Single station measurement: H/V

H/V method: what for?

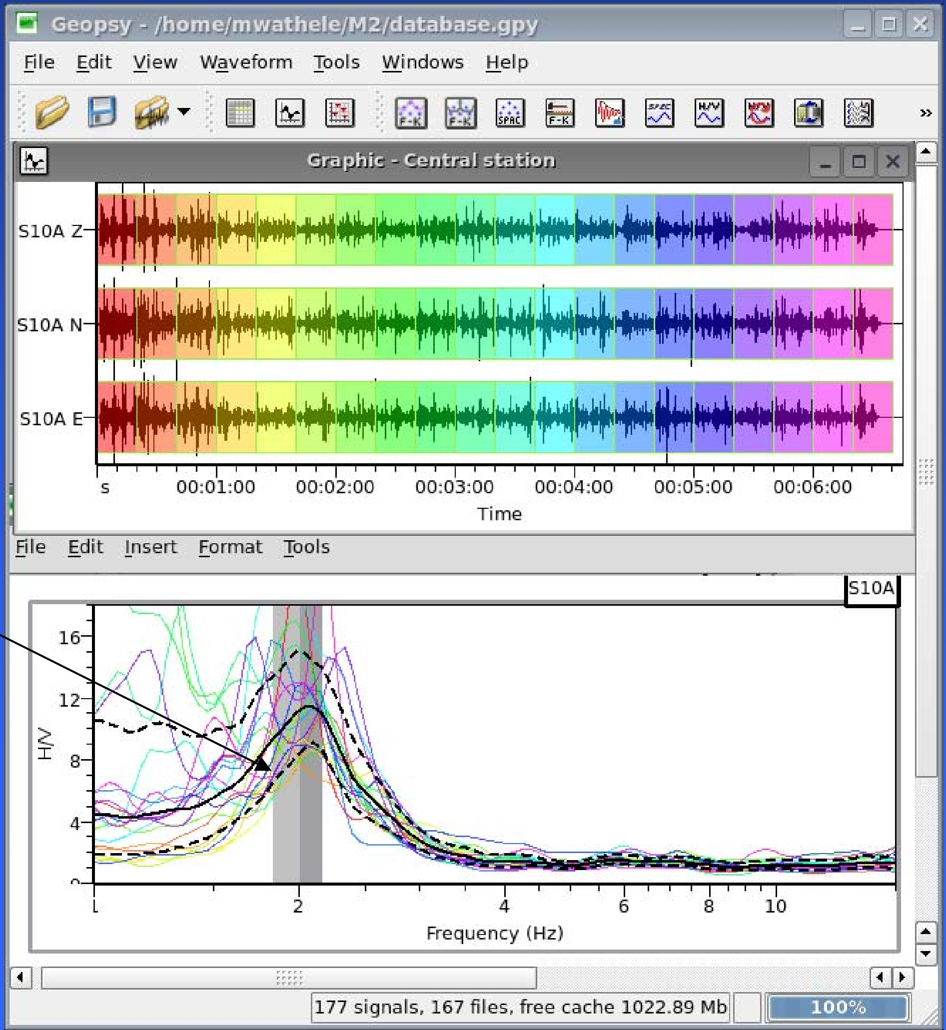
Site effect caracterization

Estimation of resonance frequency

Amplification level

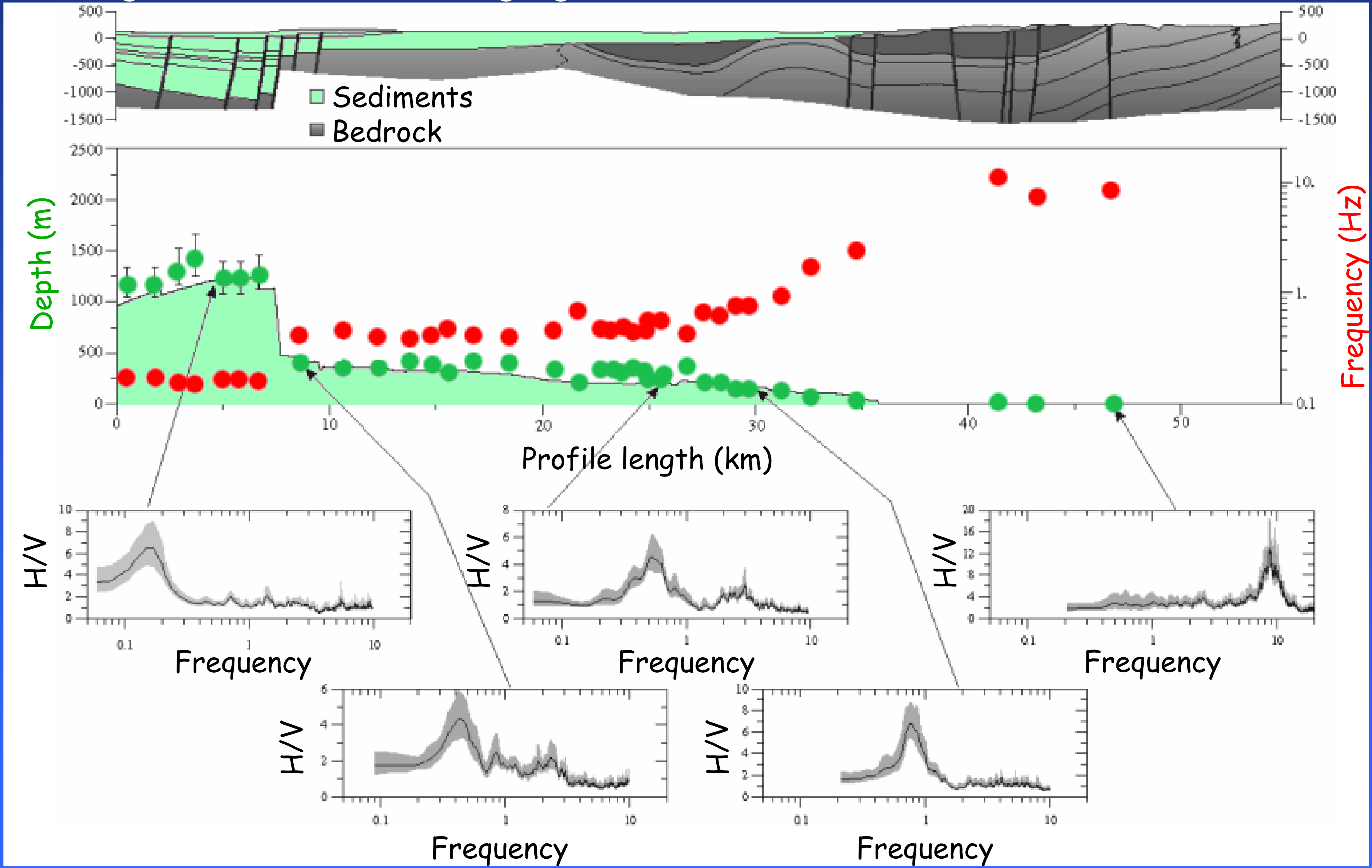
Microzonation studies

Estimation of areas with similar seismic responses



H/V method: what for?

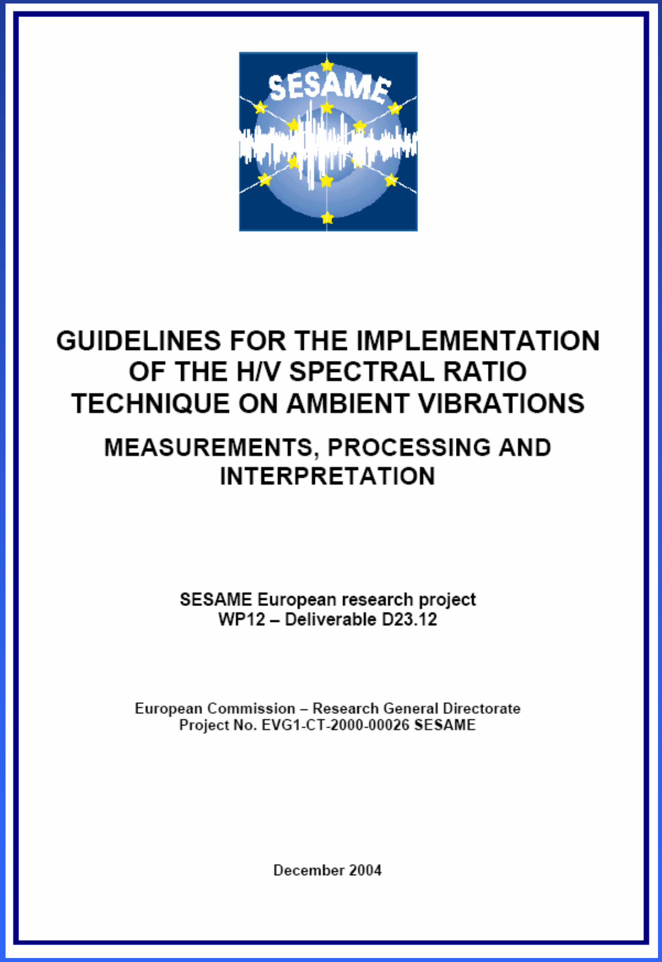
Underground structure imaging



After Hinzen et al. (2004)

Single station measurement: H/V

http://sesame-fp5.obs.ujf-grenoble.fr/SES_TechnicalDoc.htm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GUIDELINES FOR THE IMPLEMENTATION OF THE H/V SPECTRAL RATIO TECHNIQUE ON AMBIENT VIBRATIONS

MEASUREMENTS, PROCESSING AND INTERPRETATION

SESAME European research project
WP12 – Deliverable D23.12

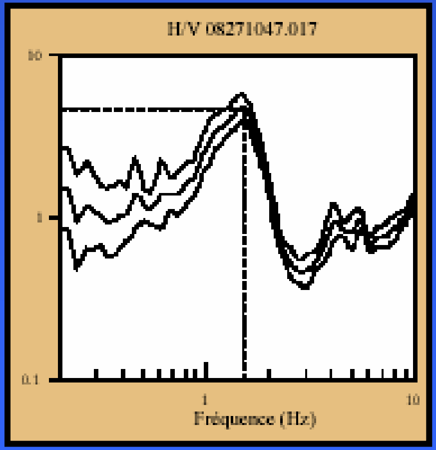
European Commission – Research General Directorate
Project No. EVG1-CT-2000-00026 SESAME

December 2004

- Interpretation of H/V curve (frequency and shape)
  - ✓ results from real and simulated data
  - ✓ case of 2D/3D structures
  - ✓ examples on the use of H/V
- Recommandations for
  - ✓ H/V measurements (duration, soil sensor coupling, …)
  - ✓ H/V computation
  - ✓ interpretation of H/V measurements

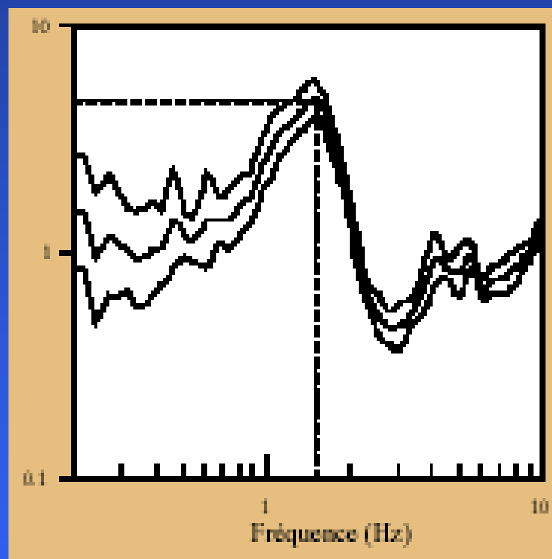
Single station measurement : H/V technique

Ratio between **H**orizontal and **V**ertical records

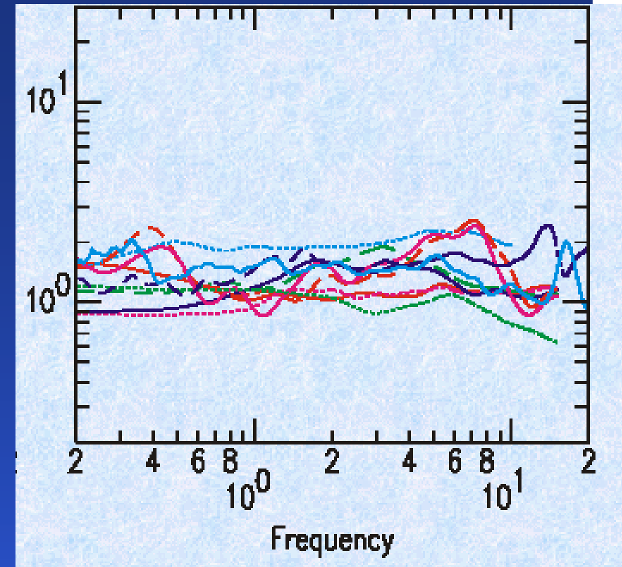


Typical H/V curves

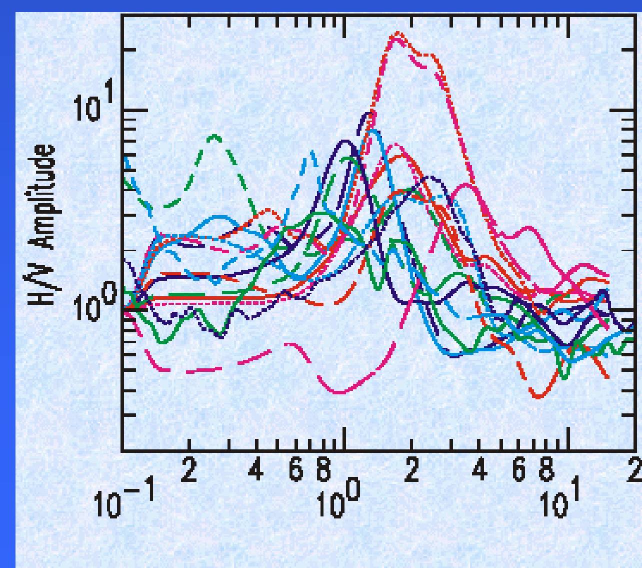
Ratio of spectral amplitudes



rock



sediments



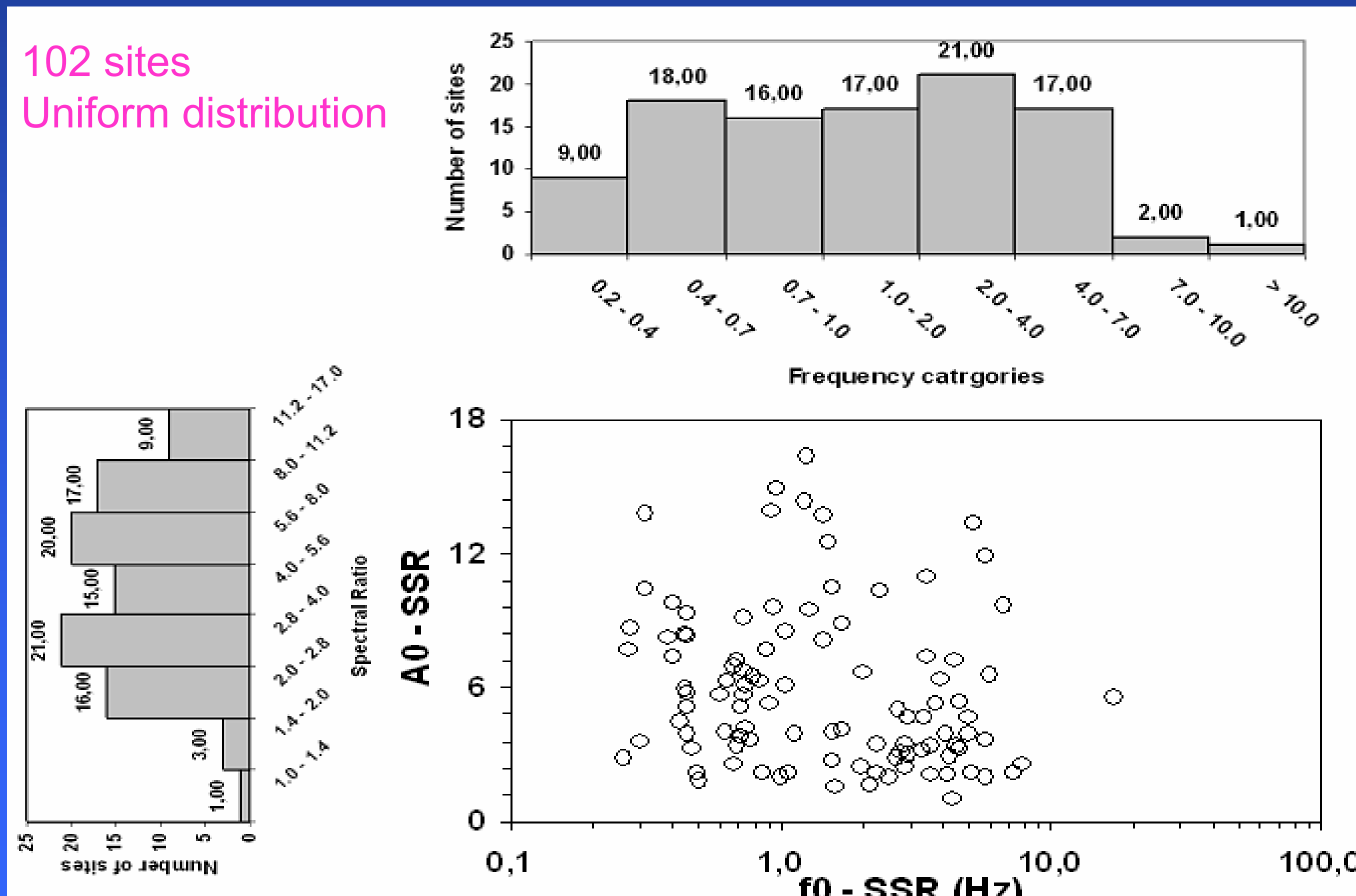
Interpretation of H/V measurements

Nakamura's interpretation
- H/V = SH transfer function
- $F_{H/V} = F_o$
- $A_{H/V} = A_o$

Alternative interpretation (most common)
- H/V = mainly effects of surface waves
  (Rayleigh waves; Love waves)
- $F_{H/V} \approx F_o$ (ellipticity peak frequency, Airy phase of Love waves)
- $A_{H/V}$?

Interpretation of H/V measurements: Results from real data (SESAME results)

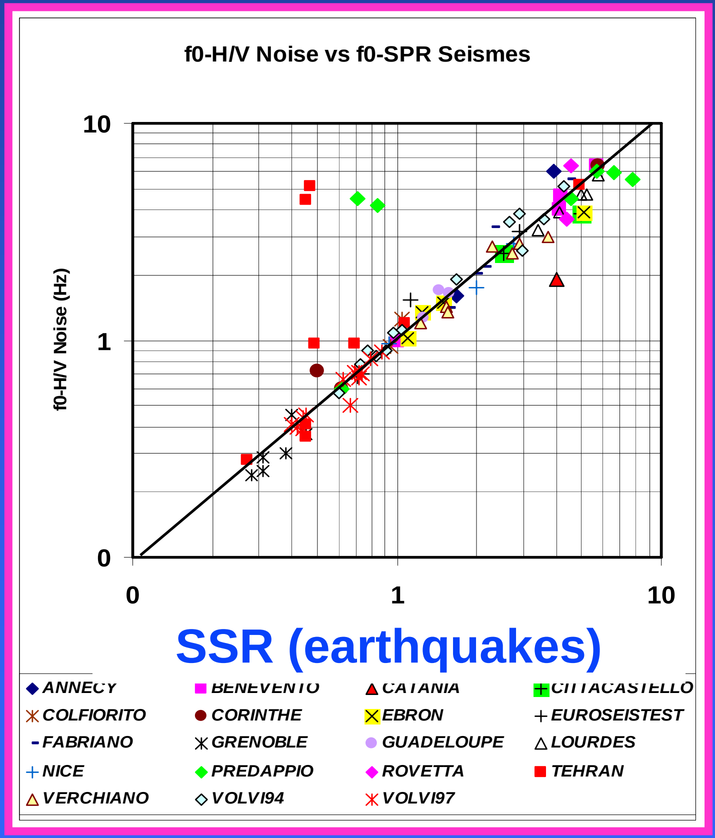
From Haghshenas et al., 2005



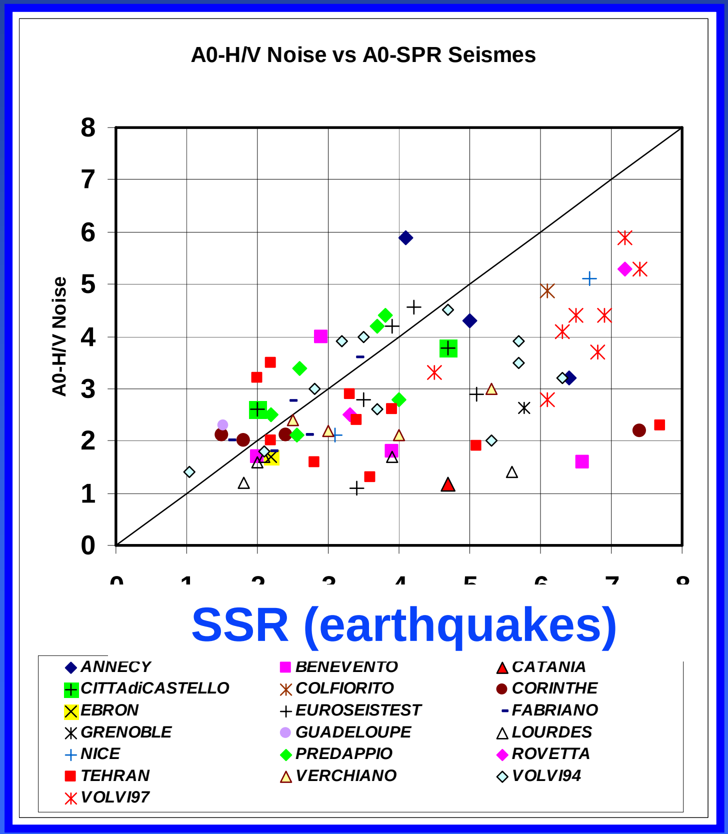
Interpretation of H/V measurements: Results from real data (SESAME results)

H/V (noise)

Frequency



Amplitude



Hagshenas, 2005

Interpretation of H/V measurements: Results from real data (SESAME results)

- **Very good overall agreement for f0**
  - 81% of cases
  - Important exceptions :
    - some low frequency sites
    - (stiff sites continental area, and/or limited contrast)

- **No correlation between H/V amplitude and actual amplification**
  - different shapes
  - different values
  - however **A(H/V) $\leq$ A(SSR)**

Interpretation of H/V measurements: Results from simulated data (SESAME results)

For 1D structures

- $F_{H/V}$ = Fo +/- 20% *(whatever the origin of H/V peak)*
- $A_{H/V}$ > Ao

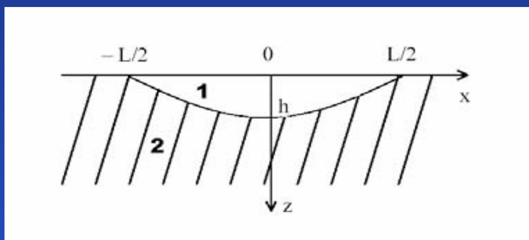
For 2D/3D structures (canonical models + real sites)

- $F_{H/V}$ overestimates/underestimates the 1D Fo
- $A_{H/V}$ differs from the 1D Ao

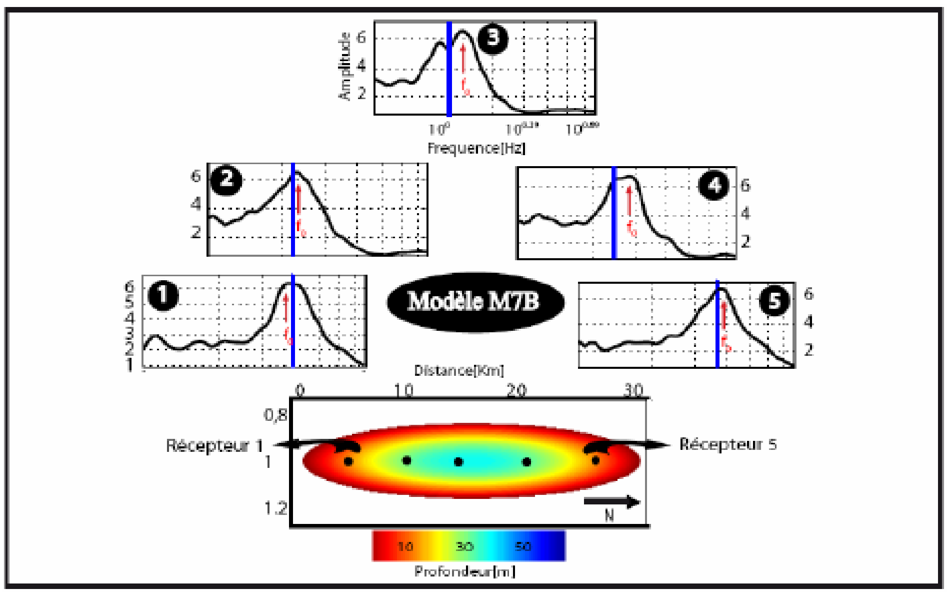
- H/V peak is not clear above steep undergroung slopes:
  - « broad » peak, multiple peaks, « plateau-like » shape, almost « flat » H/V
  - low amplitude

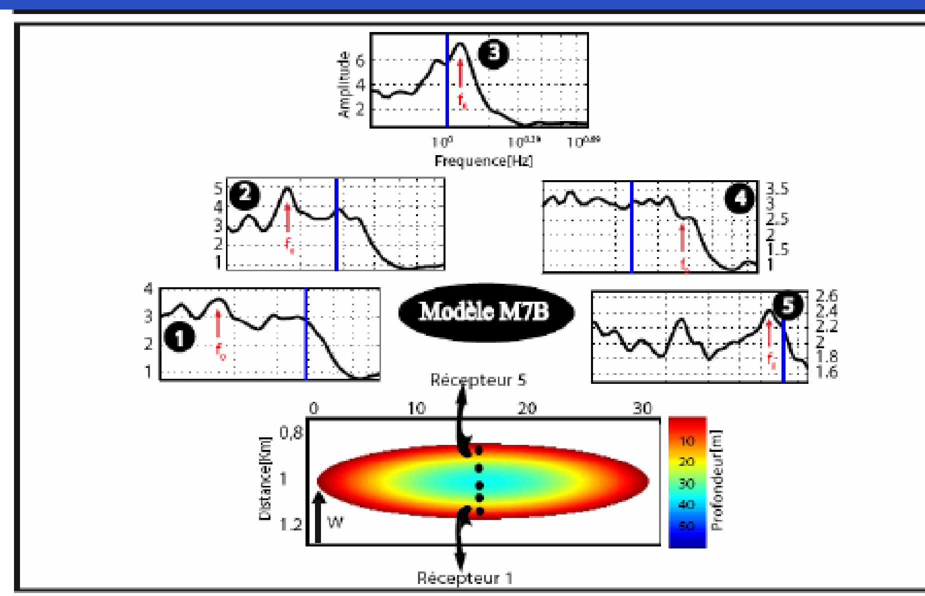
H/V for 2D/3D structures: Illustration of « broad H/V peak »

Noise synthetics



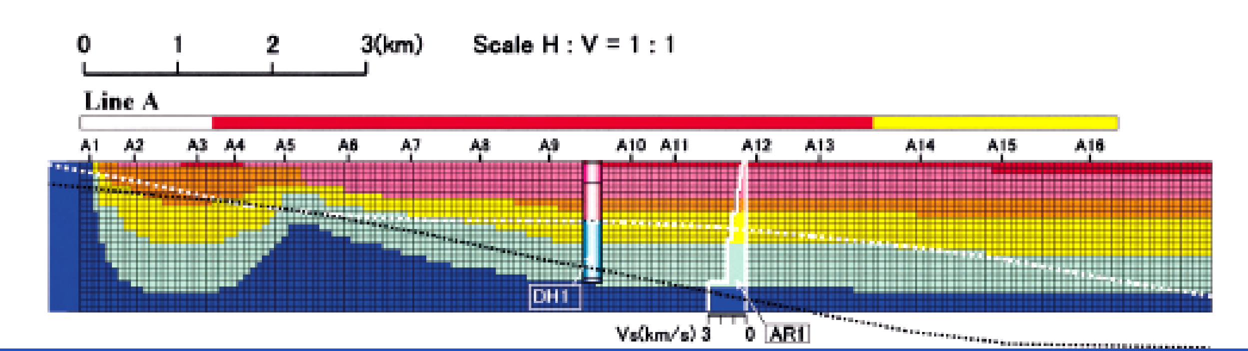
Courtesy from K. Boussoura and K. Selmi

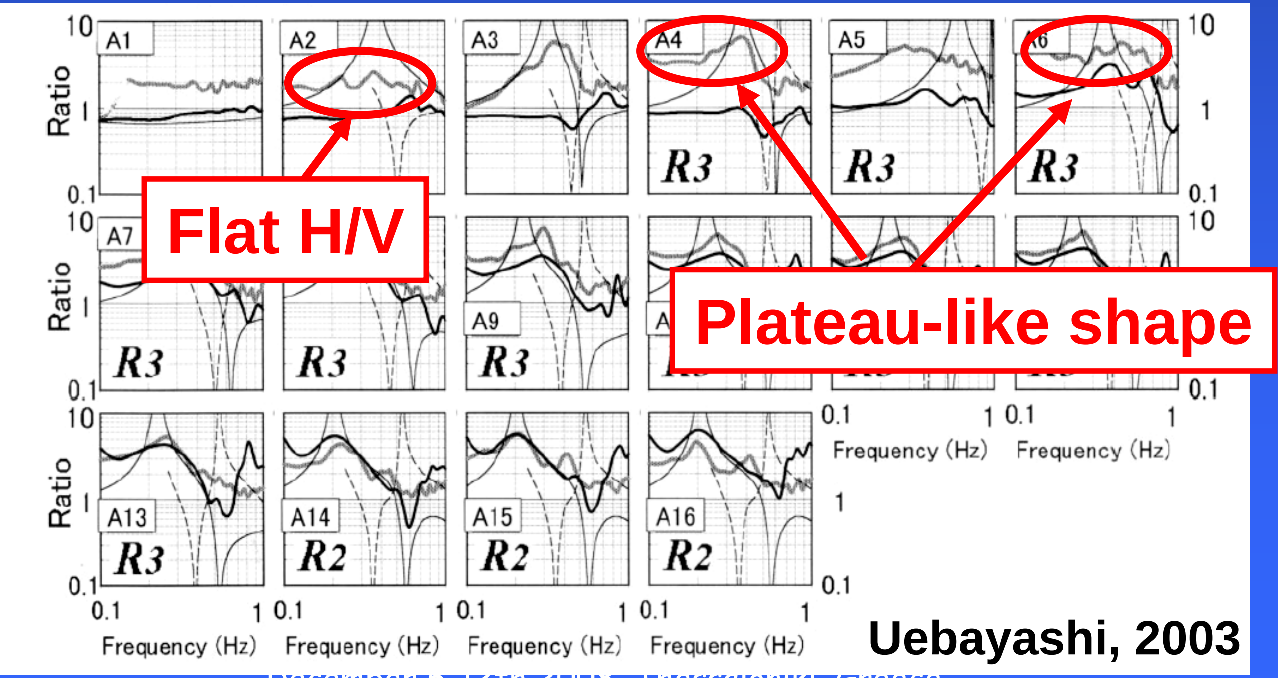




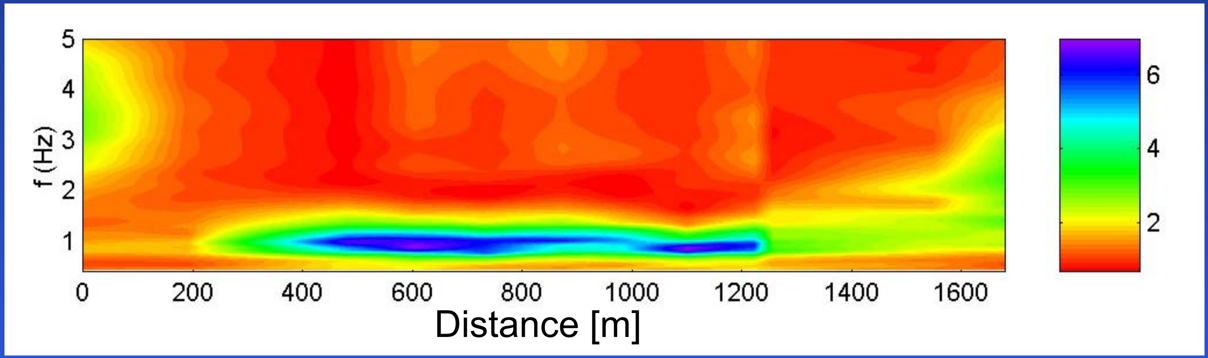
H/V for 2D/3D structures: Illustration of « plateau-like» shape

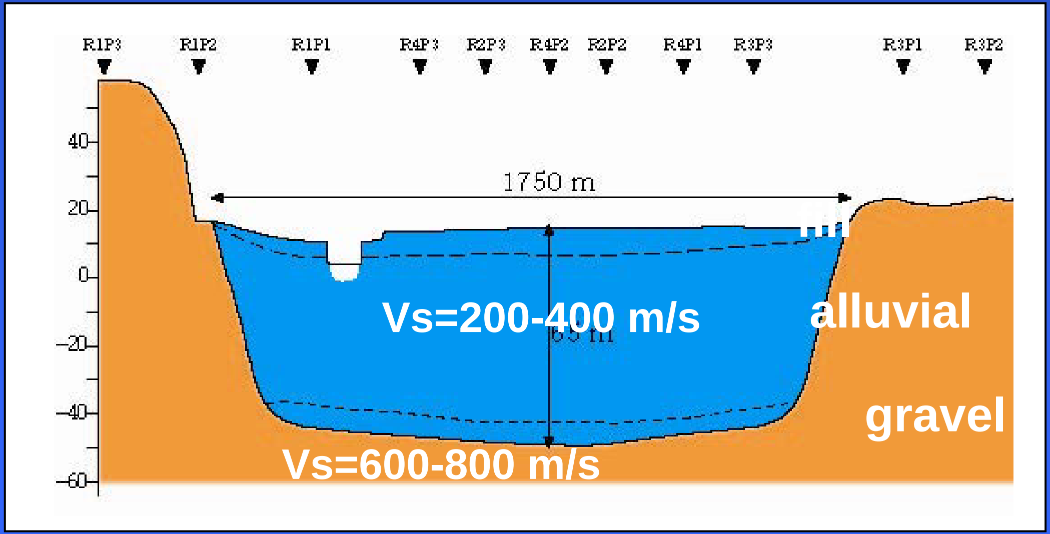
Real noise recordings





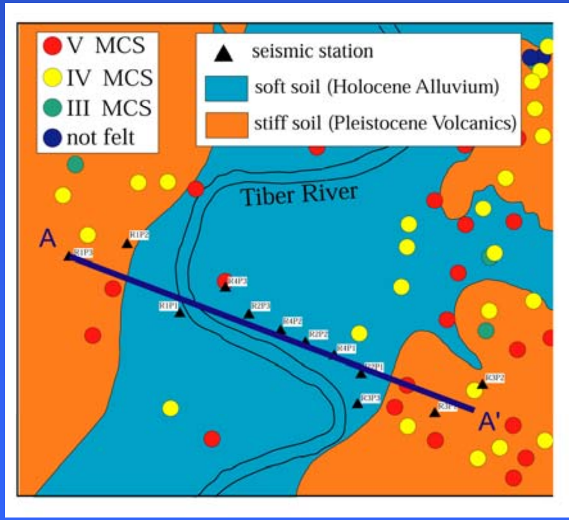
H/V peak frequency : correlation with the main geological structures



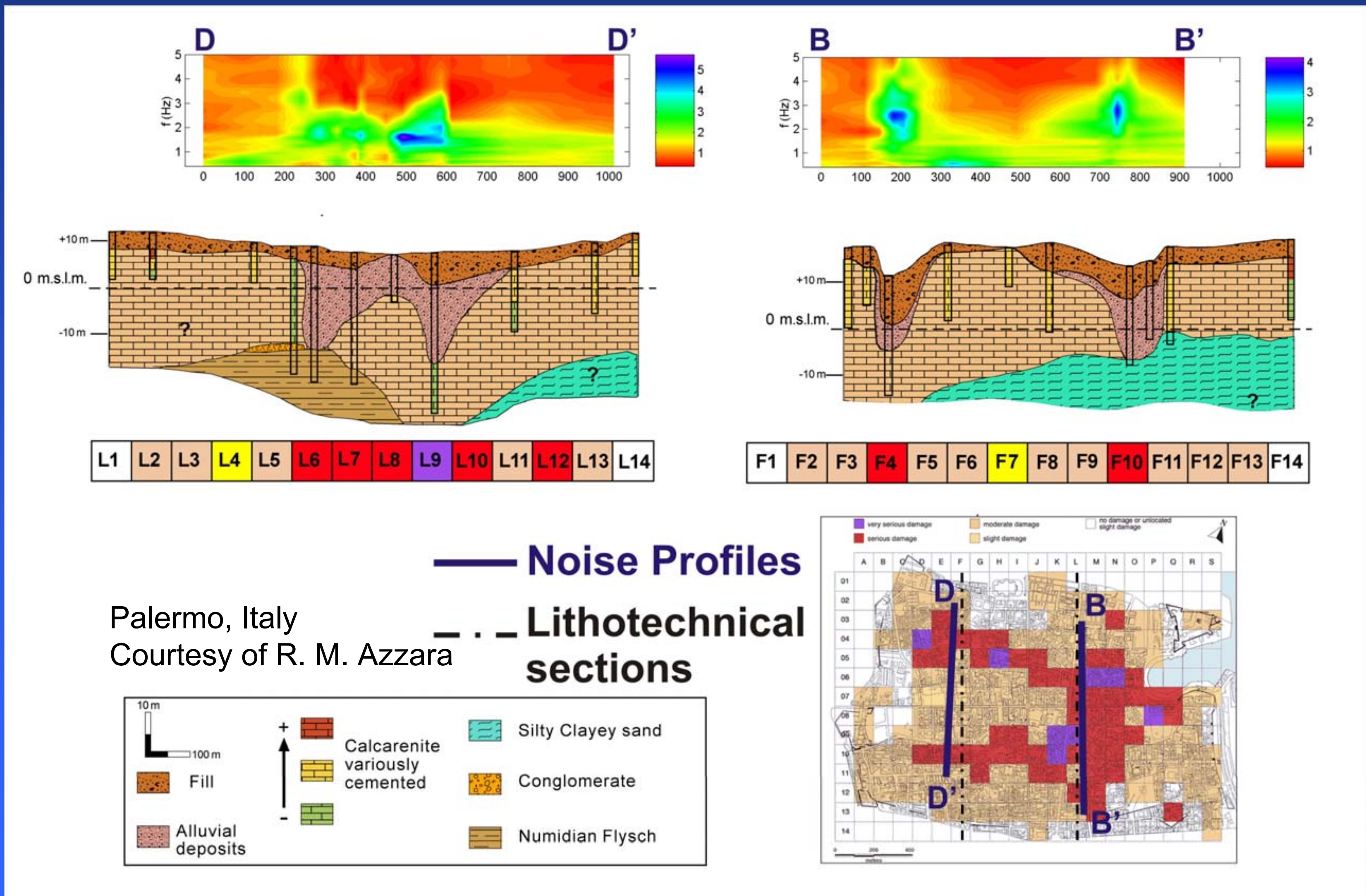


Roma, Italy

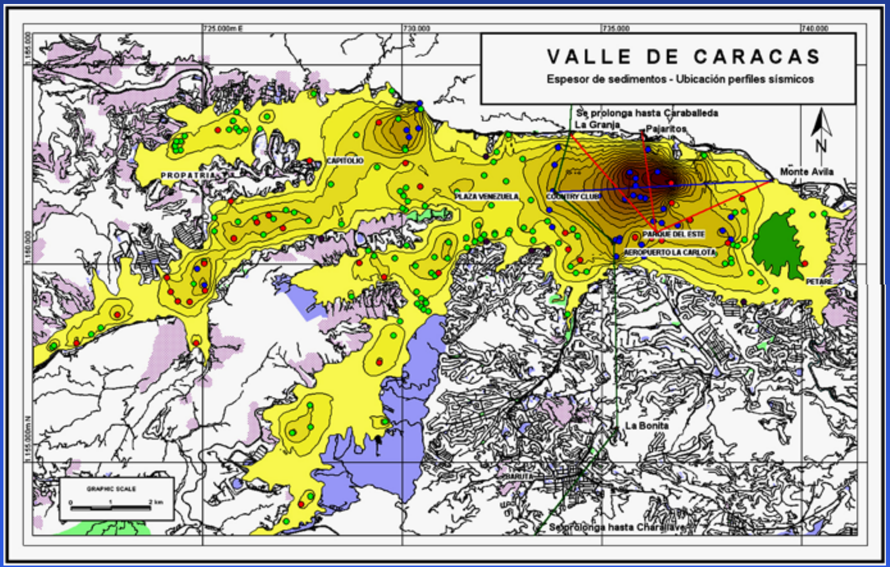
Courtesy of R. M. Azzara



H/V peak frequency : correlation with the main geological structures



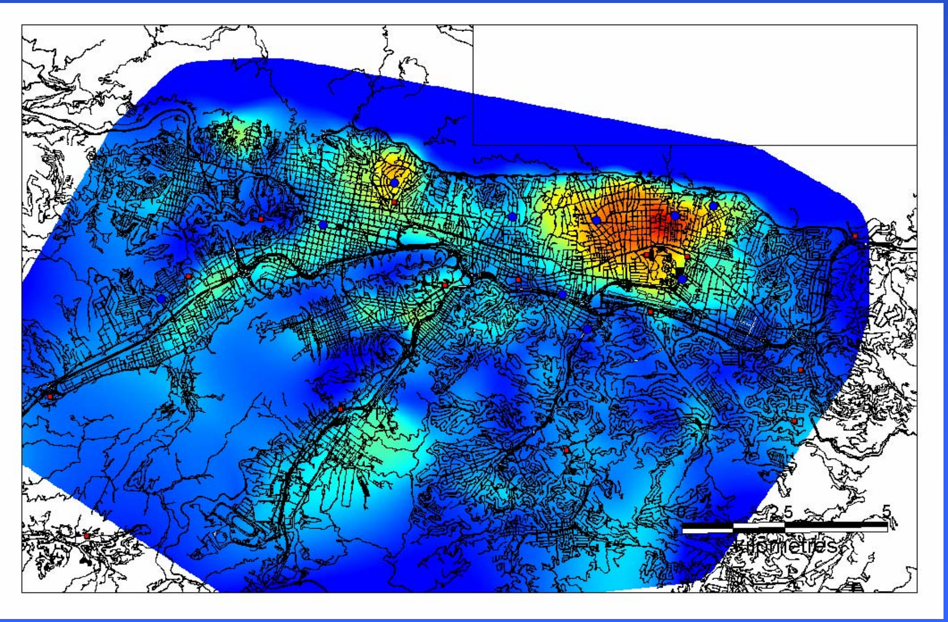
H/V peak frequency : correlation with the main geological structures



Sediment thickness

Courtesy of V. Rocabado

Resonance frequencies



Imaging sediment thickness

Under the assumption that the structure is locally 1D

$$f_{H/V} \sim f_0 = \frac{V_{s,average}}{4h}$$

Estimation of an average Vs if h is known

$$V_{s,average} \sim 4 h f_{H/V}$$

Estimation of a minimum sediment thickness if Vs is known at the surface

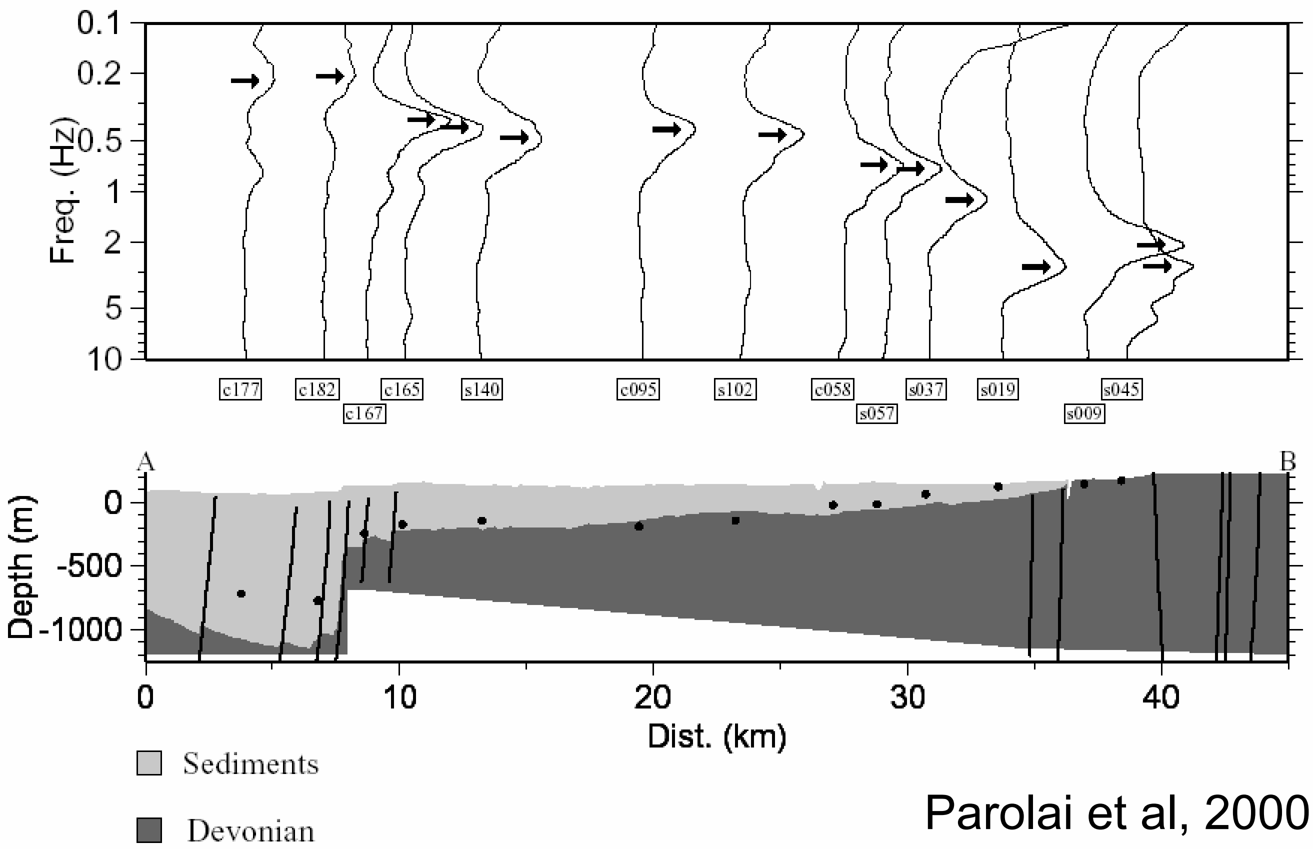
$$h_{minimum} \sim \frac{V_{s,surface}}{4 f_{H/V}}$$

Note: f_0 is estimated for the whole structure sediment+bedrock
If more than one sediment layer, $V_{s,average} \neq V_{s,surface}$

H/V peak frequency : correlation with the main geological structures

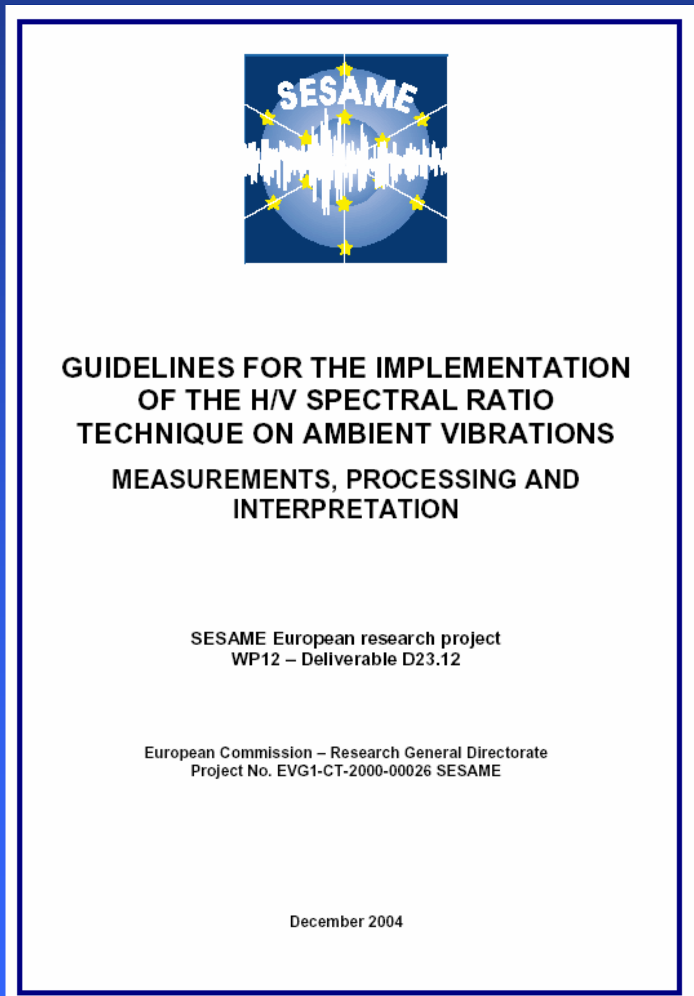
$F_{H/V} \approx V_{s,av.}/4h$

$h = V_{s,av.}/F_{H/V}$



Parolai et al, 2000

Recommandations for H/V measurements



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Project No. EVG1-CT-2000-00026 SESAME

December 2004

Chatelain et al., 2007. Evaluation of the influence of experimental conditions on H/V results from ambient noise recordings, Bull. Earth. Eng.

Guillier et al., 2007. Influence of instruments on the H/V spectral ratios of ambient vibrations, Bull. Earth. Eng.

Influence of instruments (Guillier et al., 2007)

Table 2 List of the sensors tested during the Bergen Workshop in the SESAME marks.

CODE	Type	Constructor	Characteristics
L1	LE-3Dlite 1 Hz	Lennartz	1 Hz seismometer
L2–L5	LE-3D 5 s	Lennartz	5 s seismometer
L6	LE 3D Classic	Lennartz	1 Hz seismometer
M1	Mark L4-C	Mark Product	1 Hz seismometer
M2	Mark L-22	Mark Product	2 Hz seismometer
M4	Mark L-28B	Mark Product	4.5 Hz seismometer
CH	CD-S2A	Chinese Republic	2 Hz seismometer
R1	Kinem. Ranger SS1	Kinemetrics	1 Hz seismometer
SN	Sensor GBV	Sensor Netherland	4.5 Hz seismometer
GI and GS	Guralp CMG-40T	Guralp	Broadband, 30 s
KS	Geotech KS 2000		Broadband, 100 s
KE	Episensor	Kinemetrics	Accelerometer
GA	Guralp CMG-5T	Guralp	Accelerometer
KG	Altus-Etna Internal Episensor	Kinemetrics	Accelerometer

The code name is used in the text and the figures. Note that L2 to L5 correspond to the same type sensor. In the R1 case, three 1-C seismometers were used

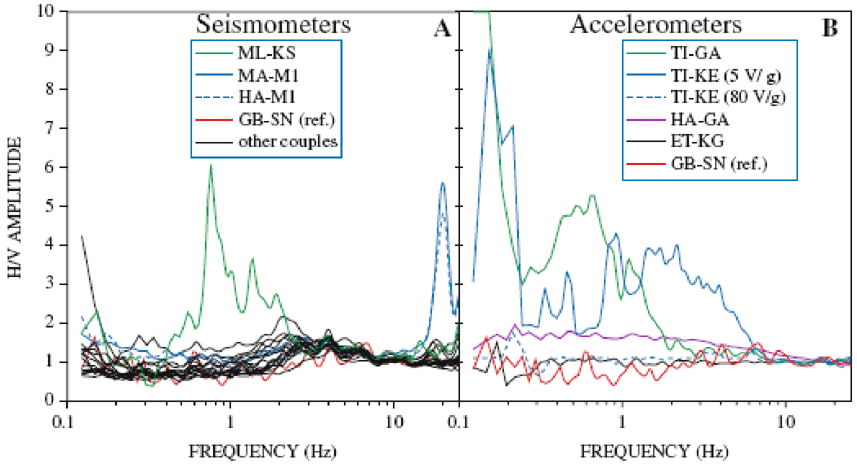


Fig. 6 Test on digitizer-sensor combinations. Records have been performed on a concrete pier coupled to bedrock. (A) H/V curves of the 19 couples using seismometers. (B) H/V curves of the five couples using accelerometers

Guillier et al., 2007

- The recording equipment, especially the sensor, has to be regularly tested
- The use of accelerometers should definitively be avoided, because of instabilities and low sensitivity (especially at low frequencies)

Influence of experimental conditions (Chatelain et al., 2007)

♦*P4 Influence of nearby structures*
- Effects within 10 m in the HF range

♦*P5 Underground structures*
- Never recommended

♦*P6 Weather*
- Large sensitivity to wind : low frequency effects
- Rain

♦*P1 Recording/instrument parameters*
- Gain (avoid saturation)

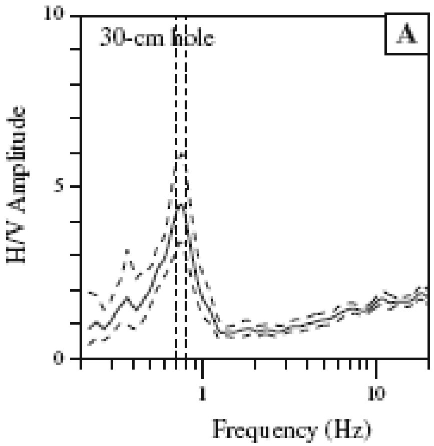
♦*P2 In situ soil-sensor coupling*
- Grass + wind
- Mud, reworked soil

♦*P3 Modified soil-sensor coupling*
- Artificial, soft interface

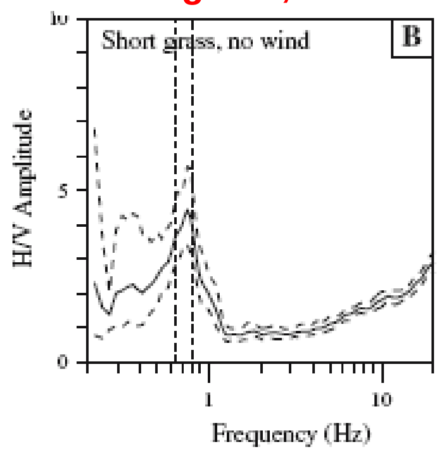
♦*P9 Proximity ot noise sources*
- Avoid cars at short distance (< 10m), …

Influence of experimental conditions

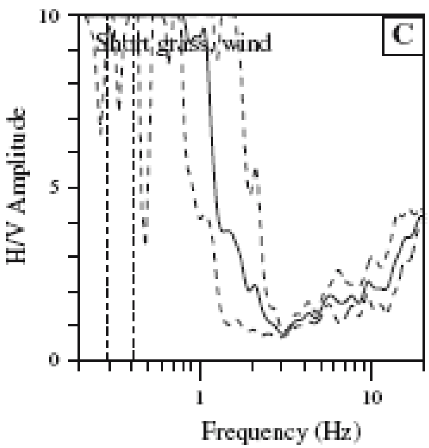
30cm hole



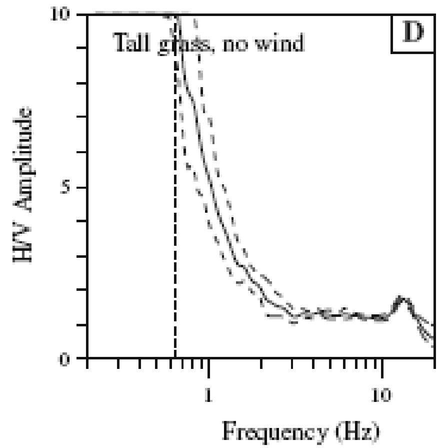
Short grass, no wind



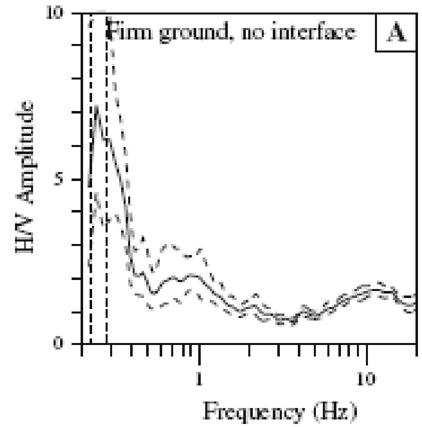
Short grass, wind



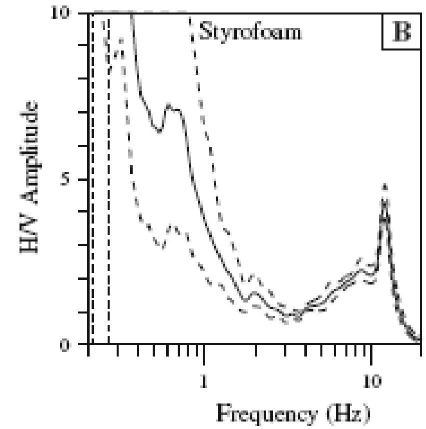
tall grass, no wind



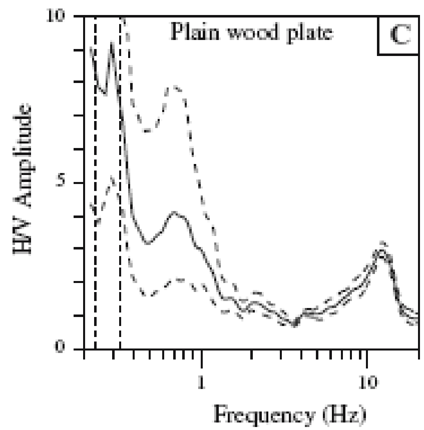
firm ground, no interface



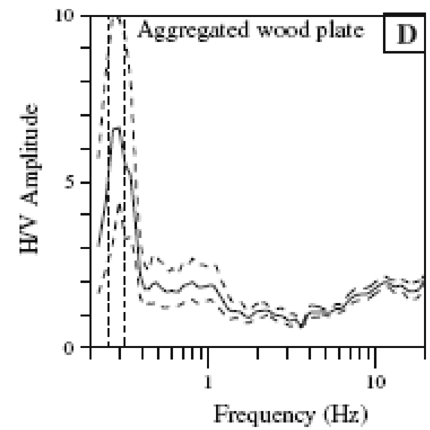
styrofon



Plain wood plate



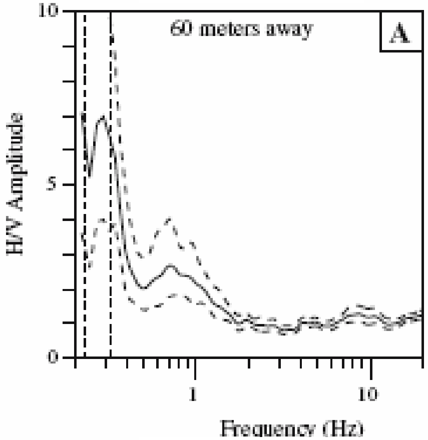
aggregated wood plate



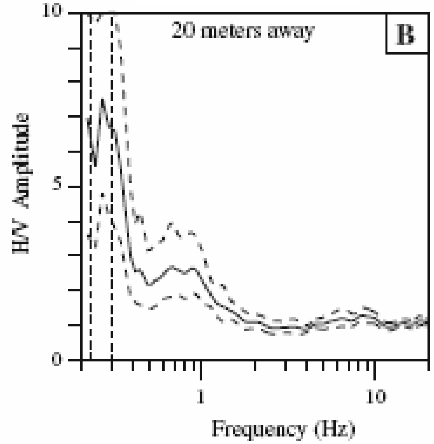
Chatelain et al., 2007

Influence of experimental conditions

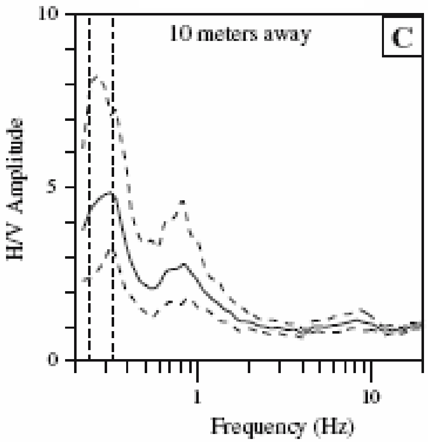
60 m away



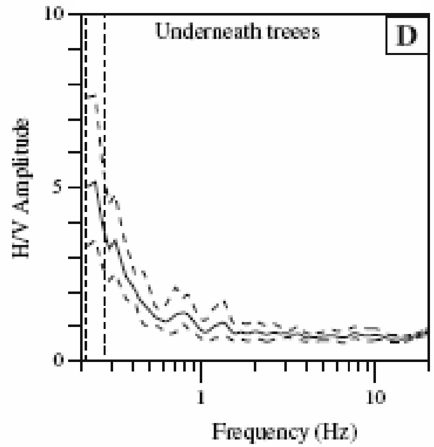
20 m away



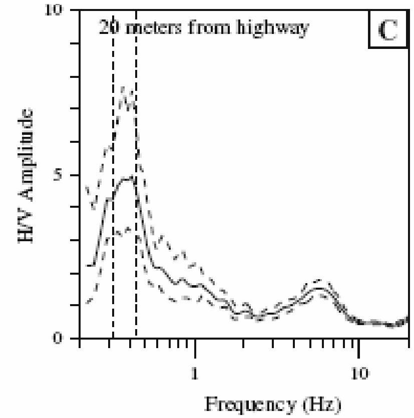
10 m away



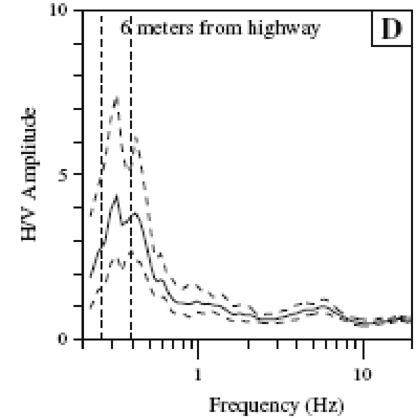
Underneath trees



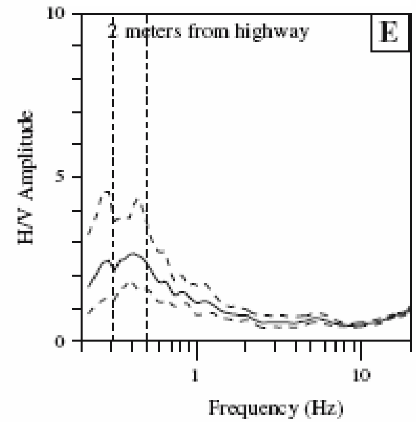
20 m from highway



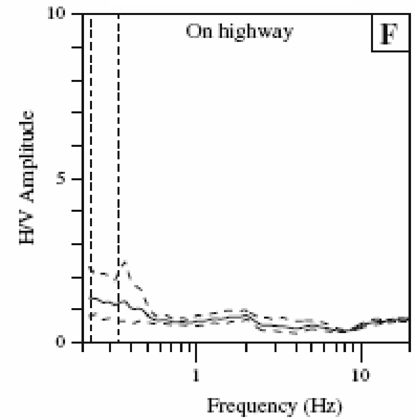
6 m from highway



2 m from highway



on highway



Chatelain et al., 2007

Recording duration

SESAME

Table 1. Recommended recording duration.

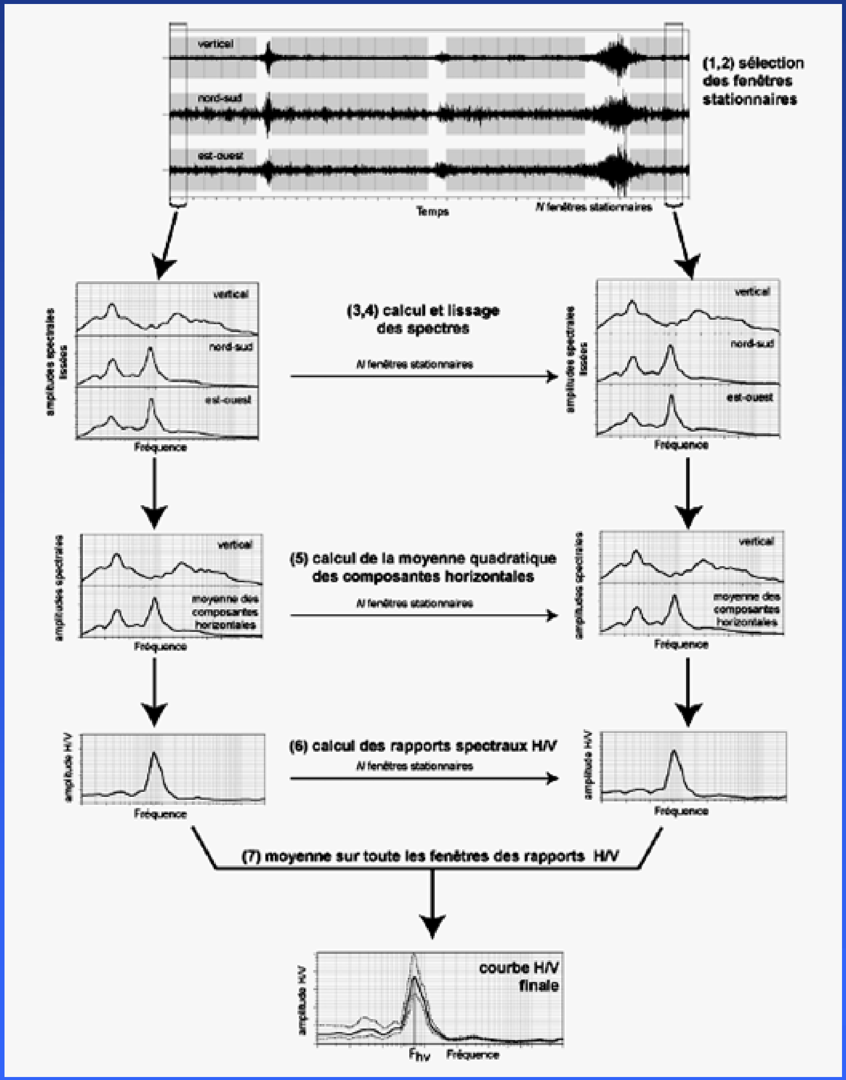
f_0 [Hz]	Minimum value for l_w [s]	Minimum number of significant cycles (n_c)	Minimum number of windows	Minimum useful signal duration [s]	Recommended minimum record duration [min]
0.2	50	200	10	1000	30'
0.5	20	200	10	400	20'
1	10	200	10	200	10'
2	5	200	10	100	5'
5	5	200	10	40	3'
10	5	200	10	20	2'

$$L_W = 10/f_o = 10 * T_o$$

Statistical study of Picozzi et al, 2005

- Time window from 20 to 60 s [0.1 – 10 Hz]
- Duration of at least 20 minutes

Computation of H/V



Selection of the *n* most stationary windows (STA/LTA anti-trigger algorithm)

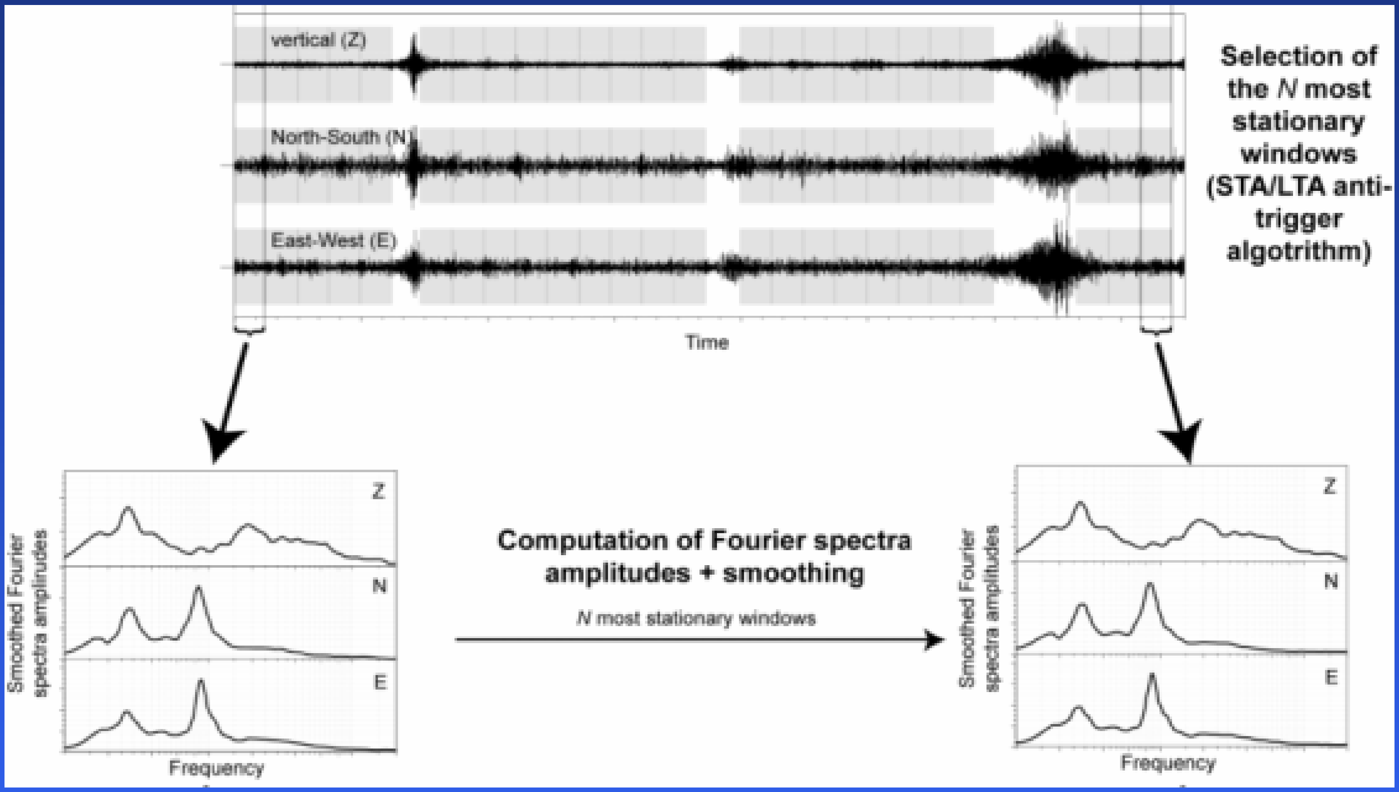
Computation of Fourier amplitude spectra + smoothing

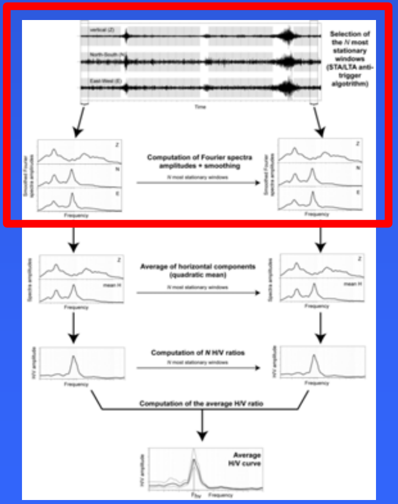
Average of horizontal components

Computation of *n* spectral ratio

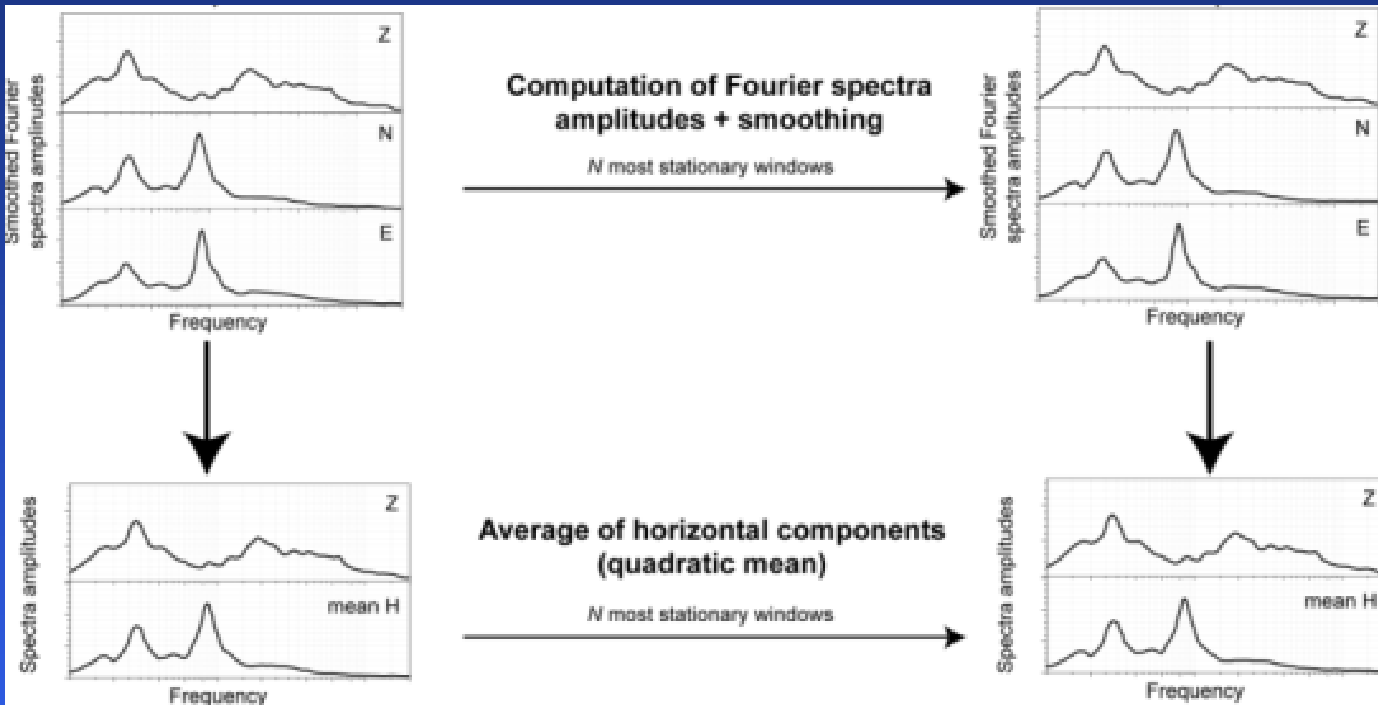
Computation of the average H/V

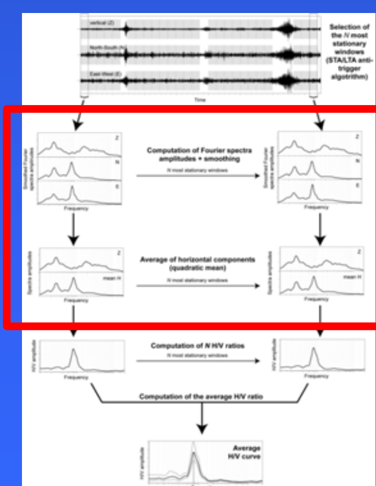
Computation of H/V curves



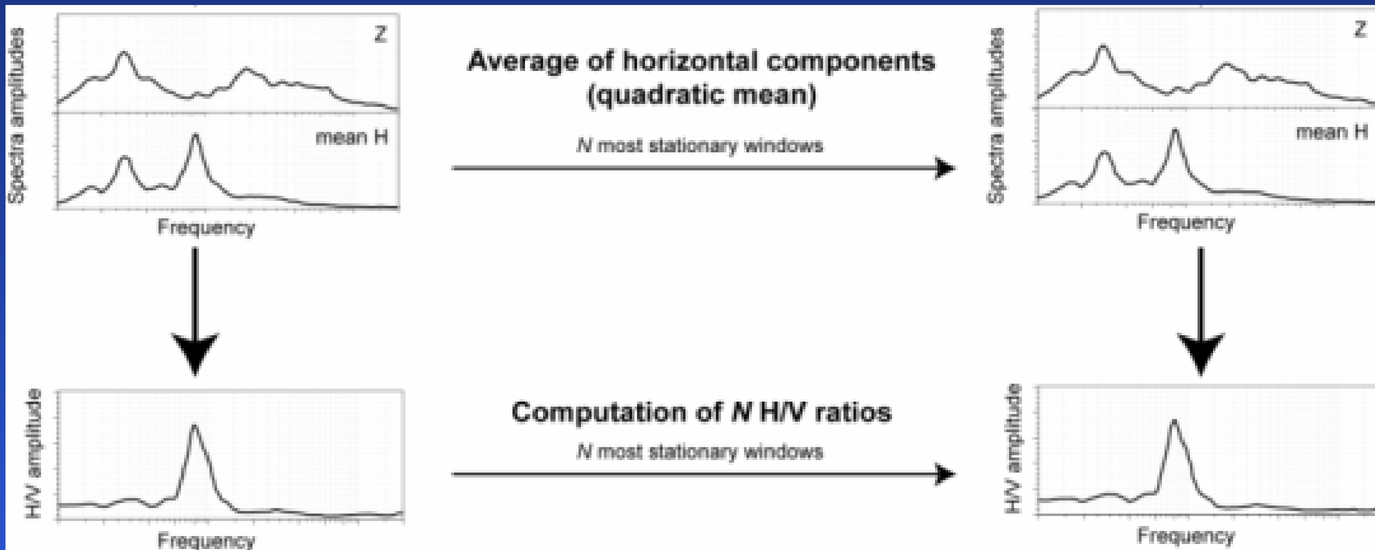


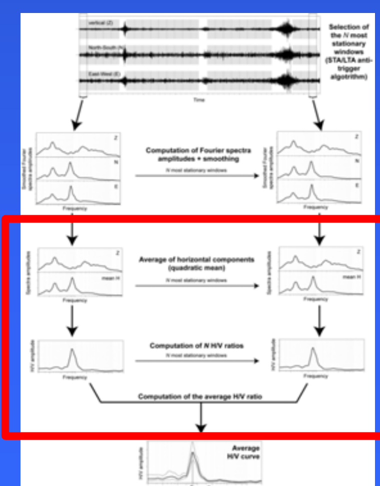
Computation of H/V curves



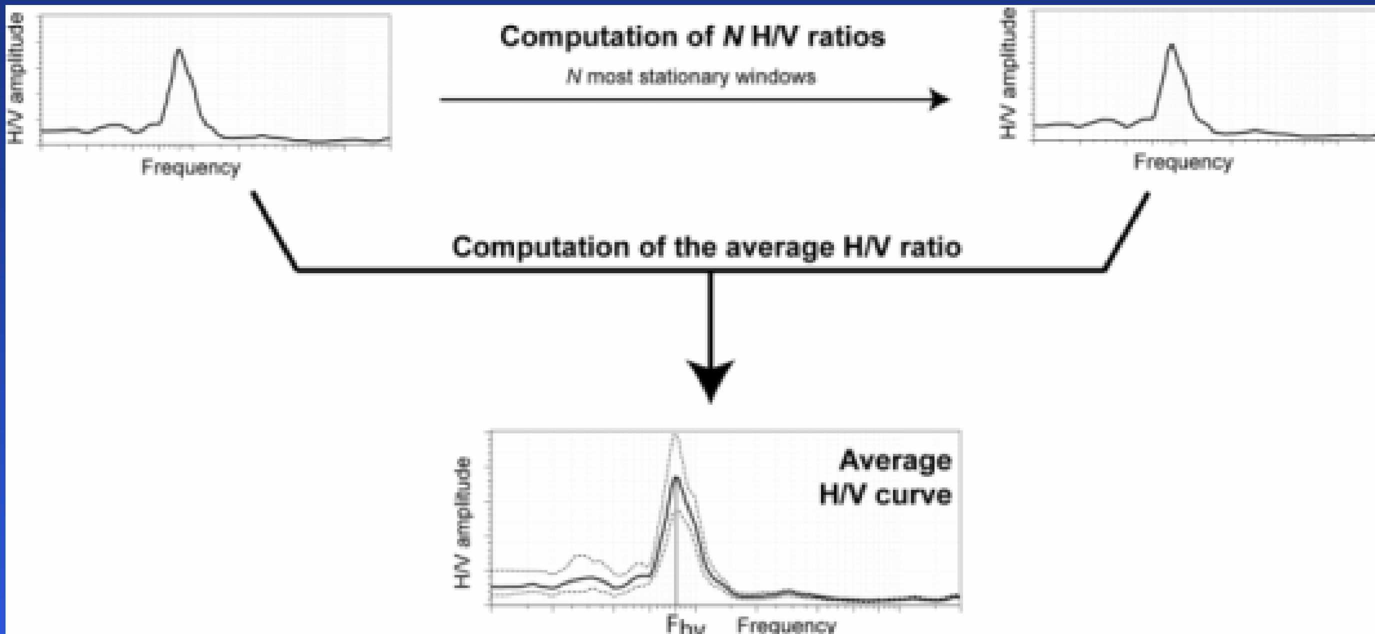


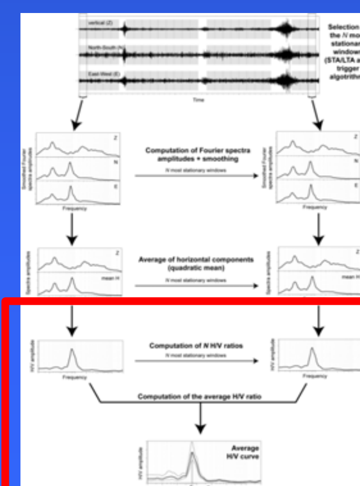
Computation of H/V curves





Computation of H/V curves





Interpretation of H/V curves

- Clear peak
- Industrial origin
- Double peak
- Unclear peak at low frequency
- Broad peak or multiple peak
- No peak on sediments

Criteria for a reliable H/V curve

Criteria for a reliable H/V curve

i) $f_0 > 10 / l_w$

and

ii) $n_c(f_0) > 200$

and

iii) $\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f0 > 0.5Hz$
or $\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f0 < 0.5Hz$

Criteria for a clear H/V peak
(at least 5 out of 6 criteria fulfilled)

i) $\exists f^- \in [f_0/4, f_0] \mid A_{H/V}(f^-) < A_0/2$

ii) $\exists f^+ \in [f_0, 4f_0] \mid A_{H/V}(f^+) < A_0/2$

iii) $A_0 > 2$

iv) $f_{peak}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$

v) $\sigma_f < \varepsilon(f_0)$

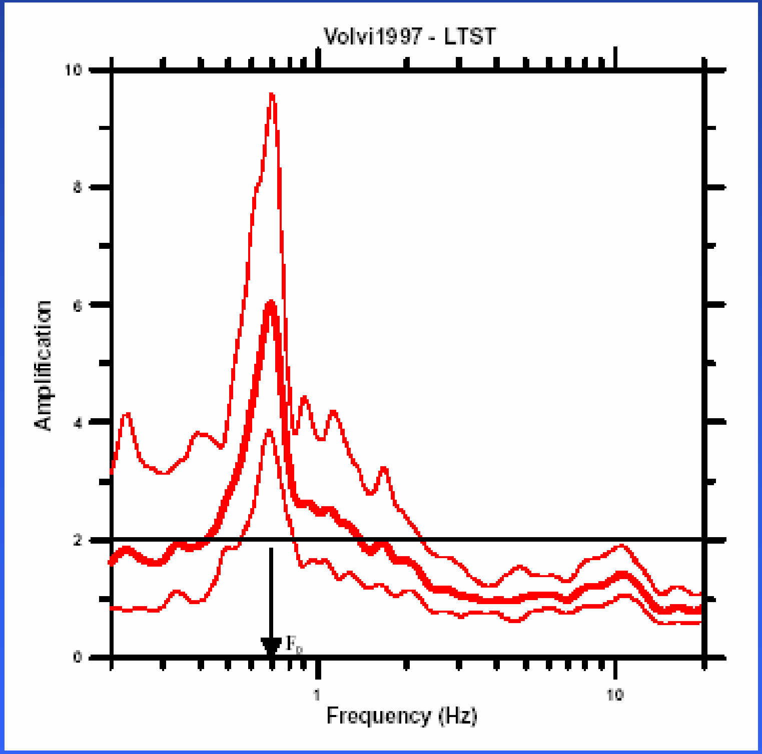
vi) $\sigma_A(f_0) < \theta(f_0)$

- l_w = window length
- n_w = number of windows selected for the average H/V curve
- $n_c = l_w \cdot n_w \cdot f_0$ = number of significant cycles
- f = current frequency
- f_{sensor} = sensor cut-off frequency
- f_0 = H/V peak frequency
- σ_f = standard deviation of H/V peak frequency ($f_0 \pm \sigma_f$)
- $\varepsilon(f_0)$ = threshold value for the stability condition $\sigma_f < \varepsilon(f_0)$
- A_0 = H/V peak amplitude at frequency f_0
- $A_{H/V}(f)$ = H/V curve amplitude at frequency f
- f^- = frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^-) < A_0/2$
- f^+ = frequency between f_0 and $4f_0$ for which $A_{H/V}(f^+) < A_0/2$
- $\sigma_A(f)$ = "standard deviation" of $A_{H/V}(f)$, $\sigma_A(f)$ is the factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided
- $\sigma_{logH/V}(f)$ = standard deviation of the $\log A_{H/V}(f)$ curve, $\sigma_{logH/V}(f)$ is an absolute value which should be added to or subtracted from the mean $\log A_{H/V}(f)$ curve
- $\theta(f_0)$ = threshold value for the stability condition $\sigma_A(f) < \theta(f_0)$
- $V_{s,av}$ = average S-wave velocity of the total deposits
- $V_{s,surf}$ = S-wave velocity of the surface layer
- h = depth to bedrock
- h_{min} = lower-bound estimate of h

Threshold Values for σ_f and $\sigma_A(f_0)$

Frequency range [Hz]	< 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0
$\varepsilon(f_0)$ [Hz]	$0.25 f_0$	$0.20 f_0$	$0.15 f_0$	$0.10 f_0$	$0.05 f_0$
$\theta(f_0)$ for $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58
$\log \theta(f_0)$ for $\sigma_{logH/V}(f_0)$	0.48	0.40	0.30	0.25	0.20

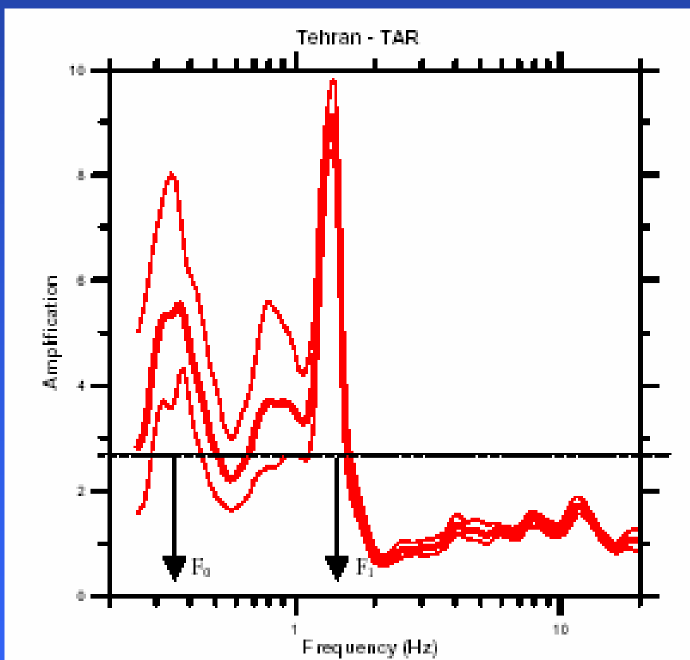
Interpretation of H/V curves: clear peak



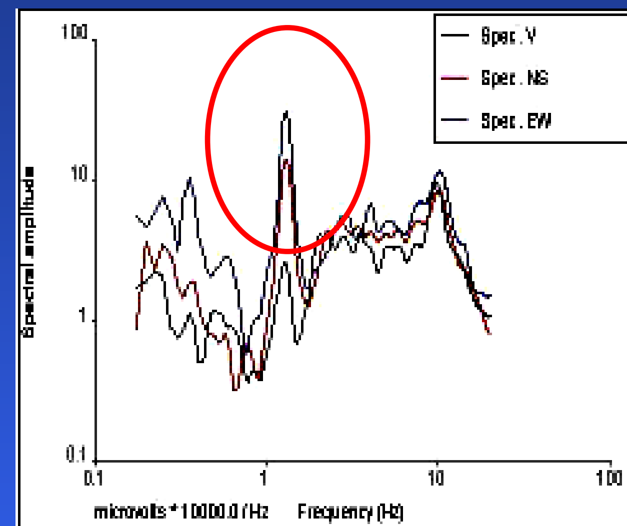
If no industrial origin:

- likely sharp contrast
- F_o = fundamental frequency
- If h is known: $V_{s,av} \sim 4h.fo$
- If $V_{s,surf}$ is known: $h_{min} \sim V_{s,surf}/4h$

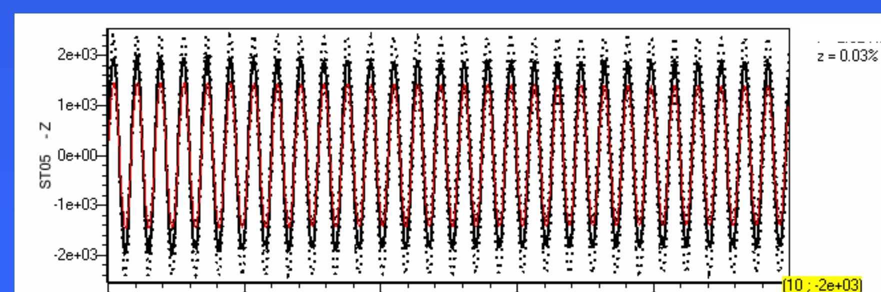
Interpretation of H/V measurements: Industrial origin



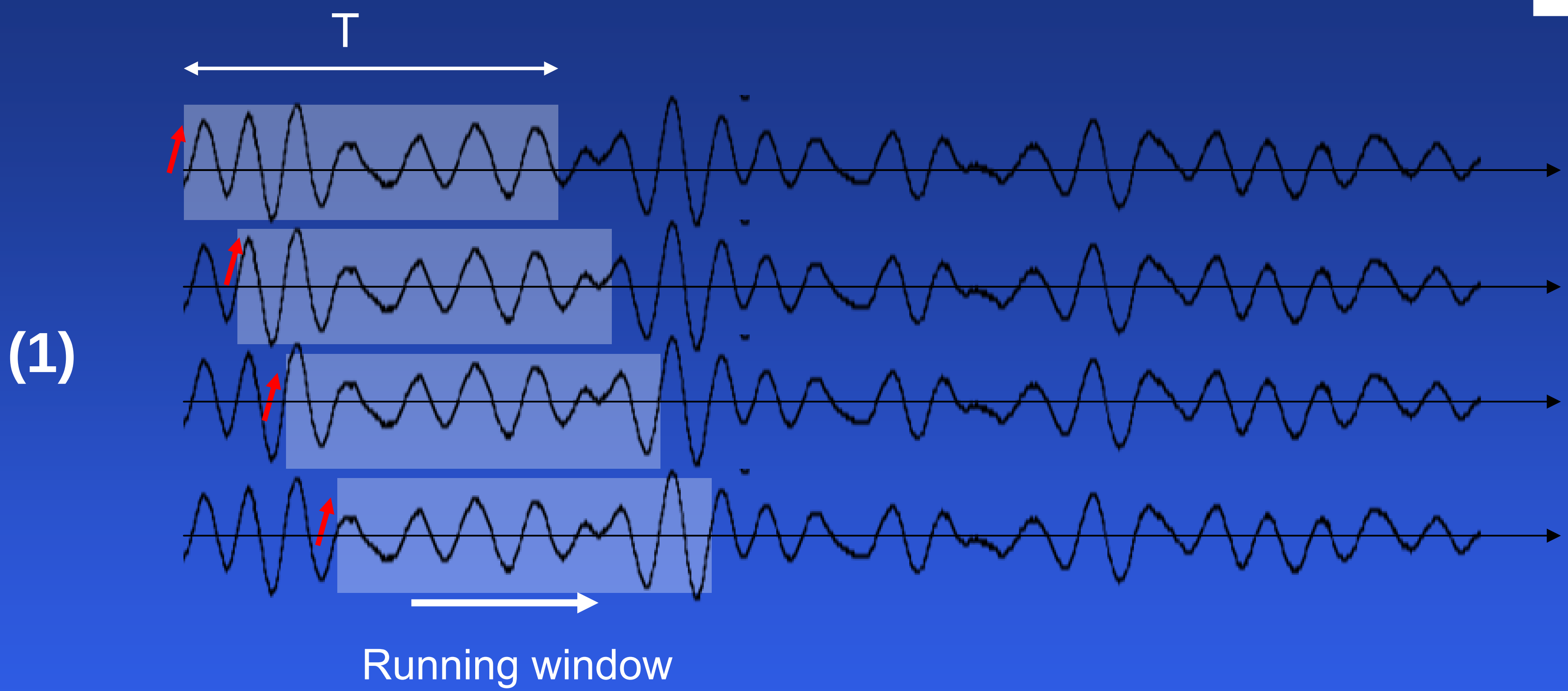
Fourier amplitude spectra



Damping (SDOF; $x(t) = A\sin(\omega_o t)e^{-\omega_o \zeta \tau}$)

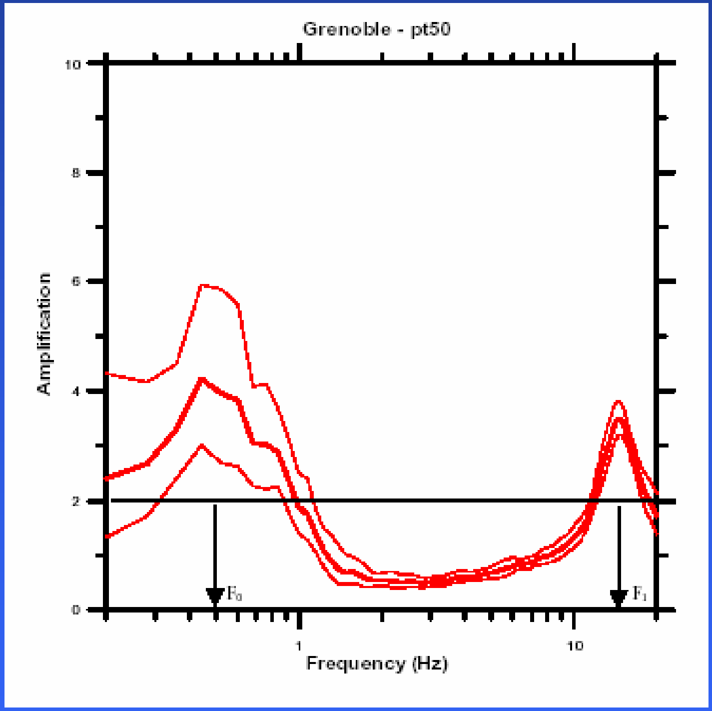


Scheme for damping computation



(1) Band-pass filtering of time series
(2) Extraction of time windows with the same initial conditions
(3) Stack of the extracted time windows -> stack(t)
(4) Estimation of the damping ζ and w_o by fitting $stack(t) = A\sin(\omega_o t)e^{-\omega_o \zeta \tau}$

Interpretation of H/V measurements: double peak



If no industrial origin:

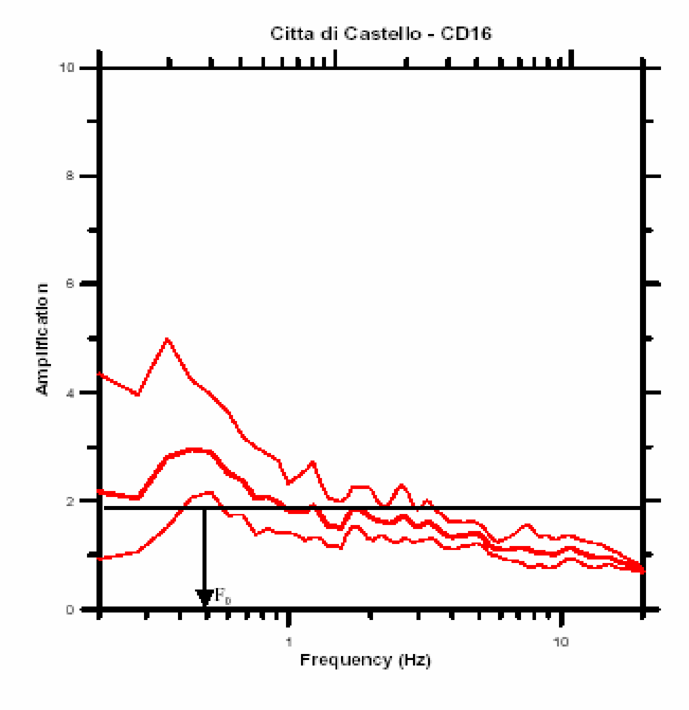
- likely two large contrasts at shallow AND large depth at two different scales ***(!!! to cross-check with geology)***

- F_o = fundamental frequency

- f1 = other natural frequency

- If $V_{s,surf}$ is known **$H_{1,min} \sim V_{s,surf} / 4 f1$**

Interpretation of H/V measurements: Unclear peak at low frequency



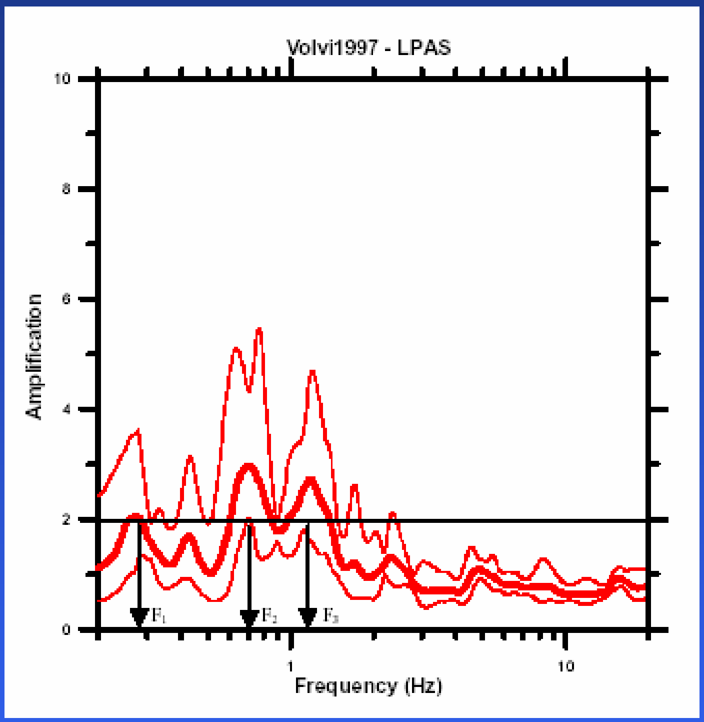
If steady increase of H/V ratio with decreasing frequency

- Check H/V curves from individual windows and eliminate windows giving spurious H/V curves
- Use longer time windows and/or more stringent window selection criteria
- Use proportional bandwidth and less smoothing

If reprocessed H/V curve fulfils the clarity criteria → **f_0 reliable**

If reprocessed H/V curve does not fulfil the clarity criteria → Perform additional measurements over a longer time and/or during night and/or quiet weather conditions and/or use earthquake recordings using also a nearby rock site

Interpretation of H/V measurements: Multiple peaks



-

Check no industrial origin of one of the peaks
Increase the smoothing bandwidth

If reprocessed H/V curve fulfils the clarity criteria → f_0 **reliable**

If reprocessed H/V curve does not fulfil the clarity criteria → Redo measurements over a longer time and/or during night

Interpretation of H/V measurements: broad peak

Decrease the smoothing bandwidth

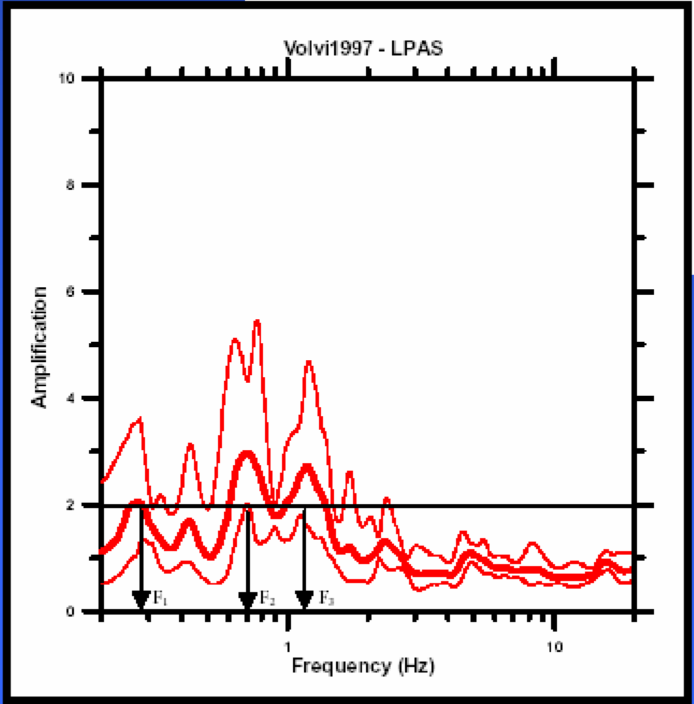
If bump peak is not stable and/or $A_{H/V}(f)$ is very large → **no reliable f_0**

If bump peak is stable and $A_{H/V}(f)$ is rather low →

- If clearer peaks are observed in the vicinity and
  - if their related frequencies lie within the frequency range of the broad peak
  - if their related frequencies exhibit significant variation from site to site

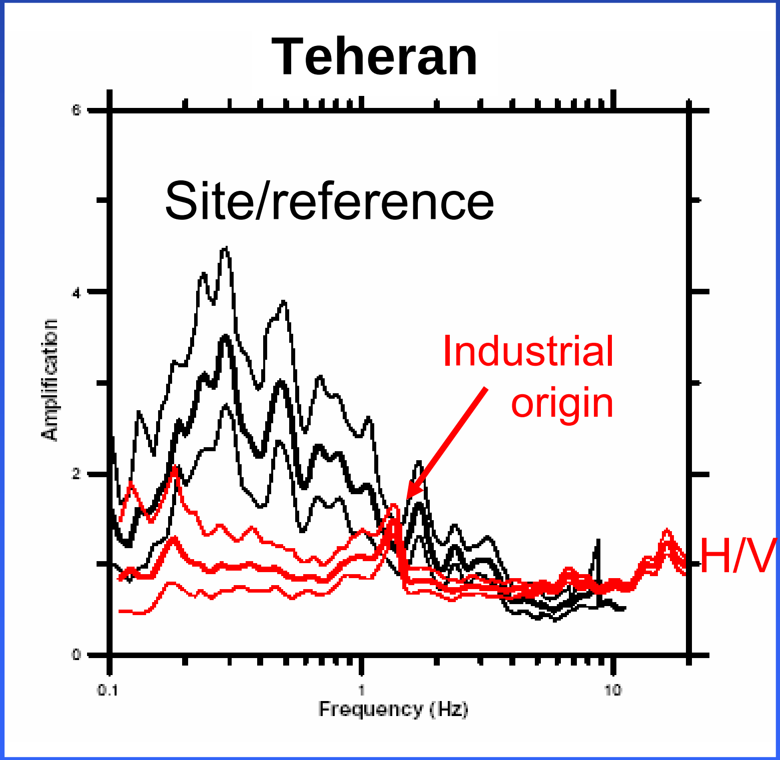
Then, examine the possibility of underground lateral variation, especially slopes.

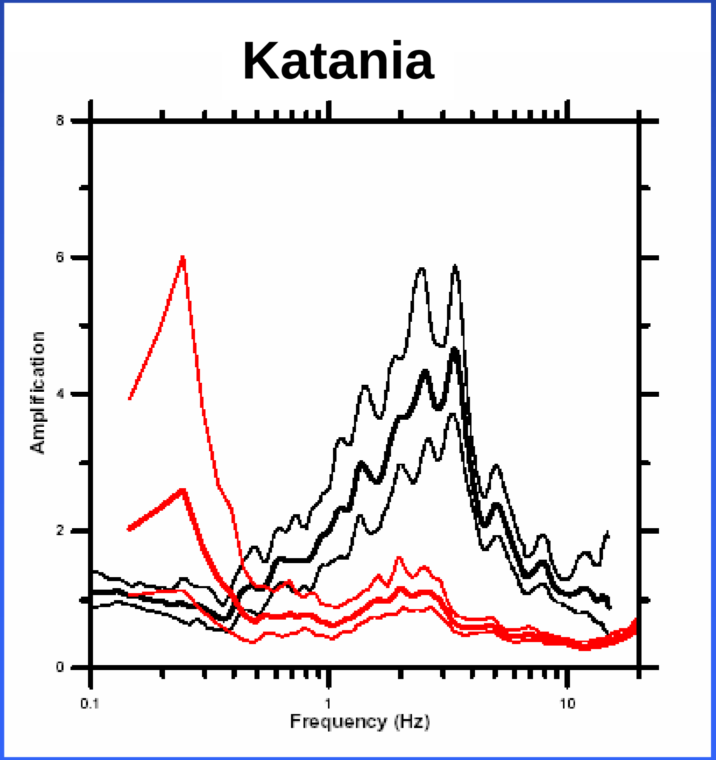
- Otherwise not recommended to extract any information



Interpretation of H/V measurements: « flat » H/V on sediments

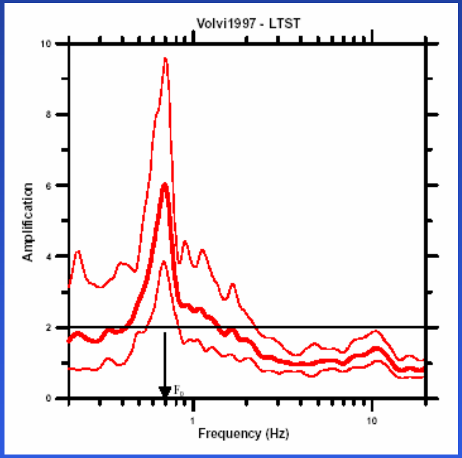
A flat H/V peak does not mean no amplification !!
-> 2D/3D site effects, low impedance contrasts, …

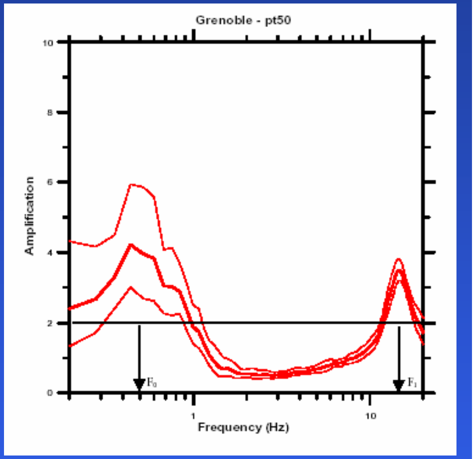




Interpretation of H/V measurements: summary

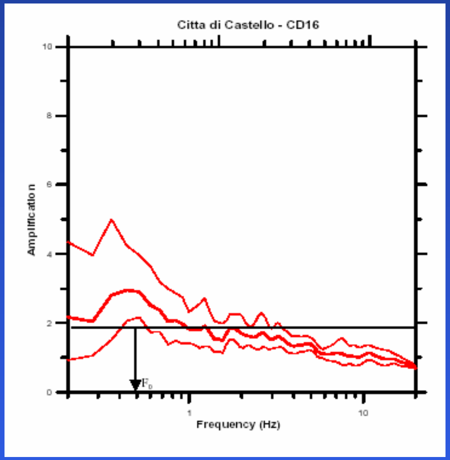
EASY CASES

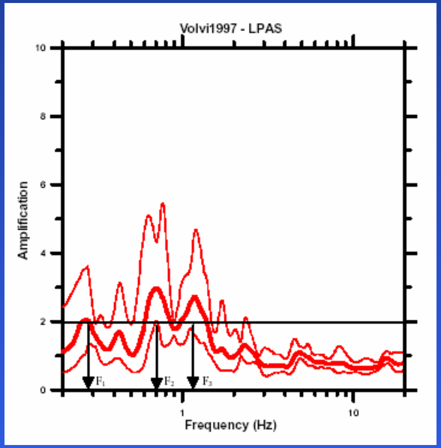




- quantitative information
- $V_{s,average}$
- H_{min}

DIFFICULT CASES





- Not recommanded to extract quantitative information
- Check the geology (stiff sediments, low contrast,basin-edge, …)
- Use earthquakes recordings