Smooth bumps in H/V curves over a broad area from single-station ambient noise recordings are meaningful and reveal the importance of Q in array processing: The Boumerdes (Algeria) case

B. Guillier, Jean-Luc Chatelain, M. Hellel, D. Machane, N. Mezouer, R. Ben Salem, E. H. Oubaiche

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Smooth bumps in H/V curves over a broad area from single-station ambient noise recordings are meaningful and reveal the importance of Q in array processing: The Boumerdes (Algeria) case

B. Guillier,[1,2] J.-L. Chatelain,[1,2] M. Hellel,[3] D. Machane,[2] N. Mezouer,[2] R. Ben Salem,[2] and E. H. Oubaiche[2]

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[1] Single-station H/V curves from ambient noise recordings in Boumerdes (Algeria) show smooth bumps around 1 and 3 Hz. A complementary microtremor study, based on two 34 and 134-meter aperture arrays, evidences that these bumps are indeed real peaks produced by two strong V_S contrasts at 37 and 118 meters depth, strongly smoothed by very high S-wave attenuation in the two sedimentary layers. These two H/V bumps, observed over a broad area, are meaningful and reveal the importance of Q in S-wave velocity modeling from microtremor array data processing. It also appears that Tertiary rocks should be, at least in some cases, taken into account, together with the Quaternary sediments, to explain single-station H/V frequency peaks, and therefore that considering only the first 30 m of soil for V_S amplification evaluation, as usually recommended, sometimes leads to flaky results by artificially eliminating non-explained low-frequency peaks from the analysis. **Citation:** Guillier, B., J.-L. Chatelain, M. Hellel, D. Machane, N. Mezouer, R. Ben Salem, and E. H. Oubaiche (2005), Smooth bumps in H/V curves over a broad area from single-station ambient noise recordings are meaningful and reveal the importance of Q in array processing: The Boumerdes (Algeria) case, *Geophys. Res. Lett.*, *32*, L24306, doi:10.1029/2005GL023726.

1. Introduction

[2] On May 21, 2003, the eastern coastal region of Algiers has been affected by a severe earthquake (Mw 6.9). The Boumerdes earthquake, located at 36.83N–3.65E and at 10 km depth [*Bounif et al.*, 2004], occurred in front of Zemmouri city, close to the line coast, and numerous aftershocks were located close to Boumerdes city [*Bounif et al.*, 2004]. Strong motion studies revealed that E-W accelerations were larger than the N-S ones, suggesting a fault related directional effect of the fault [*Laouami et al.*, 2004].

[3] Boumerdes city has been built on a mio-plio-quaternary basin deposited on a strongly deformed paleozoic micaschist basement [*Mansouri*, 1990]. The Tertiary stratigraphic column is mainly composed of more or less claystones (90%), sandstones and conglomerates, while the Quaternary is composed of unconsolidated sands (90%), clays and gravels. From 57 boreholes unpublished data, the Quaternary thickness varies from 10 to 40 m, while the paleozoic basement has never been reached in boreholes going down to 60 m.

[4] As the impact of the earthquake has been stronger in restricted well-defined constructed areas of Boumerdes, a study of the distribution of the soil fundamental frequency has been undertaken in the "Cité des 1200 Logements" [*Guillier et al.*, 2004], one of most damaged zone. The first study is based on ambient vibrations (microtremors) single-station recordings, using the spectral ratio (H/V) technique [*Nakamura*, 1989], to explain the observed uneven damage distribution. The second study used array techniques to improve the results obtained with the H/V method.

[5] In this paper, we assume "the coincidence between the shear-wave resonance frequency and the frequency of the peak of the H/V-ratio, as often used in practical applications" [*Malischewsky and Scherbaum*, 2004], as also assumed in other studies [e.g., *Scherbaum et al.*, 2003].

2. H/V From Single Stations

[6] Recording of ambient noise for H/V processing has been performed using 5-second Lennartz seismometers with CityShark stations, with a 900s recording duration and a 200 Hz sample rate. Data have been processed as in the SESAME project [*European Commission*, 2005], using 30–40 seconds windowing.

[7] For reliability of the H/V results and identification of the fundamental frequency of the soil, we follow the general assessment defined in the SESAME users guidelines [*European Commission*, 2005]. Given the window length that was used for processing, only frequencies above 0.5 Hz were considered.

[8] About 60 ambient noise recordings have been performed in the "Cité des 1200 Logements" (Figure 1a). Altogether, the resulting average-H/V curves show a fuzzy peak, defining a smooth bump in the 0.8–1.4 Hz range, with an amplitude of 1.5 to 3.4 (Figure 1b). This bump cannot be explained by the effect of the Quaternary layer, unless the geological structure of the Quaternary is too variable to be constrained by boreholes. As borehole data show that the Quaternary depth lies between 10 and 40 m, and using the formula $f_0 = V_S/4H$, V_S velocities are in the 40–160 m/s range, which are quite low values. Assuming a S-wave velocity (V_S) between 300 and 600 m/s [*Guillier et al.*, 2004], fundamental frequency peaks in the area should be between 2 and 15 Hz.

[1]Laboratoire de Géophysique Interne et Tectonophysique, Institut de Recherche Pour le Développement, Grenoble, France.
[2]Centre National de Recherche Appliquée en Génie ParaSismique, Algiers, Algeria.
[3]Institut des Sciences Maritimes et de l'Aménagement du Littoral, Algiers, Algeria.

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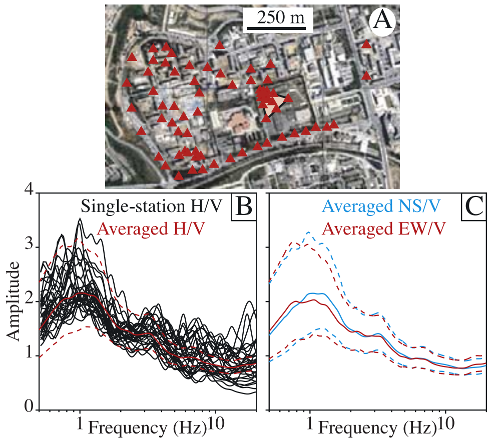

Figure 1. Single-station H/V results in the "Cité des 1200 Logements" of Boumerdes. (a) Location of H/V recordings (red triangles) and of microtremor arrays (pink triangle). (b) All single-station H/V curves (black lines) and the corresponding averaged H/V curve (red line) and standard deviations (red dashed lines). (c) Averaged N-S/V and E-W/V (solid lines) and standard deviations (dashed lines).

[9] When merging the 60 average-H/V curves of the area (Figure 1b), the 0.8–1.4 Hz bump appears more clearly, with an amplitude varying from 1.5 to 3.1, and a slight rippling appears at 3 Hz. Averaging the NS/V and EW/V curves (Figure 1c), confirms the main peak at 1.1 Hz and the undulation at 3 Hz. These later curves also argue that the EW strong motion directivity observed by *Laouami et al.* [2004] is not due to local effect, as they exhibit both a similar trend and the same amplitude level.

[10] H/V from single stations alone is unable to explain the structure as well as to get V_S velocities underneath the "Cité des 1200 Logements", in order to explain the damage distribution in the zone. The H/V study was therefore complemented by a microtremor array study.

3. Microtremor Array Study

[11] Recordings of ambient noise by small-aperture arrays showed to be a very powerful tool to evaluate V_S structure [e.g., *Horike*, 1985; *Fäh et al.*, 2001, 2003; *Scherbaum et al.*, 2003; *Picozzi et al.*, 2005]. This technique is useful due to certain plus such as the very low-cost implementation, the use of passive surrounding sources as excitation implying non-destructive measurements (important in densely populated areas) and a relatively large penetration depth, correlated to the array size.

[12] As the H/V curves from the single-station experiment do not exhibit marked peaks, it is reasonable to suspect that the geology of the area is not simple, or that there is no strong impedance contrast. Therefore, just in case and to broaden depth investigation, two arrays were installed. Each array is composed of 8 seismometers (5-second Lennartz) arranged in triangle with one sensor at each summit, one at the geometrical center, one at the middle of each side, and one randomly placed inside the triangle, with CityShark stations. Average and standard deviation of the apparent dispersion curve were obtained from these data sets using the CVFK technique [*Kvaerna and Ringdahl*, 1986], with a time analysis of 15 minutes and (7/f)-second windows. Relatively large parameters are used for inverting the dispersion curves to get P and S velocity profiles to lessen limitations on the inversion process (Tables 1 and 2).

Table 1. Parameters Used in the 34 m Array Dispersion Curve Inversion

Layer	Thickness (m)	V_P(m/s)	V_P/V_S	Velocity Gradient	Density (kg/m^3)
Sediment	10–500	500–2000	1.41–2.5	Yes	1600
Half space	–	1000–6000	1.41–2.5	No	2500

[13] The first array has a 34 m side which is normally adequate as the Quaternary depth is less than 40 m. 15-minutes records, with a 100 Hz sampling rate, were performed. As we suspected a Quaternary sediment layer over a Tertiary faster rock, the dispersion curve (Figure 2a) has been inverted using a single layer over a half space model, using the parameters of Table 1. A total of 50000 inversion models have been generated, using a neighborhood algorithm [*Wathelet et al.*, 2004], of which 17000 were selected with a maximal misfit of 0.125 (Figure 2b), which clearly show (i) a strong interface at 37 m depth, defined by a marked V_S jump from 500 to about 1200 m/s, and (ii) the presence of a slight velocity gradient in the upper layer.

[14] To check the coherency of the models with the single-station H/V results, the S_H transfer function has been computed on the best models, giving a peak close to 3 Hz (Figure 2c), in disagreement with the H/V results, which show a peak frequency in the 0.8–1.4 Hz range. However, postulating a severe S-wave attenuation in the upper layer, this 3 Hz peak may be related to the slight undulation observed at this frequency on the averaged H/V curve (Figure 1b). Anyway, as the thickness of the Quaternary is in the 10–40 m range, and V_S averages 350 m/s in the upper layer, the fundamental frequency should be above 2 Hz, which is still in disagreement with the H/V results. A second interface is now suspected. However, the array size is not wide enough to precisely evidence a deeper structure but, as expected, multi-layered inversions did not give good results. Now the second array proved to be useful.

[15] The second array has a 134 m side with 59-minutes records and sampling rate of 100 Hz. Thanks to the array size, the dispersion curve is refined down to 0.5 Hz (Figure 3a). Inversions of the dispersion curve, were obtained using a two-layer structure over a half-space, using the parameters of Table 2. From a total of 75000 inversions, 27500 have been selected using a maximal misfit of 0.157 (Figure 3b).

[16] The S-wave velocity model is compatible with the local geology profile. The shallowest contrast fits well with the interface between the Quaternary and the Mio-Pliocene,

Table 2. Parameters Used in the 134 m Array Dispersion Curve Inversion

Layer	Thickness (m)	V_P(m/s)	V_P/V_S	Velocity Gradient	Density (kg/m^3)
Sediment 1	10–200	500–2000	1.41–2.5	Yes	1600
Sediment 2	10–200	600–2500	1.41–2.5	No	1900
Half space	–	1000–6000	1.41–2.5	No	2500

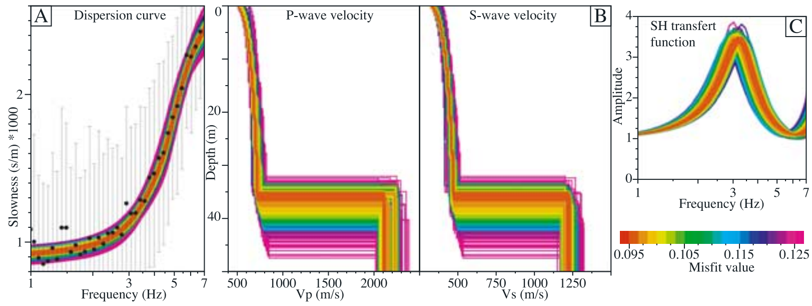

Figure 2. One-layer analysis results from the 34 m aperture array. (a) Dispersion curve (black dots) and standard deviation (vertical bars) obtained by CVFK analysis, and modeled dispersion curves (colored lines) corresponding to the selected models. (b) P-wave velocity profile (left) and S-wave velocity profile (right) obtained from inversion of the dispersion curve. An interface appears at 37 m on both velocity profiles. (c) S_H transfer functions from the synthetic V_S profiles of B, giving a 3 Hz resonance frequency of the soil. The misfit color scale shows the quality of the fitting model.

as its depth (37 m) is close to the bottom of the Quaternary layer (about 40 m). The upper layer velocity (300 m/s averaged) falls in the range expected for unconsolidated sands (100–500 m/s; e.g. *Cara*, 1989), and the velocity of the second layer (610 m/s) is a bit lower than the velocity of pure claystones (750–1500 m/s [e.g., *Cara*, 1989]). The deeper contrast is interpreted as the Mio-Pliocene-Paleozoic interface, which, according to borehole data, is over 60 m depth, and the velocity of the third layer (2100 m/s) is in the range of micaschist velocity (1200–2800 m/s [e.g., *Cara*, 1989]).

[17] The transfer functions from the best models (Figure 3c) give a main peak at about 1.2 Hz, in agreement with the H/V results from the single-station study, and the second peak around 3 Hz corresponds to the slight undulation observed on the H/V curve (Figure 1b). However, the amplitudes of these two peaks on the transfer function curves are not even close to those on the H/V curves.

4. Transfer Function Modeling

[18] The extravagant difference observed, for both array results, between the amplitudes of H/V (Figures 1b and 1c) and transfer functions (Figures 2c and 3c) peaks cannot be explained by a H/V curve smoothing effect, which, given the commonly constant value used [*European Commission*, 2005], cannot transform a clear peak into a smooth bump, neither by the S-wave velocity profile. They may therefore be due to the value of the Q factor used for the S_H modeling, which is of 100 in both the half-space and the upper layers. Therefore, transfer functions have been re-modeled with a fixed Q_s of 100 for the half-space, and, following the same procedure as *Jongmans and Campillo* [1993], four Q_s values (50, 25, 12, 7) in the two upper layers (only one Q change is allowed in the program), using the selected models from the greatest array (Figure 4). The best agreement with the single-station averaged H/V curve is obtained with Q_s = 7 (Figure 4e). This shows that (i) Q_s is a key parameter in transfer function modeling, and (ii) a single-station H/V curve can show a very smoothed shape even though the impedance contrast at depth is very strong.

5. Conclusion

[19] In the ‘‘Cité des 1200 Logements’’ the average single-station H/V curve, is characterized by a smooth peak around 1 Hz, with an undulation close to 3 Hz. Results from microtremor array studies demonstrate the presence of two interfaces in the V_S field. The first one at 37 m depth, is responsible for a sharp 3 Hz peak and the second, at 118 m depth, produces another sharp peak around 1.2 Hz. A good agreement is reached between the amplitudes of single-station H/V and calculated transfer functions, by introducing a strong attenuation in the upper layers (Q_s = 7), in accordance with the material of these layers composed of clay, clay stones and sand. These results indicates that Q_s is a key parameter in transfer function modeling and that marked impedance contrasts at depth are not always pictured in surface by sharp single-station H/V peaks. Therefore, smooth H/V curves showing only soft bump(s) should not always be considered as non-representative of the soil column, especially when they are consistent over a broad zone, and in such a case deserve a complementary investigation such as microtremor array analysis. Large mesh H/V recordings should be complemented and their curves aver-

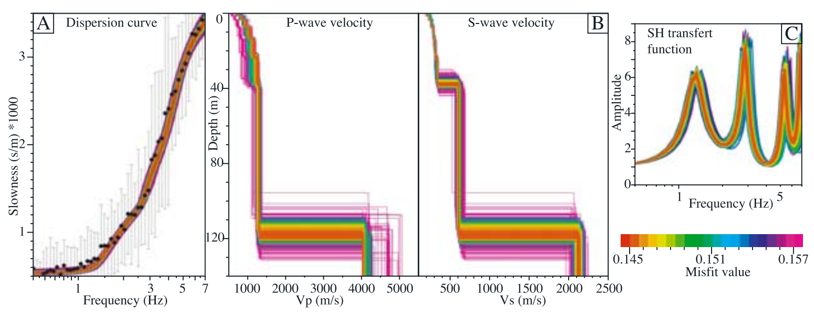

Figure 3. Two-layer analysis from the 134 m aperture array. Legend as for Figure 2. Two interfaces, at 37 m and 118 m, appear on both velocity profiles. The transfer functions exhibit two peaks at 1.3 Hz and 3 Hz.

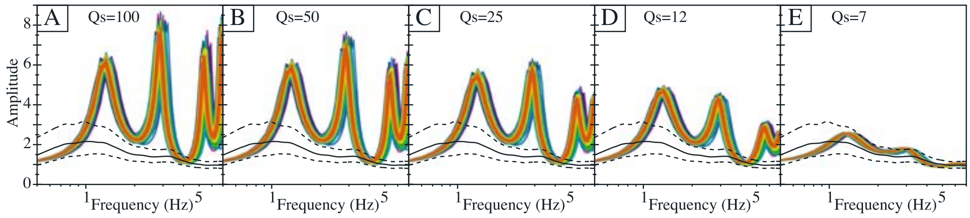

Figure 4. Averaged H/V (black solid line) and H/V standard deviation (black dashed lines), and transfer functions, from the selected models of the 134 m array, with Q_s = 100 in the underlying half-space and Q_s in the upper layers of (a) 100, (b) 50, (c) 25, (d) 12, and (e) 7.

aged to estimate the frequency value of the bump(s), in order to help sizing the array experiment.

[20] As it is not, by far, always possible to conduct array experiments in urbanized areas, and they are anyway much more difficult to set-up, we are currently pursuing our study of Boumerdes city with both array and dense single-station recordings, in order to evaluate if and how it is possible to combine these two types of studies. In particular, it is of prime interest to show if the sole single-station H/V results make it possible to extrapolate, in a zone where it is impossible to conduct array experiment, the results of a neighboring zone where such an experiment is possible, and how far away zones can be considered as neighbors.

[21] Another important issue raised, is that, in general, for V_S amplification (frequency and amplitude) is evaluated only in the topmost 30 m [e.g., *Eurocode 8*, 1988], which in the Boumerdes case would lead to a wrong evaluation. Furthermore, in the stratigraphic columns, only the Quaternary layers, assumed as soft-soils, are usually taken into account. As also observed in Belgium [*Nguyen et al.*, 2004], the Boumerdes results demonstrate that Tertiary rocks, which are not real soft-sediment, should be, at least in some cases, taken into account to explain the frequency resonance of the studied area.

[22] This study also corroborates the observation by *Laouami et al.* [2004] that the NS-EW strong motion differences are due to a fault related directional effect and not to local effect, as single-station averaged NS/V and EW/V curves exhibit both a similar trend and the same amplitude level.

[23] Finally, in the "Cité des 1200 Logements", the zone of Boumerdes the most impacted by the 21 May 2003 earthquake, the 1 Hz peak observed on the H/V curves could not explain the building collapses, given their frequency resonance at 3–4 Hz [*Dunand et al.*, 2004]. However, the secondary H/V 3 Hz peak, close to the building frequency range, could be energetic enough to provoke building collapse in the case of an earthquake.

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R. Ben Salem, J.-L. Chatelain, B. Guillier, D. Machane, N. Mezouer, and E. H. Oubaiche, CGS, 1 rue Kaddour Rahim, BP 252, Hussein-Dey, 16040 Algiers, Algeria. (guillier@bondy.ird.fr)
M. Hellel, ISMAL, Campus Universitaire, BP 19, Dély Ibrahim, 16020 Algiers, Algeria.