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THE H/V SPECTRAL RATIO TECHNIQUE: EXPERIMENTAL CONDITIONS, DATA PROCESSING AND EMPIRICAL RELIABILITY ASSESSMENT

Kuvvet ATAKAN[1], Anne-Marie DUVAL[2], Nikos THEODULIDIS[3], Bertrand GUILLIER[4], Jean-Luc CHATELAIN[4], Pierre-Yves BARD[5] and the SESAME-Team[6]

SUMMARY

Recently a European project **SESAME** (**S**ite **E**ffect**S** assessment using **AM**bient **E**xcitations) was initiated aiming to study the site effects assessment techniques using ambient vibrations. Within the framework of the SESAME, a specific task is defined to investigate the reliability of the H/V spectral ratio technique in assessing the site effects. The work is now being conducted in mainly three different lines with the following objectives: firstly to study the effect of the experimental conditions, secondly to find out the influence of the data processing and finally compare the results from different techniques and data sets to empirically assess the reliability of its usage in microzonation studies. Preliminary results indicate significant influences depending upon the instruments used, experimental conditions and the data processing routines. Careful choice of instruments, controlled experimental setup and standardized processing routines are necessary to obtain reliable results. When taking these conditions into account, the H/V ratios are stable and some of the information they provide is comparable to results from other techniques and data types. They do not however, completely reproduce the actual, frequency-dependent amplification factor. Final aim is to provide guidelines explaining the influence of different factors, and give recommendations on how the H/V technique should be applied. At the end of the project period, such documentation will be prepared and disseminated.

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[1] Department of Earth Science, University of Bergen, Allegt.41, N-5007 Bergen, Norway, E-mail: Kuvvet.Atakan@geo.uib.no Tel:+47–55-583600, Fax:+47-55-583660
[2] CETE Méditerranée, Nice, France
[3] ITSAK, Thessaloniki, Greece
[4] IRD-LGIT, Grenoble, France
[5] LGIT, Grenoble, France
[6] SESAME-Team: Acerra,C.,Alguacil,G.,Azzara,R.,Blarel,F.,Bonnefoy-Claudet,S.,Borges,A., Cara,F.,Cornou,C.,Cultrera,G.,Dimitriu,P.,Dunand,F.,Faeh,D.,Grandison,M.,Guéguen,P., Havskov,J.,Jongmans,D.,Kind,F.,Koller,M.,Marcellini,A.,Moczo,P.,Moreno,B., Ohrnberger,M.,Rao,S.,Ripperger,J.,Roquette,P.,Scherbaum,F.,Sørensen,M.B.,Tento,A., Teves-Costa,P.,Vidal,S.,Vollmer,D.,Zacharapoulos,S.

INTRODUCTION

A clear evidence for a major control of seismic damage by local geology was found very early in Japan (after the 1923 Kanto earthquake). Although it took many decades, it is now widely accepted amongst the whole earthquake engineering community, that the effects of surficial geology on seismic motion do exist and can result both in high death toll and large economic losses. Nearly all recent destructive earthquakes have brought additional evidence of the dramatic importance of site effects.

Accounting for such "site effects" in seismic regulations, land use planning or design of critical facilities thus became one goal of earthquake hazard reduction programs. An important issue is how to achieve that goal both reliably and economically. One of the aims of researchers in engineering seismology has thus been, for long, to find convenient and low cost tools for the estimation of these effects. Many different techniques exist for estimating at least some aspects of the local effects that affect the vibratory characteristics of ground motion, based on various kinds of experimental or instrumental data (macroseismic intensity, noise, weak earthquake or strong motion recordings), on many different numerical modeling approaches (propagation matrix, finite differences, finite elements, boundary integral equations, etc.) with various rheological behaviors (linear viscoelasticity, equivalent linear, non-linear, diphasic, etc.), or many different empirical correlations between some geological or geotechnical characterization and some ground motion parameter (for a review, see Kudo, 1995 [1], or the whole set of Proceedings from ESG98). Their cost varies a lot from one to another; the preliminary information they require is not always available; the results they provide are more or less quantitative, not always comparable, and cannot be systematically used in a straightforward manner in a given regulatory context; their use sometimes requires a significant degree of expertise that is not always met.

Microseisms and microtremors are terms used to denote the ambient vibrations of the ground caused by natural or ambient disturbances such as wind, sea waves, traffic, industrial machinery, etc. In practice, they are recorded using high sensitivity seismometers. Since the early work by Kanai [2], it has repeatedly been found that the spectral features of microtremors exhibit some correlation with a site's geological conditions. Microtremor measurements for site response estimates have thus been for long one of the preferred approaches in Japan, for several reasons: *i)* it can be performed at any time and at any place, *ii)* the instruments and the analysis are simple, and *iii)* it does not generate any environmental trouble (the importance of which keeps increasing). The pioneering work by Kanai et al. [2] was therefore the first amongst many investigations throughout the last half-century.
Although it has been introduced long ago in Japan, this use of microtremor recordings has long been very controversial in other parts of the World, especially the "western world" (Europe and USA). The latter mistrust followed several studies reporting mixed results (successes as well as failures), and difficulties in answering several major questions:

The characteristics of noise sources change from one site to another, even over short distances, and especially in the short period range. Thus, there exist large uncertainties in the relative spectral amplitudes, which do not only reflect site conditions, but also source and path effects.
There are also significant variations in noise level between day and night. Hence, a careful microtremor survey requires repeated, or even continuous, measurements (at least when "classical" processing techniques are used, i.e. those using absolute spectra or site-to-reference spectral ratios), which makes this method less tractable and more expensive.

Its very low cost, however, justifies any attempt to use them for qualitative or quantitative purposes: indeed, the use of microtremors has received a renewed attention in the western world after the Guerrero-

Michoacan event of 1985, where it appeared clear that the information provided by simple, low cost noise measurements was consistent with strong motion observations. The situation changed drastically in the early nineties after the publication of several papers claiming the ability of the H/V spectral ratio to provide satisfactory estimates of the site response of soft deposits. Considering both the increased emphasis put on site effects and microzonation after the damage observations in recent earthquakes, and the limited amounts of resources available for such studies, in developing countries and moderate seismicity countries as well, this low cost, convenient technique attracted many new users even though the theoretical grounding is not clear and no experimentally based consensus could ever be reached. Significant efforts have thus recently been devoted to this method in Southern Europe (Greece, Italy, Switzerland, France, Spain and Portugal), as well as in Latin America (Mexico, San Salvador, Costa Rica, Guatemala, Colombia, Venezuela, Ecuador, Peru, Chile, ...). Kudo [1] provided a very interesting historical perspective on the various controversies surrounding the use of microtremors for site response evaluations, while Bard [3] performed a review of the main - positive and negative - results over the last half-decade.

The number of site specific studies based on noise recordings thus increased dramatically in recent years, and there is a strong need for a clear assessment of the actual possibilities and limitations of the noise-based site effect estimates. The objectives of the present paper are thus to better understand, to improve and to test the H/V spectral ratio technique based on ambient vibration measurements, to assess the actual meaning in view of site effect estimation, and end up with user guidelines and processing software. This will allow assessing whether microseisms/ microtremors can offer robust routine techniques for microzonation in regular cities, and thus improve significantly the mitigation tools.

H/V SPECTRAL RATIO TECHNIQUE

The H/V ratio (i.e., the ratio between the Fourier spectra of the horizontal and vertical components of microtremors) has been introduced in the early seventies by several Japanese scientists [4] [5] [6]. They were assessing its physical significance and showed that it had a direct relationship with the elliptic trajectory of Rayleigh waves. They concluded that this ratio can be used to identify the fundamental frequency of soft soils, observing that the vertical component of Rayleigh wave motion almost systematically vanishes in the vicinity of the fundamental S wave resonant frequency. Their publications, however, were only available in Japanese, and were not known outside Japan until Kudo's review [1].

Meanwhile, Nakamura [7] proposed (in English), on the basis of qualitative arguments, that this H/V ratio is a reliable estimation of the site response to S waves: according to him, it provides reliable estimates not only about resonant frequencies but also about the corresponding amplification. In his opinion, the division by the "reference" vertical component allows removing both the source effects and the Rayleigh wave effects. In a later paper [8], however, he reconsidered this explanation, and allowed a greater role to be played by surface waves, while he later came back to his original explanation.

Although Nakamura's qualitative explanation looked at least questionable (as indicated in [9], and again in [1]), various sets of experimental data (e.g. [10] [11] [12]) confirmed that these ratios are much more stable than the raw noise spectra. In addition, on soft soil sites, they exhibit a clear peak that is well correlated with the fundamental resonant frequency. These observations are supported by several theoretical investigations (e.g. [10] [9]) showing that synthetics obtained with randomly distributed, near surface sources lead to horizontal-to-vertical ratios sharply peaked around the fundamental S-wave frequency, whenever the surface layers exhibit a sharp impedance contrast with the underlying stiffer formations.

However, the three first studies ([4],[5],[6]) also conclude that the amplitude of this peak is not well correlated with the S wave amplification at the site's resonant frequency. Instead, it is highly sensitive to some parameters such as Poisson's ratio near the surface. Furthermore, [4] proposed that the good match at the fundamental frequency is due to the horizontal-vertical polarization of the Rayleigh waves, an interpretation that is in agreement with the early Japanese studies [1]. According to this view, no straightforward relation exists between the H/V peak amplitude and the site amplification. However, this opinion is not shared unanimously. For instance, a one to one average correlation is claimed [13] on the basis of a comparison between observed H/V peaks and numerical estimates of 1-D transfer functions. On the other hand, an empirical relationship between H/V peak amplitude and local intensity increment (MM scale) was argued in [14] from a strictly experimental viewpoint. A thorough comparison (see the review in [15]) between observed amplifications derived from earthquake records and observed H/V peak amplitudes at more than 30 sites demonstrates that the latter is almost always smaller than the former. Such an experimental result, although not yet explained by theoretical or numerical work, could be very useful indeed. It would mean that the Nogoshi-Nakamura technique could provide a *lower-bound estimate* to the actual amplification. This view needs to be confirmed, however, by a larger set of experimental data.

However, this Nakamura version of the microtremor method has already proved to be one of the most inexpensive and convenient techniques to reliably estimate fundamental frequencies of soft deposits. It certainly deserves more work so as to elucidate the factors influencing peak amplitudes.

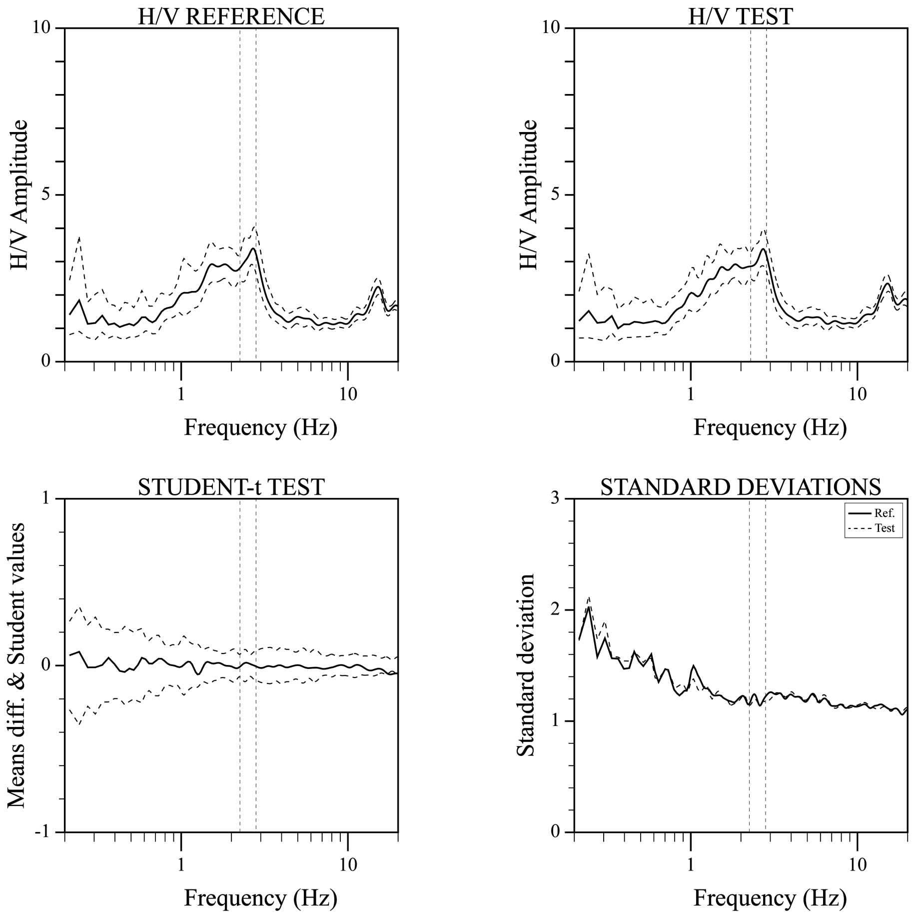
INFLUENCE OF EXPERIMENTAL CONDITIONS

H/V measurements in cities imply both reliability of the results and rapidity of data collection. It is therefore important to understand which recording parameters influence the quality and reproducibility of the results. Some review in this topic may be found in [16] [8] [17], dealing with the data acquisition system, and the processing techniques as well. However, in order to determine the influence of each of these parameters, an experimental survey was conducted within the framework of the European project SESAME. The aim of this task was to evaluate the influence of experimental parameters in stability and reproducibility of H/V on ambient vibrations. This evaluation was conducted in a purely experimental process by means of various tests. The variations of the H/V curves had to be checked both in frequency and amplitude for each tested parameter. The investigations carried out in this work package allow to precise the experimental conditions under which measurements have to be performed to provide reproducible, reliable and meaningful results. The evaluation survey was designed to obtain for each parameter a reliable estimation on its ability to influence H/V curve.

The first issue was to establish the impact of the digitizers, sensors and digitizer-sensor couples on stability, reliability and reproducibility of H/V measurements under laboratory conditions. This work was devoted to perform and analyze a set of tests in order to compare the performance of different instruments currently used (13 digitizers and 15 sensors). To reach this goal, 3 series of tests were conducted:

- Tests on digitizers. Digitizer evaluation has been carried out through 4 different tests: sensitivity, internal noise evaluation, time stability and channel consistency;
- Test on sensors. Sensor response has been evaluated for short period seismometers, long period seismometers and accelerometers;
- Tests on digitizer-sensor couples. These tests have been achieved collecting different measurements: individual recordings in the lab, simultaneous recordings in the lab and two simultaneous recordings in the free-field.

Each test allowed us to classify the instrument as a function the their capacity to deliver reliable H/V results. One of the main outcome for the tested sensors is: the velocimeters are all usable (even the 4.5 Hz) whereas the accelerometers are not appropriate due to their insensitivity to noise measurements.



	File name	f0 ($\overline{H/V}$) (Hz)	Nb win	Sample rate (Hz)	Recording duration (s)	Frequency stastistics from individual windows			
						$\overline{f0}$ (Hz)	Sigma (Hz)	Nb win	Student-t test
Ref.	01221442.saf	2.69	21	250	720	2.53	0.28	21	|diff| = 0.04 t = 0.31 Similar peak frequencies
Test	001c7dd600 96dc0.saf	2.72	20	250	720	2.57	0.28	20	
	Conclusion	NO INFLUENCE							

	Recorder	Sensor	Rec. type : simultaneous	Medium frequency site
Ref.	Mars Lite	5-second Lennartz LE3D	**P1-1-2-Grenoble Nice-test5** Influence of recorder Same type sensors with recorders of different type	
Test	Mars 88	5-second Lennartz LE3D		

Figure 1. Example of a "technical card", where statistical tests are performed on simultaneous measurements of different experimental conditions and reference records.

The second issue was to establish the influence of the experimental conditions when recording ambient noise. The experimental tested parameters were classified in nine categories. Three types of parameters were distinguished:

- Parameters relative to the acquisition system and configuration: recording/instrument parameters in free-field microtremor records.
- Parameters related to the characteristics of the site itself: in situ soil-sensor coupling; modified soil-sensor coupling; nearby structures; underground structures.
- Parameters relative to the variation of external conditions: weather conditions; water table level, pore pressure; stability in time; noise sources.

Each parameter has been tested against a reference recording. Similarity of the results (H/V amplitude and fundamental frequency) of both recordings, were checked using Student t-test. The results are presented in a technical card (Figure 1) showing the H/V curves, Student-t test statistics, and an automatic conclusion about the level of influence of the tested parameter on the results with respect to the reference.

Based on the above statistical investigations, the tested parameters can be classified into three main categories: (1) the parameters that do not influence the result, (2) those which influence the results only beyond some limits that can be easily controlled and (3) those on which there is no possible control. Some tested parameters produce rather ambiguous results and it would be necessary to conduct further testing.

One of the main conclusions is that no matter how strongly a parameter influences H/V amplitudes, the value of the frequency peak is usually not or slightly affected, with the noticeable exception of the wind in certain conditions. As mentioned, new data are required to give evidence of the influence of some parameters.

Results and conclusions of this survey will be used to write guidelines to avoid the use of recording conditions that would influence or change the H/V results and to standardize data acquisition for this type of experiment, thus making it easier to compare results from different experiments.

DATA PROCESSING AND SOFTWARE

Very few authors dare to propose practical recommendations as to data processing. The beginner would nevertheless appreciate to find somewhere clear, consensus advice on several simple questions, which do not necessarily have trivial answers.

- What is the optimum time window length?
- What is the required number of noise windows to have a good reliability?
- What is the sensitivity to transients and should only stationary signal windows be used?
- How to merge the 2 horizontal components to get the "H" component?
- How to smooth the spectra?
- Should the averaging from all the windows be applied on H and V spectra or on the H/V spectral ratio?
- Should one prefer arithmetic or geometric averages?

There exist also less known processing techniques, which may present some interest and should be tested. While almost all authors limit their investigations to the spectral amplitude, Tokeshi et al. [18] also analyzed the phase of the one-sided autocorrelogram of the horizontal components, and proposed a new way to derive the fundamental frequency, which corresponds to a change in the phase sign (from positive to negative). They recently performed time domain noise simulations [19], and claim that, even for low-impedance contrast structures where spectral peaks do not appear clearly, this technique is efficient in pointing out the right fundamental frequency.

On the other hand, Fäh et al. [20] [21] use a different way to derive average polarization curve: they do not smooth the spectra, so that the H/V values they obtain for every window present a very large dispersion. They succeed however in reaching meaningful averages by a) considering a very large number of noise windows (500) and b) weighting every H/V value by the corresponding spectral energy. Finally, Teves-Costa et al. [22] proposed to compute microtremor spectra with Maximum Entropy Methods, which has the advantage to provide more reliable estimates in the low frequency range with short noise windows.

J-SESAME: A STANDARD SOFTWARE SOLUTION

Keeping in mind the importance of processing in the H/V results, there is a need for development of robust software for data analysis applying the H/V technique. A multiplatform processing software is developed (J-SESAME) with the aim of providing a standard procedure in processing the microtremor data using H/V technique. Existing software that was previously used in processing the microtremor data using the H/V technique is tested and an optimum solution for the analysis is deduced. The J-SESAME is designed using a modular concept for the different parts, allowing flexibility for further developments. The user is guided through the browsing module (i.e. graphical user interface, GUI) of the software and the window selection and the processing modules provide the input data selection and computation of the H/V spectral ratios (Figure 2). The display module is then responsible for producing visualization of the processed data in an easy and flexible way. This modular development also allows utilizing the best possible solution for the programming language to be used. In the case of the window selection and processing modules, the software codes are in Fortran, whereas the browsing and the display modules are developed using the Java Programming language for multiplatform operational capacity.

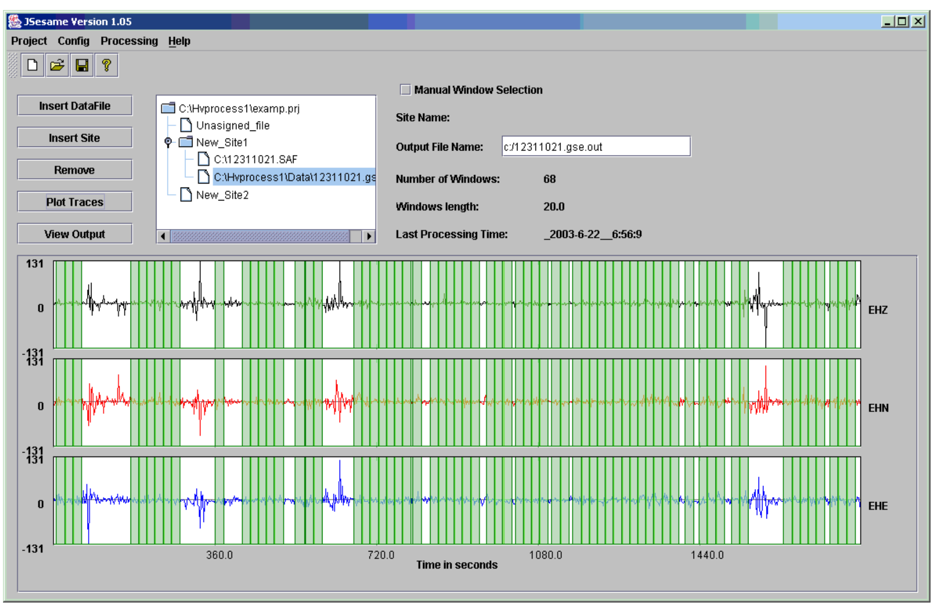


Figure 2. The general layout of the J-SESAME software. Window selection is done automatically (shown in green), where further processing is applied.

The main processing module performs the basic computations devoted to the estimation of H/V ratio. The principal steps executed by the code are the following:

- Reading the input time histories
- Offset removal
- For each selected time window inside time histories
- Tapering
- FFT
- Smoothing of Fourier spectra
- Merging of horizontal components
- H/V ratio
- Optional output of single window H/V and spectra
- Optional output of average spectra
- Average of H/V
- Automatic computation of f_0 according to a predefined scheme
- General output

In the present version two waveform file formats are supported, the GSE and SAF (SESAME ASCII Format). The latter (SAF) is designed to have a simple format where data recorded by different acquisition systems can easily be converted. It consists of header information, which contains few compulsory and a large number of optional parameters followed by a three column data corresponding to the three channels of the recording.

The main philosophy of the browsing module is to organize the data in individual projects. For each project, the corresponding waveform files are kept in a directory structure and is accessed through the configuration parameters, which keeps the filenames associated with this project with full path description on the computer. In addition, the processing parameters that are used in each project are kept in the same project file under the configuration options.

After defining a new project, the user creates different sites under which the corresponding data collected for each site are archived in the configuration as a tree-structure (i.e. each project contains several sites and each site contains several data files). This process allows the user to organize the data into individual sites easily by dragging on the directory structure or by inserting several files into each site using the mark and copy options. The default parameters for processing can then be displayed through the pull-down menu under the configuration (and if desired can be changed) and the entire project can be saved as a "project file". A saved project can be uploaded (with the same configuration and parameter settings) for later usage.

Once the data are organized under the project structure, the user then has the possibility to plot the waveform files (three components on the screen) for manual inspection. After the visual inspection, based on user defined (or default) parameters, user can select the time-windows either automatically or manually using the window selection module. The selected windows are then processed by the H/V processing module either as a single file or as a series of files usually corresponding to the same site. The H/V spectral ratios and the averages as well as other display options are then plotted using the display module.

In case there is difficulty in selection windows automatically due to transients or other problems in the data (such as spikes), there are filter options, where the user can apply either low-pass, high-pass or band-pass filter. The filtered traces are then displayed to the user for window selection. In this process, a comparison is also made between the windows selected both on the filtered and on the unfiltered trace.

The common windows are then used for further processing. Naturally, only the original unfiltered traces are used for the H/V ratios. This filtering option allows the user to work also with difficult data sets.

The display module conducts the different plotting options, however, this process is transparent to the user. The only thing the user has to do is to click on the output display button when the processing is completed (for the details of the display options see the following chapters). The different outputs are displayed through a series of windows.

EXPERIMENTAL EVALUATION

Another goal of the SESAME project was to perform a purely experimental assessment of the reliability of the H/V 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 addition, comparison of H/V results with observed damage of recent earthquakes in Europe attempted. For this purpose the scientific output of this work package are; (i) the creation of a homogeneous data set of noise and earthquake recordings at many sites, (ii) the comparisons of experimentally and theoretically estimated transfer functions with the H/V spectral ratio of ambient vibrations technique and (iii) the comparison of damage distribution in modern urban areas with results from H/V spectral ratio.

The format of data sets both for ambient noise and earthquake recordings was converted to SESAME ASCII (SAF) and for each experimental site a Standard Information Sheet (SIS) was prepared. Finally, for about two hundred sites noise and earthquake recordings are included in SIS (Table 1). In order to facilitate data selection with criteria set by the user and given that this database is open to future input of SIS, a SESAME database was constructed.

Table 1. Compiled data for the Standard Information Sheets (SIS) of the SESAME database.

INSTITUTE	***SITE NAME***	***SIS***	EVENTS	***RECORDS***
ITSAK	S.M. NETWORK	63	288	492
	EUROSEISTEST	7	56	247
INGV	BENEVENTO	6	42	188
	CATANIA	3	31	85
	CITTA-CASTELLO	15	10	140
	VERCHIANO	9	15	122
	COLFIORITO	3	23	69
CNR	FABRIANNO	6	81	326
	PREDAPPIO	18	128	1230
	ROVETTA	4	14	44
LGIT	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	S-M NETWORK	22	62	115
TOTAL		211	1227	5194

For selected sites H/V ratios of ambient noise were compared with H/V receiver functions of earthquake weak or/and strong motion recordings (Fig. 3), as well as with standard spectral ratios where data permitted. For a few sites - where geotechnical data was available - theoretically estimated transfer functions were compared with experimentally H/V ratios of ambient noise. In addition, for a few selected sites, which exhibited non-linearity during strong ground motion, H/V noise ratio was calculated to investigate the applicability of the latter.

Ambient noise measurements were performed into the city of Thessaloniki, the town of Kalamata in Greece, the city of Rome and the towns of Palermo and Fabriano in Italy, and the town of Angra-do-Heroismo in Portugal. From preliminary data analyses, it seems that in some cases (homogeneous building stock, distant event) the H/V ratio "fundamental" frequency may satisfactorily indicate areas of damage potential in urban environment. However, quantitative correlation between H/V spectral ratio "fundamental" frequency and damage is difficult to be established given the complexity of parameters involved. Correlation between the "fundamental" frequency and the near surface geology, on the other hand seems more reliable.

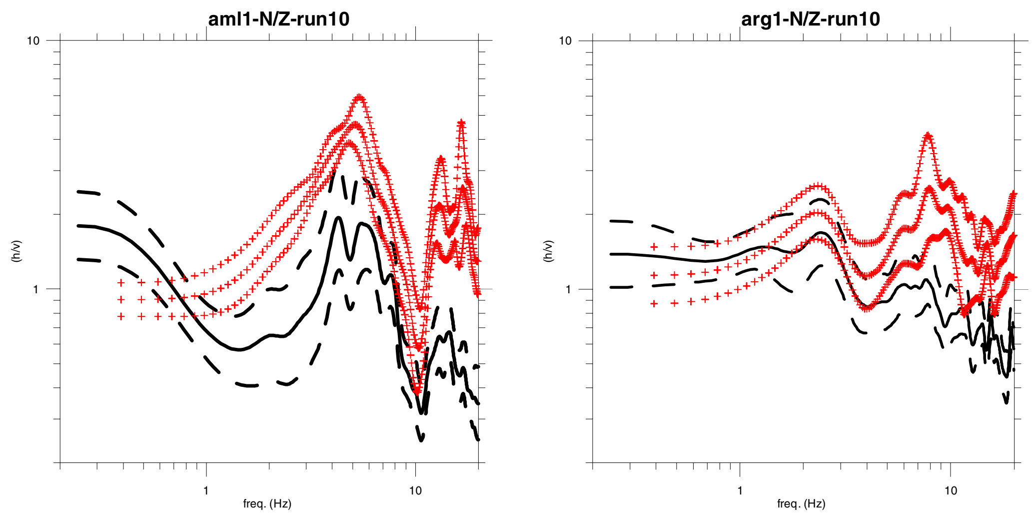


Figure 3. Comparison between the H/V spectral ratio of the noise records (average: continuous solid line, +/- one standard deviation: dashed line) and strong motion records (crosses average and +/- one standard deviation), for two sites in Greece.

CONCLUSIONS

Instrumental and experimental conditions, which may influence the H/V ratios are identified. A total of 58 different experimental conditions are tested and systematically evaluated. Among these 13 tests gave results, which show clear influence on the H/V ratios. The most critical of these seems to be the effect of wind.

Dedicated software (J-SESAME) is developed to allow standard processing routines. J-SESAME software with the user manual and various reports of the SESAME project are available on the web-site: http://sesame-fp5.obs.ujf-grenoble.fr

A database of earthquake (weak and strong) and noise records, together with standard information sheets is established. This database will be used for further analyses and will be available at the end of the project. All interested are welcome to contribute to the database.

Correlations that were performed between the H/V ratios and near-surface geology gave promising results. However, correlation with damage seems difficult to obtain due to the complex nature of damage distribution.

Guidelines are being prepared (will be available at the end of the project period) for the use of H/V spectral ratio technique, including the experimental factors affecting the results, the standardized processing software with a user manual and the recommendations with regard to the experimental evaluation.

In parallel to the work mentioned in this paper, within the SESAME project numerical simulations are also performed to better understand the nature of the noise wave-field and to investigate the actual capability of H/V technique to retrieve useful information on site conditions. However, a clear warning is warranted: H/V ratios certainly do not provide the SH transfer function, although it may appear in peculiar cases.

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