly elastic structural system subjected to an external force can be calculated as the response of a single degree of freedom oscillator subjected to simple harmonic base motion [97,98]. Damping factor,

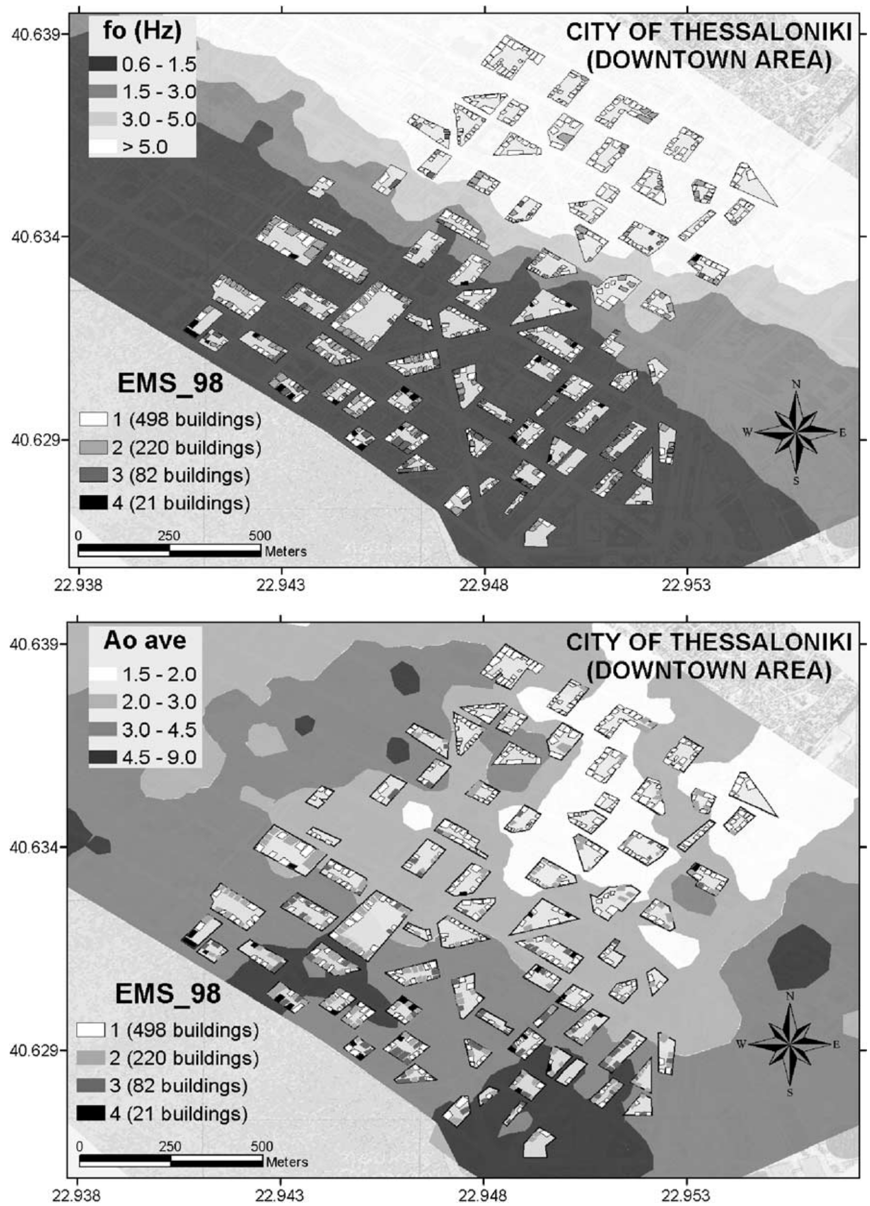

Fig. 10. Comparison of the fundamental frequencies, fo (upper part) and the *H*/*V* amplitude level at fundamental frequencies, Ao_{ave} (lower part), with the EMS_98 damage levels from the 20/6/1978 ($M=6.5$) Thessaloniki earthquake.

ζ, was taken equal to 0.05, a value corresponding to reinforced concrete buildings. Fig. 12 shows the comparison of the EMS_98 values versus $U_{\mathrm{building}}(\mathrm{To})$ (left part) and versus $U_{\mathrm{building}}(\mathrm{To})\times\mathrm{Ao}_{\mathrm{ave}}$ (right part). Fig. 12 clearly suggests that the correlation of damage and fo is a result of the proximity of the buildings fundamental period, *T*, with the soil fundamental period, To, as this is quantitatively described by Eq. (1). The incorporation of Ao as an additional local site amplification factor does not seem to improve the correlation, as this is seen from the comparison of the two plots in Fig. 12. This is also verified for the EMS_98 dataset from Fig. 11, where a very slight increase of EMS_98 intensity level (grey circles) is observed with Ao. However, the results for the MSK intensity distribution from the same figure, which correspond to a much larger part of the city, suggest that such a correlation exists, hence the values of Ao should be used in conjunction with $U_{\mathrm{building}}(\mathrm{To})$ to assess the maximum building motion at each site and obtain the optimum correlation with the damage distribution.

3. Discussion and conclusions

In this study, the validity of seismic site response characteristics inferred from 'single site' ambient noise *H*/*V* spectral ratio has been investigated. For this purpose a comparison between the ambient noise *H*/*V* spectral ratio with geological and geotechnical data was made in the downtown district of the city of Thessaloniki

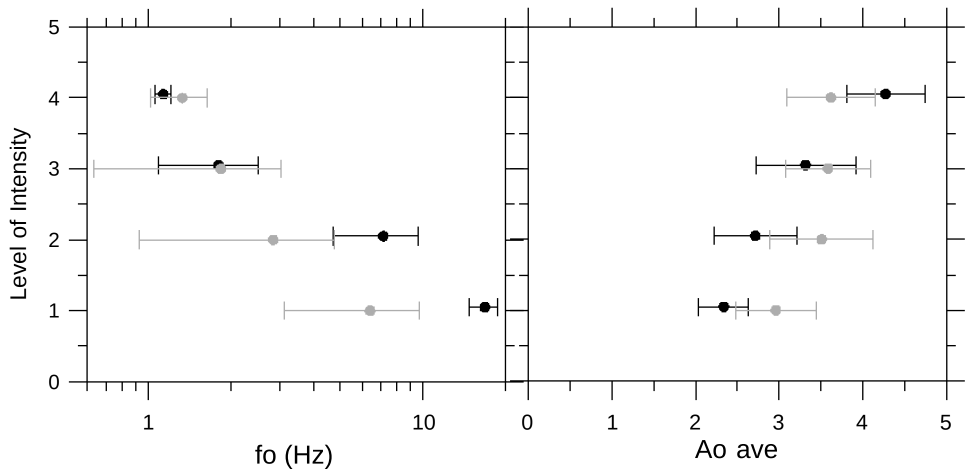

Fig. 11. Correlation between the average ± 1 SD fundamental frequency, fo (left part) and the corresponding *H*/*V* amplitude level, Ao_{ave} (right part), with macroseismic intensities *I* (Level 1: $6.0<I<6.4$; level 2: $6.5<I<6.9$; level 3: $7.0<I<7.4$; level 4: $7.5<I$; [84]) (black dots) as well as with four damage grades of EMS-98 scale (grey dots), from the 20/6/1978 ($M=6.5$) Thessaloniki earthquake.

(Northern Greece). In addition, any probable correlation of the ambient noise *H*/*V* spectral ratio with observed intensities from the 1978 ($M=6.5$, Mygdonia basin) earthquake was examined. In summary, the following results were obtained:

- There is a good correlation both of the fundamental frequency, fo, and its corresponding ambient noise *H*/*V* amplitude level, Ao, with the sediments thickness.
- Comparison of the fundamental frequency, fo, obtained both from ambient noise *H*/*V* spectral ratio and 1D theoretical simulation based on geotechnical data, found to be in good agreement throughout the whole study area.
- Both fundamental frequency, fo, and corresponding *H*/*V* spectral ratio, Ao, are well correlated with the macroseismic intensity data (MSK scale) and EMS_98 damage grades, of the 20/6/1978 earthquake.
- A simple computation of the building response at the fundamental soil period, To, showed good correlation with EMS_98 damage grades suggesting that such a correlation is due to the resonance between soil and building fundamental periods, as well as to soil amplification. The latter, at a first level approximation, seems to be proportional to the *H*/*V* amplitude level, Ao, corresponding to fundamental soil period, To.

The aforementioned results demonstrate the usefulness of the *H*/*V* spectral ratio method using ambient noise, in order to provide reliable information on the dynamic behavior of surficial layers. On the basis of these results we can suggest that the ambient noise *H*/*V* spectral ratio technique can satisfactorily indicate areas of higher damage potential in the city of Thessaloniki. Hence, it can be employed to microzonation studies in urban environments because of the fast data acquisition, low cost, limited requirements in personnel and equipment and reliable results.

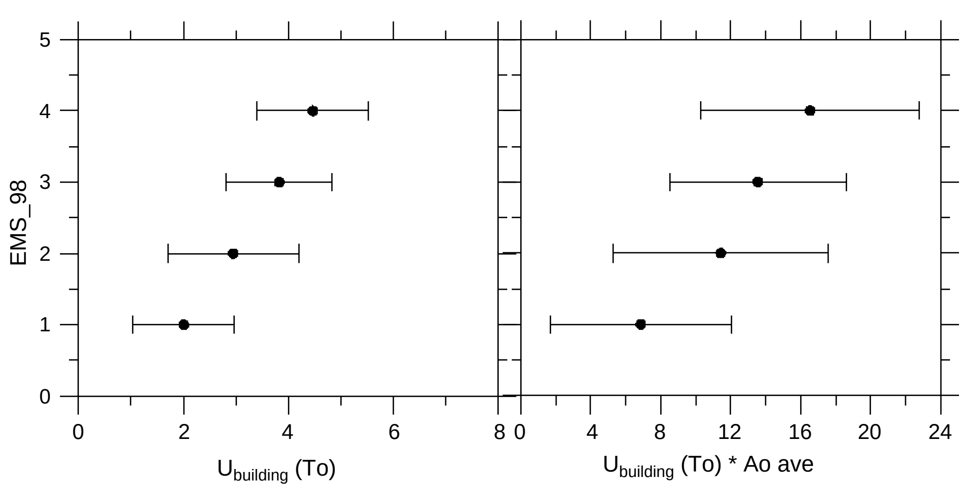

Fig. 12. Correlation of the EMS_98 damage grades from the 20/6/1978 Thessaloniki earthquake with the average ± 1 SD $U_{building}$(To) (left part) and the average ± 1 SD $U_{building}(To) \times Ao_{ave}$ (right part).

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