OPERATIVE GUIDE

PASSIVE SEISMIC

HVSR

HVSR METHODOLOGY

Passive seismic technique known as HVSR (Horizontal to Vertical Spectral Ratio) is completely non-invasive and can be applied wherever without any kind of drilling nor external energization different from environmental noise which is present everywhere in nature.

Environmental micro-tremors recording in their 3 spatial components, represent a fast and economic mean for micro-zonation, although its potentialities are still debated but capacity of detecting resonance frequencies of more superficial layers is well attested.

More in detail, environmental micro-tremors (seismic noise) are a minimum ground movement (within the range of 10^{-2} - 10^{-6} mm) present in every part of earthly surface and consist mostly of superficial waves (Rayleigh and Love) produced by constructive interference of P and S waves into superficial layers. It is also produced by wind and sea waves and at high frequencies by sources of anthropic character (industries and vehicle traffic).

It is called passive method because noise is not produced ad hoc, such as in active method and results that can be obtained are:

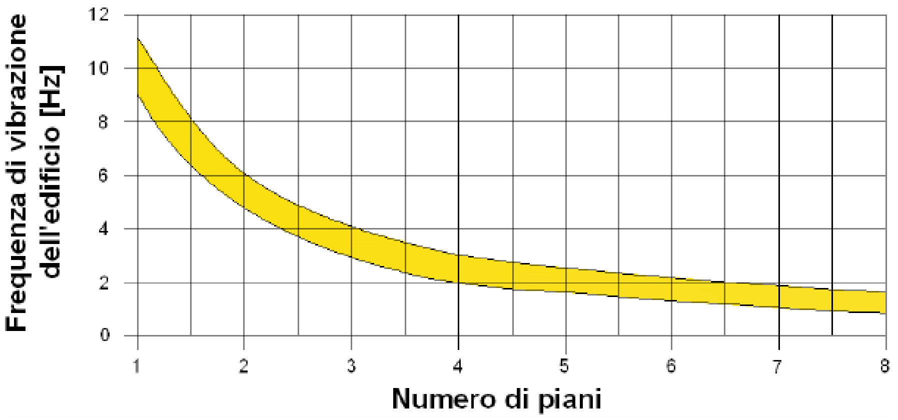
- resonance frequency characteristic of the site, main parameter for a correct dimensioning of buildings in order to avoid “double resonance” effect;
- fundamental resonance frequency of a building if measurement is performed inside it;
- estimate Vs shear waves velocity if user has additional information on subsurface geological model or there are literature information about investigated site (for example seismic bedrock depth, stratigraphies from c.c. surveys or Vs profiles from MASW or refraction seismic tests) .

In terms of subsoil stratigraphy, principle on which HVSR methodology is based is definition of layer considered as a unit different from above and below units for an impedance contrast, that is ratio between velocity products on seismic waves into the mean and density of the mean itself. Knowing position of rigidity contrast, it will be easier to determine during processing phase more conceivable Vs profile which generates a resonance pick coincident with recorded curve.

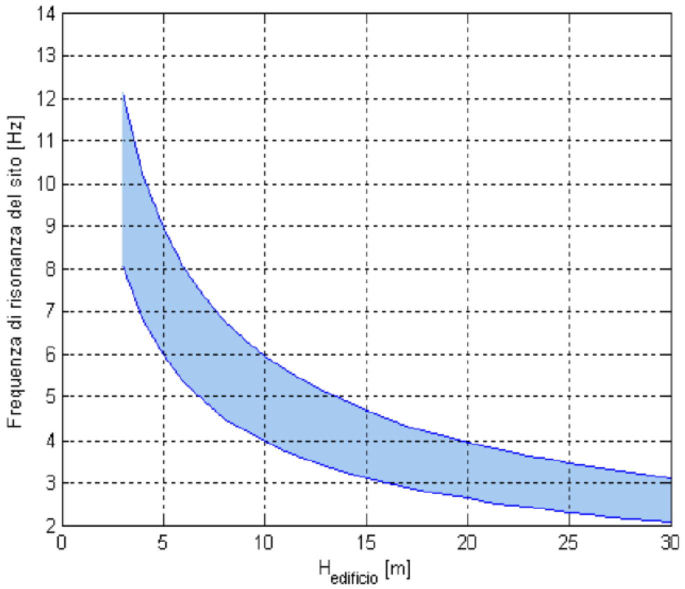
For structural reasons we refer to graphic H_i/H_0 where only horizontal displacements are evaluated at different planes frequencies (H_i) compared to foundation plane (H_0) taken as referential. This is done in order to remove from recordings subsoil effect (site effect).
Therefore, in order to determine with much more accuracy phenomena of “Double Resonance” between soil and structure, minimum recordings required are 3: one measurement at building highest floor, the other at foundation floor (to determine fundamental frequency of the building) and a third measurement outside to identify site fundamental frequency.

From an empirical point of view, resonance frequency of a building is influenced mainly by height therefore it can be calculated in first approximation with the formula:

10Hz/ number of floors.



Designers shall avoid if possible or at least take into proper consideration when dimensioning buildings, phenomena of “Double Resonance” that cause seismic amplification with consequent increasing of solicitations.
Below there is a graphic illustrating relation between height of a c.a. building and resonance frequency of the site.



PROCEDURE

Stratigraphic aims

It is recommended to start recording in areas where stratigraphy is known, better if from surveys or tests on site; moreover is recommended to avoid windy days or traffic areas.

Position sensor far away from human buildings and constant noise sources.

To reduce at maximum electromagnetic effects, it is recommended to use whole available cable to connect receiver.

Instrument must be placed on clean soil so that it is perfectly joint and protected against possible disturbing agents.

Leveling of instrument is very important to reduce at minimum errors such as “tilting effect” which may be caused by changing into level while measuring, producing disturbance of H/V curve shape resulting especially in its low frequency part. Orienting N on sensor according to geographical north, so that third channel (connection to horizontal N-S geophone) is the most excited.

Then proceed with leveling through tripods with adjustment ring and leveling bubble. To use it on grounds, replace tripods with soil tips and level sensor.

Once sensor has been placed, it is possible to start recording. Setting parameters for measure are basically sampling frequency and duration. Gain must be the same for each channel (12-36 db is recommended value).

Engineering purpose

Same instrument is ideal also on buildings for dynamic characterization (vibrational modes). Measurements must be performed at each building floor (or at least ground floor and last floor), exactly on same vertical and with instrument axis orientation corresponding to those of building (longitudinal and transversal).

Sampling frequency to set is 250 samples per seconds.

Generally speaking, given that engineering frequencies are not higher than 25Hz, sampling frequency shall not be lower than 50 Hz.

Usually for HVSR methodology is not recommended to use frequencies higher than 500 Hz, because it causes increasing of file dimensions and elaboration times, without any improvement of analysis capacity or accuracy.

Time recording shall be at least of 10 minutes and can last also 20-30 minutes to get a better stabilization of signal.

Micro-tremor measurement is a phenomenon called stochastic so, to have statistical validity, a great number of data is necessary; this is obtained by recording for a duration commensurated to resonance frequency of interest.

Therefore, to get a more concrete datum of a deep seismic bedrock (low resonance frequencies) a longer time recording will be more valid than a superficial seismic bedrock.

During recording, avoid to move in the area close to sensor.

Minimum distance from which environmental noise is not influenced by buildings and/or structures is still debated, but without any other information, is important to keep a distance not less than 15 m; this value is based on Castellaro and Mulargia study (2010), which have demonstrated that free-field conditions are respected at about 12 mt from "heavy" structures.

For a single analysis of site response is important not to trust a single measurement, at least 3 recordings are necessary and they must be performed preferably in three different moments of the day or different days, to check H/V curve stability.

When dealing with floorings, measurement can be influenced especially in high frequency part because it is such as recording was performed at roof of a structure made of a very rigid layer (flooring) above a softer layer.

For geophones with frequency lower than 4,5 phenomena of signal drift in time may happen therefore they require more duration to ”stabilize”.

In general for micro-tremors measures same amplification values are selected for each channel.

On bottom side of the instrument number of channels which will be recorded and sampling frequency are indicated; This parameter on Vibralog instrument is fixed at 250 Hz.
With Vibralog internal format of recording file is binary and it is not directly readable from most spread data processing softwares; for this reason a conversion utility which allows to export file in .seg2 format is supplied.

Recorded data processing can be done with HVLab software, an application developed to enable user to compute resonance frequency of a site or a building through micro-tremor measurement recording.

Applied methodology is with single station, originally suggested by Y. Nakamura.

In brief its characteristics:

- vibrations recording through an orthogonal triad of velocimeter sensors (geophones) for a proper time (typically some minutes);
- transforming signals into frequencies domain for each component (X, Y and Z);
- computing ratio between power spectra of horizontal component (H) and that of vertical component (V);
- detecting fo vibration frequency where the above ratio presents a significant peak.

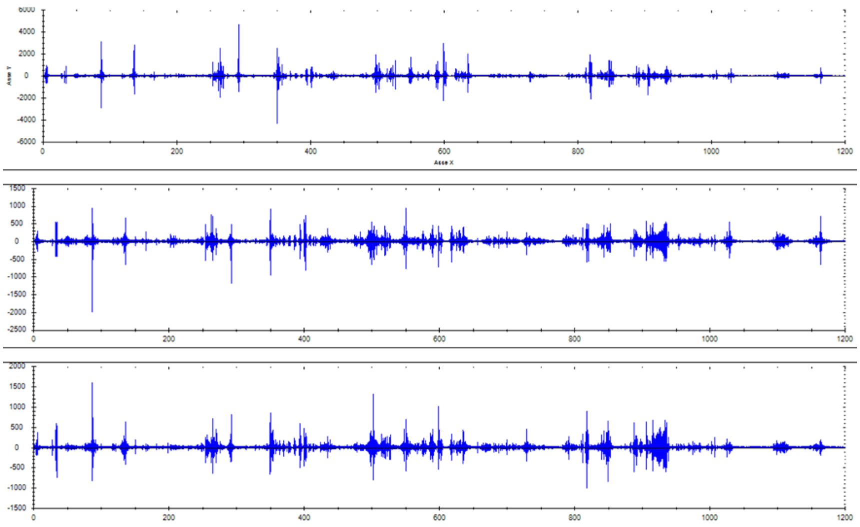
Application of the methodology, theoretically simple, requires a series of precautions to get reliable results. Document “*Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations – measurements, processing and interpretation*”, produced after European research project SESAME in 2004, is a synthesis of data acquisition and proper elaboration procedures.

HVlab is mainly based on this guideline and implements evaluation criteria of results introduced in the document, providing an instrument actually usable for a rapid classification of H/V ratio pickings.

a of elaboration

First operation is importing recorded data:
'Import...' in field 'Recorded data';
Select type of file to upload;
Move to folder where file is included, select it and click on “Open”.

Recorded trace



First trace found in file is related to vertical component sensor (z), while second and third respectively to horizontal component oriented towards East (x) and that oriented towards North (y).
This correspondence reflects configuration in which MAE instrument is supplied.

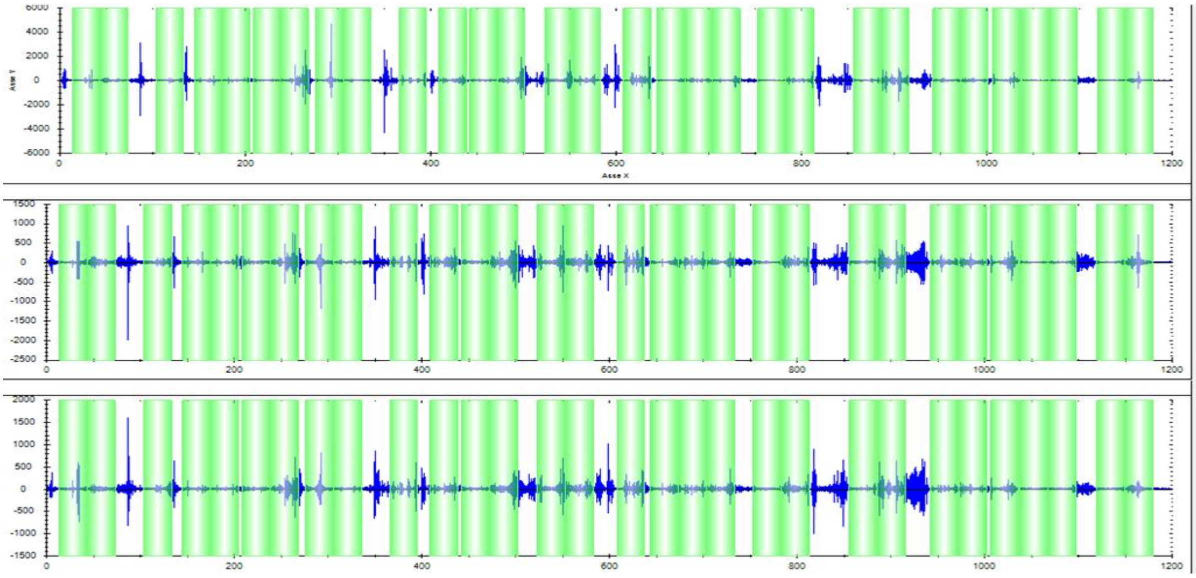
It is recommended to always check that values in fields: 'traces', 'frequency' and 'total duration' correspond to used recording modalities. Subsequent phase consist in detecting a sufficient number of temporal windows into the whole recording, ideal for HVSR analysis. Main criterions to select those screens are:

- duration, which must be suitable to ensure presence of at least ten periods for picking frequency fo (first reliability criterion according to SESAME);
- absence of transitional events caused by local sources.

Selected windows_transients removal

Selecting temporal windows can be refined manually:

- to remove one of them, keep lowered CTRL button on keypad and double click on it with mouse;
- to add a window, double click on seismograph in the point where temporal window is required to start. It is possible to use also partially overlapping windows.
- To visualize a part of seismographs in detail, trace a rectangle around it with mouse cursor, keeping pressed left button of the mouse. Other options are activated with mouse right button click on graphic.



To enhance coherence between curves it is possible to reject temporal windows which are obviously abnormal, such as those outside confidence interval. Just click on a curve to delete and select it.

In seismograms window, related temporal screen will be highlighted and it can be removed with CTRL+double-click.

Elaboration follows and graphic resulting from HVSR analysis is visualized by clicking on button 'Elaborate' and in few seconds result of HVSR analysis will be obtained.

Graphic shows cyan color curve for each window, which describes variation of H/V ratio with frequency. Red curve represents their average and light blue curves, outlined, border confidence interval at 68% around it.

HVlab can detect most parts of this ratio peaks and classify them according to criterions suggested in guidelines of SESAME project.

Reliability conditions of HVSR curve (criteria for a reliable H/V curve) are the first three in below table; clearness conditions of maximum frequency peak of HVSR curve(criteria for a clear H/V peak) are the last six (SESAME European research project). Researchers of SESAME project recommend to consider reliable an HVSR curve that satisfies all 3 reliability criteria (reliable H/V curve), while suggest to consider clear a peak that satisfies at least 5 of 6 clearness criteria (clear H/V peak).

Criteri per una curva H/V affidabile [Tutti 3 dovrebbero risultare soddisfatti]	$f_0 > 10 / L_w$ $n_c(f_0) > 200$ $\sigma_A(f) < 2$ per $0.5f_0 < f < 2f_0$ se $f_0 > 0.5Hz$ $\sigma_A(f) < 3$ per $0.5f_0 < f < 2f_0$ se $f_0 < 0.5Hz$
Criteri per un picco H/V chiaro [Almeno 5 su 6 dovrebbero essere soddisfatti]	Esiste f^- in $[f_0/4, f_0] \mid A_{H/V}(f^-) < A_0 / 2$ Esiste f^+ in $[f_0, 4f_0] \mid A_{H/V}(f^+) < A_0 / 2$ $A_0 > 2$ $f_{picco}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$ $\sigma_f < \varepsilon(f_0)$ $\sigma_A(f_0) < \theta(f_0)$

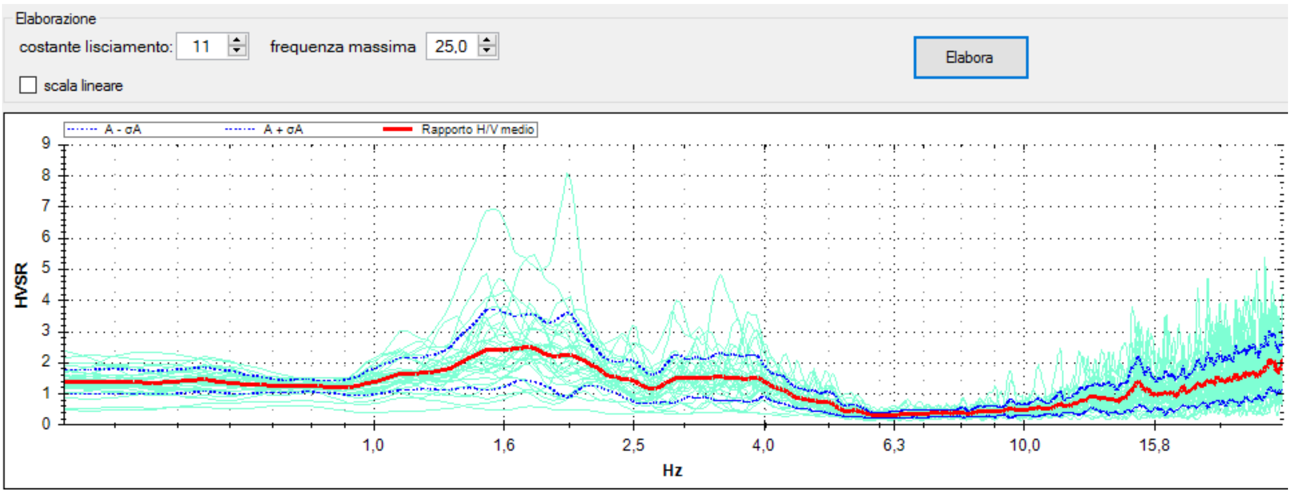
L_w	lunghezza della finestra
n_w	numero di finestre usate nell'analisi
$n_c = L_w n_w f_0$	numero di cicli significativi
f	frequenza attuale
f_0	frequenza del picco H/V
σ_f	deviazione standard della frequenza del picco H/V
$\varepsilon(f_0)$	valore di soglia per la condizione di stabilità $\sigma_f < \varepsilon(f_0)$
A_0	ampiezza media della curva H/V alla frequenza f_0
$A_{H/V}(f)$	ampiezza media della curva H/V alla frequenza f
f^-	frequenza tra $f_0/4$ e f_0 alla quale $A_{H/V}(f^-) < A_0/2$
f^+	frequenza tra f_0 e $4f_0$ alla quale $A_{H/V}(f^+) < A_0/2$
$\sigma_A(f)$	deviazione standard di $A_{H/V}(f)$, $\sigma_A(f)$ è il fattore per il quale la curva $A_{H/V}(f)$ media deve essere moltiplicata o divisa
$\sigma_{logH/V}(f)$	deviazione standard della funzione log $A_{H/V}(f)$
$\theta(f_0)$	valore di soglia per la condizione di stabilità $\sigma_A(f) < \theta(f_0)$

Valori di soglia per σ_f e $\sigma_A(f_0)$					
Intervallo di freq. [Hz]	< 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0
$\varepsilon(f_0)$ [Hz]	0.25 f_0	0.2 f_0	0.15 f_0	0.10 f_0	0.05 f_0
$\theta(f_0)$ per $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58
log $\theta(f_0)$ per $\sigma_{logH/V}(f_0)$	0.48	0.40	0.30	0.25	0.20

Curves regularity can be varied (within some limits) by acting on field values 'constant smoothing'. This determines number of elementary intervals of frequency, that is horizontal points, used to apply a filter at medium mobile weighing, with weights at triangular distribution. Higher values allow to better smooth curves, but tend to hide peaks of medium and small opening and to determine fusion of many adjacent peaks. On the contrary, lowest values can also highlight peaks of modest entity, which can have human origin more than natural. Generally speaking is important to experience different values of the parameter to find better compromise.

Sometimes it can be useful to directly compare power spectra of recorded signals on sensor three components (such as discrimination between industrial and natural peaks). Spectra frame is displayed with a click on ‘Spectra' from 'Visualize' and can be updated by selecting one of the H/V curves.

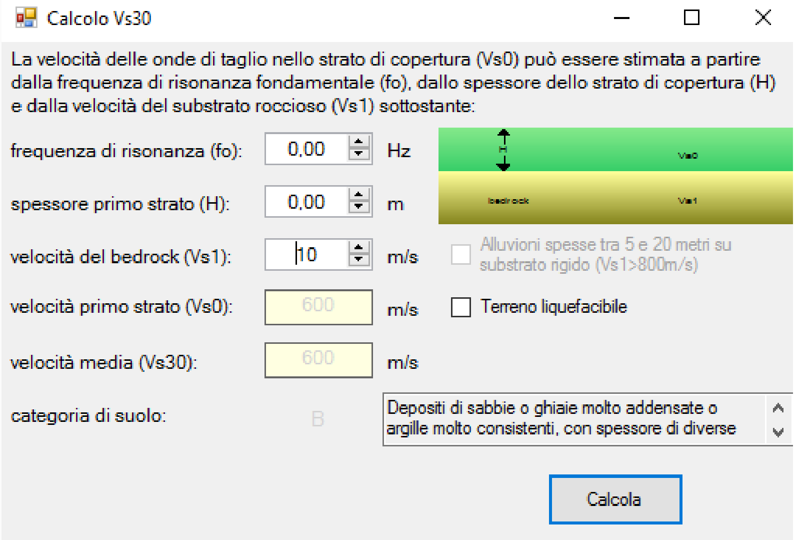
After performing modifications of curves or parameters selection, click again on button ‘Elaborate’ to check result.



Normally graphic is presented with frequencies axis in logarithmic scale, to highlight curves trend in lower frequencies band which is the more interesting.

During processing phase, first of all is important to check if all eventual peaks of industrial origin have been rejected. Therefore, in case there will be a clear peak, presence of an high impedance contrast at given depth can be supposed, which is responsible of a soil motion amplification at a characteristic frequency corresponding to f_0.

If sediments thickness above bedrock is known, S waves speed in this superficial layer can be approximately computed with relation: ***f=Vs/4h*** (simplified formula) where Vs is shear waves speed into resonant layer and h is thickness of that layer.



For what described in present guide and in particular in scientific literature, HVSR method was conceived to determine fundamental resonance frequency of the site, aiming at determining also seismic amplification which actually is still not possible.

However, if proper geological-geotechnical information from other surveys are available, such as depth of seismic bedrock, or the stratigraphic series of geotechnical units, or direct measure of Vs profile through MASW-REMI, refraction seismic, cross-hole, etc.., then site resonance peak frequency acts as a further bond for uncertainty of Vs profile and can be a valid contribution to estimate Vs,30 parameter, useful for soils seismic classification.