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PRACTICAL USER GUIDELINES AND SOFTWARE FOR THE IMPLEMENTATION OF THE H/V RATIO TECHNIQUE: MEASURING CONDITIONS, PROCESSING METHOD AND RESULTS INTERPRETATION

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SUMMARY

Reliable methods of site characterisation used for seismic site effects evaluations are too expensive for moderate seismicity or developing countries. There is a drastic need for reliable, low cost techniques. One of the objectives of the SESAME European project (**S**ite **E**ffect**S** assessment using **AM**bient **E**xcitations) is to investigate the reliability of the H/V technique using ambient vibrations. There is a need for practical recommendations and a clear assessment of the meaning of this widely used method. User guidelines providing the basis for a quality label, will prevent misuses and offer a validated, low-cost tool for site effect evaluations.

INTRODUCTION

As outlined by Bard [1], the seismological community agrees that the H/V technique gives valuable results if applied "with care" or "appropriately". However, the problem is that nobody seems to really know what this means. Too many questions are still waiting for an answer, or at least for a common answer, since different teams usually proceed and interpret differently. The key problem is that the method has been developed empirically. Only few theoretical investigations have been performed to clarify its underlying physics.

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Developing some guidelines in order to assure a reasonable quality standard for ambient noise measurements - data acquisition and treatment as well as interpretation - can be done only on the basis of

- a better understanding of the physical / theoretical background,
- comprehensive experimental / statistical comparisons with other techniques a priori thought to be "more correct" (weak and strong motion classical spectral ratios, damage distributions from earthquakes, etc.),
- a "standardisation" of the field measurement conditions and of the data processing as well, in order to insure a minimum quality.

The present paper is focused on the last item. Additional presentations and posters regarding the other aspects of the SESAME project will be given in the MTC15 Special Theme Session named "Site Characterisation for Site Effects Studies Using Ambient Vibrations".

TECHNICAL REQUIREMENTS

Instrumentation

The first step was to investigate the influence of different instruments in using H/V technique on microtremor data (WP02 SESAME project [1]). There were 4 major tasks performed which consisted of testing the digitisers, sensors, simultaneous recordings both outside in the free-field and at the lab for comparisons.

Influence of the digitiser

In order to investigate the possible influence of the digitisers, several tests were performed to quantify the experimental sensitivity, internal noise, stability and channel consistency. A total of 14 digitisers were tested. In general it was found that all digitisers need some warm up time. A value of about 10 minutes is sufficient for most instruments to assure that the baseline is more or less stable.

The influence of various parameters was checked (electronic noise, synchronism between channels, difference on gain between channels, etc.). The main impacts on the H/V ratio come from:

- The level of electronic noise compared to the level of recorded waveform.
- The lack of synchronisation between channels.
- The gain difference between channels.

Influence of the sensor

The influence of the sensors was tested by recording simultaneously two sensors on the same digitiser. In total 17 sensors were tested. In general, signals look quite similar, as expected. However, the accelerometers were not sensitive enough for lower frequencies. Stability is important for broadband sensors and accelerometers. In general a few minutes of stabilisation are required for all active sensors.

Experimental conditions

A second step was the evaluation of the influence of experimental parameters on stability and reproducibility of H/V estimations from ambient vibrations (WP02 SESAME project [2]). To achieve this goal, the influence of various types of parameters had to be tested on the results of H/V curves both in frequency and amplitude. For each tested parameter, H/V data are compared with a "reference situation". The results are average H/V amplitudes and their corresponding standard deviations. Then, a Student-t test is performed to analyse the degree of similarity between the two curves. Finally, the average frequency and standard deviation from individual windows of the two frequency peaks are computed.

H/V measurements in cities need both reliability of the results and rapidity of data collection. It is therefore important to understand which recording parameters influence data quality and reliability and can help speeding up the recording process. H/V measurements in cities are conducted within the following context:

– it is quite rare to be able to get data on the soil *per se*. Most data will be obtained on streets (i.e. asphalt, or pavement) , sidewalks (i.e. asphalt, cement or concrete), and to a lesser extent in parks (i.e. on grass or soil);
– measurements are performed in an environment dominated by buildings of various dimensions;
– recordings are not performed at the same time and under the same weather conditions.

Therefore the estimation of the possible influence of asphalt, grass, cement and concrete interfaces, that of nearby buildings, that of weather conditions and stability of the results over time are crucial issues for data quality and reliability. It is also crucial to make sure that the results are not dependent on recording parameters. The tested parameters were divided into eight categories, as following:

– recording parameters,
– in-situ soil / sensor coupling,
– artificial soil / sensor coupling,
– sensor setting,
– nearby structures,
– weather conditions,
– noise sources,
– stability with time.

The obtained results are based on 593 recordings that were used to test 60 parameters. They are summarised in Table 1. Possibly the main result is that no matter how strongly a tested parameter influences the H/V amplitudes curves, the value of the frequency peak is usually not affected, with the noticeable exception of the wind.

The main results can be summarised as follows:

– The standard recording / instrument / sensor setting parameters have no strong influence on the H/V curves.
– 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.
– 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.
– Some noise sources should be considered with care (or avoided using an anti-trigger window selection to remove the transients, see next chapter), these are: close steps, close high speed car or truck traffic, close machinery, etc.
– Results are stable with time (if other parameters, such as weather conditions, etc. are kept constant).

These results will be useful for two main reasons : avoid experiments with wrong recording parameters and somewhat standardising data acquisition, thus making it easier to compare results from different experiments.

Table 1: Synthesis of results on the tested parameters. Parameters in white cells have no influence on the H/V ratio, parameters in light grey cells should be considered with particular care, parameters in dark grey cells have a strong influence on the results and should then be avoided.

Category	Tested parameter	Details / Remarks	Result	Recommendation
Recording parameters	Sensor stabilisation time		No influence	a few tens of seconds is enough for stabilisation
	Sensor horizontality		May influence (possible control)	avoid important (>4°) tilting of the sensor
	Sensor cable length	10 to 100 m, rolled or stretched	No influence	No problem
	Sampling rate	tested 50, 100, 125, 200, 250 Hz	No influence	No problem
	Gain		May influence (possible control)	avoid signal saturation due to too high gain
	Sensor azimuth	in homogeneous sites	No influence	No problem in homogeneous sites
In situ soil / sensor coupling	Concrete	---	No influence	No problem
	Pile of gravel	---	Influence	Avoid recording on a pile of gravel or gravel in a plastic container
	Synthetic surface	tartan, one test only	Influence	avoid recording on synthetic surfaces
	Karstic filling	---	Influence	Should be absolutely avoided
	Grass	---	May influence (possible control)	Highly recommended to remove grass, especially when it is tall. Recording on grass should be avoided when wind is blowing (even lightly)
	Asphalt	---	May influence (possible control)	No real problem
	Mud	---	May influence (possible control)	avoid recording in thick mud, especially if water is present
	Ploughed soil	---	May influence (possible control)	Should be avoided when the ploughed layer is thick
	Ice	the feet of the sensor produce local ice melting	May influence (possible control)	Should be avoided

	Compacted snow	during not sunny days, snow thickness up to 30 cm	No influence	No problem without sun
	Not compacted snow	OK under the shade, under the sun, snow melting produces sensor tilting	May influence (possible control)	Avoid recording on snow under the sun
Artificial soil / sensor coupling	Stratified wooden plate	only one test	No influence	No problem, better test before use
	Agglomerated wooden plate	---	No influence	No problem
	PVC plate	---	No influence	No problem
	Metal plate with legs	---	No influence	Should only be used if really necessary
	Trihedron	installed on soil, concrete, grass and asphalt	No influence	Should only be used if really necessary
	Ceramic plate	only one test	No influence	No problem, better test before use
	Styrofoam	---	Influence	Should definitely not be used
	Cardboard plate	---	Influence	Should definitely not be used
	Foam	---	Influence	Should definitely not be used
	Empty plastic container	---	Influence	Should definitely not be used
	Cement plate	variable results	Influence	Should be avoided
	Wooden plate	variable results	May influence (possible control)	should be tested before use
	Metal plate	variable results	May influence (possible control)	should be tested before use
	Ballast on the sensor	---	Influence	Should be avoided
	Sand	pile of sand or sand in a plastic container	No influence	No problem
Sensor setting	Feet of sensor removed	Tests performed on ground, sand and gravel. No problem in sand	May influence (possible control)	Avoid recording without sensor feet on ground or gravel
	Feet of sensor not blocked	---	No influence	No problem
	Sensor anchoring	sensor in a hole (filled or not)	No influence	Usually not needed to dig a hole
	Large underground structures	tests above a large cave and next to a subway tube	Influence	Not recommended

Nearby structures	Small underground structures	mitigated results	Influence	avoid recording on top of a sewer lid, for example
	Large surface nearby structures	tests at various distances from a building, before and after its construction	May influence (without possible control)	Strong influence close to the building. No clear results
	Small surface nearby structures	tests at various distances from small structures	May influence (without possible control)	Avoid distances less than 10 m from structures, especially under windy conditions
Weather conditions	Temperature	range 17.2° - 22.7°C	No influence	No problem in the narrow tested range
	Wind	---	Influence	Avoid recording when strong wind is blowing
	Rain	---	Influence	Avoid recording under strong rain
Noise sources	High voltage cables	various distances perpendicular and underneath the line	No influence	No problem
	Music in car	slight influence in low frequencies	No influence	No problem if not too loud
	Steps	tests performed with people walking around the sensor at various distances. Not representative of people passing by along a street.	May influence (possible control)	avoid people walking very close to the sensor
	Moving cars	various distances from a highway (quiet or with heavy traffic)	May influence (possible control)	avoid recording at less that 40 m from a heavy high speed traffic
	Car engine on, not moving	---	May influence (possible control)	Not recommended to record close to a turned on car
	Machinery	---	May influence (possible control)	avoid recording close to working machinery
Stability with time	Stability with time	from hours to few years	No influence	No variation, if other parameters are not variable

DATA PROCESSING STANDARD

Within the framework of the SESAME Project one of the work packages was devoted to the development of a robust software for data analysis applying the H/V technique (WP03 SESAME project [3]). The main goal was to develop a multi-platform processing software (J-SESAME) to be used as a standard procedure in processing the microtremor data using H/V technique. Existing software that were previously used in processing the microtremor data using the H/V technique were tested and an optimum solution for the analysis was deduced. 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 of the software 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 visualisation of the processed data in an easy and flexible way. This modular development also allows utilising 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.

Besides the manual selection directly from the screen, which is often the most reliable, but also the most time consuming, an automatic window selection module has been introduced in view of processing large amounts of data. The objective is to keep the most stationery parts of noise, and to avoid the transients often associated with specific sources (walks, close traffic). This objective is exactly the opposite of the usual goal of seismologists who want to detect signals, and have developed specific "trigger" algorithm to track the unusual transients. As a consequence, an "antitrigger" algorithm was used here, which is exactly the opposite: it detects transients but it tries to avoid them. The procedure to detect transients is very classically based on a comparison between the short term average "STA", i.e., the average level of signal amplitude over a short period of time (typically around 0.5 to 2.0 s), and the long term average "LTA", i.e., the average level of signal amplitude over a much longer period of time (typically several tens of seconds). When the ratio STA/LTA exceeds an a priori determined threshold (typical values are between 3 and 5), then an "event" is detected. In the present case, windows without any energetic transients should be selected: this means that the ratio STA/LTA should remain below a small threshold value (typically around 1.5 – 2) over a long enough duration. Simultaneously, noise windows with abnormally low amplitudes should be avoided: a minimum threshold was therefore also introduced which should not be reached down throughout the selected noise window.

The main processing module conducts H/V spectral ratio computations and other associated processing such as DC-offset removal, filtering, smoothing, merging of horizontal components, etc., on the selected windows for individual files or alternatively on several files as a batch process. The instrument response is assumed to be removed by the user. Main functionalities of the processing module are described below:

- FFT (including tapering),
- Smoothing with the following options:
  - Linear / Logarithmic
  - Window shape: Triangle , boxcar, Konno & Ohmachi
- Merging two horizontal components with the following options:
  - No merging
  - Arithmetic mean
  - Geometric mean
  - Quadratic mean
  - Complex merging
- H/V Spectral ratio,
- Average of several (H/V) ratios,
- Error estimates on spectral ratios.

A display module complements the program, providing functionalities such as plotting curves, zooming, generating result figures in various formats, printing, etc.

INTERPRETATION GUIDELINES

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 technique.

Preliminary statement

As outlined by Bard [1], the explanation of H/V ratio which is the most commonly (but not unanimously) accepted – but not proven – in the seismological community may be summarised as follows:

– seismic noise is mainly consisting of surface waves (and thus of Rayleigh waves for the vertical component),
– the Rayleigh wave ellipticity is varying with frequency in layered soils,
– in presence of large impedance contrast (beyond 2.5 – 3), the vertical component of Rayleigh waves vanishes around the fundamental frequency of S-waves.

According to this interpretation, the peak in the H/V ratio should therefore coincide with the fundamental soil frequency, but there should not exist any link between H/V peak amplitude and actual amplification. However, nobody really knows in detail what kind of waves, to what proportion, are usually measured as ambient vibrations. Nobody really understands why there apparently exist, at least in some areas, some quantitative correlation between H/V peak amplitude and S-wave amplification ratio.

Nature of noise wavefield

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 (Bard [1]).

The literature review accomplished in this framework (WP08 SESAME project [5]) confirmed the fact that little has been learnt in recent years about the actual composition of noise wave fields. Most of the today's knowledge was obtained during the 60-70's. Most authors seem to agree about the origin of microtremors. At long periods (T>2s) microtremors are due to large scale oceanic meteorological conditions, at intermediate periods (1<T<2s) they are mainly generated by effect of wind and local meteorological conditions, and at short periods (T<1s) they are linked to human activities. The distinction between long period (T>2s) and short period (T<1s) noise corresponds to the traditional distinction between "microseisms" with natural origin, and "microtremors" with an artificial origin. It may, however, vary from site to site depending on the fundamental site period. The situation is much different concerning the composition of noise wavefield: this literature survey does not lead to a unique, unambiguous conclusion. While it is usually admitted and demonstrated that microseisms (natural origin) consist mainly in fundamental Rayleigh waves (which may, however, include a few higher modes), it is more difficult to define the nature of microtremors (T<1s): some authors conclude that urban noise consists of S waves, while other conclude in predominant surface waves, and sometimes a mixture of surface and body waves. Moreover, when noise wavefield is assumed or shown to consist of surface waves, there is no definite conclusion as to whether Rayleigh (fundamental and / or higher modes) or Love waves, are predominant

(Love wave proportions vary from 30% to 60%). Very little is thus known as to the proportions between surface and body waves, between Rayleigh and Love waves, between fundamental and higher modes.

H/V ratio and Rayleigh wave ellipticity

Malischewsky [6] conducted a study aimed at the analytical correlation between the ellipticity of Raylaigh waves and the H/V ratio, in the case of one layer over a half-space. For practical applications, considering that noise wavefield mainly consists of Rayleigh waves, the frequency of the peak on the H/V curves is often assumed as corresponding to the shear wave resonance in the layer. Until the work done by Malischewsky [6], this statement was never proven analytically. The results of the study conducted by Malischewsky [6] show that this statement is very well fulfilled for shear wave velocity contrasts greater than 3.5, which is in conformity with practical experience from site conditions with high impedance contrast. But it cannot be said that it is generally true. This result points out the need for additional investigations on the meaning of the H/V peak frequency, work which is still ongoing in the framework of the SESAME project.

Sources-receivers configuration tests

Furthermore, some sources-receivers configuration tests (source time functions, near / far sources, surface / deeper sources) in order to define the noise wavefield nature. H/V and array analysis on these noise synthetics have allowed linking the occurrence of H/V ratio peaks with the noise wavefield composition (SESAME [7]) :

- when sources are near and superficial, H/V curves exhibit one single peak, while the array analysis shows that the wavefield is dominated by Rayleigh waves;
- when sources are distant and located inside the sedimentary layer, two peaks show up on the H/V curve, while the array analysis indicates that both Rayleigh waves and strong S head waves are present. The first peak is due to both fundamental Rayleigh waves and resonance of head S waves, the second peak is only due to resonance of head S waves;
- when sources are deep (located inside the bedrock), whatever their distance, H/V ratio exhibit peaks at the fundamental and harmonic resonance frequencies, while array analyses indicate only non-dispersive body waves: the H/V is thus simply due to multiple reflections of S waves within the layer.

Therefore, considering that experimental H/V ratio (i.e., derived from actual noise measured in the field) exhibit in most cases only one peak, we conclude that H/V ratio is mainly controlled by local surface sources and mainly due to the ellipticity of the fundamental Rayleigh waves.

CONCLUSIONS

Practical user guidelines for single station ambient vibration measurements using the H/V technique will be elaborated on the basis of the above presented results. Minimum quality requirements for its practical use will be fixed, a standardized validated processing software will be provided on a CD-ROM, and - as far as possible - short scientific explanations will be given. These user guidelines will be submitted to international working groups and committees. A preliminary version of the guidelines will be available at the 13th WCEE.

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