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THE SESAME PROJECT : AN OVERVIEW AND MAIN RESULTS

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SUMMARY

Recent years have seen many studies using ambient vibration measurements for a priori estimations of site effects: assessing the actual reliability of such results is a major challenge for engineering seismologists in order to both foster their use and prevent their misuse, for an improved, cost-effective and reliable risk mitigation. Such an assessment has been one of the major objectives of the SESAME European project. Two techniques - the very simple H/V technique ('Nakamura'), and the more advanced array technique - have been thoroughly considered under different viewpoints, in order to a) better understand their physical basis, b) assess their actual meaning in view of site effect estimation, and c) propose user guidelines and processing software to ensure a correct use. After a brief presentation of the overall architecture of the 3-year project (2001-2004), the main accomplishments and findings are outlined. Comparing the results of noise numerical simulation with actual observations allowed to draw some conclusions on the composition of the actual noise wavefield, and on the ability of H/V and array techniques to deal with 2D or 3D structures. Comprehensive tests and checks allow to better assess the reliability and meaning of H/V measurements, especially as a standard processing software is now proposed together with user guidelines. A lot of theoretical and software development could also be achieved in relation with the array techniques, leading to a set of practical recommendations and analysis tools. The project certainly does not pretend to answer all the issues regarding noise measurements, but it is hoped that the scientific outcomes and the resulting practical recommendations and guidelines, freely distributed through the SESAME web site http://SESAME-FP5.obs.ujf-grenoble.fr, will be helpful for site effect assessment and improved seismic risk mitigation, especially in developing countries and moderate seismicity areas..

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INTRODUCTION

All recent earthquakes showed that a priori estimations of site effects are a major challenge for an efficient mitigation of seismic risk. It therefore seems logical and useful to try one's best to account for site effects in the design of new constructions, in the retrofitting of existing structures, and in land use planning as well.

As illustrated by the blind tests performed in the nineties (Turkey Flat and Odawara), the numerical prediction of site effects with a reasonable confidence level is usually possible only if some key geophysical or geotechnical parameters are known. The ideal case would be to perform a comprehensive geophysical measurement campaign in order to get a reliable S wave velocity profile of the site. On the other hand, the known experimental techniques to obtain reliable estimates of site effects (site to reference spectral ratio, generalized or parameterised inversion) require to obtain several tens of good quality earthquake recordings at the sites under study, which ends up with high costs in urban areas because of the high noise level, especially in areas of moderate seismicity where events are unfrequent.

However, although the need to consider site effects in the design of structures is more and more recognized, today's economical reality is unfortunately that the budgets allocated to site investigations diminish more and more. The few methods known as reliable then systematically appear as far too expensive for local and national authorities, especially in moderate seismicity countries or in developing countries. There is therefore a drastic need for reliable, low cost techniques, from an economical as well as from a safety point of view. Very promising developments were launched over the last decade, based on the use of ambient vibration measurements, which are very easy easy to obtain in any conditions:

- On the one hand, the H/V technique, widely known as the "Nakamura's" technique although it was initially proposed by Nogoshi and Igarashi in 1971 [1] spread all over the world after Nakamura's paper published in 1989 [2]: the spectral ratio of the horizontal components to the vertical component of ambient vibration is claimed not only to indicate the fundamental eigenfrequency of the site under investigation, but also, according to some authors, to provide some quantitative information on the actual site amplification.
- On the other hand, several groups of scientists and engineers (originally again in Japan) advocate the use of array measurements of ambient vibrations to retrieve the velocity profile, including for deep deposits. Their promising results indicate the potentialities of microtremors for geophysical exploration, which may prove therefore very useful for many applications well beyond earthquake engineering.

Ambient vibration techniques are obviously much cheaper than classical geophysical site investigations. That is why their use rapidly spread world-wide during the last decade, especially in urban areas. However, it remains also mandatory that these low cost tools be reliable. Concerning these two techniques based on ambient vibration measurements, one must admit that their physical basis and actual relevancy for site effect estimates has never reached a scientific overall agreement. The key problem is that these methods, especially the H/V one, have been developed empirically. Only few theoretical investigations have been performed to clarify their underlying physics. It is therefore most likely that these techniques, especially the H/V one, are often misused and may lead to wrong results.

The objectives of the SESAME project, launched in 2001 under funding from the European Commission through its *Environment and Sustainable Development Program* (Research Directorate General), were precisely to investigate thoroughly the reliability of these two techniques. Various european teams put together their expertise in different fields (seismology, engineering geology, surface geophysics, data processing, numerical modelling, ***Table 1***), in order to tackle these methods under different viewpoints, so as to clearly and solidly assess their physical basis, their actual relevancy and their robustness for site effect estimation, so as to issue practical recommendations for their routine implementation. This presentation summarizes the main findings, which are presented in more details in accompanying papers (see the reference list) and in a number of comprehensive reports available on the project website.

Table 1 : SESAME Partnership

1	UJFG.LGIT	University Joseph Fourier (Lab. Géophysique Interne et Tectonophysique)	Grenoble
13	CNRS.LGIT	National Center for Scientific Research	Grenoble
14	LCPC	Central Laboratory for Bridges and Roads	Paris
2	RICSA	Résonance Ingénieurs-Conseils SA	Geneva
3	UPOTS.GEO	University of Potsdam (Geophysical Department)	Potsdam
4	ULGG.DG0.GIH	University of Liège (Lab. Engineering Geology and Hydrogeology)	Liège
5	UIB.ISI	University of Bergen (Institute of Solid Earth Physics)	Bergen
6	ETH.GEOP.SSS	Polytechnic School of Zürich (Swiss Seismological Service)	Zürich
7	IESEE	Institute of Engineering Seismology and Earthquake Engineering (ITSAK)	Thessaloniki
8	ICTE.IGI	Institute of Earth and Space Sciences	Lisbon
9	INGV	National Institute of Geophysics and Volcanology	Roma
11	IGSAS.SD	Geophysical Institute – Slovak Academy of Sciences	Bratislava
10	CNR.IDPA	National Research Council (Istituto per la Dinamica dei Processi Ambientali)	Milano
12	CETEMED.LRE	CETE Méditerranée (Center of Technical Studies, Ministry of Equipment)	Nice

PROJECT ARCHITECTURE

In order to achieve our goals, the work has been divided into 4 main, complementary tasks, as illustrated in ***Figure 1***. On the upstream side, emphasis was put on the understanding of the real nature of noise, especially in urban areas, and on its numerical modelling. On the technical side, series of investigations were launched in order to clearly identify the key points in each of these techniques and their reliability, and to clearly assess the conditions under which they have to be performed: experimental conditions for the measurements, and processing techniques as well. Finally, on the downstream side, once proved that these techniques do provide useful information when applied with care, we offer a well-established framework for reliable measurements by proposing user guidelines based on the achieved results, that give explicit and precise meaning to the words "when applied with care".

The scientific work in each main task was organized as follows :

- H/V technique : experimental aspects for warranting the stability and reproducibility of measurements, investigations on the various data processing alternatives and choice of the most robust ones, and finally experimental assessment of the meaning of this ratio by a thorough comparison with instrumentally measured site effects, and damage distribution in several recent earthquakes.
- Array measurement technique : experimental aspects for an optimal adaptation of the instrumental characteristics and layout to the site under study, analysis of several multitrace signal processing techniques (f-k, spatial autocorrelation), improvements in the inversion of velocity profiles with an optimum use of a priori information, and implementation of the whole process within a robust and convenient software.
- Physical background and numerical modelling for cross-checks with observed data: investigations on the actual composition of noise wavefield in urban areas, development and validation of numerical models (FD) with random surface sources, numerical analysis of the H/V and array techniques on noise synthetics, and finally cross checking of observations, numerical simulations, and known structure and site effects for a few well-known test-sites.
- Finally, organisation of the dissemination of the scientific knowledge and technical know-how through various means. One of the main outcome is a multi-platform basic free software for

H/V processing, distributed with user manual and user guidelines on a CD-ROM or from a web site.

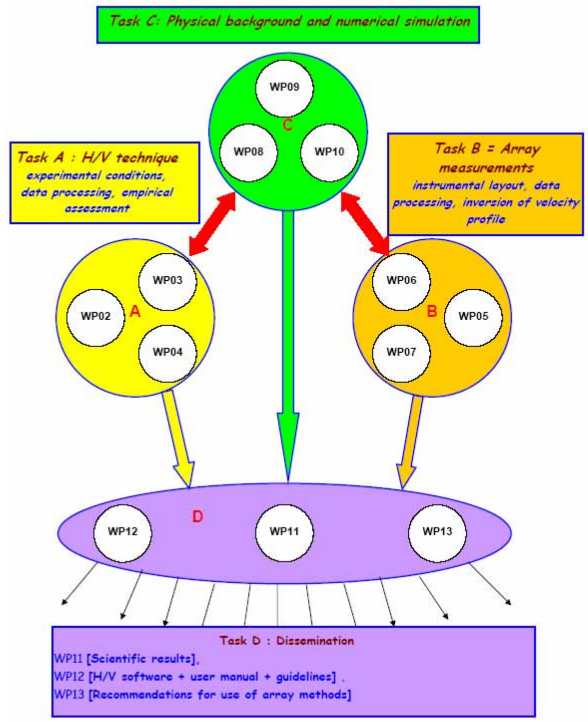

Figure 1: General architecture of the SESAME project

SCIENTIFIC ISSUES and MAIN ACCOMPLISHMENTS

Nature of noise wavefield and lessons from noise simulation

One basic aim of the SESAME project was to better understand the physical nature and composition of ambient seismic noise wavefield, especially in urban areas, and to develop and validate numerical tools to generate realistic noise synthetics, in view of thoroughly testing the H/V and array techniques for well-controlled conditions.

A thorough literature review has first been accomplished [3], though limited to the "western" literature (Europe + Americas) for language reasons. It was essentially targeted at gathering answers to the 3 following questions: a) what is the proportion between body and surface waves in the noise wavefield ? b) within surface waves, what is the proportion between Rayleigh and Love waves ? c) again within surface waves, what is the proportion between fundamental mode and higher modes ? One must admit that very few and only partial answers could be found, so that our main conclusion is that a lot of experimental and theoretical work is still ahead: useful information can certainly be obtained from array measurements, but it also requires the development of specific and innovative processing techniques.

Another indirect but valuable source of information lies in the numerical simulation of noise. A specific program package was thus developed aiming at the simulation of ambient noise generated by human activity, for sites with heterogeneous subsurface structures. It consists in two modules [4]. The first one allows to generate a source distribution with random spatial and temporal characteristics, represented by surface or subsurface point forces with arbitrary direction and higly variable time functions (from Dirac-like pulse to quasi monochromatic carrier, representing impulsive as well as machinery sources). The second one propagates the wavefield generated by these random source distribution within either a horizontally stratified half-space (computation with the Discrete Wavenumber method as improved by Hisada [5, 6], or an arbitrary 3D structure (the computation is then performed with an explicit Finite Difference Displacement-Velocity-Stress scheme solving equations of motion in the heterogeneous visco-elastic medium with material discontinuities [7]; the only limitation is the requirement of a flat surface topography). Details about that program may be found in [4**]**. This program package was intially designed to account for anthropic noise sources (i.e., "microtremorsé associated with local sources), but it was thought useful, after some time, to also include the natural sources ("microseisms", generally associated with ocean waves) for the low frequency sites: therefore a new numerical development has been undertaken to frame the 3D FD model with an "excitation box" along which the motion associated with surface waves generated by distant sources can be specified. As the implementation of such an excitation box could be completed only recently, no numerical result were yet available at of Spring 2004.

Table 2 : List of deliverables available on the SESAME web site
(grey background: not yet available in March 2004, but which will be ready by October 2004)

Del. ID #	*Deliverable Name/Title*
D01.02	Controlled instrumental specifications
D02.09	FD code to generate noise synthetics
D04.04	Homogeneous data set of noise and earthquake recordings at many sites
D05.06	Quality control software for in-situ checks
D06.05	Array data set for different sites
D07.05	Optimum deployment strategy and quality measure for array layout in view of obtaining surface wave dispersion curves
D08.02	Measurement guidelines
D09.03	Multi-platform H/V processing software
D11.10	Set of noise synthetics for H/V and array studies from simulation of real sites
D12.09	Report on parameter studies
D13.08	Report on the nature of noise
D14.07	Report on the inversion of velocity profile and Version 0 of the inversion software
D15.06	Interface software
D16.04	Report providing comparisons of experimentally and theoretically estimated transfer functions with (H/V) ratios
D17.10	Overall comparison for test sites
D18.06	FK/SPAC Continuous array processing software (laboratory post-processing)
D19.06	Report on the FK/SPAC capabilities and limitations
D20.04	Report including comparisons of damage distribution in modern urban areas with results from (H/V) spectra
D21.07	PC version of the Inversion software
D22.11	Scientific papers (special issue in an international journal, or book)
D23.12	H/V User guidelines + CD ROM software
D24.13	Recommendations for array measurements and processing
D25.01	Final report

This program has then been used to perform simulations both for a set of 1D, 2D and 3D "canonical models", and for several real sites (Basel in Switzerland, Colfiorito in Italy, Grenoble in France, Liège and

Uccle in Belgium, Thessaloniki in Greece). The noise synthetics were then analysed with the H/V and array techniques, and the corresponding results could then be compared with the known model structure (fundamental frequencies, velocity profile) and/or with the actual field measurements. The results of this comparaison are very rich and partly summarized in [8] and [9]. In a very brief and caricatural way, the main learnings may be summarized as follows:

1) Composition of noise wavefield

Actual H/V ratios derived from in-situ recordings most often display one single peak. Numerical simulations clearly show that harmonics occur on the synthetic H/V ratios in two cases : distant, surface sources, or deep sources located beneath the interface with the main impedance contrast. This strongly suggests that the noise wavefield – at least in the intermediate and high frequency range corresponding to anthropic origin ("mircotremors") - is essentially due to local, surface sources. Under such circumstances, the wavefield is therefore a mixture of Love, Rayleigh and body waves, and the predominant surface wave modes are, by far, the fundamental modes.

As a consequence, the origin of the H/V peak is multiple: Rayleigh wave ellipticity, Airy phase of fundamental Love wave mode, and partly fundamental resonance of S body waves.

2) Capabities of H/V and array techniques for 1D structures

A number of simple 1D structures (with one or two homogeneous layers, or one gradient layer overlying a half-space) has been considered, with varying impedance contrasts and Poisson's ratio. In all cases, the application of the H/V technique on the noise synthetics did lead to the right value as to the fundamental frequency of the structure (within ± 20%). Very satisfactory results were also obtained with the array techniques, which did allow to derive the right S-wave velocity profile in most cases. The only cases where it did not work properly correspond to internal layering within the sediments with only moderate (i.e. < 50%) velocity contrast: array analysis techniques alone do not have a sufficient resolution to clearly identifiy slight velocity changes with depth, and provide good estimates only of the wave velocity value for the superficial layer. It was also shownthat the resolution on P-wave velocity, especially within the bedrock, is very poor, and that such information should probably be looked for with other geophysical techniques.

Further investigations were also performed to try to derive additional information from the H/V curve, following the pioneering work of Fäh et al., 2002: sophisticated signal processing (based on wavelet analysis) proved succesful in extracting the Rayleigh wavelets from the synthetics (which in fact are a complex mixture of ove, Rayleigh and body waves), from which it was then possible to pick not only the H/V peak frequency, but also the Rayleigh wave ellipticity: it is then possible to invert this ellipticity curve in terms of velocity profile

3) Capabities of H/V and array techniques for 2D or 3D structures

Several "canonical" 2D and 3D structures were considered first: dipping layer (i.e., 2D valley edge with gentle subsurface slope), and deep alluvial valley. It was found that the resonance frequency given by the H/V technique generally slightly overestimates the theoretical 1D resonance frequency taking into account the local soil column, with a deviation range of about 20%. The H/V peaks, however, are much less clear on sites with rapidly varying thickness, for instance on valley edges. Similarly, the S-wave velocity profile inverted from virtual arrays located over underground slopes is basically related with the average thickness and S-wave velocity of the structure under the array, while, for areas where the underground structure does not present rapid lateral variations, the inverted velocity profiles are as satisfactory as in fully 1D structures.

Similar simulations were then performed for real sites [9], starting with two alluvial basins with pronounced 3D structures, a shallow one (Colfiorito, Italy: $h \approx 100$ m, $w \approx 2$ km, $f_0 \approx 1$ Hz) and a deep one (Grenoble, France: $h \approx 900$ m, $w \approx 5$ km, $f_0 \approx 0.3$ Hz). The primary interest of these sites is that their

structures are sufficiently well known to allow crosschecking with observations. In each case, as the modelling could not be performed up to very high frequencies, i.e., around 10 Hz, it was focused on the frequency range of primary interest, i.e., 0.3-3 Hz for Colfiorito, and 0.2 – 1.0 Hz for Grenoble.
As detailed in [9], one very encouraging outcome of these simulations is the overall very satisfactory correlation between synthetics and actual noise characteristics at both sites. It first indicates that our modelling of ambient noise as due to surface forces seems appropriate. It also emphasizes the capability of the H/V technique to provide a satisfactory map of the sediment thickness: for the shallow Colfiorito basin, the simulated H/V frequencies are in very close agreement with the 1D resonance frequencies, while for deeper Grenoble basin, the simulated H/V frequencies, though significantly differing from the 1D frequencies (overstimation by about 50% in average), still exhibit a good correlation with the sediment thickness, and are closer to to the actual 3D resonance frequency of the basin. The capability of the array technique in retrieving relevant information about the site velocity structure proved also rather satisfactory for both sites. For the shallow Colfiorito basin, an almost perfect agreement between the known soil profile and the inverted seismic profiles derived from synthetics and observed noise could be reached. For the deeper Grenoble site, the velocity profiles derived from synthetc and actual recordings provide a velocity gradient that is in rather good agreement with the right gradient, and a sediment thickness slightly underestimating the average thickness below the array.

Another interesting common feature observed both in the synthetics and actual recordings is the existence of predominant back-azimuths for the waves identified by the array techniques: these back-azimuths systematically point at subsurface diffractors such as the closest valley edges. Therefore, array analysis of noise recordings proves to be an interesting tool also for identifying, at a given site, the main subsurface structures responsible for deviations from the "routine" 1D response.

Although these numerical investigations do point out some limitations for the array analysis techniques, their ability to give the superficial S-wave velocity is highlighted. One way to obtain the S-wave velocity profile of a complex structure over the whole depth interval (down to bedrock) could be to couple geophysical methods such as seismic refraction, which provids very good constraints on layer thickness.

H/V method

The theoretical and numerical results briefly summarized in the previous section do emphasize the potential usefulness of the H/V technique. This result supports the general feeling of the the seismological community, that the H/V technique gives valuable results if applied "with care" or "appropriately". However, these words are fuzzy enough to allow many different subjective interpretations. Most of the work that has been undertaken within the SESAME project was essentially aimed at giving an explicit and precise meaning to these fuzzy words.
Three main directions have been considered in that objective: firstly to study the effect of the experimental conditions (instruments and field conditions), secondly to find out the influence of the data processing in order to propose a "standard" software with "optimal" options, and finally to empirically assess its reliability for microzonation studies through a thorough comparison of its results with those of other different, well established techniques.

Experimental conditions
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. A series of specific lab and field tests was designed and applied to a representative sample of commonly used instruments, involving 13 digitizers and 15 sensors (short period and broad band, velocimeters and accelerometers). These tests and their results are detailed in [10]. One of their main outcomes concerns the

sensors: the use of accelerometers was not found appropriate due to their very poor sensitivity, especially at low to intermediate frequencies. Such a result, however, may not apply to the most recent generation of accelerometer sensors based on overdamped coils. On the other hand, velocimeter sensors were quite surprisingly found to provide very similar results whatever their natural frequency (satisfactory results were obtained even with a 4.5 Hz sensor on a low frequency – 0.3 Hz - site). We recommend, however, the use of lower cut-off frequency sensors (≤ 1 Hz) for low frequency sites, especially in continental areas where low frequency oceanic waves carry little energy.

The second issue was to establish the influence of field conditions when recording ambient noise. After a careful analysis based on the experience of the member teams, the tested experimental parameters to be tested were identified (58 in total), and classified in three main categories, as described in [11, 12, 13, 14]:

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

A total of almost 600 test measurements were performed by different teams, with in each case a reference recording, and as much redundancy as possible (i.e., the effects of a given parameter were tested several times by different teams on different sites). The similarity of the results between the test and the reference was quantified, both in terms of fundamental frequency and H/V frequency dependence, using Student t-test (see [11] for details). All these test recordings have been archived on a DVD that may be availbale on request for further tests.

Based on the above statistical investigations, the tested parameters could be classified into three main categories:

i) the parameters that do not influence the result,
ii) those which influence the results only beyond some limits that can be easily controlled and
iii) those which do influence the results and on which there is no possible control.

Some tested parameters produced rather ambiguous results and it would be necessary to conduct further testing: it has therefore been decided to make available the software allowing a quasi automatic comparison between test recordings and reference recordings [11].

In very brief, the main learnings may be summarized as follows:

- In situ soil / sensor coupling should be handled with care. Concrete and asphalt provide good results, whereas measuring on soft / irregular soils such as mud, grass, ploughed soil, ice, gravel, not compacted snow, etc. should be avoided. Artificial soil / sensor coupling should be avoided unless it is absolutely necessary, for example, to compensate a strong inclination of the soil. In such a case, either a pile of sand, or a trihedron should be used. This soil/senor coupling issue proves to be particularly important under windy conditions.
- It is recommended not to measure above underground structures. Nearby surface structures should be considered with care, particularly under windy conditions.
- Measurements under wind or strong rain should be avoided. Wind has been found to induce very significant low frequency perturbations.
- The proximity of some specific noise sources should be considered with care (or avoided using an anti-trigger window selection to remove the transients): nearby walking, high speed car or truck traffic, industrial machinery, etc.
- Results are stable with time (if other parameters, such as weather conditions, etc. are kept constant).
- 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.

Data processing software

Deriving the H/V ratio from the noise recordings may be done, and actually is done, in many different ways, so that it is very difficult to compare results from one study to another. Amongst the various issues that one has to face when processing the data, some are related with the selection of windows (length, number, avoiding transients or not, ...), some other with the actual computation of the average H/V ratio (what kind of spectral smoothing, what kind of averaging, how to merge the horizontal components ?). Although these choices do have a strong influence on the final results, very few authors dare, up to now, to propose practical recommendations on these issues, that would greatly help and guide the new user.

We therefore felt the duty to propose a robust software for data analysis applying the H/V technique, that could help and guide beginners (and possibly also some already experienced users) with clear, consensus advice, and provide him with a standard procedure. A multiplatform processing software (J-SESAME) has thus been developed, which may be operated under different environments (Windows, Linux, Mac).

The J-SESAME software was designed using a modular concept for the different parts, allowing flexibility for further developments. It is based on pieces of software that were previously used in the various involved teams, and have been, after thorough discussions, incorporated into a single, "optimum" software. The user is guided through a browsing module (i.e. graphical user interface, GUI), and the window selection and the processing modules provide the input data selection and computation of the H/V spectral ratios. 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. The software codes for the window selection and processing modules are in Fortran, whereas the browsing and the display modules are developed using the Java Programming language: despite its slowness, this language was selected because of its free multiplatform operational capacity.

A more detailed description of the various functionalities of this software may be found in [15]; it will be distributed freely, together with a user manual and H/V guidelines, to any individual that will request it.

Empirical assessment of the H/V method

The last work direction was to attempt an empirical assessment of the reliability of the H/V technique, by comparing its results a) with experimental site transfer functions derived from well established experimental techniques, and b) with damage actually observed during several recent European earthquakes.

For item a), a seismic data base was created, gathering data from two hundred sites within Europe, for which both microtremor, and weak (or strong) motion data are available. For each of them, a standard Information Sheet (SIS) has been prepared and entered in an Access data base, in order to archive in a standardized way qualitative and quantitative information about the site conditions and the available earthquake and noise recordings [16, 17]. This database may be used for further analyses and will be available at the end of the project. All research teams interested in it are welcome to contribute to the database, so that this effort can survive after the end of the SESAME project, scheduled fo late 2004.

For each site, all noise recordings were then processed with the same software to calculate (H/V) spectral ratio, whereas weak and strong motion earthquake recordings were also processed with a similarly standardized procedure: both (H/V) receiver function for all sites were calculated and, whenever possible (i.e. for about 60% of the sites), experimental site transfer functions obtained from earthquake recordings pairs at the site and at a nearby reference site. In particularly, processing of noise and earthquake recordings used the same smoothing and averaging techniques. It was then possible to derive a statistically meaningful comparison of H/V results and standard site-to-reference spectral ratios in terms of fundamental frequency, amplification bandwidth and amplification level.

The main lessons of that comprehensive and homogeneous comparison may be summarized as follows:

i) in most cases (i.e., around 90%), the noise H/V ratio does allow to identify the site fundamental frequency. However, for a small proportion of sites (around 10%), noise H/V ratio is not able to detect low frequency amplification that appear clearly on the standard site-to-reference spectral ratios. The physical reason for this failure is not yet completely clear, although it generally corresponds to thick and stiff sites, where either the velocity contrast at depth is not very large, or the sedimentary cover probably exhibit significant velocity gradient.
ii) For almost all examined sites (> 90%), the noise H/V peak amplitude is smaller than the actual spectral amplification factor measured on site-to-reference spectral ratio, both at the fundamzenatl frequency and at the the peak frequency. This intriguing empirical observation is certainly worth further investigations, as it may be an indication that the H/V peak amplitude may be a lower-bound estimate of the true amplification factor. Additional results, such as those from the KIK-NET strong motion network, will be very welcome to tell whether this result may considered as general.
iii) The shapes of the noise H/V ratio and the site-to-reference spectral ratio, are, in most cases, very different from each other. A clear warning must therefore be issued : H/V ratios certainly do not provide estimates of the SH transfer function: amplitudes and amplification bandwidth are larger, sometimes much larger, on site-to-reference spectral ratios).
iv) Comparions of H/V ratios from noise and eartqhauke recordings also yield similar conclusions, i.e., similarity of fundamental frequencies, and lower amplitudes on noise H/V ratios.

For item b), a series of ambient noise measurements were performed in several cities recently affected by damaging earthquakes: Thessaloniki (Greece), Kalamata (Greece), Rome (Italy), Palermo (Italy), Fabrianno (Italy), and Angra-do-Heroismo (Azores). For each of these cities, damage maps were available either in MSK64 / EMS98 intensity scale, or even in local damage grades, together with geological maps. These series of maps were then compared with maps derived from the noise survey and subsequent H/V processing, using some gross and simple information such as the peak frequency and the maximum amplitude. Besides qualitative, visual comparison maps, some quantitative correlations were also attempted, as described in [17], [18] and [19]. For the few cities investigated, correlations between the H/V information and near-surface geology generally gave promising results, in both terms of fundamental frequency and H/V amplitude. However, correlation with damage seems is much less easy to establish, except in the case of rather distant earthquakes and homogeneous building stock, such as for the cases of Thessaloniki (1978) and Angra-do-Heroismo (1980).
While some partial results may already be found in [17], [18], [19], they will be all gathered in a final report (D20.04 in Table 2), that will be available from the web site. The concluding recommendations will probably be to use noise surveys and H/V information mainly as a kind of geotechnical index related essentially with subsurface geology, which in turn may significantly affect damage characteristics. But certainly no direct quantitative correlation between damage and H/V values will be given.

Array measurements, dispersion curves and velocity profile

As mentioned earlier, one of the great need for numerical prediction of site effects is to feed the models with reliable parameter values concerning the geometry and mechanical characteristics of the subsurface structure. Many geophysical tools do exist, but they are not used so often for common projects. In addition their use is often very limited in urban areas, because either of the difficulties to install some heavy equipment or of their ability to provide information only for the very surficial layers (upper 30-50 m). [Although there do exist tools for deeper investigations - such as seismic reflection or borehole drilling -, they are only very seldom used for seismic design purpose, at least in Europe and in developing countries, because of their prohibitive –or estimated so - cost].

This need for "urban" geophysical exploration tools, allowing deep investigations (down to several hundred meters), and complementing very surficial geophysical tools, can be met by array measurements of ambient vibrations. Several Japanese teams have indeed claimed the possibility to retrieve the dispersion curves of surface waves from array measurements, with either a classical frequency - wavenumber analysis, or the spatial autocorrelation technique put forward by Aki [20]), and thus to invert the velocity profile for both S and P waves down to large depths (several kilometers with a 2-4 km aperture array). This of course requires the assumption of a horizontally stratified structure, a condition that is not always met in reality.

By the time this project was initiated, only a few groups in Japan used these noise array techniques, and almost none in Europe or USA (where there have been however, some attempts to use array techniques for very particular signals, the volcanic tremors). Our objective was therefore to get some experience in these techniques and investigate their ability to provide useful information on site conditions, for simple (1D) as well as for less simple (2D, 3D) geological structures. Besides theoretical and signal processing developments, an important component of our work was dedicated to the use of existing data for exploiting array noise measurements, e.g. introduce the a priori information in the inversion of the dispersion curves. This information may come from shallow geophysical experiments and/or geotechnical investigations which are usually numerous in towns.

Derivation of dispersion curves

Several array processing techniques are available for the estimation of phase velocities and dispersion curves: CVFK, CVFK2, Capon, Music, and SPAC. The first four are aimed at the detection of plane waves crossing the array (phase velocity + back-azimuth), while the last one (SPAC) is based on the assumption that the wavefield is stochastic and stationary in both time and space, and allows to retrieve only the phase velocity.

- CVFK, after [21], is a conventional, semblance-based, frequency-wavenumber method operated with sliding time windows and narrow frequency bands.
- CVFK2 is also a conventional frequency wavenumber estimate, based on the evaluation of the cross-correlation spectral matrix $\mathbf{R}(\omega)$
- Capon's high-resolution frequency wavenumber approach is also based, after [Capon 22], on the Cross correlation spectral matrix $\mathbf{R}(\omega)$. This f-k technique is widely used within the context of microtremor analysis (see [23, 24, 25]).
- "MUSIC" is another high-resolution frequency wavenumber method introduced by [26], based on the decomposition of the cross-spectral matrix into signal and noise subspace.
- SPAC (Spatial autocorrelation method), first introduced by Aki [20], was later developped by various authors, initially mainly for volcanological applications. Its original formulation requires many recording pairs with uniform azimutal distribution and constant inter-station distance. Bettig et al. [27] thus suggested a modification to allow less ideal experimental array configurations.

In order to thoroughly test and assess the respective pros and cons of each technique, they were implemented in a common software ("CAP", see [28]), and applied to a series of well controlled synthetics, and to real data as well. The objective was to determine under which circumstances high-quality site-specific surface wave dispersion characteristics can be obtained from the analysis of microtremor wavefields.

The first series of tests on simulated ambient vibration wavefields allowed to evaluate the coupled influence of array configuration (number of sensors, geometry and interstation distances), source distribution and propagation effects, and array technique on the estimation of dispersion curves. For realistic wavefield situations with randomly distributed sources, the direct interpretation of frequency-slowness values is not straightforward, because either of insufficient resolution capabilities of the array configurations that induce significant bias in slowness values, or of the contributions of higher mode

Rayleigh waves which lead to mixed dispersion curve characteristics. Inverting the shear velocity profiles then requires advanced, non-standard strategies trying to "guess" the mode number at each frequency.

The performed tests showed that the frequency band over f-k techniques provide reliable estimates of dispersion curves is limited on both sides. For low frequencies, the origins of this limitation are two-fold : insufficient resolving capabilities of the array geometry, or the vanishing spectral energy of Rayleigh wave on the vertical component. For high frequencies, the limit is most often controlled by aliasing patterns linked with too large interstation distance. Compared to f-k methods, the SPAC technique gives reliable estimates of the dispersion characteristics over a wider frequency band, and allows additionally an easier recognition of the presence of higher modes from the unexpected occurrence of oscillations in the autocorrelation curves.

As described in [28], these results allowed to derive practical recommendations for the derivation of dispersion curves:

- the first one is to systematically use not only one technique, but a combination of methods both for determining the valid frequency range and obtaining uncertainty limits.
- The second one is to emphasize some of these techniques. Although all f-k methods perform reasonably well in general, two are especially recommended: CVFK and Capon's. The conventional f-k technique proves to be the more stable and robust, and in addition allows reasonable uncertainty estimates – which largely compensates its low resolution capabilities. A valuable additional information can then be provided by the Capon's high-resolution technique, because of less biased estimates and a larger efficiency against aliasing at high frequency. In addition to these f-k techniques, the SPAC method is also recommended for further cross-checks of the results and detecting possible higher modes. Contradictory results obtained from the individual methods may be indicative of a poor reliability for the dispersion curves.
- The third one is a field recommendation for the use of adaptive array deployment strategies, starting from short wavelengths (small arrays) and going to longer wavelengths (large aperture arrays). The optimization of such adaptive field strategies requires however the development of a "field quasi real-time software" that is not yet ready.

Derivation of velocity profile

Considering the high non-linearity and the non-uniqueness of solutions, a new inversion software has been written [29] based on the neighbourhood algorithm initially proposed by Sambridge [30, 31]. This approach allowed to accelerate significantly the inversion process, to account for the uncertainty in the dispersion curves, and to incorporate a priori information (for instance from H/V peak frequency, or from independent estimates of sediment thickness and/or P wave velocity). Its results are not a single velocity profile, but a whole set of profiles considered as leading to a satisfactory fit with the data (i.e., within some misfit value for the error function). Besides a very flexible way of defining the rnage of values for the parameters to invert, it allows a direct inversion of autocorrelation curves (jumping directly from autocorrelation curves to velocity profile), an automatic multi mode inversion, a joint inversion of dispersion and H/V curves, and computation of the site transfer for the ensemble of models.

The automatic multi mode inversion is in itself a significant breakthrough: for some sites, it was noticed that the dispersion curves derived from the f-k methods do not always correspond to the fundamental Rayleigh wave mode, in particular at high frequencies when the dispersion curves can also be measured with active sources. Tests on simple synthetics with 2 to 4 layers clearly showed that a misinterpretation of one mode, even on a reduced frequency range, can drastically change the final results, especially in tgerms of depth. It was thus important to develop an inversion scheme that takes this aspect into account. In the classical approach, for each frequency sample, the misfit is based on the difference between the calculated velocity for the fundamental mode and the measured velocity. If various modes are clearly identified, each measured velocity is compared with its corresponding calculated value. If they are not clearly identified but only suspected, the misfit for a particular frequency is then defined as the minimum misfit among the

misfits calculated between the measured velocity and the calculated velocities for all modes (the maximum number of modes is fixed a priori by the user). In order to avoid oscillations between modes across the frequency range, a rule states that the best fitting mode index must not increase when the frequency decreases. This improved, "guess-mode" inversion scheme led to satisfactory results: the non-uniqueness of the problem is not increased too much, while one may be sure not to "forget" one mode, or misinterpret one phase velocity value.
On the other hand, as the constraint of H/V curves is essentially related with the travel time between the surface and the top of the bed-rock, including it in the inversion is an excellent way to remove from resulting models the ones with wrong depths. The joint inversion of the H/V and of the mixed mode dispersion curves was tested and showed an excellent constraint on the Vs profile across the sediment layers and even in the bed-rock.
This inversion software has recently been connected both with the array analysis software (CAP) and with a seismic signal data base, which now provides a very powerful and convenient tool to analyse array data (noise synthetics as well real recordings).

CONCLUDING COMMENTS

Only a short summary of the SESAME project and of its main results could been presented here: readers interested in more details could find them in the other papers presented in this conference ([8, 9, 13, 14, 15, 17, 18, 19, 28, 32, 33, 34], and the numerous reports, including many explanatory figures, directly available from the project web site (http://SESAME-FP5.obs.ujf-grenoble.fr). We do hope this short presentation project will excite the interest of many scientists, engineers and managers involved in seismic risk mitigation. All those who are interested are thus kindly invited to visit the web site and to make us know their opinion, experience, data, etc. : all will be welcome, so that we can build upon an as wide as possible basis.
Four years ago, when writing the proposal, most of us were essentially interested in investigating the H/V technique, and one key objective was the world-wide, free dissemination of the H/V package including a platform-free software and user guidelines. Simultaneously, we felt somewhat sceptical about array measurements (and so were also the project reviewers !...), the results obtained after 3 years of exciting work, considerably raised our enthusiasm for these techniques which appear to be a very powerful geophysical exploration tool – as claimed years ago by our Japanese colleagues -, and would probably also deserve some "standard" software to avoid misuses : we hope to reach such a goal rather soon. Accounting also for horizontal motion would certainly be very beneficial for such a tool, while all the developments performed within the SESAME project were basically limited to the vertical component.
We are also aware that a huge amount of work based on ambient vibration recordings is carried by many teams throughout the world (Latin-America, Asia, Africa, Near-East, India / Indonesia, CEI, South Pacific, North America): we hope this project will be an opportunity to fruitful exchanges allowing to reach a worldwide consensus regarding some sensitive issues such the H/V technique – which might possibly be discussed within the framework of the IAEE/IASPEI kjoint working group on Effects of Surface Geology -, and that the SESAME project will thus help opening the door to sustainable development by offering a carefully assessed, low cost tool for safer urban planning and seismic design.

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