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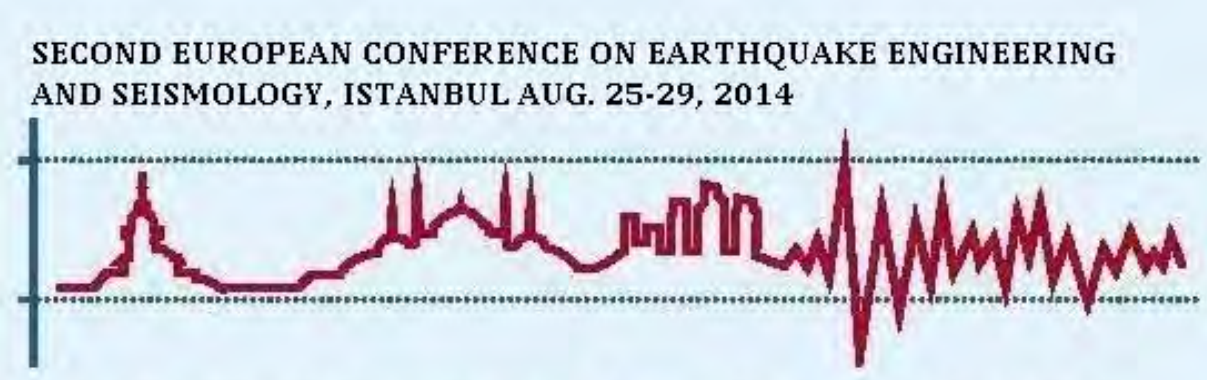

MAPPING THE FUNDAMENTAL FREQUENCIES IN THE CITY OF BEIRUT USING AMBIENT NOISE MEASUREMENTS

Marleine BRAX [1], Cécile CORNOU [2], Christophe VOISIN [3] and Pierre-Yves BARD [4]

ABSTRACT

Historically, Beirut the capital of Lebanon has been destroyed several times by earthquakes, the most devastating of which was the 551 A.D. offshore earthquake. Assessing the local seismic hazard and risk is therefore of primary importance for the whole country. The present study is part of a comprehensive set of experimental surveys providing physical insights and quantitative constraints on the site response variability within the city (Brax, 2013).

The geology of Beirut constitutes an exception to the geological landscape in the area, in relation with its sub-horizontal platform (Fig.1). Stiff to hard Miocene and Cenomanian units are outcropping on two hills whereas the rest of the platform is covered by alluviums or sandy soils, resulting in highly variable near surface geological conditions throughout the city, which may in turn result in highly variable ground shaking characteristics

In order to evaluate the soil effects, 30' long ambient noise measurements were conducted in 615 sites distributed over a region that covers the city of Beirut and parts of its suburbs. The dataset has been processed with the horizontal to vertical spectral ratio technique HVSR according to the SESAME guidelines, resulting in the identification of fundamental frequencies over the study area. Different assessments of the predominant frequencies were made individually by the authors in order to test the robustness of the results. A good correlation between H/V frequencies and the geology of the soil was found. Different zones with large amplitude peaks have also been identified.

A detailed map of the fundamental frequencies of the soil was derived for the whole region of study. Despite its limitations, such a map provides a useful information on sub-surface conditions of the city, and highlights several zones where possible amplifications can be expected in future earthquakes, and result in higher risk. It also allows identifying zones, which should be the focus of further investigations. This map could be an important step on the way towards a seismic microzonation of the Greater Beirut area, which is essential for city planning and the optimal design of earthquake resistant structures.

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INTRODUCTION

Local geological conditions can change the characteristics of seismic waves, which can be amplified considerably at variable frequencies depending on the velocity and thickness of near-surface deposits. Analyzing the geology of Beirut (Fig.1) in view of such site–specific amplification thus deserves specific and careful attention; a 6-month measurement campaign at 10 sites carried out in 2006 revealed significant amplification (Brax, 2013), emphasizing the need for an extrapolation throughout the whole urbanized area. Such an extrapolation has been attempted on the basis of microtremor measurements and H/V processing at a large number of points over the whole area.

The experimental HVSR technique based on ambient noise recordings appeared first in the early seventies (Nogoshi and Igarashi, 1971) but became popular in 1989 with the work of Yutaka Nakamura that showed resemblance between the spectral ratio of the horizontal and vertical components of microtremor recordings, and the transfer function of surface layers for horizontal motion (Nakamura, 1989). This technique proved to be useful to estimate the fundamental frequency without a reference station and with only one station, and also to provide information on the local amplification level at least in some example cases (Lermo and Chavez-Garcia, 1993). After these early papers, researchers began paying interest on this technique trying to clarify the physical background, the capabilities and limitations of this technique (Lachet and Bard, 1994; Nakamura, 2000; Parolai et al. 2004; Bard, 2008) and to understand the composition of the ambient noise wavefield, by identifying the type and proportions of body and surface waves, including its possible frequency dependence (Bonnefoy-Claudet et al. 2008; Endrun, 2011). Others suggested improved and somewhat standardized field protocol and processing techniques in order to obtain stable and reliable results (Chatelain et al. 2008; Guillier et al. 2008; Haghshenas et al. 2008).

Many studies used the HVSR technique to map the fundamental resonance frequency of the surface soil (D'amico et al. 2008, among others). The ultimate goal of the study presented here is to take profit from this inexpensive and useful method to estimate the fundamental frequencies of different sites with the objective to characterize the soil in Beirut and close suburbs. An ambient noise campaign was conducted at a total of 615 sites in Beirut. The results and their robustness are analyzed and discussed in terms of fundamental resonance frequency values and maps.

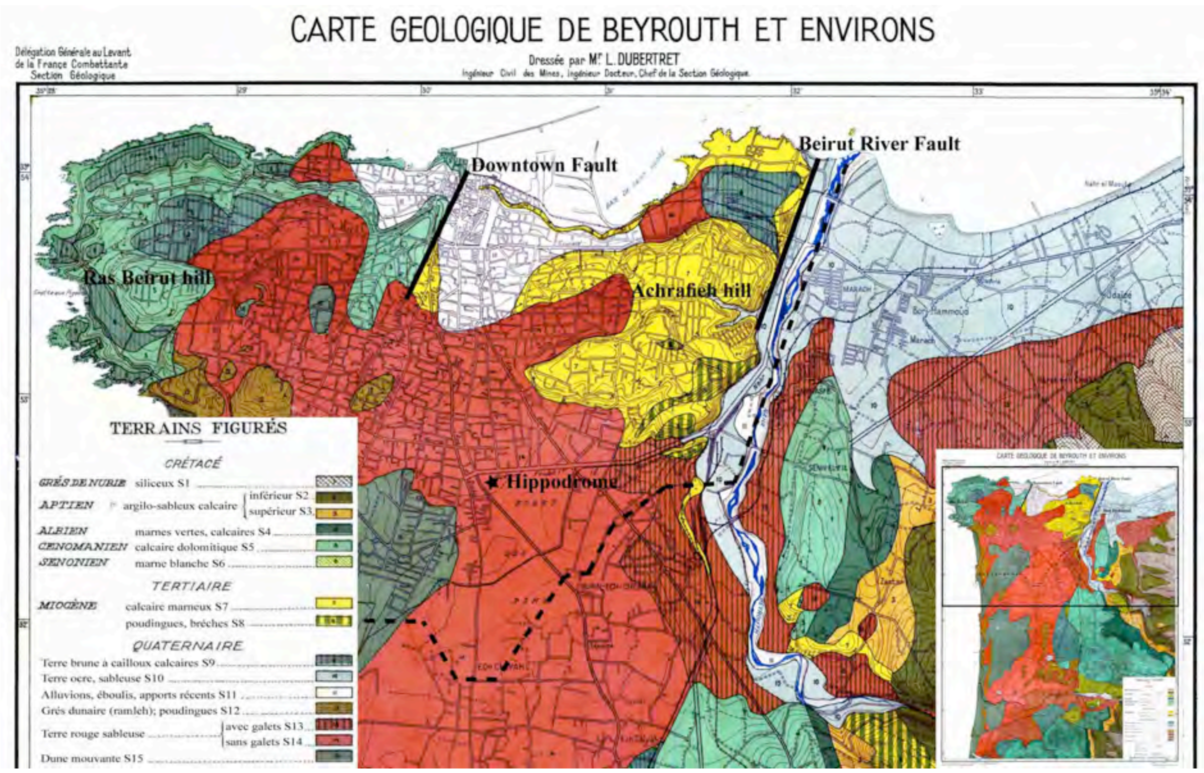

Figure 1. Geological map of Beirut from Dubertret (1945), with layouts of Beirut faults (continuous lines) and the Beirut municipality's limits (dashed lines)

INSTRUMENTATION, ACQUISITION AND ANALYSIS PARAMETERS

The campaign of measurements was conducted following an approximately 400 m spacing grid covering the city of Beirut and parts of its suburbs. This grid was adopted as initial locations for the potential measurements points. In the areas close to limits between different geological structures or where fast underground lateral variations were expected, the measurement grid was densified and the mesh size was decreased down to 200 m. The equipments used were composed of broadband velocity sensors Guralp CMG40-30s connected to Taurus stations. Only the recordings at a few sites were performed using the Lennartz sensor LE-3D/5s with a Geosig GSR24 station. The sensors were installed directly on the surface of the ground without any interface. Depending on the site, the type of surface varied between asphalt, pavement of the sidewalks, concrete or gardens. The recordings were sometimes nearby buildings and other times in free field far from structures. All the recordings were performed during daytime and most of them during the same season under the same, usually sunny, weather conditions.

In order to evaluate the soil effects on broad frequency band, the recording duration was fixed to 30 minutes. The acquisition sampling rate was 100 sps for the Guralp/Taurus and 200 sps for Lennartz/Geosig. The difference in sampling rate came from the fact that a sampling rate of 200 sps was first adopted then was replaced by 100 sps as this latter is enough as the maximum frequency of interest is not higher than 20 Hz and higher sampling rates do not influence H/V results (SESAME guidelines and recommendations). A total of 615 microtremor measurements could be performed over the city of Beirut and suburbs (Fig.2).

The recordings dataset has been processed with the horizontal to vertical spectral ratio technique HVSR according to the European project SESAME guidelines and recommendations. The data processing was done using Geopsy software (http://www.geopsy.org). For each recording, the three signal components (East/West, North/South and vertical) were processed as follows:

- First, the offset was removed by subtracting the mean of the signal.
- 60 seconds long windows, free from transient noise were automatically selected. The removal of transient noise was performed by an automatic anti trigger selection based on STA/LTA applied on raw signal. A check on the resulted automatic selection was done and unwanted windows that still contain transient noise were manually discarded. A minimum of 10 windows had to be automatically selected otherwise an overlap of 20 to 30% was applied and the automatic selection was done again.

After the windows selection, the followed processing is applied to each window.

- In order to minimize the border effect, a cosine tapering of 5% was applied on the three components.
- The Fourier spectrum of each component was calculated and the geometric mean of the N/S and E/W components computed.
- Once, the horizontal and vertical spectral amplitudes were obtained, they were smoothed according to Konno and Ohmachi (1998), with a bandwidth parameter equal to 40.
- Then, the H/V spectral ratio is computed at each frequency.

At the end, the geometrical mean H/V as well as the corresponding standard deviations were calculated by averaging the H/V coming from all the individual windows. All the H/V ratios were calculated for the frequency range of 0.2 to 20 Hz but only results for frequencies higher than 0.5 Hz were considered reliable, as the low frequency spectra exhibit an increasing amplitude, that has unclear reasons (proximity to the sea, wind issues as sensors were not buried, or else) that alter the interpretation of the H/V ratio at very low frequencies.

Figure 2. (Left) The initial 400m spacing grid of the ambient noise measurements sites. (Right) The effective measurements sites. The white continuous line represents the borders of Beirut municipality. The black rectangular delineates the area of the grid shown in the left image

DIFFICULTIES IN THE INTERPRETATION OF THE RESULTS FOR SOME SITES

The analysis of the H/V measurements points and subsequently the identification of the frequency corresponding to the H/V peak was an easy task only for about 25 % of the total number of points, for which the peak was very clear (Fig.3a), and tricky in other sites.

The rock sites exhibited three types of results: 60 % of the points showed flat spectral ratios that confirmed the geological characteristics of the sites (Fig.3b), high-frequency H/V peaks were visible at 15 % of the points (Fig.3c) while the remaining 25 % displayed peaks within the range 1 to 6 Hz with amplitudes reaching sometimes the value of 4. In a few cases (8 sites), flat curves were also obtained at sediment sites, where the H/V ratios did not exhibit any clear peaks or the small amplitudes made difficult the identification of the H/V peaks (Fig.3d). In these cases, the locations of the sites on the geological map in addition to the comparison between the graphs of the Fourier spectra of the three components and the spectral ratios H/V were necessary to confirm the choice of the H/V peak values. These cases may correspond to sites without strong impedance contrast at depth.

The systematic comparison between the Fourier spectra of the three components and the H/V spectral ratios was also useful on many sites when two peaks could be seen. The Fourier spectra permitted to discard the industrial peak and to keep the fundamental frequency relative to the site (Fig.3e and 3f). At some sites, the industrial frequency coincided with the natural frequency of the soil. The Fourier spectra were also used to confirm this coincidence and to deduce the natural H/V peak amplitude by visually subtracting the spectral amplitude corresponding to the industrial peak from the horizontal and vertical components.

Another point to highlight is the presence of low fundamental frequencies (< 1 Hz). Due to the limit of reliability of the results at low frequencies (in relation to the window length and the sensor frequency), the fundamental frequencies were searched only at frequencies higher than 0.5 Hz. Nevertheless, at some sites, an increase in amplitude at frequencies lower than 1 Hz led us to hesitate between two possible fundamental frequencies. An example of this case is shown in Fig.3g. When looking to the H/V curve of the site B316, one could consider the fundamental frequency is around 5 Hz, although an increase in amplitudes is also visible at frequencies lower than 1 Hz. However, by looking to the spectra of the three components, they displayed a clear increase in the energy at frequencies lower than 1 Hz and down to 0.6 Hz, while below the latter value the significant increase in energy of the horizontal components led us to consider it as unreliable (Fig.3h). Another reason was the location of this point in a region known by the thickness of the red sand. Consequently, the fundamental frequency selected for this example was 0.8 Hz and not 5 Hz.

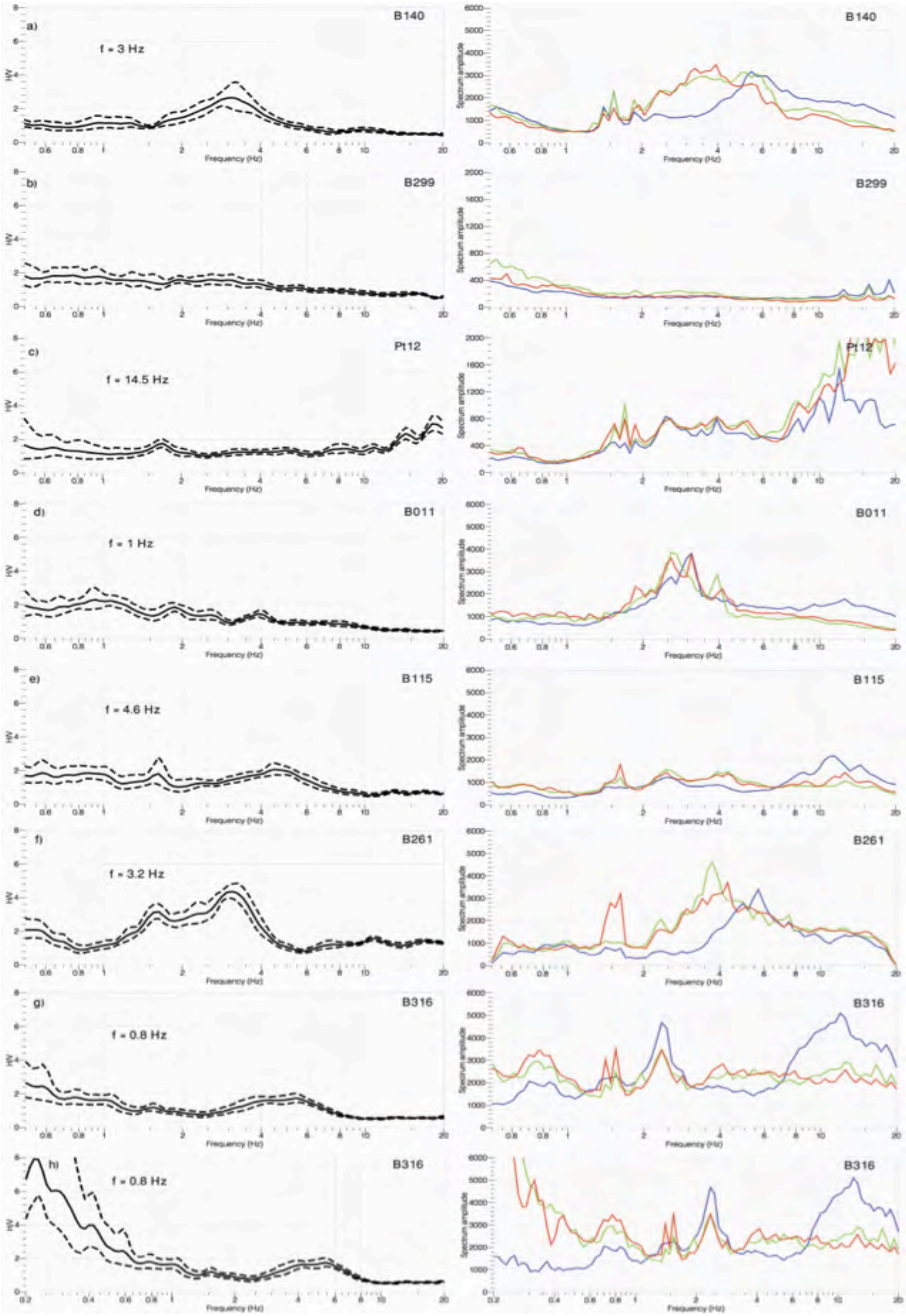

Figure 3. Examples of curves obtained in the analysis of the ambient noise measurements : (Left) H/V spectral ratios (mean ± standard deviations) and (right) their corresponding Fourier spectra (blue: Z component, green: N/S component and red: E/W component). 3a : clear peak; 3b : flat curve on rock site; 3c : HF peak on rock site; 3d : flat curve on sediment site; 3e and 3f : sites with industrial peaks; 3g and 3h : high amplitudes at LF (<1 Hz)

HVSR RESULTS

The HVSR analysis was thus systematically complemented with a careful look at the individual spectra of each component, and only then was the fundamental frequency estimated. Fig.4 displays the fundamental frequencies of all the measurements points in Beirut and suburbs. All the sites that displayed flat curves or gave H/V peak at frequency higher than 20 Hz were given a frequency equal to 20 Hz. Consequently the dark red squares represent the sites with “flat” H/V curves, which in principle can be interpreted as rock sites of the studied region. In order to get continuity in the results, a spatial interpolation of the frequencies obtained was performed (Fig.5). The density of the measurements points permitted to have a good continuity and so a good confidence in the quality of the interpolation. The comparison between the frequencies and the geological maps shows, visually, a good consistency (Fig.5).

- The rock sites are directly identified with the highest frequencies and the two hills, Ras Beirut and Achrafieh, appear clearly in Fig.5.
- On the other extreme, the H/V analysis reveals the existence of four low fundamental frequency regions ($f0 < 1.5$ Hz): Antelias and Borj Hammoud on the eastern side of the Beirut river, and the areas around Forn el chebbak and Jnah on the western side. In the area delimited by Mazraa, El Horch, Chyah and Forn el Chebbak, the frequencies are around 1 Hz, which is consistent with the presence of thick deposits as mentioned in the literature (Duberteret, 1945). Similar values were also found at Jnah, Borj Hammoud and Antelias.
- A part of the southern suburbs of Beirut could not be surveyed for both time constraints and security reasons. A H/V survey should be conducted in this area in the near future in order to verify whether the two low fundamental frequency regions of Forn el Chebbak and Jnah are connected or constitute two independent low frequency areas.

The amplitudes were also displayed (Fig.6) even though they are not necessary representing the exact soil amplifications. According to what was found in Brax (2013), these amplitudes could be considered as a lower bound for the actual amplifications. Different zones with large amplitude peaks can be identified.

- All the regions on the eastern side of the river of Beirut from Borj Hammoud till Antelias to the north exhibit relatively high amplitudes (> 3), that sometimes exceed a value of 9.
- On the west side, the area along the river witnesses also high amplitudes. This area is getting wider and wider from the east slope of the Achrafieh hill, where it is narrow, to the south in the direction of Forn el chebbak and Chyah.

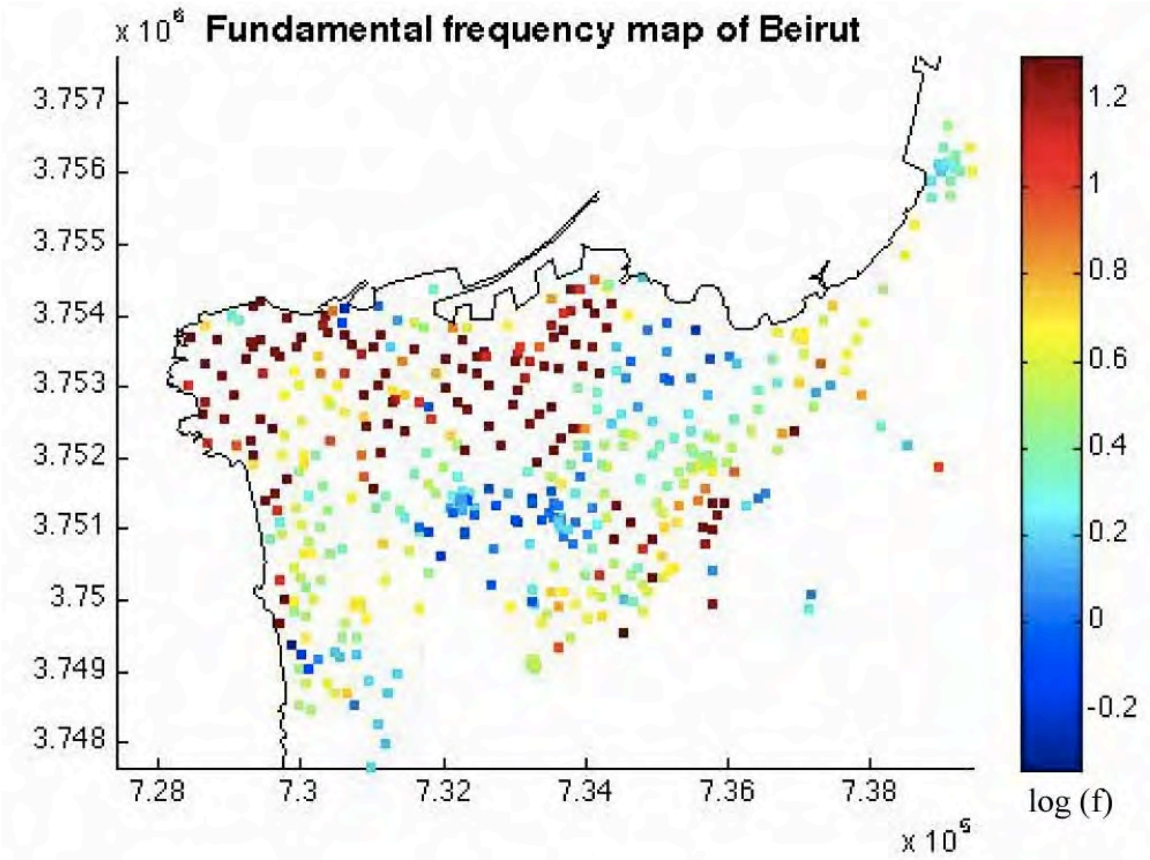

Figure 4. Distribution of the fundamental frequencies of the measurements points in Beirut and suburbs, estimated from H/V technique. All the sites with flat curves are reported in the graph as sites with peak frequency equal to 20 Hz.

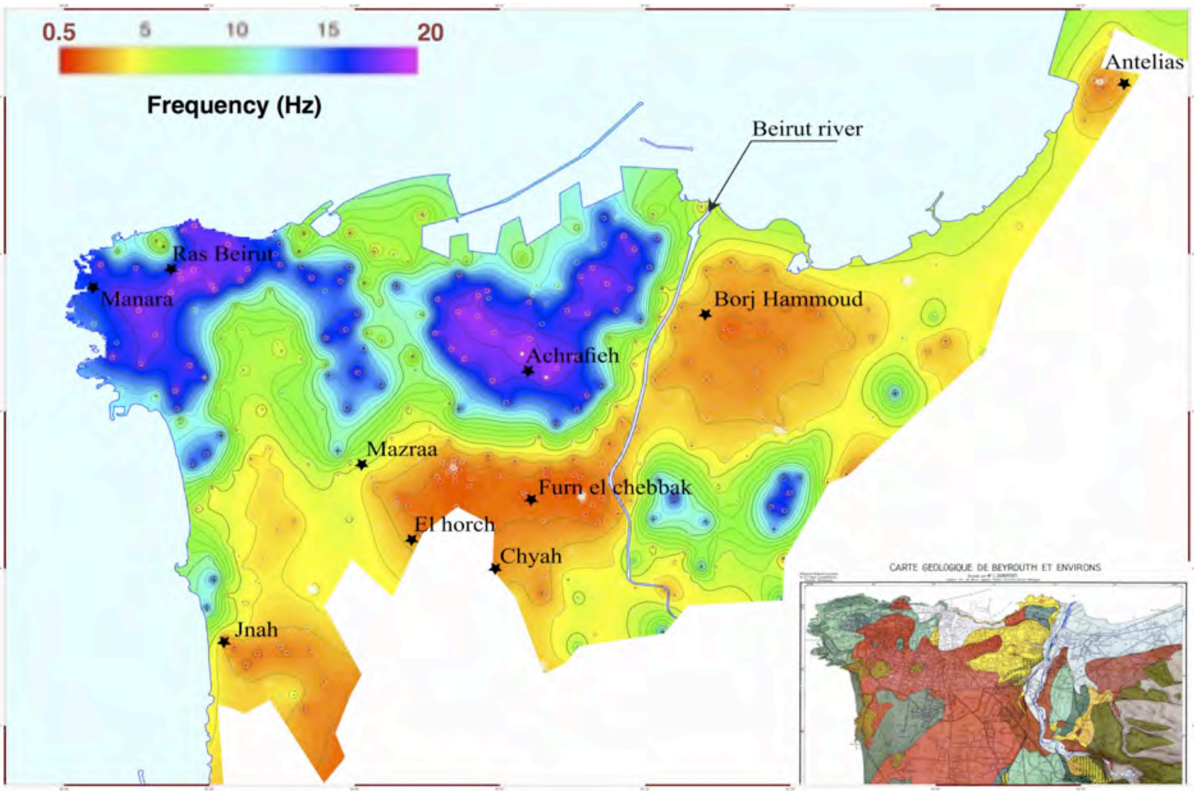

Figure 5. Map of the interpolated fundamental frequencies in the region of Beirut. Frequency is given in Hz. Bottom right : the geological map of the studied area

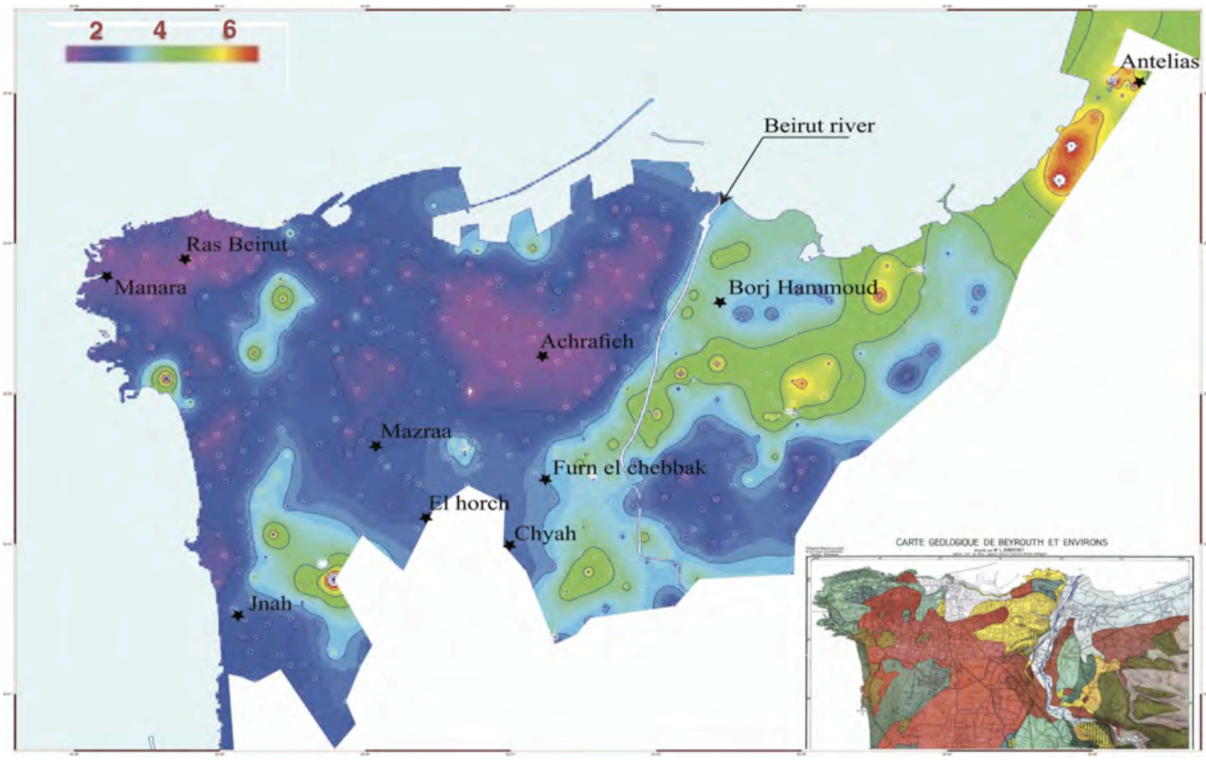

Figure 6. Map of the interpolated H/V amplitude in the region of Beirut. Bottom right : the geological map of the studied area

ROBUSTNESS OF THE RESULTS

In the analysis of the H/V measurements especially at some critical points where the peak is not very clear, identifying the fundamental frequency may vary from one person to another. The comparison of the H/V curves with the spectra played a role in reducing the subjectivity in the identification of the fundamental frequency. However, in order to check the robustness of the results, two additional independent assessments of the predominant frequencies (Pickings P2 and P3, Fig.7) were performed by the co-authors of this paper in addition to our own assessment (Picking P1, Fig.7). An example of a comparison of the fundamental frequency values between P1 and P3 is shown in Fig.8 and a summary of this test of robustness is displayed in Table.1. By looking to the Fig.7 and Fig.8, some remarks could be noticed and are as follows:

- The three maps resulting from each individual picking exhibit the same overall patterns. Most of the sites show similar values.
- When the three pickings were compared together, differences were of course found, but in the whole set, there was a very good accordance between the results. 64% of the points were found to be attributed by P1, P2 and P3 simultaneously, fundamental frequencies within ±20% of one of the values and 75% within ±50% of the values. The difficulties were mainly found in low frequencies where the industrial peak around 1.7 Hz biased the results and could have been easily taken as the fundamental frequency of the site (Fig.8).
- The two hills of Beirut can be identified in the three pickings. However, the main difference between P1, P2 and P3 remains the area of these high-frequency zones that is subjective (Fig.7 and 8). It is slightly larger and more consistent with the geological map for P1. In P2, these regions display some points with fundamental frequencies below 1 Hz while in P3, the pickings give more consistent results and values close to picking P1.
- In the southern region around Forn el chebbak and delimited by Mazraa, El Horch and Chyah, the three pickings do witness a low fundamental frequency area, but they do not agree on the extent of the region with frequencies lower than 1 Hz.

- Around Jnah to the South-West of Beirut, P1, P2 and P3 display almost similar values with a tendency in P2 to give higher frequencies at the south east of the area.
- In the port region, significant differences are found between P1 and (P2-P3), the two latter being very similar. While P2 and P3 attribute to the zone, at the west of the port, frequencies around 2 Hz, P1 indicates predominantly flat H/V curves (interpreted as rock sites), with a few low frequency sites right along the coast.

As a conclusion, this comparison between different pickings permits to test the robustness of the results, and highlights the regions that may need further investigations i.e. the regions around Forn el chebbak, around Jnah and the port region. For the rest of the surveyed area, the results prove to be very consistent and thus can be considered as reliable.

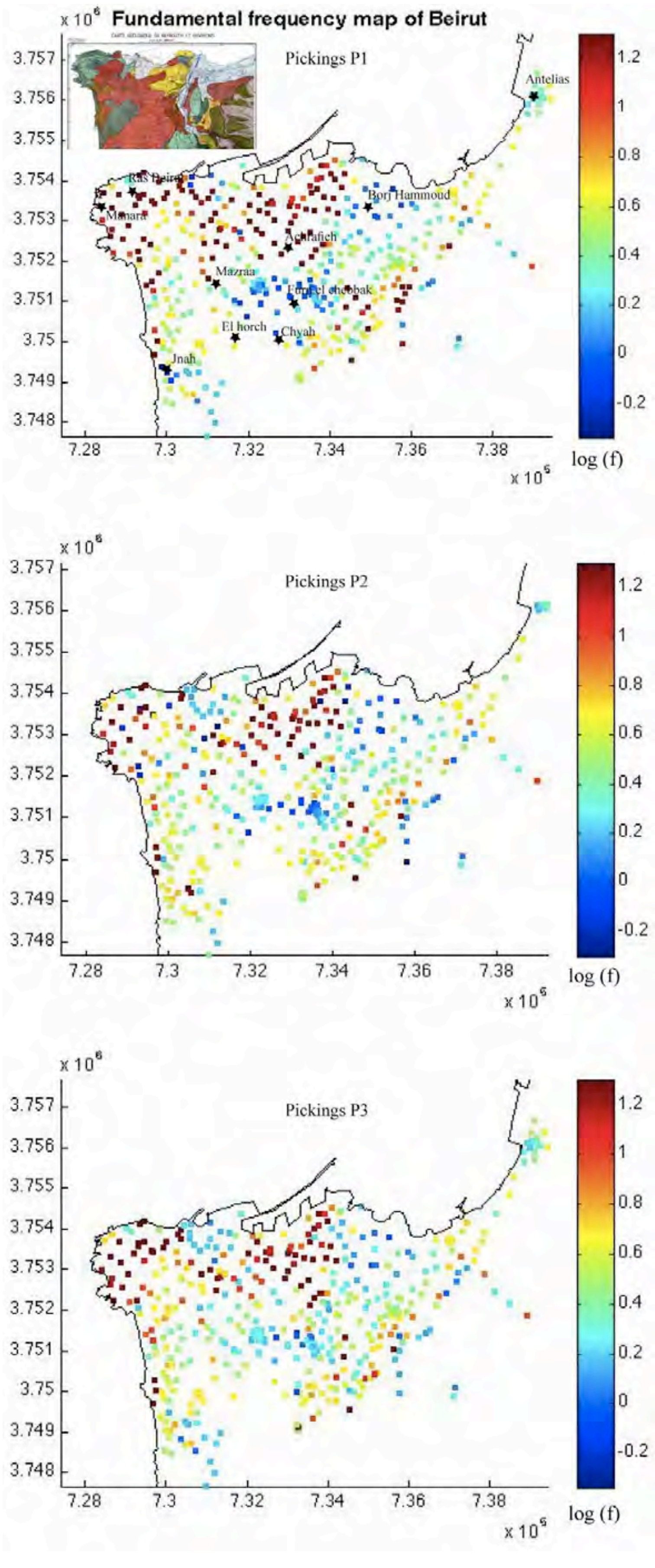

Figure 7. Comparison of the fundamental frequencies obtained by three independent pickings (P1, P2 and P3) of the H/V peaks. The color code on the right stands for the log10 of the H/V peak frequency

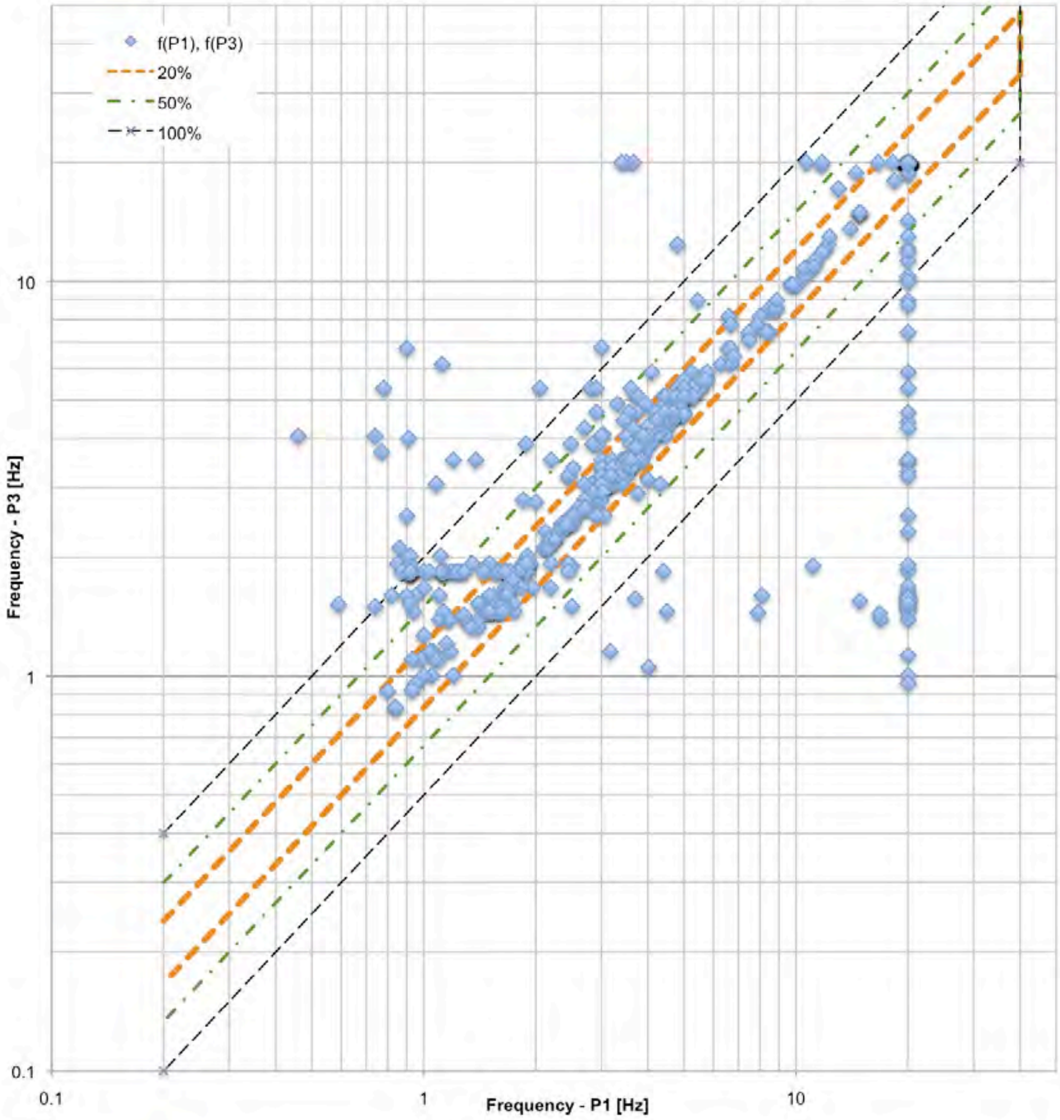

Figure 8. Graph displaying the correlation between the pickings P1 and P3. Graphs corresponding to variations of ± 20%, 50% and 100% are also displayed.

CONCLUSIONS

The inexpensive H/V technique was used for a site characterization of the Beirut area: ambient noise measurements performed at 615 sites provided estimates of the fundamental frequencies for a 6 x 10 km2 area including the Beirut municipality. The results of the 615 ambient noise measurements could be interpolated to derive a map of fundamental frequencies for the Beirut area. The H/V spectral ratios prove to be fairly well correlated with surface geology. Such a map provides useful information on sub-surface conditions of the city:

- It highlights zones, like Borj Hammoud, Forn el Chebbak, Antelias and the east of Jnah that present low frequencies and high amplitudes. The risk in these regions is significant especially where the population density is high. Possible amplifications of the ground motion and subsequently site effects can be expected in future strong earthquakes. These zones should be the focus of further investigations to better delineate the extent of these zones and to understand better the risk.

- It also shows the urgent needs to complete the frequencies and amplitudes map by surveying the highly populated region located in the South between Jnah and Chyah in order to identify the seismic hazard and risk there.
- This map is an important step on the way towards a seismic microzonation of the Greater Beirut area, which is essential for city planning and the optimal design of earthquake resistant structures.

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