Seismic soil characterization through HVSR inversion and high resolution SPAC in Bogotá

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ABSTRACT: The city of Bogotá corresponds to a large sedimentary basin of fluvial and lacustrine origin that was filled by soil deposits over the last 3.2 million years. The deposits present a transition from the edges where there are predominantly granular alluvial-coluvial soils, towards the central part of the basin where very soft lacustrine clays and silts are predominant in the upper layers. Maximum thicknesses of sediments are in the order of 500 m, with very soft soils in the upper 50 to 150m. Recent strong motion records have shown important soil amplification. Investigation shear wave velocity profiles are of prime interest for foundations and earthquake site effect studies.
Passive surface wave methods have several advantages over active methods, allowing to characterize deep soil deposits, such as those located in the Bogotá basin. We use microtremor survey methods (HVSR & SPAC) from strong ground motion records and ambient noise measurements to characterize the full depth of the Bogotá city basin. Currently, modelling and inversion of the microtremor HVSR with the diffuse field approach has proven to be useful to estimate shear wave velocity structure. Join inversion using both microtremor HVSR and high resolution SPAC applied to five sites in Bogotá City, allowed to obtain shear wave-velocity values to depths of 90-480 m with greater precision than conventional methods.
The results showed that the joint inversion of surface waves dispersion curves obtained by high resolution SPAC and HVSR can be used to improve or constrain the soil shear wave velocity profile obtained from other methods, especially for very low frequencies, allowing to characterize deep soil deposits, such as those located in the Bogotá basin, which can be better used for seismic site-response analysis, contributing to a better definition of seismic hazard microzonation.

Keywords: SPAC; HVSR; Shear wave velocity; Inversion; Bogotá

1. Introduction

In seismic site effect analysis, the most important aspects to know are the amplitude, frequency, composition and duration of the horizontal and vertical components of ground vibration produced by seismic waves at foundation level.

Those aspects are highly influenced by local geological conditions. In particular, sites characterized by large deposits of soft soils amplify the movement of the ground for a certain frequency range, producing concentrated damage in these areas.

Therefore, particular soil conditions are of prime interest, and should be the fundamental part of site effect studies.

Shear wave velocity is the soil parameter with greatest importance for site effects. Such velocity can be obtained from geotechnical and geophysical surveys by applying active seismic methods in situ, surface wave dispersion measurements and borehole measurements, as well as from geotechnical surveys and laboratory tests.

In deep soil deposits such as those found in the Bogotá basin, traditional methods have limitations in terms of resolution, penetration depth and costs. Recently, passive seismic methods such as the spectral relationship of the horizontal and vertical components HVSR [1, 2] have been used as one of the most cost effective and fastest ways to quantify site effects. This technique uses the ratio between the horizontal and vertical components of the Fourier spectral amplitude, in order to know the fundamental periods of ground vibration.

Multiple authors have made several empirical and theoretical proposals to interpret the HVSR curve characteristics. For example, it was assumed that microtremors were mainly composed of surface waves. In fact, the HVSR curve has been related to the ellipticity of Rayleigh waves [3, 4], and from this hypothesis, successful inversion schemes have been used [5, 6]. However, when Rayleigh and Love waves come from several directions, an ellipticity analysis becomes very complicated. On the other hand, other authors affirm that body waves predominance around the peak of the HVSR [2, 7, and 8].

Sánchez-Sesma et al. [9] introduced an innovative method inspired by the possibility of recovering the Green 3D elastodynamic tensor between two stations within an elastic medium from the average of the cross-correlation in the time domain for environmental noise records (noise interferometry). This method is based on the fact that microtremors form a diffuse field containing all types of elastic waves (body and surface waves) in fixed energy proportions (although structure dependent).

This diffuse field can be associated with Green's functions (GF) because there is proportionality between the average energy densities of a diffuse field and the imaginary part of Green's functions at the source[10]. Some applications of this method have been developed by Salinas et al. [11], Kawase et al. [12], Lontsi et al. [13], Spica [14], among others. The fundaments of this general theory were developed in several research papers [15, 16] and confirmed in experiments with microtremors by Shapiro and Campillo [17]. Sánchez-Sesma et al. [9] formulated a first algorithm for the direct calculation of HVSR under this approach based on the discrete integration of wave numbers and the matrix method described by Knopoff [18].

The HVSR curve could be combined with Spatial autocorrelation technique (SPAC) for a joint inversion of the HVSR curve plus dispersion curve, in order to minimize uncertainty and lead to a more accurate shear wave velocity model.

The objective of the present research consists in the calculation and interpretation of the shear wave velocities profiles from the joint inversion of HVSR + SPAC obtained in different accelerographic stations in the city of Bogotá.

2. Motivation

The city of Bogotá corresponds to a large sedimentary basin of alluvial and lacustrine origin that was filled by soil deposits over the past 3.2 million years [19]. The deposits present a transition from the edges where alluvial and colluvial predominantly granular soils forming fans and cones, towards the central part of the old lake are found. In the center of the basin very soft clays and silty clays of lacustrine origin are found down to 120m. These are followed by a secuence of alluvial oring.The total maximum thickness of the deposits reaches about 500 m, as shown in Figure 1.

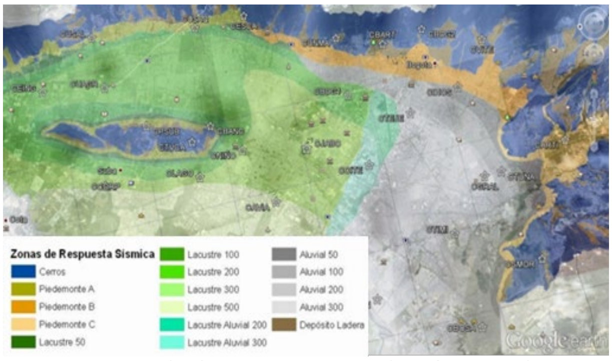

Figure 1. Seismic response map zonation of Bogota City.

3. Theoretical framework

3.1. Diffuse field in dynamic elasticity

Consider a non-homogeneous, anisotropic elastic medium, subject to a set of uncorrelated random forces. The correlation properties of the resulting field and a field of multiple dispersed waves are equivalent. Since the latter are well described by equations similar to those of diffusion, it is possible to use the term "diffuse" for the field of noise waves. In this case, Green's functions (GF) can be recovered from the average cross correlations of recorded movements[10, 20].

For a diffuse field it can be established that the “average autocorrelation” of movement for a given direction at a given point is proportional to the “directional energy density” (DED). Therefore, the energy densities in given directions are proportional to the imaginary part of the tensor components of Green's function at that point. The relationships between energy densities and their partitions have recently been studied by Perton et al. [21] and by Margerin et al. [22]. The connection between deterministic results (with respect to energy partitions in a semi-space due to surface loads) and diffuse fields has been clearly established [9].

3.2. Green's function recovery from correlations

It has been shown [21] that if a harmonic and equipartioned vector displacement field, diffused in 3-D u_i (x, ω), is established within an elastic medium, the average cross correlations of movements in points X_A and X_B can be written as;

$$\langle u_i(X_A,\omega)u_j^*(X_B,\omega)\rangle = -2\pi E_S k^{-3} Im\left[G_{ij}(X_A,X_B,\omega)\right] \quad (1)$$

Where, the Green function G_{ij} (X_A, X_B, ω) = displacement in X_A with direction i, produced by a unit harmonic load acting in X_B with direction j = $\delta_{ij}\delta$ ($|X-X_B|$) exp (i ωt), i = √(-1) = imaginary unit, ω = angular frequency, t = time, k = ω/β = shear wave number, β = shear wave propagation velocity, Es = $\rho\omega^2 S^2$ = shear waves average energy density, ρ = mass density and S^2 = shear waves average spectral density. The asterisk means the complex conjugate and the angle brackets denote the azimuthal average. Ec. 1 is the analytical consequence of a correlation-type elastic representation theorem and has been verified in canonical examples of a whole space [16] and for inclusions in that space [10].

3.3. Spectral density in given points and directions.

The energy density at point X_A can be obtained by rewriting Ec. 1 assuming $X_A = X_B$.

$$E(X_A) = \rho\omega^2\langle u_m(X_A)u_m^*(X_A)\rangle = -2\pi\mu E_S k^{-1} Im\left[G_{mm}(X_A,X_A)\right] \quad (2)$$

The total energy density at one point is proportional to the imaginary part of the Green tensor trace for coincident sources and receivers. The imaginary part represents the power injected by the unit harmonic load. This amount "detects" energies that are radiated and returned to the source and can be used to represent images. In that case $E(X_A) = Em(X_A)$ = DED along the m direction.

3.4. Equipartition

Equipartition, in general, cannot be observed directly, but it can be inferred by its consequences. Within an infinite and homogeneous elastic medium [21, 23, 24] a diffuse field shows energy densities in any direction with a third of the available energy. This is known as "classical" equipartition in terms of degrees of freedom. Alternatively, equipartition can be obtained for wave modes. Weaver [23] showed that the ratio of shear and dilation energy densities is 2α3/β3, where α = P waves velocity. Therefore, the fractions of energy density available for shear and compression waves are

2R3/(1+2R3) and 1/(1+2R3), respectively, where R = α/β. This is usually called "elastic" equipartition.

Although for the whole space, the equivalence between classical and elastic equipartition is trivial, in the semi-space this is somewhat more complicated, but has already been established [21, 24]. On real Earth, it is difficult to observe the equipartition explicitly. This has been determined in the earthquake coda from detailed analysis of arrays [22].

3.5. Seismic noise

If a seismic field of microtremors is supposed to be diffuse. The stabilized spectral densities are interpreted as DED. The HVSR can be written as;

$$[H/V](\omega) = \sqrt{\frac{E_1(x,\omega)+E_2(x,\omega)}{E_3(x,\omega)}} \tag{3}$$

Where E1, E2 and E3 are the DEDs corresponding to horizontal and vertical degrees of freedom, respectively. This is essentially the definition given by Arai & Tokimatsu [5]. To interpret the microtremor H/V curve, a first ingredient has been the ellipticity of Rayleigh waves [3]; Fah et al. [25]; Arai & Tokimatsu [5].

In this way, the H/V curves of ambient noise can be expressed in terms of energy density of a diffuse field that is proportional to the imaginary part of Green's functions at the source. Now, if equations 2 and 3 are considered and rewritten;

$$[H/V](\omega) = \sqrt{\frac{Im[G_{11}(x,x;\omega)]+Im[G_{22}(x,x;\omega)]}{Im[G_{33}(x,x;\omega)]}} \tag{4}$$

This equation [26] links "average" measures expressed on the left side of the equation with a medium intrinsic property on the right side of it, and naturally allows the inversion of H/V (ratio of Nakamura) taking into account the contributions of body, Rayleigh and Love waves.

4. Methodology

4.1. Field measurements

4.1.1. H/V curves

To compute the H/V ratios we used in this study a data set which consists of ambiental noise recordings of 60 minutes length. The noise measurements were carried out at 5 sites within the city of Bogotá. The noise recordings were recorded with a Canterbury digital accelerometer station equipped with three acceleration sensor having the natural period of 5 seconds.

The data was processed using the Microtremor software developed by Geogiga®. To determine the H/V ratios the following procedure was applied:

- windows of 30 seconds length were automatically selected using an anti-STA/LTA filter algorithm;
- Fourier spectra of the three components (NS, EW, Z) were calculated;
- calculated Fourier spectra of the three components were smoothed with Hanning window;
- the horizontal components were merged by geometric mean;
- the H/V spectral ratios were calculated by dividing the spectra of the merged horizontal components to the spectra of the vertical component

4.1.2. SPAC dispersion curves

In this study, a maximum 345 m aperture array composed of 48 receivers located at the surface has been considered. The minimum distance between receivers is 5 m. At each sites we used 41 4.5 Hz and 7 1Hz sensors in L shape configuration. This can be one of the most convenient arrays when working in highly urbanized areas.

In most cases the sensors recorded 60 minutes of continuous noise. From these records, dispersion curves were obtained using a standart SPAC processing, with surface plus software developed by Geogiga®. Figure 2 shows a tipical array used for this research.

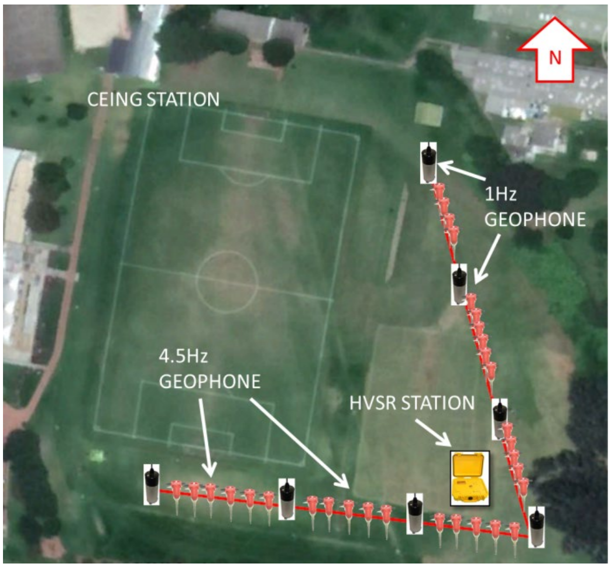

Figure 2. Typical SPAC array.

Figure 3 shows a tipical dispersion curve obtained for CUAGR station. It is important to note that dispersion curve has a high resolution even at frequencies lower than 1 Hz.

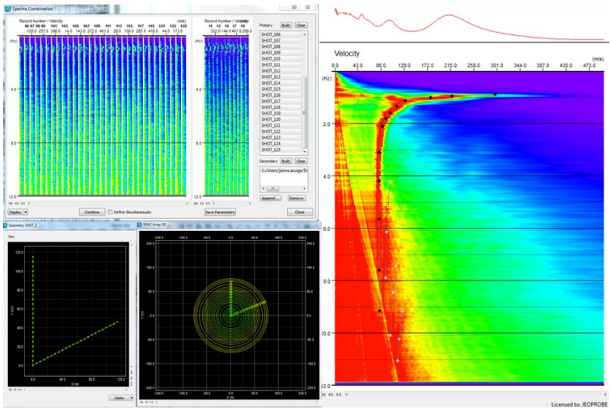

Figure 3. Typical curve dispersion obtained by SPAC surveys.

4.2. Algorithms

The method used to obtain the shear wave profile consists in the application of algorithms developed by Sánchez Sesma [9] and García Jeréz [27]. Such routine make velocity profile inversion based on the adjustment of the experimental HVSR curve. For this, we used HV-Inv software, developed by García Jerez, et al. [27], based on the diffuse field model, in which it is assumed that the structure can be approximated locally by flat-parallel elastic layers. Among the advantages offered by this program, is that the inversion can be made in two ways. First, global methods based on genetic algorithms can be used, and the inversion can be refined, using local optimization, which is very convenient when a joint inversion of HVSR curve and Rayleigh/Love wave dispersion curve is applied.

4.3. Ground motion records

In order to validate the proposed methodology, we selected only accelerographic stations with a well known soil velocity profile from surface to rock. In this sense, this study includes the Foothill, Lacustrine 200 and Lacustrine 500 seismic response zones, according to Bogota seismic microzonation [28].

4.3.1. Foothill.

The foothill zone corresponds to deposits that are between the hills and the plains (Colluvial and alluvial) predominantly composed of hard soils of less than 50 m thickness. According to this, the PUJ accelerographic station was used, which has accelerometers on surface and in rock. The stratigraphic soil profile of the Javeriana University has been determined based on geotechnical surveys and Laboratory tests [29]. The velocity profile used as a comparison parameter was that proposed by Cardozo [29], obtained from bender elements, cyclic triaxials and Down hole tests. The seismic record selected for the PUJ station corresponds to the 5.2Mw magnitude Huila earthquake, registered on July 19th, 2018. In Figure 2, at the top, the seismic records for the PUJ station are showed, highlighting the presence of the surface wave package between 67 and 90 seconds. When analyzing the hodograms of the vertical-longitudinal and longitudinal-transverse components (Figure 2b and Figure 2c, respectively), it is observed that there is a large predominance of Love waves within the seismic register.

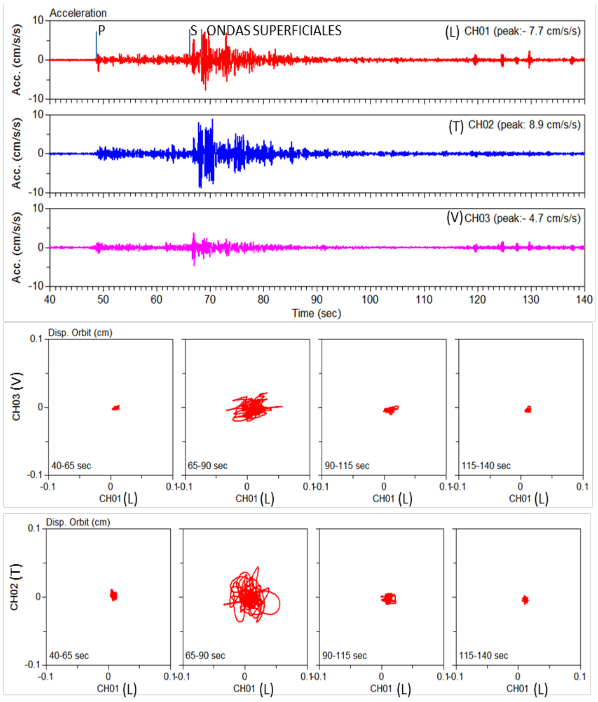

Figure 4. Ground motion record from Huila earthquake, PUPJSUP station.

Figure 3 shows the Fourier spectrum of the surface signal. Greatest amplitudes for the three components are between 1 and 5 Hz.

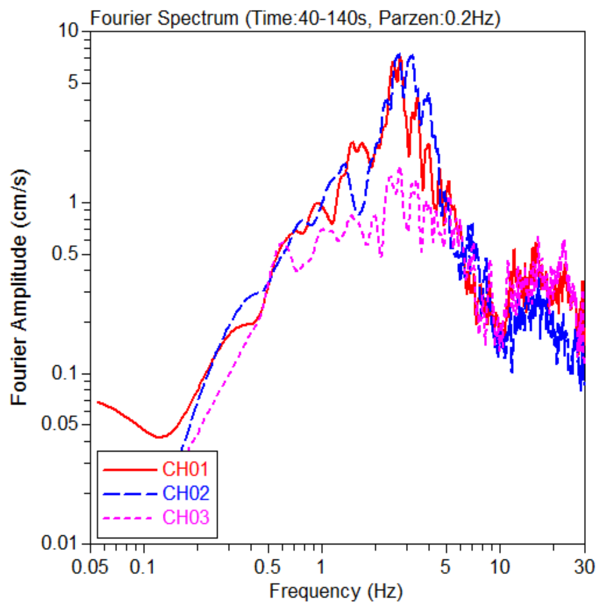

Figure 5. Fourier spectrum from Huila earthquake, PUPJSUP station.

4.3.2. Lacustrine 200

It corresponds to the sectors composed of lacustrine soils with thickness between 100 and 200 m, in this area there are 3 stations with rock and surface accelerometers and a complete description of the stratigraphic profile. The first one is part of the national accelerograohic network (RNAC) and is owned by the Colombian Geological Survey (CBOG1). The second and third stations belong to the Bogotá accelerographic network (RAB) and are located at the campus of the Uniagraria University (CUAGR) and Escuela de Ingeniería University (CEING), respectively. The seismic records selected for the stations CBOG1, CUAGR and CEING corresponds to the 5.7Mw magnitude earthquake, ocurred on May 24th, 2008, with epicenter in Quetame, Cundinamarca. Figure 6 and Figure 7 show the records and fourier spectrum for CBOG1 station, respectively. In this station, the predominance of Love waves is observed (25-75 s), although, an important content of Rayleigh waves is observed (25-50 s).

The highest frequency content is located in a band between 0.1 and 2 Hz, characteristic values of the Lacustrine 200 seismic response zone.

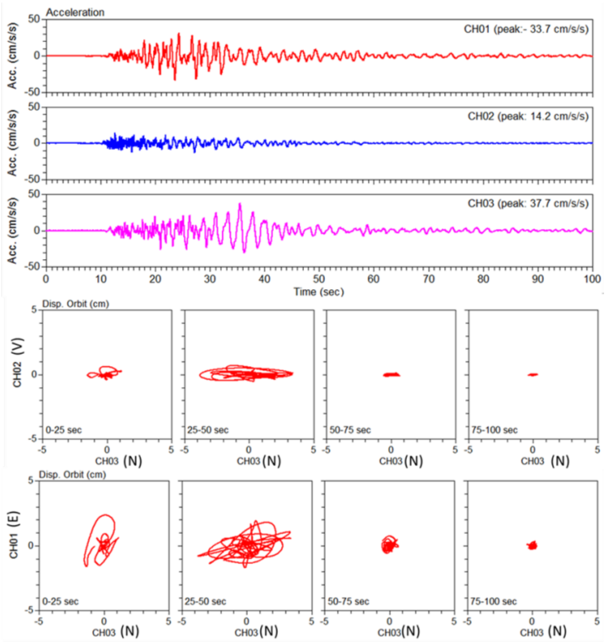

Figure 6. Ground motion record from Quetame earthquake, CBOG1 station.

Figure 8 shows the record for CUAGR stations. In this station, the predominance of Love waves is broadly observed (25-75 s), mainly in channel 3, located in E-W direction.

The displacement chart shows that highest values occur after the strong motion, mainly related with the basin response. Furthermore, the soil response has a duration much greater than the incoming earhquake record.

Figure 9 shows the fourier spectrum for CUAGR station. The highest frequency content is located in a band between 0.1 and 2 Hz, characteristic values of the Lacustrine 200 seismic response zone.

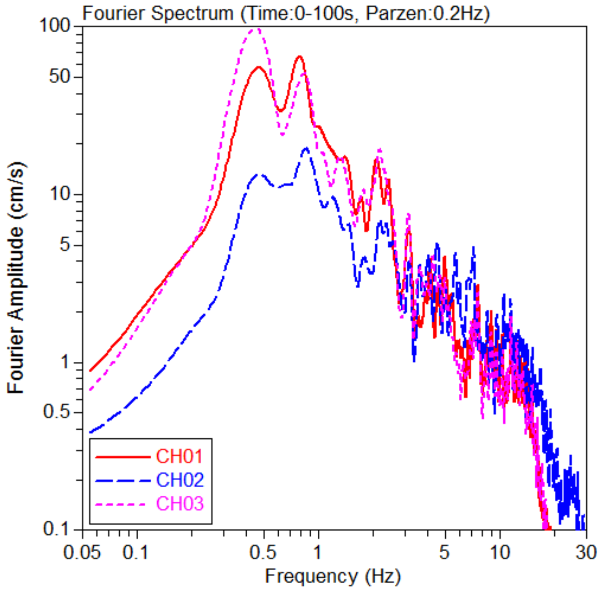

Figure 7. Fourier spectrum from Quetame earthquake, CBOG1 station.

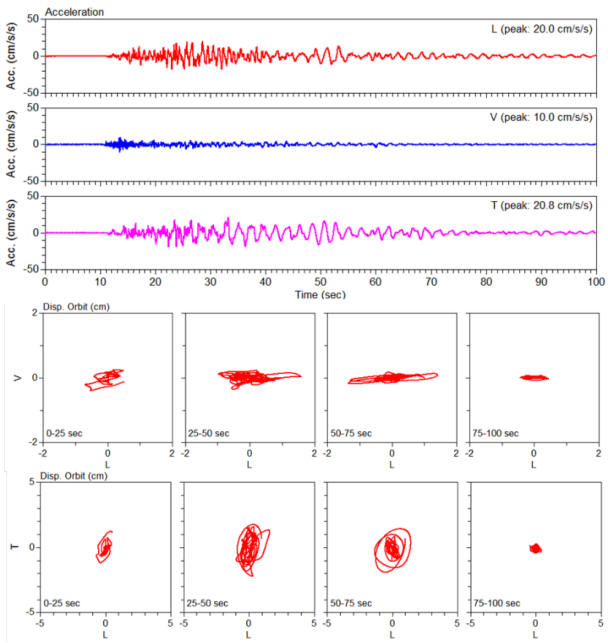

Figure 8. Ground motion record from Quetame earthquake, CUAGR station.

Figure 10 shows the record for CEING stations. In this station, the predominance of Love waves is broadly observed (25-75 s), mainly in channel 3, located in E-W direction. No Rayleigh waves predominance were observed.

Highest displacement can be seen between 25 and 50 seconds.

Figure 11 shows the fourier spectrum for CEING station. The highest frequency content is located in a band between 0.1 and 2 Hz, characteristic values of the Lacustrine 200 seismic response zone.

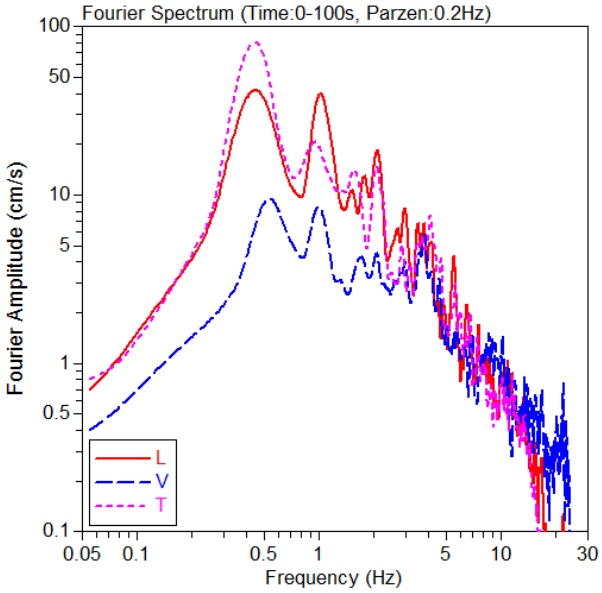

Figure 9. Fourier spectrum from Quetame earthquake, CUAGR station.

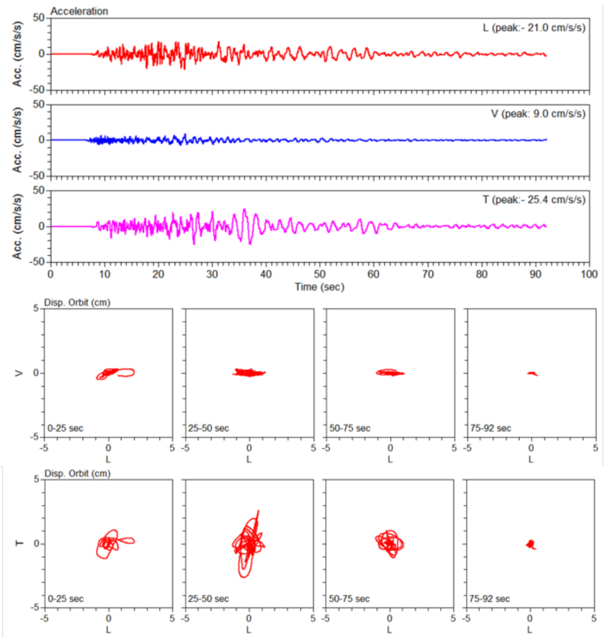

Figure 10. Ground motion record from Quetame earthquake, CEING station.

One of the characteristics to be highlighted in those records is that the effect of surface waves is reflected much more broadly in channel 03, located in the E-W direction. This phenomenon is due to the intrinsic bidimensional effects of the basin, therefore, the signals corresponding to component 03 have greater amplification than those of channel 01 N-S component. This phenomenon ocurrs because of edge conditions imposed by the eastern and Suba Hills.

Recents studies have shown that narrow basin effects can amplify the displacement in the E-W component twice and three times the N-S values [30].

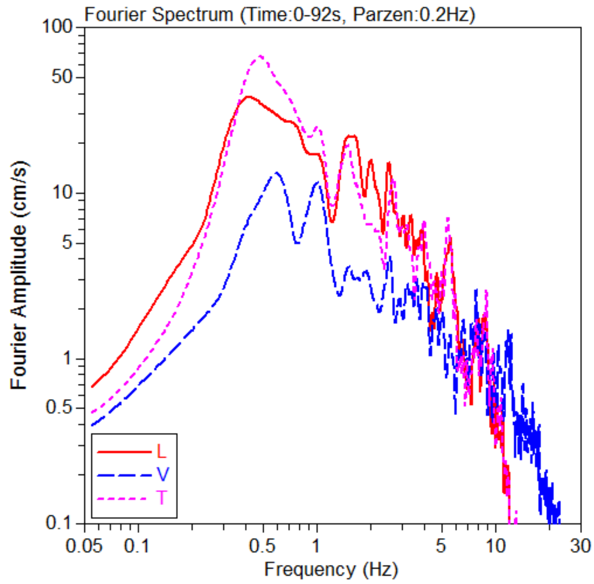

Figure 11. Fourier spectrum from Quetame earthquake, CEING station.

4.3.3. Lacustrine 500

It corresponds to the western of Bogotá City, composed of 120 m of lacustrine soils, followed for an alluvial formation with a total thickness between 400 and 500 m. Even when some boreholes made in projects near this location show that rock thickness of the basin is greater than 330 meters, there is still large uncertainty about the deposit velocity structure. One of the limitations of the seismic microzonation of Bogota is that there were no measurements of shear wave velocity at great depths.

The station object of analysis belong to the RAB and is located at the La Florida Park (CFLOD), in Engativá locality. The seismic records selected for the station CFLOD correspond to the 5.7Mw magnitude earthquake, ocurred on May 24th, 2008, with epicenter in Quetame, Cundinamarca. Figure 12 and Figure 13 show the records and fourier spectrum for CFLOD station, respectively. In this station, the predominance of Love waves is observed (25-67 s).

Western zone of Bogotá basin seems not to have the anisotropy observed in the northeastern zone, with a very similar signal being noted both in the E-W component and in the N-S component. This behavior can be explained because in this location there is no nearby restriction of the edge of the basin imposed by the eastern hills of Bogota.

The highest frequency content is located in a band between 0.1 and 1 Hz, characteristic values of the Lacustrine 500 seismic response zone.

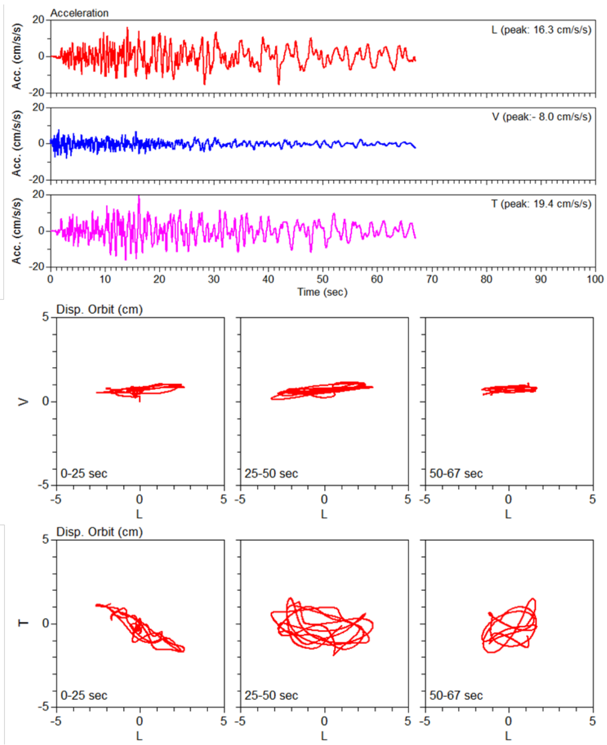

Figure 12. Ground motion record from Quetame earthquake, CFLOD station.

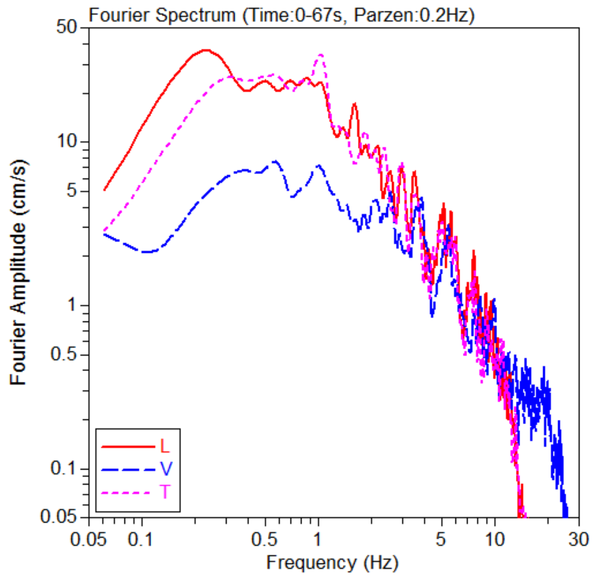

Figure 13. Fourier spectrum from Quetame earthquake, CFLOD station.

5. Results

Figure 14 shows the inversion results for the site corresponding to the Pontificia Universidad Javeriana (PUJ). In Figure 14 on the left, the black line represents the experimental curve and the red line shows the best fit obtained by inversion. The fundamental mode presents an adjustment quite close to that of the experimental curve. Below 2 Hz, the inverted curve is much smoother than the experimental curve, which translates into slight uncertainties in the deeper layers. At 8 Hz, a second peak is observed in the experimental dispersion curve, which is adjusted reasonably well by inversion. From 10 Hz, the inverted curve slightly distances itself from the experimental curve, which can generate certain uncertainties in thin shallow layers. In the Figure 14 on the right, the solid black line represents the average profile obtained during the inversion. The dotted blue line represents the velocity profile proposed by Cardozo (2015), obtained from geotechnical surveys, laboratory tests and Down Hole tests. As can be seen from 0 to 15 meters, the adjustment between the inverted curve and the measured curve is very good, demonstrating that the uncertainties generated in the inversion from 10 Hz do not significantly affect the results of the shallow strata, and even more, they may be less than the uncertainties associated with other conventional seismic methods. From 15 meters up to 25 meters deep, the values obtained in the inverted profile are slightly greater than the measured velocities, however, these differences do not exceed 15% on average. The inversion identifies very well the contrast of the deposits with the underlying rock.

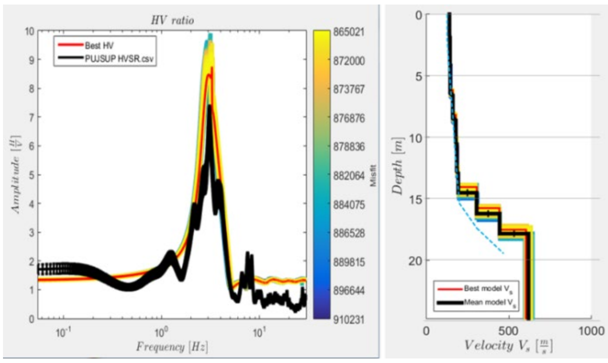

Figure 14. Inversion results, PUPJSUP station.

Figure 15 shows the inversion results for the site corresponding to the Geological Survey site (CBOG1). The fundamental mode presents an adjustment quite close to the experimental curve, although slightly to the right. This might suggest that the rock could be found at a depth close to 200 meters. Below 0.2 Hz, the inverted curve is much smoother than the experimental curve, which translates into slight uncertainties in the deeper layers. From 0.6 Hz, the inverted curve follows the trend of the experimental curve, however the peaks of the curve are not rigorously adjusted, which translates into a smoothing of the resulting shear wave profile, which reflects average values and it does not discretize the different thin layer intercalations observed in the Down Hole measurements. In the Figure 15 on the right, the solid black line represents the average profile obtained during the inversion. The dotted blue line represents the proposed velocity profile obtained for the seismic microzonation of Bogotá [28], obtained from geotechnical surveys, laboratory tests and Down Hole tests. As can be seen from 0 to 70 meters deep, the adjustment between the experimental curve and the measured curve is very good, clearly representing even the observed velocity inversion between 10 and 40 meters deep. Although average values are shown, the adjustment corresponds quite well with the velocity profiles obtained by direct methods. From 70 meters deep, there is a greater variation in the inverted and experimental velocity profile, however, the average difference is in the order of 10%. Again, the inversion identifies very well the contrast of the deposits with the underlying rock.

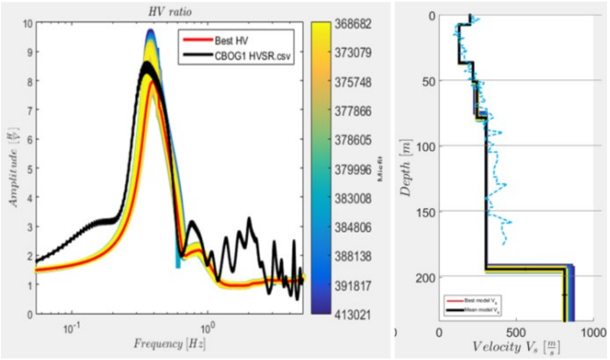

Figure 15. Inversion results, CBOG1 station.

Figure 16 shows the inversion results for the site corresponding to the Agrarian University (CUAGR). The fundamental mode presents an adjustment quite close to that of the experimental curve. Below 0.3 Hz, the inverted curve is very close to the experimental curve, so that a good deep layer adjustment is expected. From 0.8 Hz, the inverted curve follows the trend of the experimental curve, however the peaks of the curve are not rigorously adjusted, which translates into a smoothing of the resulting shear wave profile, which reflects average values and it does not discretize the different interleaves of thin layers observed in the more superficial strata. In the Figure 16 on the right, the solid black line represents the average profile obtained during the inversion. The dotted blue line represents the proposed velocity profile obtained for the seismic microzonation of Bogotá [28], obtained from geotechnical surveys, laboratory tests and Down Hole tests. As can be seen throughout the entire profile, the fit between the inverted curve and the measured curve is very good. Although average values are shown in the upper layers, the adjustment corresponds quite well with the velocity profiles obtained by direct methods. The inversion identifies very well the contrast of the deposits with the underlying rock.

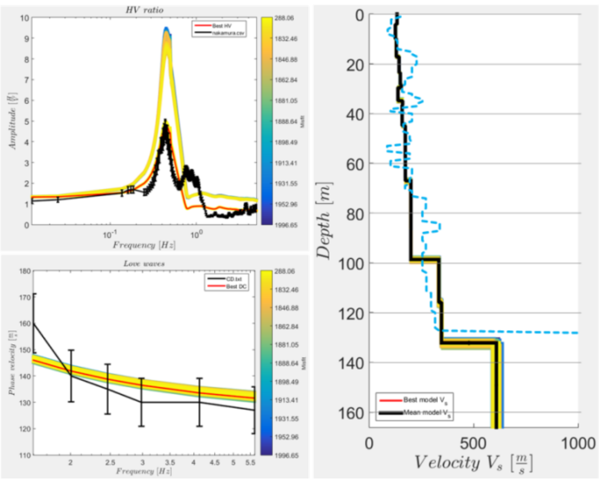

Figure 16. Inversion results, CUAGR station.

Figure 17 shows the inversion results for the site corresponding to the Escuela de Ingeniería University (CEING). The fundamental mode presents an adjustment quite close to that of the experimental curve although slightly to the right. This might suggest that the rock could be found deeper than we estimated. Below 0.3 Hz, the inverted curve deviates from the experimental curve, so that the velocity of the deeper layer has some uncertainty. In the Figure 16 on the right, the solid black line represents the average profile obtained during the inversion. The dotted blue line represents the velocity profile obtained from conventional seismic methods and borehole correlations. As can be seen throughout the entire profile, the fit between the experimental curve and the measured curve is very good until 100 m. The adjustment corresponds quite well with the velocity profiles obtained by direct methods. However, for depths greater than 100 m, the adjustment is not so good. The inversion doesn´t identify very well the contrast of the deposits with the underlying rock. It could be because of uncertainties in the H/V curve definition, as well as, imprecision in the correlated shear wave profile. More surveys could be performed at that site in order to establish a velocity model constrain.

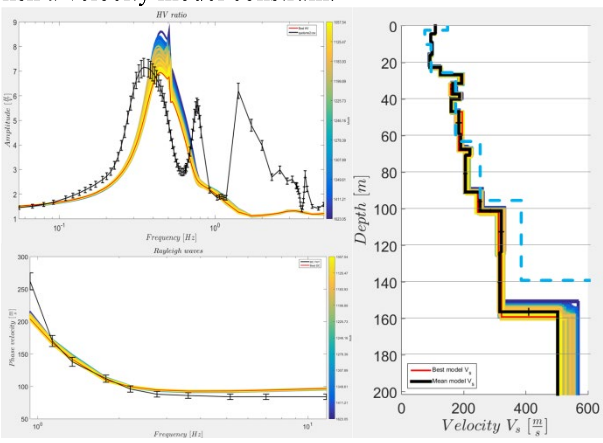

Figure 17. Inversion results, CEING station.

Figure 18 shows the inversion results for the site corresponding to the Florida Park (CEING). The fundamental mode presents an adjustment quite close to that of the experimental curve, even when it is wider than experimental curve. Inverted curve follows the trend of the experimental curve, however the peaks of the curve are not rigorously adjusted, which translates into a smoothing of the resulting shear wave profile, which reflects average values and it does not discretize the different interleaves of thin layers expected on the soil profile. In the Figure 18 on the right, the solid black line represents the average profile obtained during the inversion. The dotted blue line represents the proposed velocity profile obtained for the seismic microzonation of Bogotá [28], from bore hole correlations. As can be seen throughout the entire profile, the fit between the inverted curve and the measured curve is very good. Even when average values are shown in the upper layers, the adjustment corresponds quite well with the velocity profiles obtained by direct methods. The inversion identifies very well the contrast of the deposits with the underlying rock.

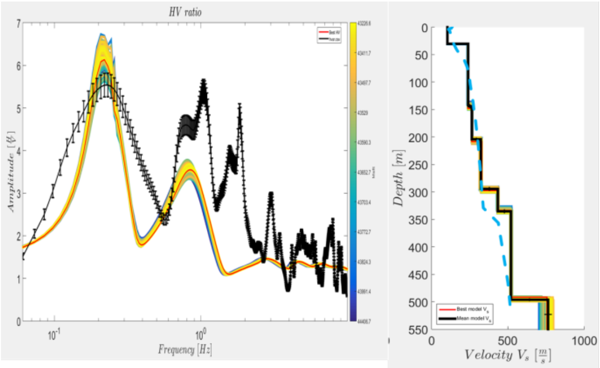

Figure 18. Inversion results, CFLOD station.

6. Conclusions

The results obtained show that the HVSR curve inversion under the diffuse field approach are very useful to obtain the velocity profiles of shear waves, especially for deep soil deposits, such as those located in Bogotá city.

Five accelerographic stations with records of the Quetame and Huila earthquake were used. Three of the stations were according to the seismic response map in the Lacustrine 200 m deep zone, one of them in the Foothill area and the last one in Lacustrine 500 m deep zone. One of the main characteristics of five records used is the high content of Love waves observed in the hodograms, a characteristic that can be modeled under the diffuse field approach, through the Green´s functions, since they consider the contribution of both body waves, as well as Rayleigh and Love waves.

The velocity profiles obtained from the inversion of the HVSR curves were very well adjusted to the experimental profiles obtained from geotechnical surveys, laboratory tests and down hole tests.

The formulation and versatility of the method allow it to be used in conjunction with other conventional geophysical techniques, allowing joint inversion of HVSR curves and Rayleigh or Love wave dispersion curves. Joint inversion with Rayleigh dispersion curves obtained by SPAC methods shows a considerable improvement in the definition of shear wave velocity profiles in all the sites selected in Bogotá City.

Results demonstrate that shear wave velocity profiles obtained from these methodologies can be advantageously used for seismic site-response analysis, contributing to a better definition of seismic hazard microzonation.

More detailed studies will be performed in order to improve the HVSR curve definition and constrain the inversion fitting, overall in zones with thicknesses greater than 200 meters.

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