Revista de la Facultad de Ingeniería U.C.V., Vol. 25, N° 2, pp. 5–6, 2011

SHEAR-WAVE VELOCITIES IN CARACAS INFERRED FROM INVERSION OF PHASE VELOCITIES AND ELLIPTICITIES OF RAYLEIGH WAVES

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Recibido: octubre de 2009 Recibido en forma final revisado: julio de 2011

ABSTRACT

Reliable knowledge of soil mechanical properties, especially shear wave velocities, is important to estimate useful parameters in earthquake engineering (Vs30, response spectra, etc.) and to allow reliable numerical prediction of strong ground motion at frequencies of interest in earthquake engineering. Shear-wave velocity structure can be inferred either from borehole measurements (e.g. cross-hole or down-hole measurements) or from active or passive techniques using body- or surface-waves, respectively. Recent studies have also shown that ellipticity of Rayleigh waves can be extracted from microtremor measurements and subsequently jointly inverted with phase velocities in order to get reliable shear wave velocity profile down to seismic bedrock. In this paper, we present shear-wave profiles derived from joint inversion of phase velocity and ellipticity of Rayleigh waves obtained from microtremor array measurements at five different sites in Caracas. Phase velocities and ellipticities are extracted by using microtremor measurements. Derived shear-wave velocity profiles are consistent with available geotechnical and geophysical information.

Keywords: Microtremor arrays, Shear-wave profile, Ellipticity of Rayleigh waves, Joint inversion, Caracas.

VELOCIDADES DE ONDAS DE CORTE EN CARACAS OBTENIDOS MEDIANTE INVERSIÓN DE VELOCIDADES DE FASE Y ELIPTICIDADES DE ONDAS DE RAYLEIGH

RESUMEN

El conocimiento de las propiedades mecánicas del suelo, en específico de velocidades de propagación de las ondas de corte, resulta importante para estimar parámetros útiles en la ingeniería sísmica (Vs30, espectros de respuesta, entre otros), y para permitir predicciones numéricas confiables de los movimientos fuertes del terreno en los rangos de frecuencia de interés para la ingeniería sísmica. La estructura de la velocidad de propagación de las ondas de corte puede inferirse de mediciones de pozo (mediciones cross-hole o down-hole) o de técnicas de aplicación de ondas superficiales activas o pasivas. Además estudios recientes han demostrado que se puede extraer la elipticidad de ondas de Rayleigh de mediciones de microtremores, y que estos datos pueden ser invertidos conjuntamente con las velocidades de fase con el fin de obtener un perfil confiable de velocidades de ondas de corte hasta el tope del basamento sísmico. En este trabajo presentamos perfiles de velocidad de ondas de corte obtenidos de la inversión conjunta de las velocidades de la fase y de la elipticidad de las ondas de Rayleigh obtenidos en cinco sitios en Caracas. Las velocidades de fase y las elipticidades han sido extraídos de las mediciones de microtremores. Los perfiles de velocidad de las ondas de corte resultantes están consistentes con la información geotécnica y geofísica disponible.

Palabras clave: Arreglos de microtremores, Perfiles de velocidad de ondas de corte, Elipticidad de ondas de Rayleigh, Inversión conjunta, Caracas.

INTRODUCTION

During its history, Caracas has undergone several destructive earthquakes. The most recent one, the July 1967 Caracas earthquake, a magnitude 6.6 earthquake which occurred about 25 km northwest of Caracas (Suárez & Nábělek, 1990) caused damage to numerous buildings and the collapse of 4 multi-story buildings (Briceño *et al*. 1978). Since then, numerous studies have been performed in order to better assess building characteristics, seismic response and ground shaking characteristics (Seed *at al*. 1970; Papageorgiou & Kim, 1991; Abeki *et al*. 1998; Schmitz *et al*. 2002; Yamazaki *et al*. 2005). Especially, geological and geotechnical (about 170 drill holes down to bedrock) and geophysical surveys (seismic refraction, gravimetric measurements, H/V measurements) have allowed to derive a subsurface velocity model suitable for ground motion simulation (Weston, 1969; Kantak *et al*. 2005; Sánchez *et al*. 2005; Rocabado *et al*. 2006; Amarís *et al*. 2009). First 2D and 3D simulations of strong ground motion have thus outlined large 2D-3D site effects such as focusing effects and generation of surface waves diffracted at valley edges and in narrowing areas of the basin (Semblat *et al*. 2002; Delavaud, 2007). As outlined in Delavaud (2007) however, simulations are now missing a subsurface shear-wave velocity model enough detailed to enable reliable ground motion prediction up to frequencies of interest for earthquake engineering purposes.

Detailed shear-wave structure can be derived either from borehole measurements (cross-hole or down-hole measurements) or from active or passive techniques, using body- or surface-waves, respectively (Aki, 1957). Being non-invasive, passive surface-wave techniques are very useful to extract shear-wave velocities in urban environment. During spring 2006, microtremor array measurements have thus been carried out at five different locations in Cacaras, which have also been instrumented during five months in early 2006 for recording earthquakes. Phase velocities of Rayleigh waves were extracted by applying both SPAC and FK techniques (Wathelet *et al*. 2008), while Rayleigh waves ellipticities were measured by applying a newly developed technique within the framework of the on-going NERIES European project (NERIES, Deliverable D4, 2008). Estimation of ellipticity of Rayleigh waves is indeed very useful to retrieve information on the dispersive characteristics of Rayleigh waves (Fäh *et al*. 2003; Arai & Tokimatsu, 2004) in the low frequency range that is not easily investigable by using microtremor array measurement due to limited array apertures. Phase velocities and ellipticities of Rayleigh waves are then jointly inverted to get the shear-wave velocities over a large depth range (Arai & Tokimatsu, 2005). Reliability of derived shear-wave velocity profiles are then compared to available geophysical knowledge (borehole and SPT measurements).

AMBIENT SEISMIC NOISE MEASUREMENT: DATA, PROCESSING, SHEAR-WAVE VELOCITIES

Microtremor measurements have been performed by using seismological stations from the French mobile network (SISMOB) composed of Minititan3XT for the acquisition unit and Le3D-5s velocimeters having a cut-off frequency of 0.2 Hz. Sites location are indicated in figure 1 and array layouts in figure 2. Microtremors were recorded during thirty minutes to one hour by using array of different apertures in order to measure phase velocities over a wide range of frequencies. Dispersion curves of Rayleigh waves were estimated by using the FK and SPAC techniques as implemented in the SESARRAY package (http://www.geopsy.org; Wathelet *et al*. 2008). Minimum and maximum measured wavelengths as well as minimum inter-station distance

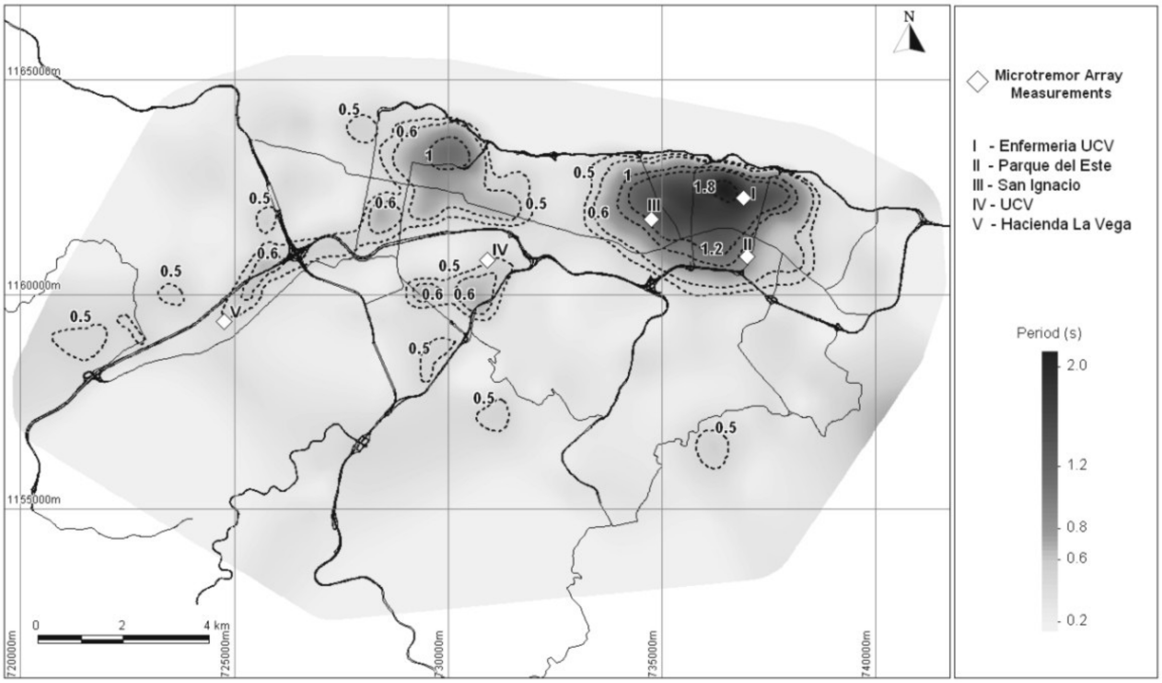

Figura 1. Approximate location of microtremor array measurements within Caracas sedimentary valley. Predominant periods from analysis of microtremor measurements (Rocabado *et al*. 2006).

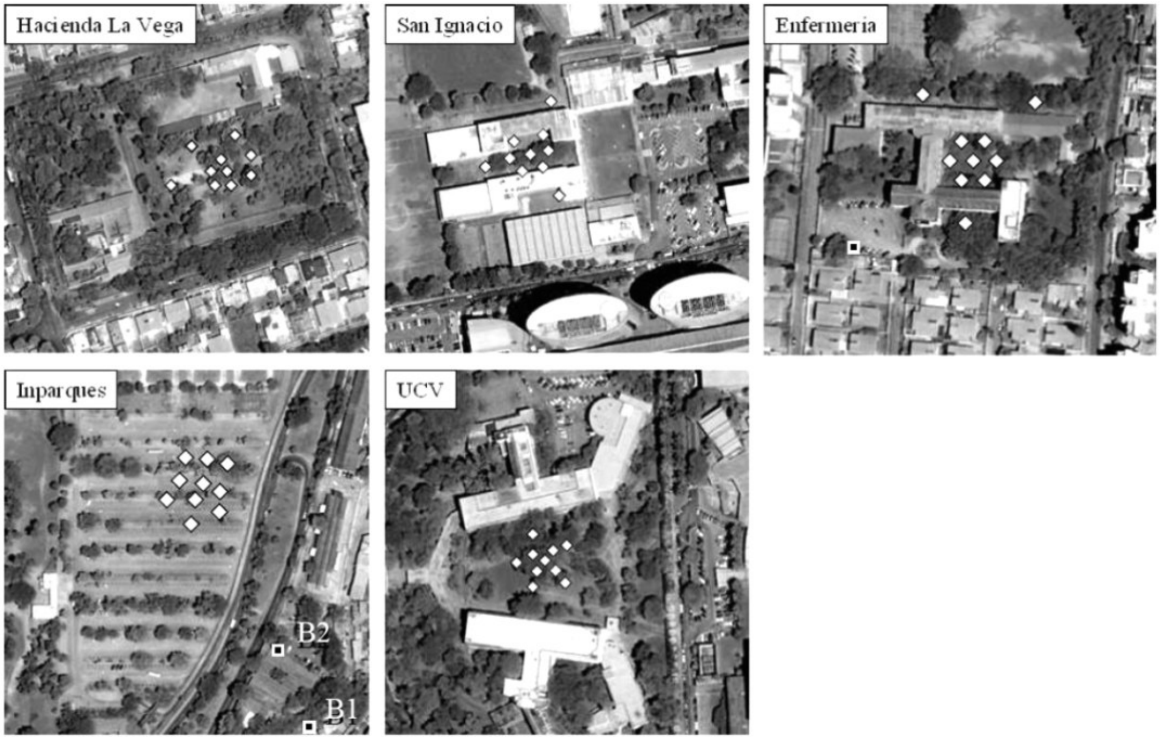

Figura 2. Array layouts. White rhombus indicate location of sensors for different arrays, black squares indicate boreholes at Enfermeria and Parque del Este (Inparques) sites.

and array aperture are indicated in table 1. Whenever dispersion curves could not be retrieved down to the resonance frequency of the site, we have used the Time Frequency Analysis (TFA) technique (NERIES, Devlliverable D4, 2008) to extract the left flank of ellipticity curves of fundamental Rayleigh wave mode. This technique is based on the use of the modified Morlet wavelet for extracting time windows that consist predominantly of Rayleigh waves. This technique was applied to the deepest sites: Enfermeria, Parque del Este and San Ignacio (Location in figure 1). Then dispersion curves and ellipticity of Rayleigh waves –when used– were jointly inverted by using the Conditional Neighborhood Algorithm (Wathelet, 2008). In the inversion, parameterization of the model space consisted in a small number of layers (2 to 4) overlaying a homogeneous bedrock. Such simple parameterization has been shown to be suitable for reliable estimates (Savvaidis *et al*. 2009; Renalier *et al*. 2009). Joint inversion of phase velocities and ellipticities was done by considering an equal weight in the misfit computation for both data type. Figure 3 shows, for each array, the set of shear-wave profiles having a misfit lower than one Sigma, i.e. explaining the data within its uncertainty bounds.

Bedrock depths derived from microtremor array measurements are consistent with known bedrock depth at 4 sites: Enfermeria (300 m), Hacienda La Vega (75 m), Parque del Este (110 m), UCV (55 m). As already known, such techniques are however not suitable to precisely estimate bedrock velocity (Cornou *et al*. 2009). Regarding shear-wave velocities averaged over the uppermost 10, 20 and 30 meters, velocities were computed by averaging the extreme average

Tabla 1. Minimum inter-sensor distance (Dmin), array aperture (Dmax), minimum (λmin) and maximum (λmax) measured wavelengths.

Sites	Dmín (m)	Dmáx (m)	λmáx (m)	λmáx (m)
Enfermería	8	153.5	11	628
Hacienda de La Vega	8	242	28	504
Parque del Este	10	174	10	296
San Ignacio	8	324	43	309
UCV	3	179	10	328

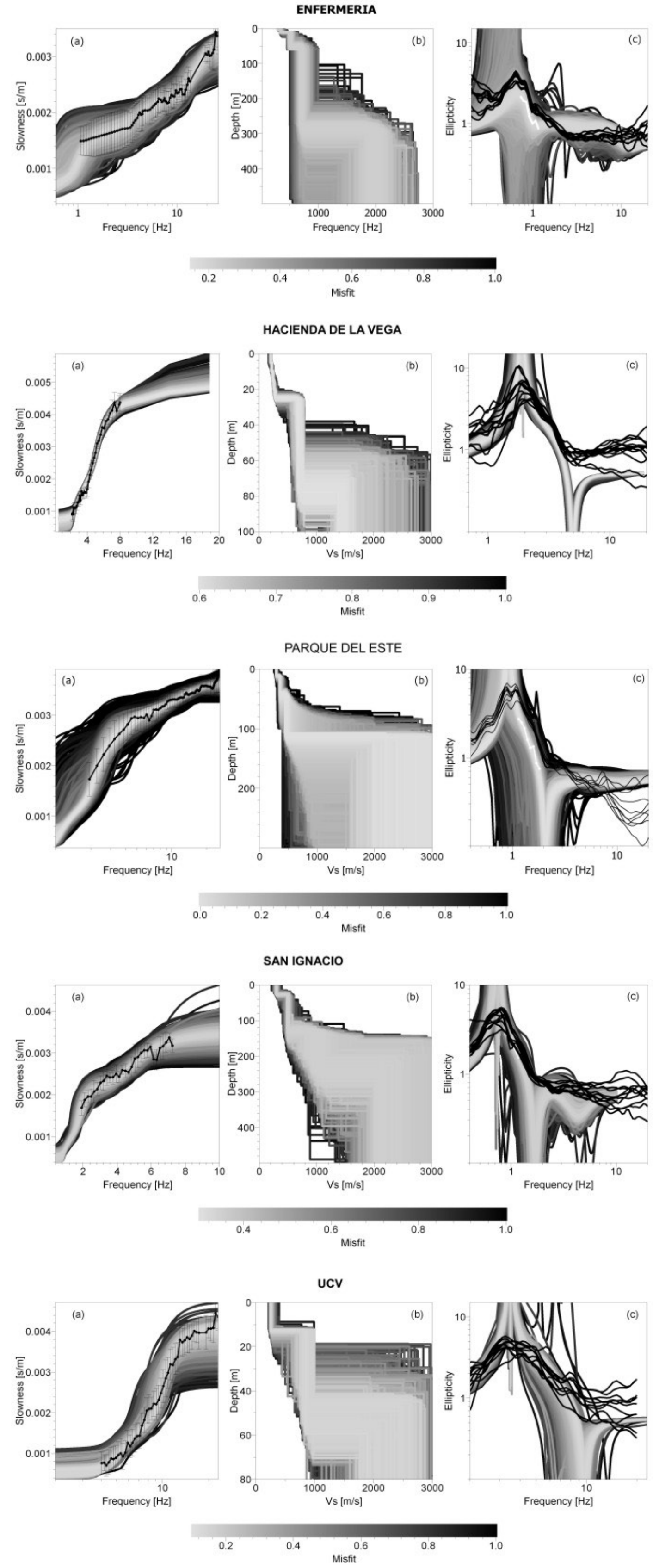

Figure 3. (left panel) Theoretical dispersion curves computed from the inverted shear-wave velocity profiles overlaid by measured phase velocities (black dots +/- standard deviation); (mid panel) Inverted shear-wave velocity profiles; (right panel) Theoretical ellipticities computed from the inverted shear-wave velocity profiles overlaid by observed H/V curves (black lines) and extracted ellipticity of Rayleigh waves (white line). Grey scale indicates the misfit.

velocities extracted from the envelope of the set of average velocity profiles.

Average velocities are very consistent with borehole measurements in Enfermeria and Parque del Este (Inparques) sites, and they are within the range of the standard deviations (Table 2). For the San Ignacio site, discrepancy between average shear-wave velocity derived from borehole and microtremor array measurement is probably due to the fact that the minimum measured wavelength is too large (43 m) to allow reliable estimate at shallow depth (Cornou *et al*., 2009). Comparison between average shear-wave velocity derived from microtremor array measurement and SPT correlation (Cadet, 2008) shows SPT-derived velocities systematically lower than velocities derived from microtremor array measurements, except in San Ignacio and Hacienda La Vega sites.

Table 2. Shear-wave velocity averaged over the uppermost 10 m , 20 m and 30 m derived from correlation between SPT values and shear-wave velocity (Cadet, 2008), borehole(s) measurements (denoted as B) and ambient vibration technique (AMV).

Enfermería

	Mean from SPT correlation (m/s)	STD (m/s)	B1 (m/s)	B2 (m/s)	AMV (m/s)	STD (m/s)
Vs30	313	29	504		441	82
Vs20	285	70	467		395	79
Vs10	173	62	423		363	72

Parque del Este

	Mean from SPT correlation (m/s)	STD (m/s)	B1 (m/s)	B2 (m/s)	AMV (m/s)	STD (m/s)
Vs30	293	8	331	277	336	57
Vs20	273	11	329	267	313	41
Vs10	247	29	365	239	302	43

UCV

	Mean from SPT correlation (m/s)	STD (m/s)	B1 (m/s)	B2 (m/s)	AMV (m/s)	STD (m/s)
Vs30	213	13			433	113
Vs20	193	20			349	92
Vs10	185	20			310	125

San Ignacio

	Mean from SPT correlation (m/s)	STD (m/s)	B1 (m/s)	B2 (m/s)	AMV (m/s)	STD (m/s)
Vs30	334	25	437		312	8
Vs20	314	25	399		302	9
Vs10	275	32	374		302	10

Hacienda de La Vega

	Mean from SPT correlation (m/s)	STD (m/s)	B1 (m/s)	B2 (m/s)	AMV (m/s)	STD (m/s)
Vs30	250	26			267	17
Vs20	239	35			234	19
Vs10	230	33			206	27

CONCLUSIONS

We have shown that microtremor array measurements can be very useful to estimate shear-wave velocity profiles in Caracas. Since shear-wave velocities found in surficial layers (from 200 to 500 m/s) are much lower than the homogeneous shear-wave velocity (650 m/s) used in numerical modelling, such measurements should be repeated at various sites in Caracas valley in order to build a detailed subsurface shear-wave velocity model. Important variations are observed for the shear wave velocities down to bedrock, where velocities between 500 and 800 m/s prevail. As investigated sites in this paper have been also instrumented for several months in order to record earthquakes, the next step is to compare 1D amplification predicted by the 1D shear-wave velocity profiles with actual amplification in order to quantify the part of amplification due to 2D/3D site effects and, hereafter, to define an amplification correction function to apply to 1D transfer functions for accounting such 2D-3D site effects.

ACKNOWLEDGEMENTS

This work was supported by FONACIT/ECOS-Nord project Nr. 2004000347 and IRD. We aknowledge Myriam Kristekova and Donat Fäh for providing us the HVTFA algorithm. We also thank all participants of the microtremor measurements.

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