POTENTIALITY OF MICROTREMOR TO EVALUATE SITE EFFECTS AT SHALLOW DEPTHS IN THE DEEP BASIN OF SANTIAGO DE CHILE

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ABSTRACT :

Ambient noise arrays measurements were performed in the deep basin of Santiago de Chile (Chile) where site effects were clearly revealed by the 1985 Valparaiso earthquake. The significant seismic intensities reported for one-storey houses outlined the resonance of a shallow soft sedimentary layer during the Valparaiso earthquake. We look for testing the Horizontal-to-Vertical spectral ratio (H/V) and the more complex array techniques HRFK (High Resolution Frequency-wavenumber method) as a tool to provide qualitative and quantitative information of site effects for the top most soil layers. Although we show the robustness of the H/V method to map the fundamental resonance frequency of the deep basin, we outline its limitation to identify the resonance frequency at shallow depths. We conclude by emphasizing that the H/V method alone may not be enough to assess the seismic hazard in urban area especially when there is a large variety of building type: from small-size residential houses to high rise business buildings. We also show that small-size arrays measurement are a powerful tool to provide the site effect estimates (resonance frequency and amplification factor) for the shallow sedimentary layers.

KEYWORDS: Site effects, microtremor, H/V, arrays technique, Santiago de Chile

1. INTRODUCTION

Chile is one of the most seismic areas in the world. Before the great Sumatra - Andaman earthquake (2004, Mw=9.1), 46 percent of the seismic energy spread out during the last century was in Chile. The largest events which occurred in Chile are mostly due to the subduction of the Nazca plate beneath the South American plate. In central Chile, the subduction raises a relative velocity of about 8 cm/yr in a N78°E direction and generates mostly interplate earthquakes. The recurrence of the largest events in the Metropolitan region - Santiago de Chile area - is about 80 years. In Chile, although most of the seismological studies focus on the properties of the subduction processes, recent study has shown that local site effects may happen in Santiago de Chile. Past investigations were conducted in Santiago de Chile to evaluate site effects: an array of accelerometers (SMACH array) has been deployed since 1989 and local site effects have been evaluated from strong ground motion records (Midorikawa et al. 1991, Cruz et al. 1993). Ambient vibrations measurements were also carried out in the city in order to correlate the site effects evaluated by strong ground motions (Gueguen 1994, Toshinawa et al. 1996). Ambient vibration studies such as the H/V technique (Nakamura 1989) and the more complex array techniques (Capon 1969) are powerful tools to study local soil site effects. Past studies in Santiago focused on the identification of the low fundamental frequency of the deep basin. However, the strong damages observed on small-size houses in Santiago during the 1985 Valparaiso earthquake suggest that site effect related to unconsolidated sediments at shallow depth may occur. The scope of this work is thus to verify the possibilities of the methods based on ambient noise measurements (H/V and array techniques) to identify site effects at shallow depths.

2. GEOLOGICAL SETTING

The city of Santiago de Chile is located in the so-called Central Depression, which is a basin surrounded by the Main and Coastal ranges of the Andes (western 70° and southern 33°). This basin spans for 80 km long and 30 km wide and it is mainly elongated in the north-south direction. Due to the geomorphological setting, this basin is essentially filled with alluvial sediments (Valenzuela 1978). They are composed by pebbles, gravels, clays and volcanic ashes. The pebbles and gravels are mainly located in the eastern and southern part of the basin. Clayey material is mostly present in the north; whereas a transition zone is found in the centre of the valley. In addition, volcanic ashes are also observed at the surface of the basin; their thickness can reach more than 40 m in some areas. In addition, compilation of geophysical surveys (Bravo 1992) and borehole data (Iriarte-Diaz 2003, Morales-Jerez 2002) revealed the presence of unconsolidated sediment at shallow depths (< 20 meters deep) in the basin.

3. METHODS

3.1. H/V

The microtremor H/V technique (Nakamura 1989) consists in estimating the ratio between the Fourier amplitude spectra of the horizontal and the vertical components of ambient noise vibrations and provides the resonance frequency of the site under study. The H/V ratios are calculated using the GEOPSY software (www.geopsy.org), for the frequency range 0.2 to 20 Hz, using 50 s time windows and removing time windows contaminated by transients. The interpretation of the H/V curve was carried out conformably to international consensus criteria (see SESAME European project (Bard and SESAME-Team 2005)). According to these, firstly we verified the curve reliability (i.e., sufficient number of windows and significant cycles for a given f0, acceptably low scattering between all windows over a given frequency range around f0) and after we checked the clarity and reliability of the H/V peak (i.e., fulfilment of amplitude and stability criteria).

3.2. Array technique and S-wave velocity profile from inversion

In this study, we have used the high-resolution frequency-wavenumber analysis scheme proposed by (Capon 1969) on vertical component. Operating with sliding time windows and narrow frequency bands, the HRFK method implemented in the cap software (Ohrnberger 2004) provides the wave propagation parameters (azimuth and the so-called dispersion curve: the phase velocity as a function of frequency) of the most coherent plane wave arrivals. We use a wave number grid layout sampled equidistantly in slowness and azimuth.
The dispersion curves are inverted to 1D-layered velocity models using the neighbourhood algorithm (Sambridge 1999) as implemented by Wathelet et al. (2004). The neighbourhood algorithm performs a stochastic search of the parameter space, that is, body-wave velocities and the thickness and the density of the soil layers. As input of the inversion algorithm, we considered the measured dispersion curves of the vertical ambient vibration component. Several a priori soil models have been tested at each site and we show here only results for models fitting the dispersion curve with the best misfit.

4. ESTIMATION OF THE RESONANCE FREQUENCIES

Extensive ambient noise measurements were performed in the basin of Santiago from April 2005 to spring 2007. The ambient noise vibrations were recorded using Cityshark I and Cityshark II data loggers coupled to sensors Lennartz LE-3D (three components velocimeters having a 5 seconds natural period). 264 measurements of ambient noise were collected in the city (Fig. 1). The sampling rate was 125 Hz and the duration of recording 15 minutes, except at some points where the recording duration was extended to 20 minutes because of a strongly disturbed environment (dense and close car traffic, pedestrians...). Some signals, however, were still dominated by transients, thus 37 records were rejected. Finally, 227 measurements of ambient noise were considered for the H/V processing. The application of the reliability and clarity criteria (see section [3.1]) to the Santiago data set results in 199 reliable data that show 47 sites with flat H/V curves and 152 sites with peaked H/V curve. Most of these peaks are clear and often sharp (77 of data), but at a number of sites exhibit peaks of low amplitude (namely below 2) or broad maxima. After the SESAME recommendation, the site fundamental frequency can be safely inferred only from clear peaked H/V data.

4.1. Distribution of the resonance frequencies

In the scientific literature dealing with site effects assessment and seismic microzonation, the usual practice is to plot the spatial distribution of site amplification frequencies as contour map. This representation, however, may become inappropriate in the case of Santiago because we have a low number of data (clear H/V peaks) non-equally distributed at the surface of the basin. We have then decided to depict the spatial location of H/V peak frequencies with respect to their frequency: 0.3 – 0.5 Hz, 0.501 – 1.2 Hz, 1.201 – 5 Hz and 5.01 – 20 Hz. The frequency intervals have been arbitrary chosen so that there is a roughly similar number of data for the first three intervals. H/V peak frequencies are displaying in Fig. 1 and we can make the following comments:

- Data with peak frequency between 0.3 – 0.5 Hz are located above the thickest parts of the basin, from 550 to 150 m, outlying the good correlation between low fundamental frequency and thick sediment deposits given by gravimetric study, at least at a first order.
- Data with peak frequency between 0.501 – 1.2 Hz are in great majority located above thinner sediment deposit, from 150 to 50 m, outlying once again the good correlation between fundamental frequency and sediment thickness.
- Some data with peak frequency between 1.201 – 5 Hz are located near basin edges and outcrops where the thickness of the sediment deposit is rather thin (about 50 m), outlying once again the good correlation between fundamental frequency and sediment thickness. However a large number of data are located above deep depressions. These data can not be related to the resonance of the deep sediment deposits (more than 300-400 m); they are more likely linked to the resonance of superficial deposits. Clear evidence can be found in the Pudahuel district where high frequency H/V peaks are distributed at the surface of the stiff pumice deposits.
- Finally, data with peak frequency above 5.01 Hz are scattered at the surface of the basin, suggesting the presence of a topmost soft sedimentary layer (few meters thick).

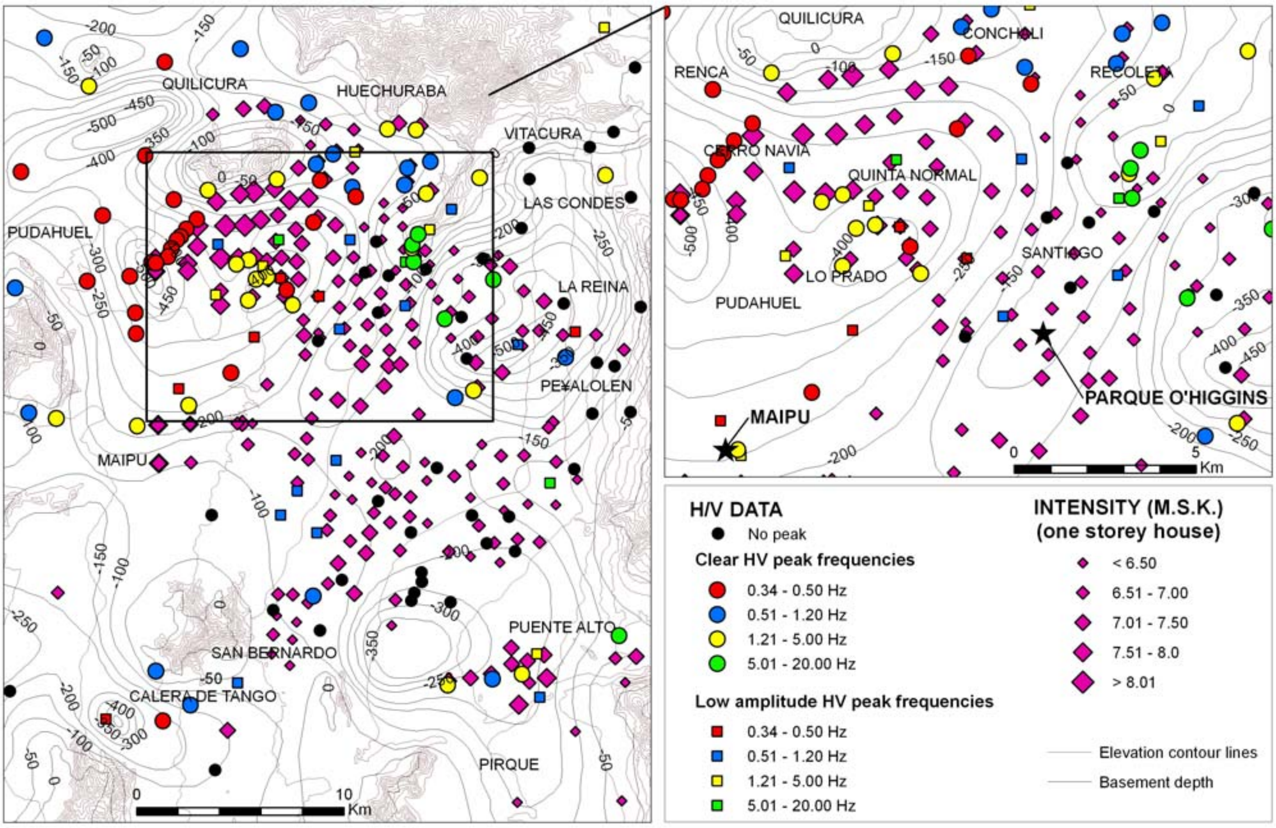

Figure 1 Comparison between the H/V peaks frequencies observed in the basin of Santiago and the seismic intensities reported after the 1985 Valparaiso earthquake. The seismic intensities are based on damage reports of one storey adobe and masonry houses. Circles and squares filled symbols indicate if the H/V peaks amplitude is respectively greater or lower than 2. Black stars display the location of the ambient noise arrays measurements.

4.2. Comparison with seismic intensities

The damage pattern in urban areas during an earthquake depends on the characteristics of the event and on the interaction between site response and vulnerability of the exposed structures. During the last fifteen years several efforts have been made to correlate damage with surface geology properties estimated from ambient noise measurements. Several papers presented comparison between the fundamental frequency and corresponding H/V amplitude level and damage distribution or macroseismic intensities after significant earthquakes (Theodoulidis et al. (2008) and references therein). Some of the studies indicate that the H/V results are correlated with the spatial distribution of damage, especially when damage variation is mostly controlled by near-surface geology.

In the case of Santiago, during the 1985 Valparaiso earthquake (Ms 7.8, 17 Km deep, 33.13°S – 71°87W), there was considerable damage to small-sized adobe structures, while the many high rise structures in the 10-to-20 story range performed well with minor damage to finishes and non-structural features (Wyllie et al. 1986). The intensity data for the Valparaiso earthquake were estimated based on damages report of one story adobe and one story masonry houses (Astroza and Monge 1991). Most of the damages was mainly concentrated in areas with poor soils conditions located in the northwest of the city (Fig. 1), especially in the fine-grained alluvial deposits (Quilicura, Renca and Cerro Navia districts), in the stiff pumices (Pudahuel and Lo Prado), and in the transition zone (Quinta Normal). In addition, a cluster of damage is also reported in consolidated sediment (gravels) in the southern of the city (Puente Alto district).

In the area of the highest intensities, the comparison between the H/V peak frequencies and damages on small-size houses reveals a discrepancy: while the H/V peak frequencies do not exceed 4-5Hz, much damages was observed on small-size houses which have a natural frequency higher than 5 Hz. This discrepancy contradicts with previous studies that show the correlation between the H/V data and the observed damage distribution. It could be due to the fact that the H/V method is not able to identify different site effects. Here, the low frequency H/V peaks are linked to the deep velocity contrasts at the basement and do not reflect the resonance of surficial soil layer. The origin of the discrepancy could be due to other processes than site effects that could have contributed to the damage and they are not captured by the noise measurements (vulnerability of structures, for instance). Beyond the possible explanations, this study shows the limits of the H/V technique in providing information about damage distribution for the 1985 Valparaiso earthquake. The H/V method should not be used alone to assess a comprehensive seismic hazard zonation in urbanized area characterised by a large variety of buildings (from small-size houses to high buildings) such as Santiago de Chile.

5. ESTIMATION OF THE VS PROFILE AT SHALLOW DEPTHS

In the case of Santiago, we show the limitation of the H/V method to identify the resonance of unconsolidated sediments at shallow depths. We are now looking for testing the capabilities of the more advanced array technique HRFK (Capon 1969) to evaluate the site effect of shallow sedimentary layer.

5.1 Experimental setup

The ambient noise arrays analysis were performed at five sites in Santiago. Here, we will show results for only two sites (Fig. 1). At Maipu, the rock substratum reaches 250 m deep; and the soil column is constituted, at depth, by dense sediments (Santiago gravels) and, at the surface, by ashes (stiff pumices). At Parque O'Higgins, the rock substratum reaches 100 m deep; and the soil column is constituted by the Santiago gravels.

A set of homogeneous instrumentation was used; it is composed of Cityshark II digitizers and six 3-C Lennartz (Le3D-5s) sensors with an eigenfrequency of 0.2 Hz. The sampling rate was settled to 125 Hz. All receivers were installed in free field and oriented to the geographic north. The layouts of the arrays are very similar: a central station surrounded by 5 stations deployed on rings with increasing radii. The duration of time recording is set according to the array radius: 20 min for radius strictly lower than 30 m and 30 min otherwise.

5.2. Maipu site (Fig. 2)

The receivers geometry used in the field is shown Fig. 2(a), and the corresponding Rayleigh wave phase velocities computed for frequencies range between 6.5 and 19 Hz with HRFK analysis is displayed Fig. 2(b).

The inverted Vs profiles associated to models fitting the observed dispersion curve with the best misfit are displayed Fig. 2(c). The resulting Vs profiles show a relatively low scattering of the soil parameter estimates (Table 1) and exhibit two layers. The top most sediment layer is well defined: S-wave velocity at the surface is rather low (~ 200 m/s); at 4 – 7 m deep depth the S-wave velocity increases up to ~ 500 m/s. A fine reconstruction of deeper soil is not possible because the array aperture and the inter-sensors distances are too small to properly capture the lower frequency (< 6 Hz) wavefield properties. In addition, for selected models, the theoretical Rayleigh wave dispersion curves (Fig. 2(b)) and the 1D soil transfer functions (computed for vertically incident S-wave) (Fig. 2(d)) are also shown for the frequency range [6.5 - 19] Hz. The 1D theoretical transfer function agrees well with the H/V curve averaging over all array receivers (Fig. 2(d)). In particular, the 1D resonance frequency matches the H/V peak frequency observed at ~ 9 Hz, highlighting the reliability of the inverted Vs profile. And finally, the 1D theoretically S-wave transfer function outline a moderate amplification (2.24 +/- 0.10).

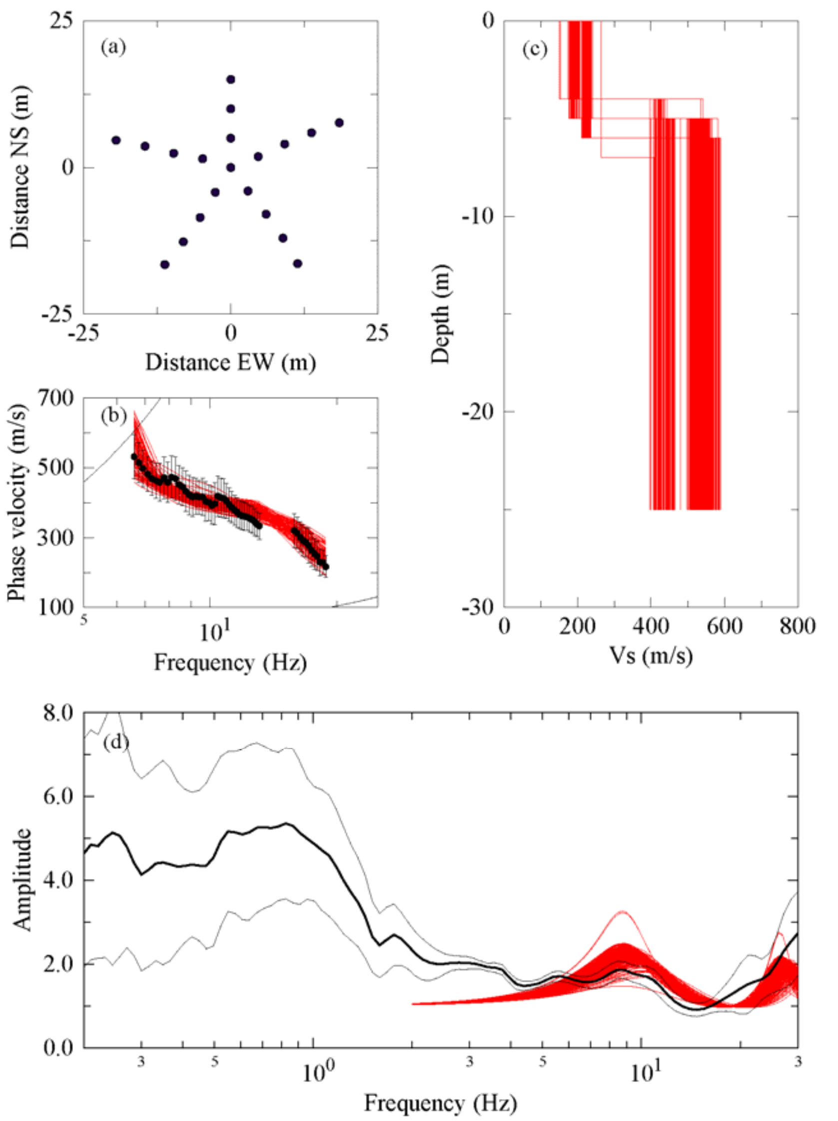

Figure 2 Results for the Maipu site. (a) Array receiver's geometry. (b) Mean phase velocity and standard deviation of Rayleigh wave (black dots), Rayleigh dispersion curves computed for the inverted Vs profile (red lines), and array aliasing limits (black lines). (c) Inverted Vs profile (red lines). (d) Mean H/V ratios and standard deviation (black lines) observed at the arrays receivers. 1D soil transfer functions for vertically incident S-wave computed for the inverted Vs profiles (red lines).

5.3 Results for Parque O'Higgins site (Fig. 3)

The Rayleigh wave phase velocities are estimated for frequencies range between 10 and 35 Hz (Figure 3(b)). The inverted Vs profiles associated to models fitting the observed dispersion curve with the best misfit exhibit two layers (Figure 3(c)). The resulting Vs profiles show a relatively low scattering of the soil parameter estimates (Table 1) and the shallow part is well defined. The surface S-wave velocity (~ 375 m/s) is higher than those estimated for Maipu site. The top most layer is also slightly thicker (6 – 8 m) and the S-wave velocity in deeper sediment is estimated at ~ 950 m/s. For the frequency range [10 - 35] Hz, the 1D theoretical transfer functions computed for the resulting Vs profiles do not reproduce well the shape of the observed average H/V curve (Figure 3(d)). And finally, the 1D theoretically S-wave transfer function outline a moderate amplification (2.33 +/- 0.03).

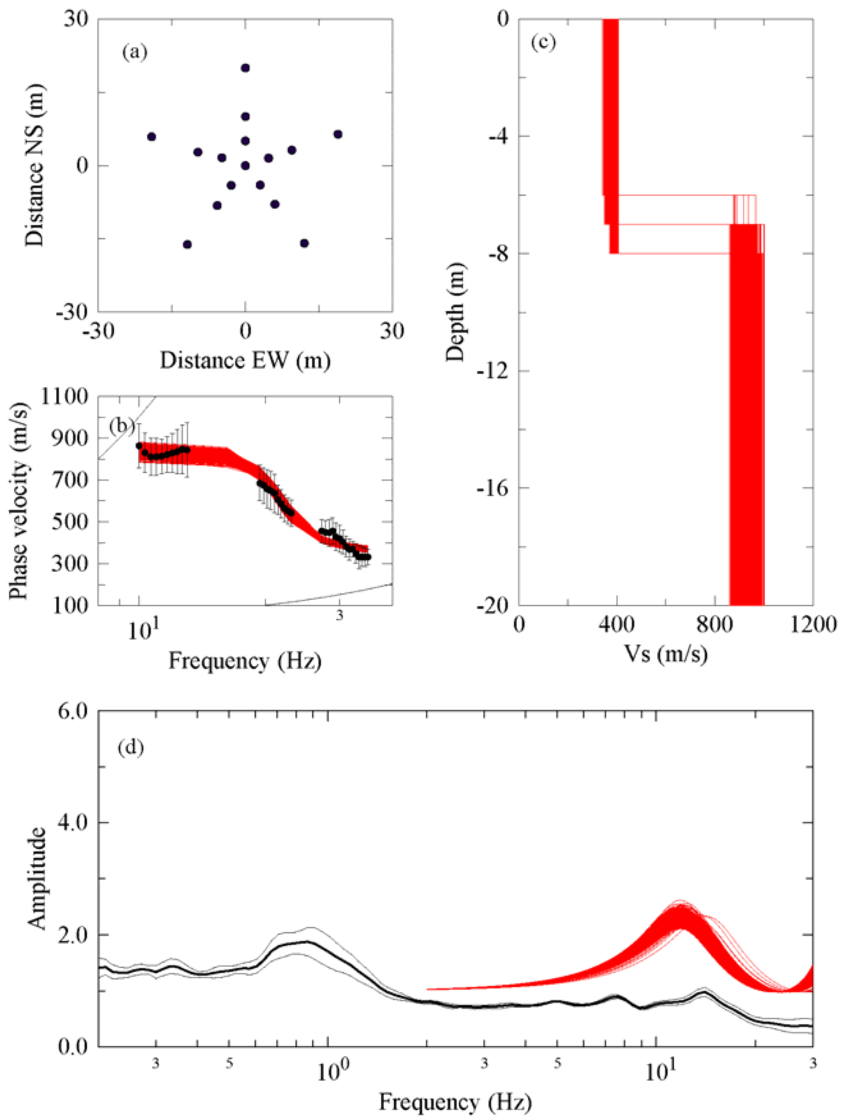

Figure 3 Results for the Parque O'Higgins site. (a) Array receiver's geometry. (b) Mean phase velocity and standard deviation of Rayleigh wave (black dots), Rayleigh dispersion curves computed for the inverted Vs profile (red lines), and array aliasing limits (black lines). (c) Inverted Vs profile (red lines). (d) Mean H/V ratios and standard deviation (black lines) observed at the arrays receivers. 1D soil transfer functions for vertically incident S-wave computed for the inverted Vs profiles (red lines).

6. DISCUSSION AND CONCLUSIONS

Extensive ambient vibrations measurements (264 H/V data and 5 sites for ambient noise arrays measurements) were performed in the basin of Santiago de Chile. We were looking to verify the possibilities and limitations of the H/V spectral ratios (Nakamura 1989) and the more advanced array (Capon 1969) techniques to evaluate site effects at shallow depths.
First, the H/V data were analyzed and interpreted conformably to international consensus criteria (Bard and SEAME-Team 2005). This procedure allows keeping only reliable data for mapping resonance frequencies in the Santiago basin. Reliable and meaningful H/V data were compared with felt intensities reported in Santiago after the 1985 Valparaiso earthquake where significant seismic intensities (VI to VIII in MSK.) were reported for one-storey adobe and masonry houses which have a natural frequency higher than 5 Hz. The resonance frequencies computed with H/V method are in great majority below 5Hz and are mostly related to the low fundamental resonance frequency of the deep basin. The discrepancy between the H/V results and the distribution of seismic intensities points out the limitation of the H/V method in providing valuable information about the damage distribution in Santiago for the 1985 Valparaiso earthquake. In conclusion, although the H/V method is reliable to map the fundamental resonance frequency of the deep basin, we outline its limitation to identify the resonance frequency of the top most layers. The H/V method alone may not be not enough to assess the seismic hazard in urbanized area especially when there is a large variety of buildings type: from small-size residential houses to high rise business buildings. A comprehensive seismic-risk evaluation could not be based only on H/V results. However, despite its limitation, the H/V microtremor spectral ratios technique is informative for site effects estimate and remain a valuable input in urban seismic microzonation, in the elaboration of a large earthquake scenario, and in seismic hazard mitigation.
In the other hand, the ambient noise array measurements outline the robustness of the array technique (Capon 1969) to identify the site conditions at shallow depths. At the two sites shown here (Maipu and Parque O'Higgins), the inverted Vs profiles clearly show the presence of unconsolidated sediments at shallow depths. For the Maipu site, the origin of the top most layer may be associated to ashes deposits coming from a major eruption of the Maipo volcano which is located 120 km SE of Santiago. This hypothesis, however, is not satisfactory for the site Parque O'Higgins: none of the geological, geophysical or geotechnical studies carried out have revealed the presence of ashes in this area, they have only reported the presence of dense sediments covered by artificial fill. Although the origin of the top most layer may be different at surface of the Santiago basin, its resonance frequency occurs at relatively high frequency (> 9 Hz) and the associated 1D amplification factor is comprised between 2 and 3, outlying a moderate amplification factor. These results agree well with the distribution of damages observed on small-size houses in Santiago during the Valparaiso earthquake. The coincidence of their fundamental frequency with the resonance frequency of the top most layer may explain the observed distribution of damages. It is worth concluding by emphasizing that small-size arrays measurement are a powerful tool to provide the site effect estimate (resonance frequency and amplification factor) for shallow sedimentary layers.

REFERENCES

Astroza, M. and Monge, J. (1991). Seismic microzones in the city of Santiago. Relation damage-geological unit. *Proceedings of the Fourth International Conference on Seismic Zonation* **3**, 595-601.

Bard, P.-Y. and SESAME-Team (2005). Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations - measurements, processing and interpretations. *SESAME European research project* EVG1-CT-2000-00026 D23.12. Available online at http://sesame-fp5.obs.ujf-grenoble.fr.

Bravo, P.R. (1992). Estudio geofisico de los suelos de fundacion para una zonificacion sismica del area urbana de Santiago Norte. *PhD Thesis*, University of Chile, Santiago de Chile, Chile. (In Spanish).

Capon, J. (1969). High-resolution frequency-wavenumber spectrum analysis. IEE **57**, 1408–1419.

Cruz, E., Riddell, R. and Midorikawa, S. (1993). A study of site amplification effects on ground motions in Santiago, Chile. *Tectonophysics* **218**, 273–280.

Gueguen, P. (1994). Microzonage de Santiago du Chili (technique de Nakamura). *Master Thesis*, University Joseph Fourier, Grenoble, France. (In French).

Iriarte-Diaz, S. (2003). Impact of urban recharge on long-term management of Santiago Norte aquifer, Santiago – Chile. *Master Thesis*, Waterloo University, Notario, Canada.

Midorikawa, S., Riddell, R. and Cruz, E. (1991). Strong-ground accelerograph array in Santiago, Chile, and preliminary evaluation of site effects. *Earthquake Engineering and Structural Dynamics* **20**, 403–407.

Morales-Jerez, F.R. (2002). Definicion de aquiferos en la Cuenca del Rio Maipo. *Master Thesis*, University of Chile, Santiago de Chile, Chile. (In Spanish).

Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Report Railway Tech. Res. Inst.* **30:1**, 25-30.

Ohrnberger, M. (2004). User manual for software package CAP – a continuous array processing toolkit for ambient vibration array analysis. *SESAME European research project EVG1-CT-2000-00026* D18.06.

Sambridge, M. (1999). Geophysical inversion with a neighbourhood algorithm – I. Searching a parameter space. *Geophysical Journal International* **138:2**, 479-494.

Theodoulidis, N., Cultrera, G., De Rubeis, V., Cara, F., Panou, A., Pagani, M. and Teves-Costa, P. (2008). Correlation between damage and ambient noise H/V spectral ratio: the SESAME project results. *Bulletin of Earthquake Engineering* **6:1**, 109-140.

Toshinawa, T., Matsuoka, M. and Yamazaki, Y. (1996). Ground-motion characteristics in Santiago, Chile, obtained by microtremor observations. *Proceedings of the 11th World Conference on Earthquake Engineering* 1764.

Valenzuela, G.B. (1978). Suelo de fundacion del gran Santiago. *Instituto de Investigaciones Geologicas* **33**. (In Spanish with English abstract).

Wathelet, M., Jongmans, D. and Ohnberger, M. (2004). Surface wave inversion using a direct search algorithm and its application to ambient vibration measurements. *Near Surface Geophysics* **2**, 211-221.

Wyllie, L., Bolt, B., Durkin, M., Gates, J., McCormick, D., Smith, P., Abrahamson, N., Castro, G., Escalante, L., Luft, R., Olson, R. and Vallenas, J. (1986). The Chile earthquake of March 3, 1985. *Earthquake Spectra* **2:2**, 293-371.