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# EMPIRICAL EVALUATION OF THE HORIZONTAL-TO-VERTICAL SPECTRAL RATIO TECHNIQUE: RESULTS FROM THE "SESAME" PROJECT

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## SUMMARY

In order to empirically evaluate the horizontal-to-vertical (H/V) spectral ratio technique, ambient noise measurements performed in about two hundred sites mainly in Europe where weak or/and strong motion data was recorded. **S**tandard **I**nformation **S**heets (**SIS**) and earthquake information data were included in the SESAME [**S**ite **E**ffect**S** assessment using **AM**bient **E**xcitations] project database, specially designed to facilitate data selection. All noise recordings were processed with JSESAME software to calculate (H/V) spectral ratio, whereas weak and strong motion earthquake recordings were processed with a similarly standardized procedure. For the latter, (H/V) receiver function for all sites were calculated. Experimental site transfer functions obtained from earthquake recordings were compared with the (H/V) spectral ratios from noise recordings in terms of fundamental frequency, amplification bandwidth and amplification level. Similarities and differences between (H/V) spectral ratio of noise and earthquake recordings are presented and discussed. In addition, a dense grid of noise measurements were performed within urban environment of cities affected by strong earthquake (Greece: Thessaloniki, Kalamata, Italy: Palermo). It seems that the (H/V) spectral ratio may satisfactorily indicate areas favorable to the occurrence of higher damage in urban environment. However, quantitative correlation between (H/V) spectral ratio properties and damage distribution (macroseismic intensity, damage grades) in some cases, is difficult to be established given the complexity of parameters involved.

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## INTRODUCTION

In the case of moderate magnitude earthquakes, or moderate amplitude motion at some distance from large events, severe damage are often limited to zones of unfavorable geotechnical conditions that give rise to significant site effects. In the case of large events, one might think that damage distribution in the near-source area is no longer controlled by site conditions, but by fault geometry and slip distribution on the fault, as well as because of non-linear effects in soft soils which would drastically reduce amplification effects; however, there exist famous examples of tremendous site effects even in the near-field of large events (Northridge 1994, Kobe 1995, Kocaeli 1999). This underlines how important it is to account for site effects in the design of new constructions, in the retrofitting of existing structures - including the assessment of retrofitting priorities - as well as in land use planning.

Blind prediction tests performed in the nineties (Turkey Flat and Ashigara valley) pointed out that the numerical prediction of site effects with a reasonable confidence level is usually possible only if some key parameters of geophysical or geotechnical nature are known. The ideal case would be to perform a geophysical measurement campaign, with for instance cross-hole tests in order to get a reliable S-wave velocity profile of the site. On the other hand, known techniques to obtain reliable estimates of site effects (site to reference spectral ratio, generalised or parameterised inversion) require to record several tens of good quality earthquake recordings at the sites under study, which ends up with high costs, especially in urban areas of moderate seismicity where events are non-frequent. Therefore, it is crucial to develop "low cost tools" for seismic site investigations, from an economical as well as from a safety point of view. It remains however also crucial that these low cost tools have to be reliable and used only within their validity domain.

During the last years very promising studies have been done using ambient vibration measurement as a low cost tool for site characterization. It is well known the so-called Nakamura or H/V spectral ratio technique: the spectral ratio of the horizontal-to-vertical component of ambient vibration that indicates the fundamental eigenfrequency of the site under investigation (Nogoshi [1], Nakamura [2]). Furthermore, many researchers believe that the amplitude of the H/V spectral ratio gives at least a relative indication of how pronounced site amplifications might be (Bard [3]).

The aim of this work is to achieve a purely empirical, experimental assessment of the meaning of the horizontal-to-vertical component spectral ratio based on ambient noise measurements, in order to examine whether H/V spectral ratio: (a) provides a reliable estimate of the fundamental frequency at a given site, (b) indicates the frequency band over which the ground motion is amplified, (c) provides a quantitative estimate of the corresponding amplification or a lower bound estimate, (d) compares with damage distribution in modern cities.

The basic effort of this work consists in comparing the site effect estimates obtained with classical, well accepted methods (e.g. site-to-reference spectral ratio and receiver functions on earthquakes) with H/V spectral ratio on noise recorded at the same sites. To accomplish this task a large amount of data was compiled and analysed in a common and homogeneous way. In addition, ambient noise measurements performed in urban environment of modern cities affected by damaging earthquakes. All aforementioned data was compiled and imported in the SESAME database created for this reason.

## THE " SESAME" DATABASE

A goal of the SESAME project was to perform an objective, purely experimental assessment of the reliability of the H/V spectral ratio technique, by comparing its results with those of well established experimental techniques, based on a homogeneous data set of ambient noise and earthquake recordings.

In order to better organize the noise and earthquake recordings compiled for the SESAME project, it was decided to generate for each single site a Standard Information Sheets (SIS) including all necessary information. That is, site geographical information, available noise and earthquake recordings, geological, geotechnical and geophysical data, sensors' coupling, information about noise and earthquake recordings and contact information. All information included in a SIS are helpful to the user who is going to process and analyze earthquake and noise recordings for the purposes of the SESAME project. A brief presentation of the number of SIS, noise files, earthquakes and earthquake recordings contributed by various institutes is given in the Table 1.

Since a homogeneous data set should be of the same format to be easily analysed by any user, earthquake and noise recordings are given either in standard GSE format or in a newly formed within the project, the so called SAF format (SESAME ASCII Format). SAF format consists of a header followed by three columns corresponding to three components of an earthquake or noise recording, namely in the order, vertical (Z), horizontal north (N), horizontal east (E). Although SAF format does not include certain sensor or recording instrument parameters (e.g. sensor's response file) due to its simplicity it was selected as a homogeneous data format for the needs of the project.

In order to easily manage the Standard Information Sheets (SIS) and search for data set that fulfill certain criteria, a simple SESAME SIS-database has been generated. This relational SIS-database relates data tables of the SIS with the available earthquake and noise recordings. For single site, certain search criteria can be also applied (e.g. magnitude, time period etc.) to create a report with earthquake recordings with respect to the site. The SIS-database has been designed to remain open in future data sets of earthquake and noise recordings.

**Table 1. Information on the Standard Information Sheets (SIS) of the SESAME SIS-database.**

| INSTITUTE | EXPERIMENT NAME | SIS | EVENTS | RECORDS |
|---|---|---|---|---|
| **ITSAK** *[GREECE]* | S.M. NETWORK | 63 | 288 | 492 |
| | EUROSEISTEST | 7 | 56 | 247 |
| **INGV** *[ITALY]* | BENEVENTO | 6 | 42 | 188 |
| | CATANIA | 3 | 31 | 85 |
| | CITTA-CASTELLO | 15 | 10 | 140 |
| | VERCHIANO | 9 | 15 | 122 |
| | COLFIORITO | 3 | 23 | 69 |
| **CNR** *[ITALY]* | FABRIANO | 6 | 81 | 326 |
| | PREDAPPIO | 18 | 128 | 1230 |
| | ROVETTA | 4 | 14 | 44 |
| **LGIT** *[FRANCE]* | NICE | 5 | 16 | 57 |
| | EBRON | 4 | 16 | 67 |
| | GUADELUPE | 7 | 17 | 85 |
| | TEHRAN | 14 | 149 | 1347 |
| | LOURDES | 10 | 21 | 149 |
| | GRENOBLE | 15 | 31 | 208 |
| **ETHZ** *[SWITZERLAND]* | S.M. NETWORK | 22 | 62 | 115 |
| **TOTAL** | | **211** | **1227** | **5194** |

## EMPIRICAL EVALUATION OF (H/V) SPECTRAL RATIO ON NOISE TECHNIQUE: PRELIMINARY RESULTS

Our first effort consisted in comparing the site effect estimates obtained with classical, well accepted methods (site-to-reference spectral ratio) and H/V spectral ratios on noise recorded at the same sites. The main goal was to compile the huge amount of data available within the consortium and to analyse them in a common, homogeneous way. In that aim earthquake and noise recordings obtained for site effect estimation at more than two hundred sites throughout Europe and elsewhere were used. The noise recordings were processed with the JSESAME [4] software developed within the project while the site-to-reference spectral ratios were recomputed with a similarly standardized procedure (window length, smoothing, signal to noise ratio threshold, etc.). Then the experimental site transfer functions obtained from earthquake recordings can be compared with the H/V spectral ratios obtained from noise recordings, in terms of fundamental frequency, amplification bandwidth and amplitude level.

In order to compare the results of ambient noise measurement with the standard spectral ratio method, the available earthquakes and ambient noise data of more than 50 sites in Europe and Iran were processed (Bard[5]). The earthquakes spectra were computed over a window including the whole signal (including P and S phases) and the site-to-reference spectral ratio has been calculated only at frequencies for which the signal to noise ratio (S/N) at both stations, reference and site under consideration, was greater than 3. Average spectral ratios and corresponding standard deviations were then derived from all available recording pairs. The H/V spectral ratios of ambient noise were computed using the continuous recordings or the pre-event window of earthquake data for the site where specific noise measurement had not been performed. For other sites analyzed noise windows were selected so as to avoid non-stationary transients. The Konno-Ohmachi smoothing method (Konno [6]) was used, with b=40 for all the data.

In Figures 1 & 2 the preliminary results are presented by comparing the fundamental eigenfrequency and amplification amplitude obtained from ambient noise and earthquake data. For some sites the noise data cannot show the fundamental frequency predicted at low bands by standard spectral ratio method. In general, the amplification factor obtained from noise are smaller than those obtained by earthquakes. However, the aforementioned results are to be revised and verified for the observed differences.

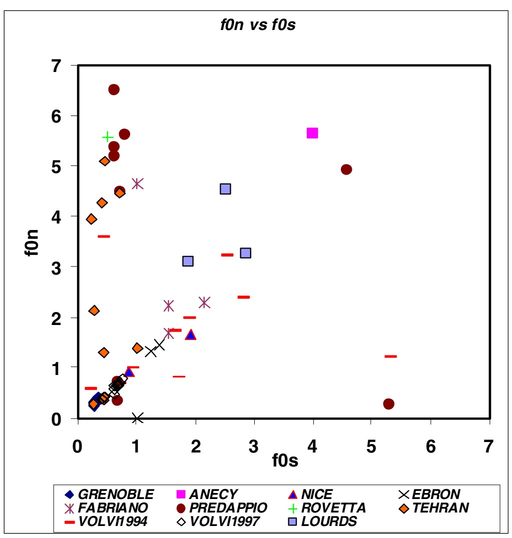


**Figure 1. H/V spectral ratio fundamental frequency obtained from noise portion of earthquakes signals (f0n) versus those obtained by site-to-reference spectral ratio (f0s) (Bard [5]).**

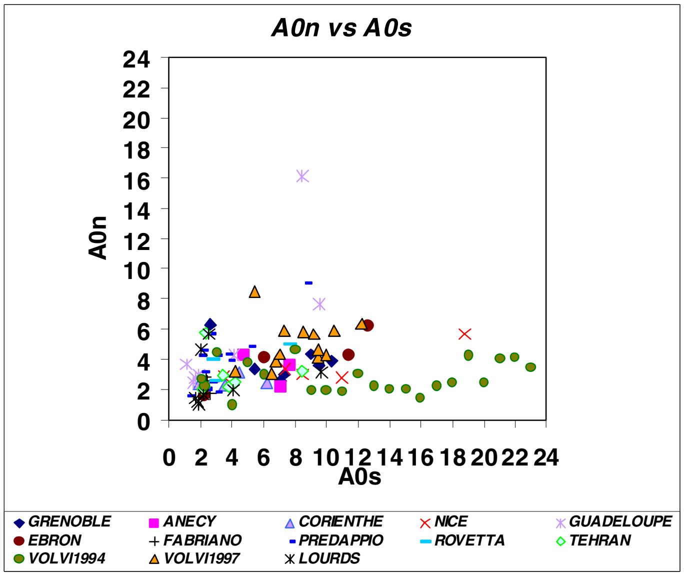


**Figure 2. H/V spectral ratio amplification factors obtained from noise portion of earthquakes signals (A0n) versus those obtained by site-to-reference spectral ratio (A0s) (Bard [5]).**

For selected sites of accelerometric network stations H/V spectral ratios of ambient noise was compared with H/V receiver functions of earthquake strong motion recordings (Fig. 3). Sites in Figure 3 are characterized according to NEHRP-94 [7] as B (aml1) and C (arg1). The majority of sites analyzed showed characteristics similar to those of Figure 3. Fundamental frequency - where clear - is similar in both noise and earthquake recordings. Furthermore, the (H/V) spectral shape of noise recording is comparable with that of earthquake recordings whereas amplitude level of noise is systematically lower in almost all frequency bands (Theodulidis [8]). For selected strong motion recording stations where geotechnical data are available, theoretical methods (1D, 2D) will be also applied to explain similarities or/and divergence observed in the applied empirical approach.

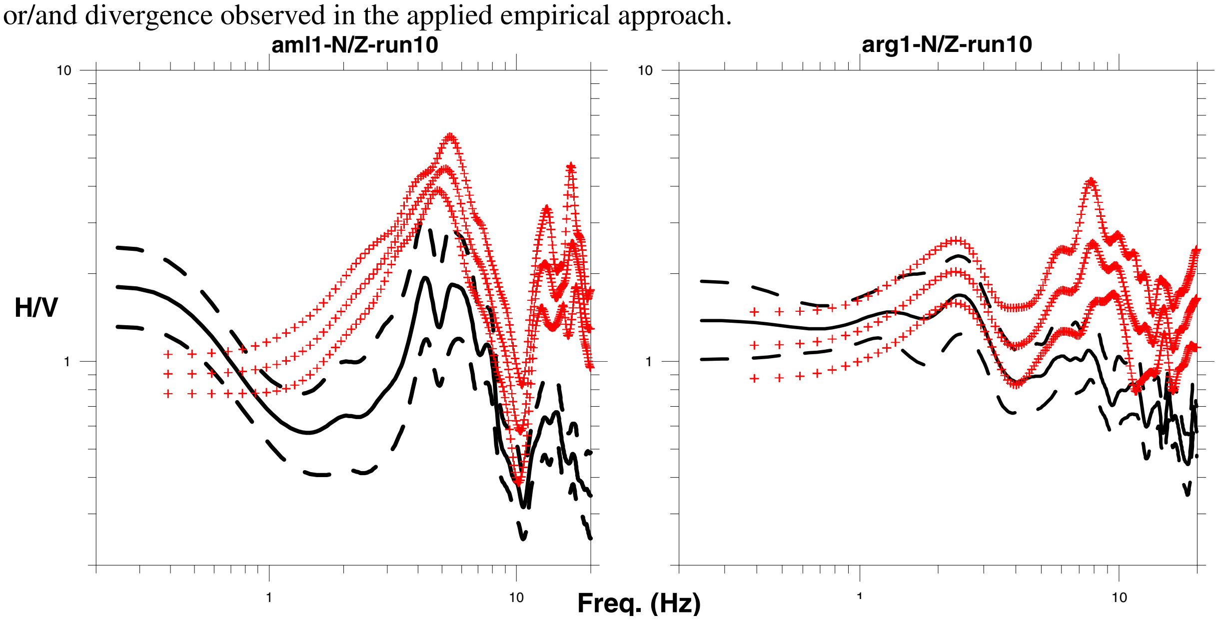


**Figure 3. Comparison of the H/V spectral ratio between noise recordings (black lines: average ± 1 standard deviation) and H/V receiver function of strong motion recordings (red crosses: average ± 1 standard deviation), for two sites in Greece (Theodulidis [8]).**

## COMPARISON OF (H/V) AMBIENT NOISE SPECTRAL RATIO WITH DAMAGE

During the SESAME project, ambient noise measurements were performed in modern cities recently affected by damaging earthquakes in Euro-Mediterranean area. The experiments were performed in the cities of Thessaloniki and Kalamata in Greece, the cities of Rome, Palermo and Fabriano in Italy, and the city of Angra-do-Heroismo in Portugal. In this paper results only from the city of Thessaloniki (Panou[9]), Kalamata (Theodulidis [10]) and Palermo (Cultrera [11]), are presented.

### The case of Thessaloniki

The city of Thessaloniki was strongly affected by the June 20, 1978 earthquake (M6.5) that occurred at an epicentral distance of about 30km. Observed macroseismic intensities in modified Mercalli scale varied even within the historical center from VI to IX (Leventakis[12]). The historical center of Thessaloniki at the time of the earthquake consisted mainly of reinforced concrete buildings of six to nine stories height and selected as a test area for comparing (H/V) ambient noise spectral ratio characteristics with damage distribution. For this purpose 250 '*in situ*' ambient noise recordings were performed in a dense grid of about 150mX150m (Panou [9]). Using the JSESAME [4] software the ambient noise H/V spectral ratio for each site was calculated and the fundamental frequencies (fo) as well as their corresponding H/V amplitudes (Ao) were estimated. Contour maps of both fundamental frequency (fo) and H/V amplitude (Ao) were compared with the macroseismic data of the 1978 earthquake and found to be satisfactorily correlated (Panou[9]). In Figure 4, comparison of the fo, with the isoseismal intensity curves in terms of modified Mercalli scale, from the 1978 Thessaloniki earthquake, is shown. High intensities, greater than VII, are observed at intermediate to low frequency range, (fo<3 Hz). To the contrary, intensities smaller than VII are observed at frequencies higher than 3Hz. In Figure 5 a good correlation between average fo, Ao values and modified Mercalli intensities from the 1978 Thessaloniki earthquake, is shown. Such a qualitative conclusion was further confirmed after converting observed intensities for each building to EMS-98 scale (Panou [9]).

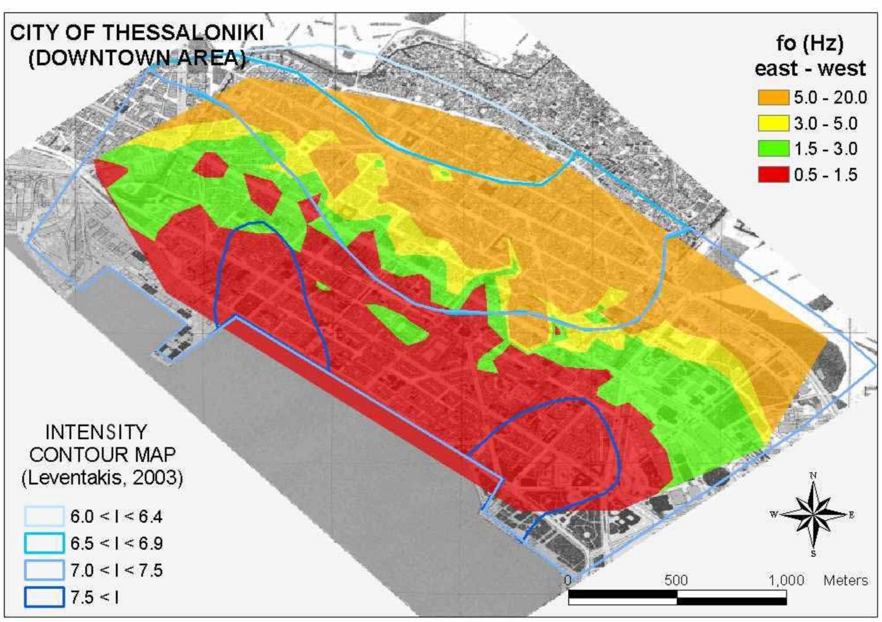


**Figure 4. Comparison of the fundamental frequencies, with the isoseismal intensity curves from the 1978 Thessaloniki Earthquake (Panou [9]).**

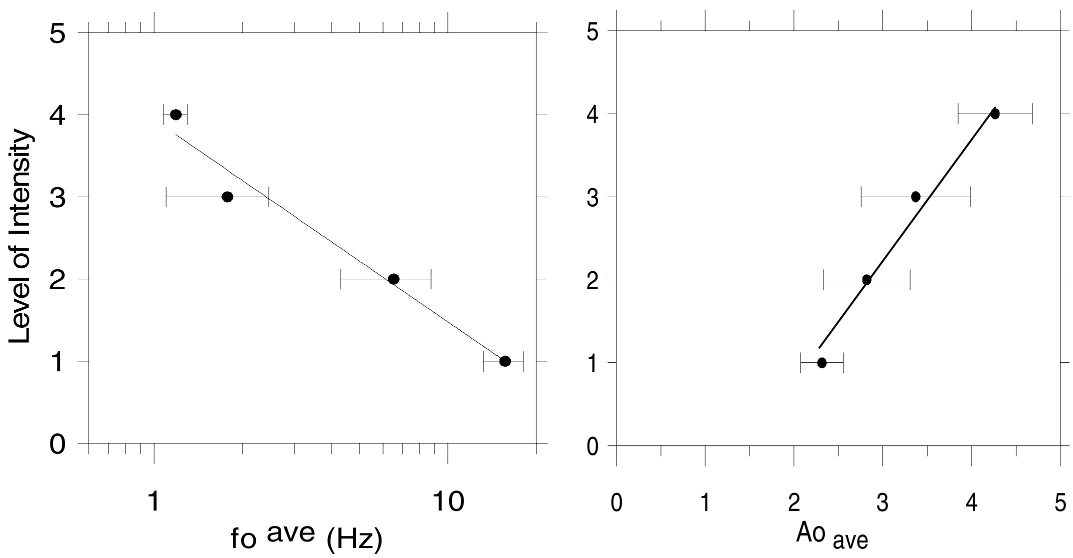


**Figure 5. Correlation between fundamental frequency (fo) and corresponding average amplitude (Ao), with level of modified Mercalli intensities (1:*6.0<I<6.4*, 2:*6.5<I<6.9*, 3:*7.0<I<7.4*, 4:*7.5<I*), from the 1978 Thessaloniki earthquake (Panou [9]).**

**The case of Kalamata**

The city of Kalamata was strongly affected by the September 13, 1986 earthquake (M6.0) that occurred at an epicentral distance of less than 10km. Modified Mercalli intensity within the city varied between VI and IX (Leventakis [13]). A microtremor survey at 80 sites within Kalamata took place and using the JSESAME [4] software the fundamental frequencies (fo) and their corresponding H/V amplitude (Ao) were then estimated (Theodulidis [10]).The fundamental frequency (fo) and corresponding H/V amplitude level (Ao) were compared with the macroseismic data of the 1986 earthquake. In Figure 6 comparison between fo and macroseismic intensities shows that higher intensities, >VII, are observed generally at the sites with fo≥3Hz. This qualitative observation is further enhanced when correlating average fo values with macroseismic modified Mercalli intensity (Figure 7). However, it is obvious from Figure 7 that there is no correlation of Ao with macroseismic intensity.

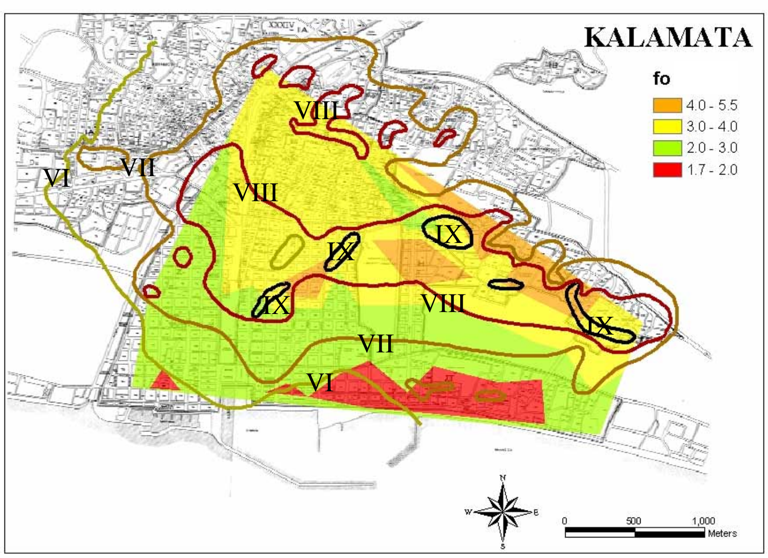


**Figure 6. Map of modified Mercalli intensities for the city of Kalamata due to 1986 earthquake [13], superimposed to 4 categories (H/V) ambient noise fundamental frequencies (Theodulidis [10]).**

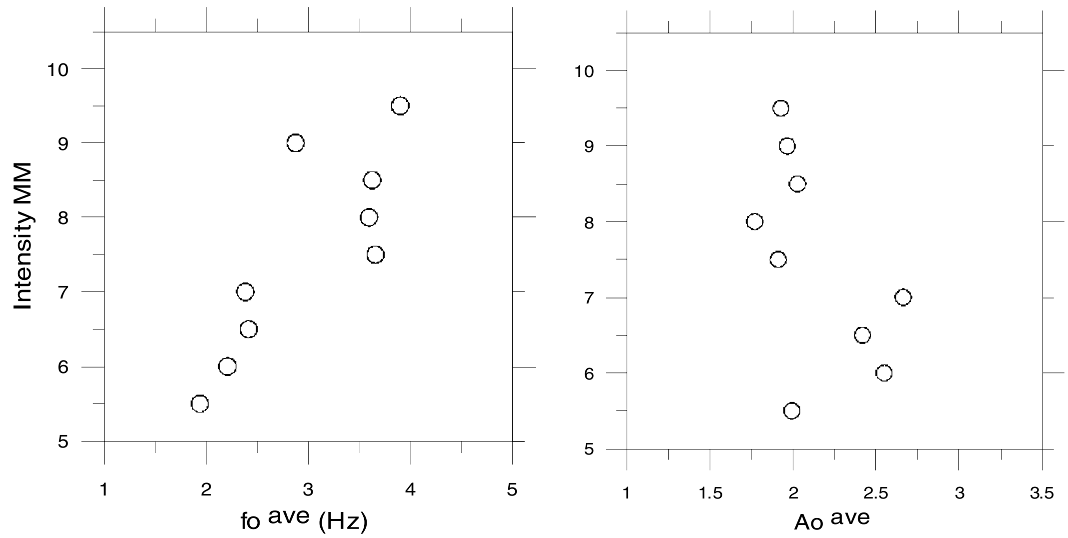


**Figure 7. Correlation between the fundamental frequency (fo) and corresponding average amplitude (Ao), with modified Mercalli intensities from the 1986 Kalamata earthquake (Theodulidis [10]).**

**The case of Palermo**

Palermo was strongly affected by the 1726 (M5.7), 1823 (M6.0) and 1940 (M5.3) earthquakes that caused various levels of MCS macroseismic intensity (VII-IX) within the historical city. The damage description attempted by Guidoboni [14] is very similar to that adopted for the European Macroseismic Scale 1998 (EMS-98), allowing for direct conversion to EMS-98 damage grades. Possible correlation between the H/V ambient noise spectral ratio characteristics and damage level in Palermo for past earthquakes - among which the 1726 event - was investigated by Cultrera [11 ].

In Figure 8 a cumulative damage map is superimposed to the H/V spectral ratio fundamental frequency and corresponding amplitude classification of the measurement points. The damage distribution is well correlated with the presence of peaked frequencies. The comprehensive variation of fundamental frequency is within 0.6 to 2.8 Hz, a range potentially dangerous for the buildings in downtown (3 to 5 stories), whose age and type of construction is quite uniform (Figure 9). The correlation between damage and H/V amplitudes (Figure 8) is difficult to quantify. However, the largest H/V amplitudes are recorded close to the zones where the highest grade of damage has been observed (Cultrera [11]. Figure 9 shows that the lowest frequencies (f<1Hz) and the lowest amplitudes (amplitude<2.5) correspond to lowest damage grades, whereas the largest amplitudes are correlated with the highest grades (Cultrera [11]). However, the resonance frequencies above 1 Hz could be responsible for each of the 3 different damage grades, and a wide range of amplitudes corresponds to damage grade 3.

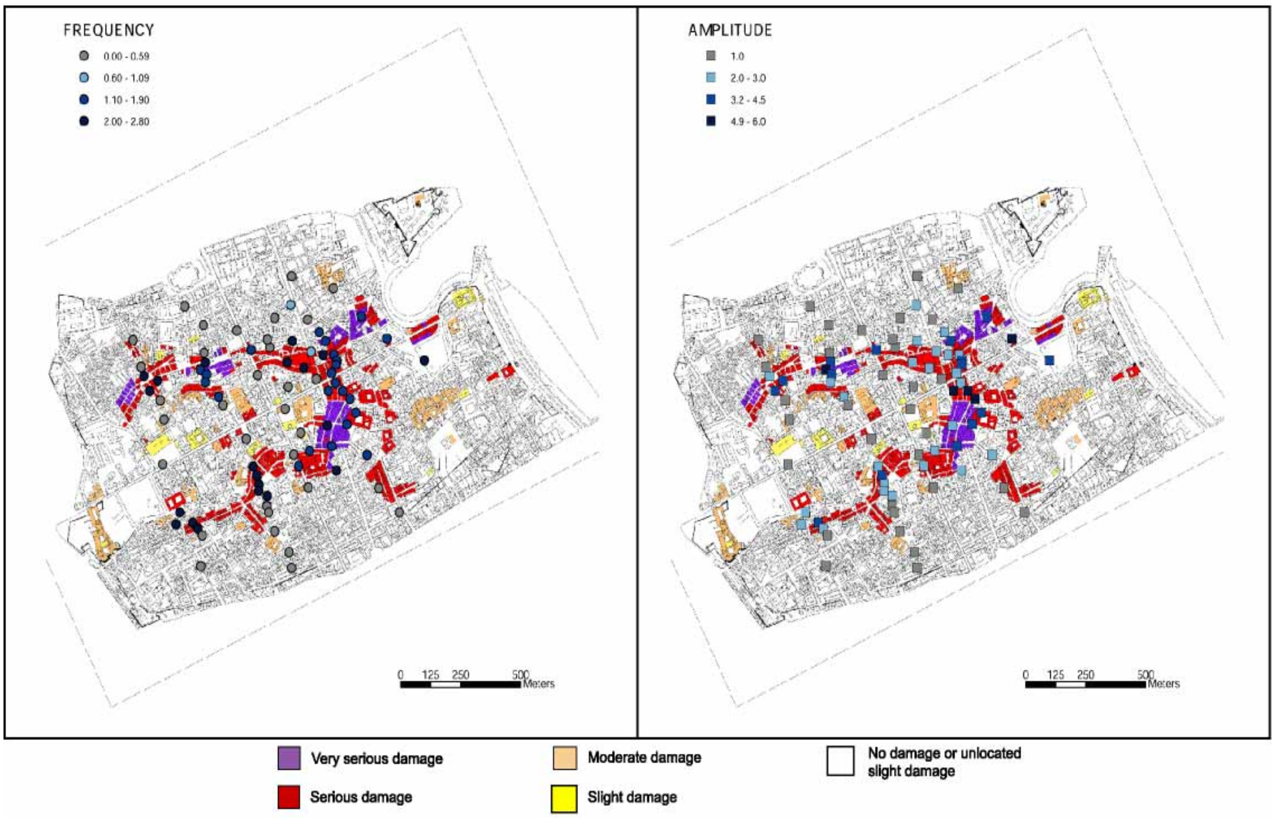


**Figure 8. The damage map for the 1726 earthquake (Guidoboni [14]) is superimposed to the H/V fundamental frequency classification of the noise survey (left) as well as to the corresponding amplitude of the measurement points (right) (Cultrera [11]).**

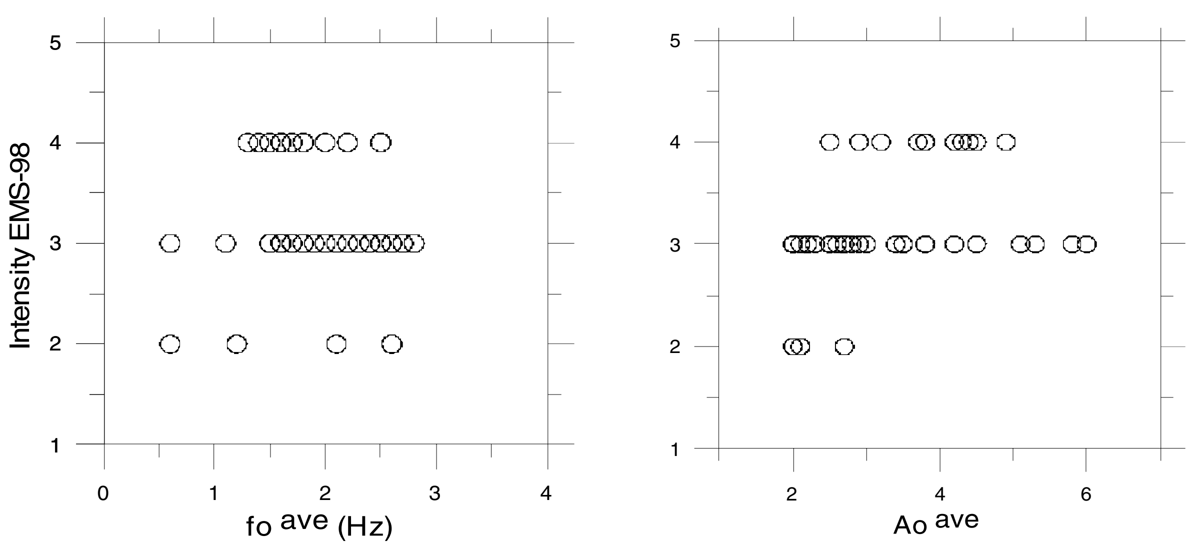


**Figure 9. Correlation of the H/V spectral ratio fundamental frequencies (left) and corresponding amplitudes (right) with the EMS-98 damage grades, for the 1726 earthquake (Cultrera [11]).**

## DISCUSSION AND CONCLUSIONS

In this paper an approach for empirical evaluation of the horizontal-to-vertical (H/V) ambient noise spectral ratio technique developed within the SESAME [15] project, is briefly presented. The SESAME SIS-database is created as a tool for selecting noise and earthquake recordings at the same site for which a "reference" earthquake recording site is available. Few comparisons of fundamental frequency and amplification amplitude of the H/V ambient noise spectral ratios with corresponding standard spectral ratio factors, are given. It seems that in some of the selected sites there is a coincidence of the fundamental frequencies while in others, mainly in low frequency band (<1Hz), H/V ambient noise spectral ratio do not reveal the fundamental frequency. For almost all examined sites, amplification factors obtained from ambient noise are smaller than those from earthquakes recordings. Comparison of the H/V ambient noise spectral ratio, for frequency band $0.2 \leq f \leq 20$Hz, with H/V spectral ratio receiver function from strong motion recordings generally showed similarity of fundamental frequencies and spectral shapes as well. To the contrary, amplitude factors of H/V receiver function spectral ratio from strong motion recordings are systematically higher than those of ambient noise recordings. The aforementioned results are of preliminary nature and further investigation - both theoretical and empirical - to justify the observed differences is under way.

Comparison of damage distribution in terms of macroseismic intensity and EMS-98 damage grades with H/V ambient noise fundamental frequency and corresponding amplification factor is presented for the city of Thessaloniki, Kalamata and Palermo. For the city of Thessaloniki it seems that H/V ambient noise spectral ratio technique may satisfactorily indicate areas of damage potential in urban environment, exhibiting good correlation between fundamental frequency and amplification factor with damage grades. However, for the cities of Kalamata and Palermo, although qualitatively areas of higher damage are identified, quantitative correlation is not clear leading to the conclusion that such a correlation is difficult to be established given the complexity of parameters involved.

## AKNOWLEDGEMENTS

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