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COMPARISON OF H/V MEASUREMENTS WITH STRONG MOTION RECORDS AT ACELOROGRAPHIC STATIONS IN BOGOTÁ AND ESTIMATION OF DYNAMIC PROPERTIES OF THE SOIL PROFILE

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Abstract: This article shows the results of seismic measurements of environmental noise in two specific sites in the city of Bogotá where there are records of drilling into the rock and accelerometer stations in rock and on the surface. The results of the measurements obtained, in terms of the HV spectral relations (HVSR), are compared with the transfer functions measured for two intermediate source earthquakes recorded at the seismic stations, to obtain the fundamental frequency of the deposit. Additionally, the information from the HVSR measurements allows the average dynamic properties of the deposit to be estimated by inverting the HV curve obtained from the measurements.

INTRODUCTION

The H/V spectral relationship technique, originally proposed by (Nakamura, 1989) has been a widely used methodology for the evaluation of site seismic response since it allows identifying the fundamental vibration frequency of the deposit from the relationship between the spectrum of horizontal and vertical movement. The method was heavily criticized in the 90s since different authors have argued that the H/V peak is attributed to the fundamental mode of Rayleigh waves (Lachet & Bard, 1994), (Konno & Ohmachi, 1998), (Bard, 1998); However (Nakamura, 2000) argues that the maximum energy of Rayleigh waves is reached at a frequency close to which the minimum of the H/V relationship occurs, and for large impedance ratios this relationship cannot be justified by the presence of Rayleigh waves, while the vertical incidence of SH waves is adequately supported by the H/V peak response.

During the first decade of the 21st century, different methods based on diffuse field theory have been developed (Campillo, 2006), (Sanchez-Sesma, et al., 2008), (Sanchez-Sesma, et al., 2011), in which which non-transient energy conditions (equiption principle) are established in microtremor records. These studies conclude that the autocorrelation functions evaluated at the source point are related to the imaginary part of the Green tensor. The determination of the Green's function provides the different components of the movement and allows the calculation of the H/V spectral relationship, in energy terms, obtaining analytical equations for elastic media. These equations open the possibility of performing inversions of the H/V relationship to calculate the shear wave velocity profiles Vs.

One of the big problems with the inversion of the H/V curves is associated with the lack of uniqueness in the solution (Sanchez-Sesma, 2017), however, these inversions can be restricted considering the dispersion of the surface waves and obtain more reliable Vs profiles (Castellaro, 2016). These techniques are becoming increasingly popular and the development of solid theories that allow reducing the range of uncertainty in the dynamic properties of the soil profile makes them very efficient and low-cost methods for geotechnical exploration.

Below, the experimental results of measurements of environmental vibrations are shown in which there are records from seismic stations in rock and on the surface, with which the direct response of the soil profile can be calculated. The data not only show great coherence, but also allow us to infer several parameters of interest to evaluate the seismic response of the site under study through the H/V curve inversion process.

HV SPECTRAL RATIO (HVSR) METHOD

The HVSR method was initially developed to evaluate seismic risk in Japan (Nogoshi & Igarashi, 1971), (Nakamura, 1989). It is well known that surface sediments produce an amplification of the movement during an earthquake, partially, as a consequence of oscillations of the shear waves that come from the basement at the natural frequency of the deposit. At this frequency much of the shear wave energy is trapped in the deposit causing constructive interference. As a result, the horizontal vibrations are amplified comparatively with the vertical component, and therefore in a 3-component seismic record, the spectral relationship between the horizontal and vertical components produces a peak at the fundamental frequency of vibration.

The European project (SESAME Project, 2004) and different authors (Lachet & Bard, 1994), (Lermo & Chavez-Garcia, 1994), (Malischewsky & Scherbaum, 2004), (Malischewsky, et al., 2008), (Haghshenas, et al., 2008), argue that the frequency where the HV peak occurs has a great coincidence with the resonance frequency of the SH waves, which depends on the value of the shear wave velocity (Vs) and the thickness (H) layer. Considering a simple layer model on the bedrock, the resonance frequency is expressed as:

$$f_o = \frac{V_s}{4H}(2n-1), \qquad n = 1,2,3 \ldots \ldots$$

Where n is the vibration mode number. (Bonnefoy-Claudet, et al., 2008) demonstrate that this relationship is valid when microtremors are made up of any type of waves, body and/or surface waves.

Equation 1 implies the definition of at least two parameters for determining the resonance frequency of the first mode (n=1), the shear wave speed or the thickness of the deposit. Measurements of environmental vibrations allow us to approximately establish the vibration frequency through the H/V spectral relationship, from the records in a seismic station where the three components of movement are recorded; However, in order to estimate any of the other parameters, it is necessary to have redundant measurements of either the profile Vs information or the rock depth. If additional information is available, it is possible to invert the H/V curve to obtain more information about the profile.

MEASUREMENT SITES

For the case study, two measurements were made in the middle zones of the lake basin of the Sabana de Bogotá, which classify within the limits of the Lake 200 zone, according to the Seismic Microzoning study of Bogotá (FOPAE, 2009).). The measurement sites were chosen given that the depth of the rock is certain, and accelerometer stations installed both at the rock basement level and at the surface level, with which the transfer function can be estimated based on records. seismic movements of strong movements. Table 1 shows the location of each of the measurement sites, along with the depths of the rock (Ingeominas - UNIANDES, 1997).

The sectors are characterized by presenting lacustrine sediments from the Sabana formation, made up of layers of soft clays of very high humidity and plasticity, with sporadic intercalations of peat layers and thin lenses of fine sands.

The environmental vibration measurements were carried out using a TROMINO digital tromograph, which is instrumented with three electrodynamic speedometers oriented in NS, EW and vertical directions. The equipment's sensors allow the gain to be adjusted in different dynamic ranges and can measure signals in a frequency range between 0.1 and 300 Hz. The great lightness and versatility of the equipment allows measurements to be made in any type of terrain and in areas where there is no Vehicle access. The equipment was positioned superficially on natural soil, in green areas adjacent to the city's main roads, previously stripping the vegetation cover and horizontally leveling the instrument. At each site, 30-minute records were taken to subsequently calculate the H/V relationships.

CALCULATION OF H/V SPECTRAL RATIOS OF MEASUREMENTS

The H/V records were processed using GRILLA® Software, from MOHO, in which 20s windows and a triangular filter with a smoothing factor of 10% were used. For each record, minute-by-minute spectral relationships were calculated in order to identify anomalous spectra and be able to select the best records for the statistical process. The vibration records had a recording time of 30 min, giving a total of 90 H/V spectra to perform the stacking and establish the measurement reliability ranges.

Figure 1 presents the measured H/V spectra (upper figures) and the Fourier spectra calculated for each of the components of the record (lower figures). It is observed that the HV peak occurs just in the area where the spectrum of the vertical component presents a minimum and the spectra of the horizontal components are located above the vertical spectrum, forming an eye shape in the Fourier spectrum. The red curves in the H/V figures show the geometric mean of the measurements and the black lines the range of variation with a reliability of 95%. It is observed that the variation ranges of the HV curve are very low and the peaks are very marked at both measurement sites. For the SCG site, the response peak occurs at a frequency of 0.56 Hz, while for the CAGR sector the peak occurs at a frequency of 0.53 Hz. The amplification ratios are similar in both sites, whose values are 3.8 and 4.2 respectively.

Taking into account that the depths to the rock are known in each sector, it is possible to approximately estimate the average value of Vs at each measurement site by applying equation 1 for the fundamental mode. The mean Vs values calculated at each measurement site are presented in Table 2. It can be seen that for the SGC sector, which presents a deeper profile, the average values of shear wave speed have considerably higher magnitudes than those evident in the CAGR sector.

The CAGR sector is located in the northern part of the City, in an area where the soils are evidently softer. There are records of Vs in this sector up to depths of 50m, measured in down hole tests, CPT'u, bender elements, (SAICON SAS, 2020), where the average Vs profile is about 160m/s, while the Velocity record reported (Ingeominas - UNIANDES, 1997) up to 30m depth at the SGC site presents Vs values greater than 280m/s from 27m depth.

ESTIMATION OF TRANSFER FUNCTIONS FOR STRONG MOTION

In order to compare the H/V measurements carried out at each of the sites, with direct measurements of the response in rock and on the surface of records of strong movements recorded in the city of Bogotá, the accelerograms of two earthquakes recorded in the city of Bogotá with magnitudes (Mw) greater than 5.7. Table 3 presents the characteristics of the earthquakes analyzed at each recording station.

The transfer functions at each recording site were calculated as the ratio between the surface and rock Fourier amplitude spectrum. Figure 2 shows the transfer functions calculated at each site for the EW and NS component, normalized by the maximum amplification factor in order to easily compare the frequencies for which the response peak is found. For the SGC site the peak response of the EW component occurs at 0.53 Hz and of the NS component at 0.46Hz. On the other hand, for the CAGR site the peak is identified

PLACE	ID	LATITUDE	LENGTH	ROCK DEPTH (m)
1	SGC	4°38’34”	74°04’52”	180
2	CAGR	4°45’13”	74°03’15”	119

Table 1. Location of measurement sites.

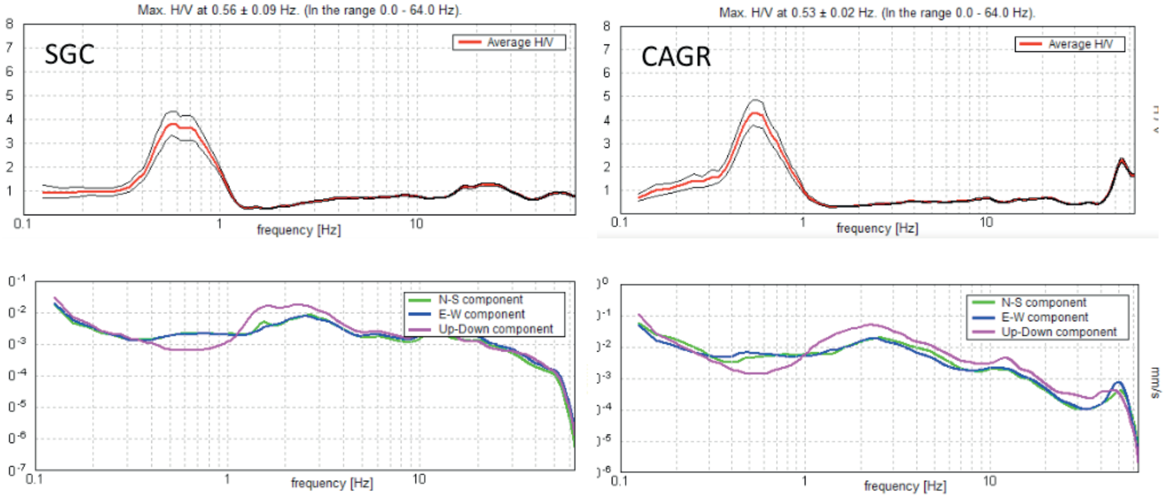


Figure 1. H/V curves and Fourier spectra of the motion components measured at each site.

PLACE	fo (Hz)	H (m)	Vsprom (m/s)
CAGR	0.53	119	252
SGC	0.56	180	403

Table 2. Estimation of average shear wave velocities at each measurement site.

PLACE	EARTHQUAKE	DATA	Mw (-)	Distance (km)	Amax (gal)
CAGR	Quetame	24/05/2008	5.7	48	24.8
SGC	Mesetas	24/12/2019	6.0	102	11.3

Table 3. Earthquakes used to estimate transfer functions in seismic stations.

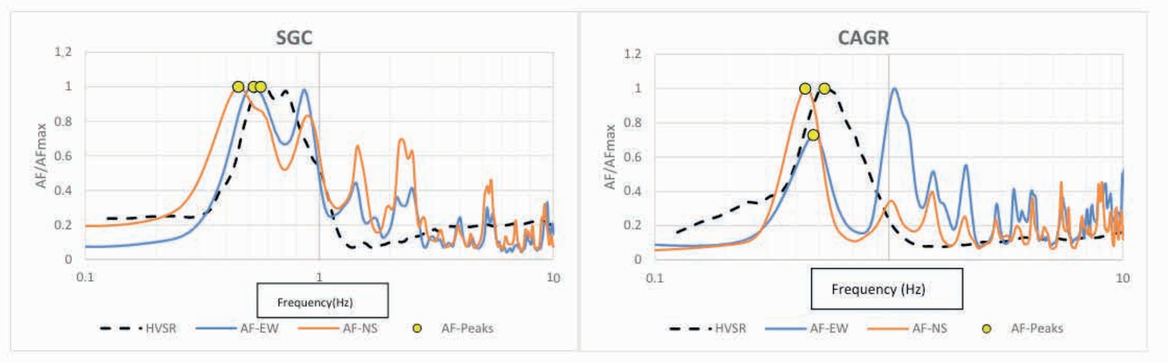


Figure 2. H/V curves and Fourier spectra of the motion components measured at each site.

between 0.44Hz and 0.47 Hz respectively for the NS and EW component, thus confirming the lower stiffness of the materials at the CAGR station, as revealed by the H/V measurements.

Additionally, in Figure 2, the HVSR measurements at each measurement site are presented in a dashed black line. In general, it is observed that the measurements show a slight shift in the frequency response and it is coherent in both records. This shift is attributed to the non-linear effects generated in the soil profile due to the magnitude of the deformations that are mobilized during seismic events, generating degradation of the shear modulus, and a slight reduction in the vibration frequency of the fundamental mode.

The results obtained in terms of fundamental vibration frequencies of the deposits, obtained with ambient noise and by recordings of strong movements can be used to estimate the non-linear effect of the system response. If a two-layer elastic model is considered, with an elastic deposit on rigid rock, an analytical function is obtained for the transfer function described by the following equation (Kramer, 1996).

$$F \approx \frac{1}{\sqrt{\left(cos\left(\frac{\omega H}{Vs}\right)^{2} + \left(\xi\left[\frac{\omega H}{Vs}\right]\right)^{2} \right)}}$$

Where ξ is the damping, w is the circular frequency, H is the thickness of the deposit and Vs is the shear wave velocity of the deposit. In this equation, the damping effect has a great impact on the amplitudes of the transfer function at the frequencies of each vibration mode, but it has a minimal impact on the shift of the frequency response peaks. The parameter that has the most impact on shifting the transfer function in frequency is the argument ωH/Vs.

Since the depths of the deposit are known at each measurement site, the value of Vs that generates the shift of the transfer function measured in the earthquake records can be calibrated. Table 4 shows the average Vs values obtained for very low deformations (HVSR measurements) and the reduced Vs values that generate the frequency values where the response peaks are identified in the seismic records. The shear modulus reduction factor calculated for the earthquakes at each site are 0.74 and 0.78. Considering typical dynamic curves for high plasticity soils (Vucetic et al 1991), for this degradation factor shear deformations are mobilized in the range between 0.03 and 0.08% for which damping is expected in the range of 2% and 4%.

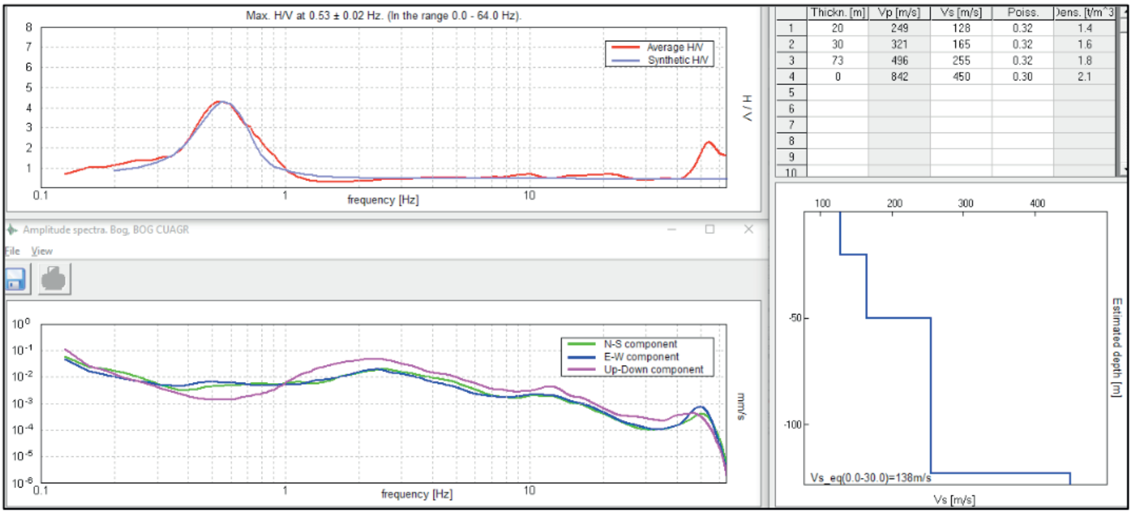
INVERSION OF VS PROFILES

From the environmental measurement data, the H/V spectral ratios were calculated and inversions of the HV curve were performed taking as constraints the depth of the rock basement known at each measurement site, and the wave velocity profile of cut of the first 30m of depth, which are known from information measured in down hole tests in the specific measurement areas.

With the restrictions described above, the velocity profile that best fits the measured curve was found, thus finding the Vs values up to the rock and the approximate Vs values of the basement in the contact zone. Figure 3 presents the results of the investments obtained at the CAGR site. It is observed that the value of Vs in the first 50m of depth report values between 120 and 160m/s, and from 50m onwards an important change in impedance is identified and the profile speeds increase to 260m/s on average. In the contact zone, a Vs value of 450m/s is obtained, which is attributed to soft rocks of the Guaduas formation. According to the deep drilling record, the rock basement is made up of claystone sequences. It is likely that the rock in the contact zone presents a high degree

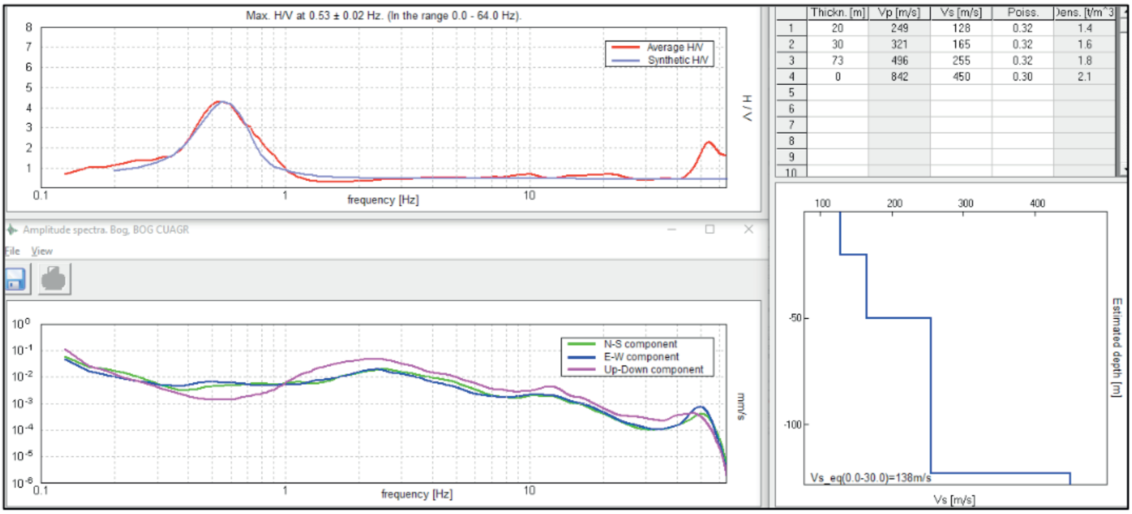
PLACE	fo (HVSR) (Hz)	fo (Sismo) (Hz)	H (m)	Vs_{max} (m/s)	Vs_{red} (m/s)	G_{max} (kPa)	G_{red} (kPa)	G_{red}/G_{max} (-)
CAGR	0.53	0.455	119	252	217	114561	84760	0.74
SGC	0.56	0.495	180	403	357	292626	229408	0.78

Table 4. Parameters compatible with strong motion response.



	Thickn. [m]	Vp [m/s]	Vs [m/s]	Poiss.	Dens. [t/m^3
1	20	249	128	0.32	1.4
2	30	321	165	0.32	1.6
3	73	496	255	0.32	1.8
4	0	842	450	0.30	2.1
5					
6					
7					
8					
9					
10					

Figure 3. Inversion of the H/V curve in the CAGR zone.



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4	0	842	450	0.30	2.1
5					
6					
7					
8					
9					
10					

Figure 4. Inversion of the H/V curve in the SGC zone.

of alteration, which is reflected in low values of Vs. According to measurements of Vs of claystones of the Guaduas formation in sectors of the city where said formation emerges, the values Vs expected for healthy rock ranges around 700m/s.

Finally, Figure 4 shows the investment made in the SGC area. In this sector there is a record of Vs of the first 30m of profile published by (Ingeominas - UNIANDES, 1997). It is evident that in this sector the Vs values are much higher than those obtained at the CAGR site. In this case the shear wave speed is less than 180m/s in the first 20m of depth, but from 20m onwards it increases progressively until reaching values close to 400m/s in the contact zone. In this sector, the velocity of the basement shows values of the order of 700m/s, values that are consistent with those expected in claystones of the Guaduas formation in a healthy state.

CONCLUSIONS

The results of measurements of environmental vibrations with a high-sensitivity and broadband tromograph are presented, with which the spectral relations of the horizontal and vertical component are calculated for the estimation of the fundamental frequency in deep deposits. The results obtained are compared with records of strong movement in nearby stations where there is a record in rock and on the surface. The results show a great coincidence in the reservoir response peaks.

Comparing the frequencies measured by environmental vibrations, a slight shift in the frequency response is observed, which is attributed to the nonlinear effect generated by the deformations mobilized during strong movements. This shift in the response can be reproduced with simple analytical models that allow establishing degradation characteristics of the modules and estimating the levels of deformation mobilized during the earthquake.

Finally, inversions of the HV curve are carried out, using diffuse field models, using the known stratigraphic restrictions in terms of basement depth and the velocity profiles of the first meters of the profile. These inversions allow the shear wave velocity profiles to be extrapolated to the rock and the velocity values in the rock basement to be estimated.

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