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MICROTREMOR ANALYSIS TO CALCULATE SHEAR WAVES VELOCITY PROFILES USING THE SPATIAL AUTOCORRELATION METHOD (SPAC) IN ARMENIA, COLOMBIA

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Abstract

An analysis of microtremors records was performed to determine shear-wave velocity profiles by using linear arrays of seismograph and accelerograph stations and based on the Spatial Auto Correlation Method – SPAC. Five linear arrays with three hours duration for each distribution were deployed on site Puerto Espejo in Armenia city. By means of an inversion procedure velocity profiles were determined for shear waves from the autocorrelation and dispersion curves. For the arrays a profile up to 400 m composed of three layers with velocities in the range 110 m/s – 800 m/s was obtained and coincide with downhole studies in first 30 meters.

Keywords: Microtremors; Spatial autocorrelation; Shear wave velocity

1. Introduction

In recent years, the effects of shaking for several major earthquakes (Colombia, 1999; Indonesia, 2004; Peru, 2007; China, 2008, Haiti, Chile and New Zealand, 2010; Japan, 2011) have been responsible for hundreds and even thousands of fatalities. The impact on infrastructure and damage to human lives represent an incalculable cost to national and local authorities. Most of the cities and populated areas in Colombia, are settled on soft sediments (such as fillings river valleys, recent deposits, estuaries and artificial fillers) in which the soil structure acts as an amplifying medium for seismic waves (Bard, 1994). This phenomenon is called site effect (also known as local effect, site response), since the amplitude of the seismic movement depends largely on local soil properties.

Surface waves are defined as waves that are produced in a medium with a free surface, it propagates in all directions parallel to the surface of the Earth are generated by the energy transmitted body waves incidents and its amplitude decreases depth (Flores, 2004). Microtremors are considered mainly composed of surface waves which constitute a stationary and homogeneous field, allowing the use of dispersion property (Tokimatsu., 1997; Chouet et al, 1998), its velocity varies depending on the frequency (or period) and can determine the phase velocity of Rayleigh waves by an inversion process (Herrmann, 1994; Wathelet et al., 2004 Wathelet, 2005). Exploration methods with microtremors are a geophysical technique to obtain the shear waves velocity and other physical properties of the subsurface structure (Okada et al., 1990), in near-surface layers (a few hundred meters depth) without the use of destructive methods, with the advantage over other conventional exploration techniques generally require drilling invasive and expensive in urban areas, involving inconvenience for residents. In the analysis of the ground response to passing of seismic waves, the shear waves velocity (*Vs*) structure determination is more important than the speed of compression waves (*Vp*) subsurface (Okada, 2003), also it has been theoretically shown that such waves exert a greater influence on the phenomenon of soil amplification effect of seismic motion (Kramer, 1996).

Within exploration methods with microtremor, is the spatial autocorrelation method (SPAC), this technique reveals the characteristics of the propagation medium, using arrangements perfect circular shape (Aki, 1957). A modification to the original SPAC method was proposed by Chavez - Garcia et al. (2006) where a linear geometry is used with different spacings between the stations composing the array, eliminating the restriction of a particular geometry if the conditions of stationarity of microtremors are fulfilled and has become a useful technique for studies in urban areas where it is difficult to obtain circular geometries arrays. The analysis includes the calculation of the correlation between two simultaneous records of a pair of separate sensors. Through a process of inversion, shear wave velocity profiles are obtained from autocorrelation curves (correlation coefficients averaged versus frequency). In what has to do with the implementation of the method, there is a software package for storage, display and analysis of the recorded signals named SESARRAY (Wathelet., 2005 Wathelet et al, 2005).

In this work for the first time in the city of Armenia, determination of shear wave velocity model from records microtremor analysis by the SPAC method using linear geometry (Chavez - Garcia et al., 2006) is made, through deployment of seismometers and accelerometers arrays in the city mentioned and possible correlations of geophysical results with drilling data and local geology are discussed. Integrating the use of microtremors, building autocorrelation curves, the velocity profiles modeling and calculating transfer functions allow us to calculate the dynamic soil response. The location of the city of Armenia in an area of high seismic hazard (AIS 2010), implies that, during the occurrence of seismic events, there is increased likelihood of high accelerations are reached that cause damage to the population and buildings. The Colombian Building Code Earthquake Resistant NSR-10 (AIS 2010), states that the departmental capitals and cities with more than 100,000 people located in areas of intermediate and high seismic hazard should harmonize municipal regulations ordering the use of land with microzonation studies.

The significance of this project, is that most of the urban development and buildings that are currently taking place in the city of Armenia, are located on sediments correspond to volcanic ashes, for this reason this city was chosen to install arrays seismographic and accelerographic stations intended to estimate a shear wave velocity model, which is indispensable for modeling the dynamic response and amplification of ground against the occurrence of a seismic event, as well as becoming a good contribution for future studies microzonation.

2. The SPAC Method

The original idea to analyze ambient vibration records was made by Aki (1957), who proposed to analyze the spatial correlation of noise and determine the information about the stratification of the site from the interpretation of surface waves. Ambient seismic noise measured by an array of stations has become a promising method for determining the shear wave velocity profile (Vs) (Milana et al., 1996, Scherbaum, 2003, Wathelet, 2005) and has been revised to respond to practical problems, especially in irregular arrays deployed on the ground (Bettig et al., 2001, Chavez - Garcia et al., 2006).

The basis of this analysis consists in computing the average correlation coefficient between two simultaneous recordings of two sensors separated by a distance r, angular frequency ω and oriented in different θ azimuths (Figure 1), using equation (1) (Aki, 1957).

$$\bar{\rho}(r, \omega_0) = \frac{1}{2\pi \cdot \emptyset(\omega; 0,0)} \int_0^{\pi} \emptyset(\omega, r, \theta)\, d\theta \qquad (1)$$

Where $\emptyset(\omega; 0,0)$ is the autocorrelation function in the center of the array C(0,0) and $\emptyset(\omega, r, \theta)$ represents the function of spatial autocorrelation at point X(r, θ). Using a mathematical simplification, equation (1) can be rewritten as:

$$\rho(\omega; r) = J_0\left(\frac{\omega r}{c(\omega)}\right) \qquad (2)$$

Where J_0 is the Bessel function of first kind with zero order and $c(\omega)$ it is the phase velocity in frequency ω, to the fundamental mode of Rayleigh waves. In Figure 2 the analysis procedure is illustrated by the SPAC method, which consists of the following steps:
A. Definition of the geometry of the array of stations to record microtremor.
B. Determination of spatial autocorrelation coefficients for the different distances between stations and then averaging these coefficients to obtain a spatial autocorrelation curve.
C. Calculation of the phase velocity using the relationship presented in equation (2).
D. Determination of the velocity profile shear wave by inversion of the dispersion curve (phase velocity with respect to frequency) obtained in step C

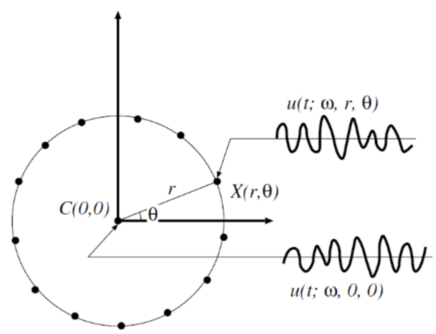

Figure 1. Schematic of an array of observation and records of the vertical component of microtremor. *u(t, ω, 0.0)* and *u(t, ω, r, θ)* represent the record in the vertical component of waves in a frequency *ω* obtained in the center of the array *C(0,0)* and the point on *X(r, θ)* circle. Source: Morikawa et al., 2004.

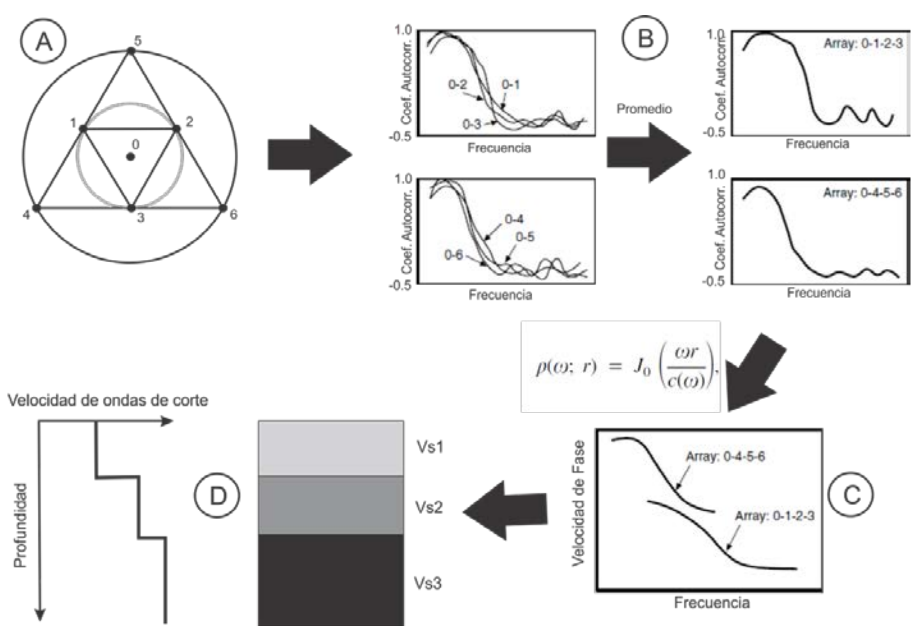

Figure 2. Procedure for the analysis SPAC method proposed by Aki (1957) SPAC. (A) Array of stations to record microtremor. (B) Calculation of spatial autocorrelation curves averaged. (C) Calculation of curves phase velocity of surface waves. (D) Construction of the shear wave velocity profile. Modified Morikawa (2004).

3. SPAC Method - line geometry

Chávez - García et al. (2006), employed a geometry line array for analysis with the SPAC method, based on the presumed that the microtremor fulfill conditions of stationarity in time and space, using records obtained from seismological stations broadband for different distances between stations of 5 m, 10 m, 20 m and 40 m. A general scheme of this modification to the SPAC method is shown in Figure 3, with the following steps: First, deployment of the linear array of stations in the study area starting with a distance between stations "x" with a total length of array of 2x, then the distance between stations is increased to 2x for a total length of 4x (Figure 3A). Second, autocorrelation curves averaged for each of the distances between the stations that compose the linear array (Figure 3B) are determined. Third, using equation 2 is possible to obtain the phase velocity curve of surface wave versus frequency for each of the spatial autocorrelation curves. Fourth, construction of shear wave velocity profiles from the inversion of the dispersion curves of phase velocity (Lozano, 2013).

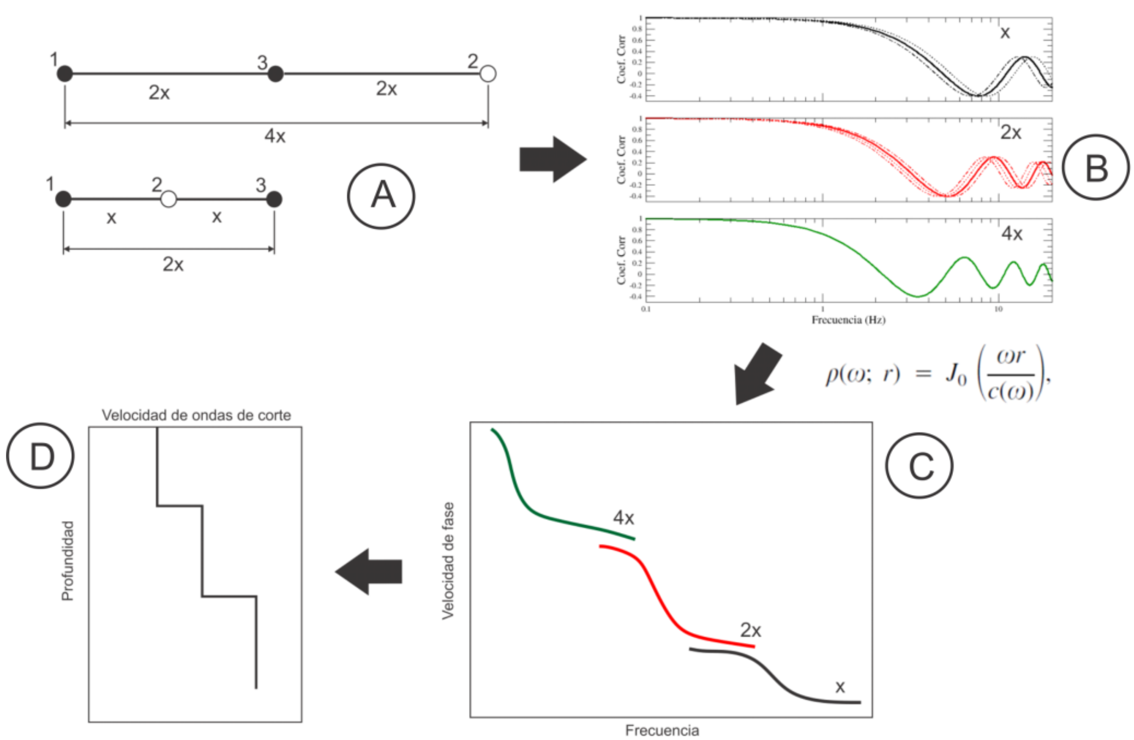

Figure 3. Procedure for analysis with the SPAC method proposed by Chavez - García et al. (2006). (A) Array of stations to record microtremor. (B) Calculation of spatial autocorrelation curves averaged. (C) Calculation of phase velocity curves of surface waves. D. Construction of the shear wave velocity profile. Source: Lozano, 2013.

4. Acquisition of records microtremor

The study area comprises two morphologies associated with lithological contrasts of different ages: An area located east, composed of metamorphic and igneous rocks of Paleozoic and Mesozoic ages, and a flatter area to the west, formed by deposits Quindío Fan of Cenozoic age. The depth of the Quindío Fan is still under discussion, however, some researchers estimate more than 100 m thickness. The microtremor array was carried out on site Puerto Espejo is located in a rural area of the city of Armenia (Figure 4) corresponds to the fan of Quindio and is a sequence of pyroclastic fall unconsolidated made up of layers of volcanic ash, the first 15 m are sandy silt soils. Geotechnically this is a weak unit, porosity and permeability medium to high, acting as one of the main factors of instability in the slopes of the city.

Figure 4. Satellite image of Puerto Espejo site, located south of Armenia, in the Quindio Fan. The P1 and P2 circles indicate the location of the line array. Modified Google Earth.

Microtremor data recorded along a line in Puerto Espejo site were used. Five seismological stations conformed by broadband seismometers Trillium (Nanometrics, 2006) coupled to digitizers Taurus (Nanometrics, 2007) and five accelerographic stations conformed by accelerometers Episensor (Kinemetrics, 2005) and digitizers Basalt (Kinemetrics, 2011), were employed in the experiment (Figure 5). Digitizers feature 24-bit resolution and synchronized using a GPS antenna at each station. The five stations were located along a line, with a separation between stations 5 m measuring microtremors for 3 hours at a sampling rate of 100 mps (samples per second) for seismological stations and 200 mps for accelerographic stations. Then the spacing between stations was increased to 10 m, 20 m, 40 m and 80 m, recording microtremor in a lapse of 3 hours for each configuration, reaching lengths of 20 m, 40 m, 80 m, 160 m and 320 m (Figure 6).


Figure 5. Seismological and accelerographic station installed on the ground to record microtremor.

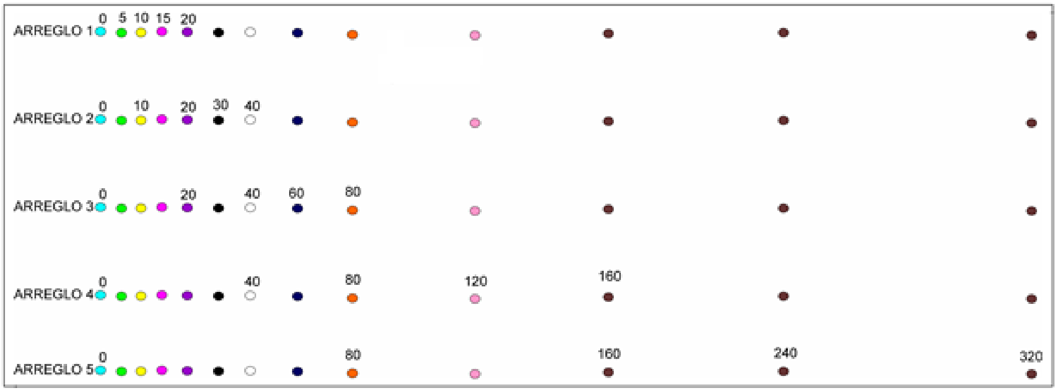

Figure 6. Linear array configuration on site Puerto mirror, point 0 (blue) corresponds fixed station during the experiment and the other dots indicate the location of stations for each of the configurations. Lengths of 20, 40, 80, 160 and 320 m were achieved.

5. Results

5.1 Spatial autocorrelation curves

The averaged spatial autocorrelation coefficients were determined for each of the distances between stations line array configurations with lengths of 20 m, 40 m, 80 m, 160 m and 320 m. Of the curves shown in Figures 7 and 8 it shows that the autocorrelation coefficients for the distance 240 m not resemble a Bessel function of zero order.

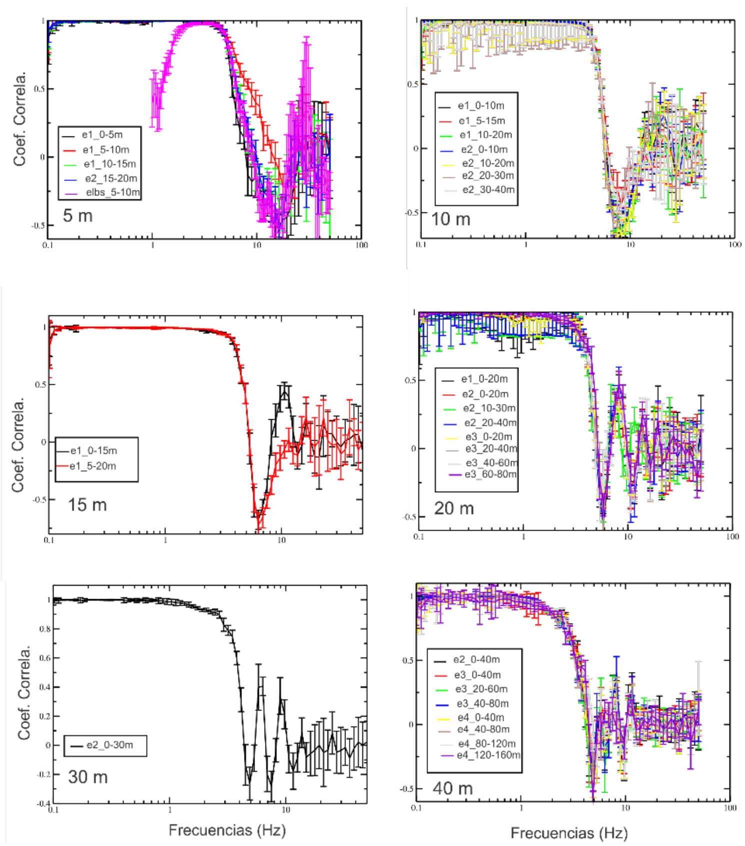

Figure 7. Spatial autocorrelation curves obtained for linear array configuration, distance between stations 5 m, 10 m, 15 m, 20 m, 30 m and 40 m.

For other distances between stations, the curves exhibit similar to a Bessel function of zero order form and used to calculate the phase velocity curves. At distances of 240 m, autocorrelation curves obtained from records accelerographic equipment were used, in which it is observed that for frequencies near 1Hz a decline occurs, limiting its use at short distances (Figure 8). Figures 7 and 8 shows that the frequency with respect to the first zero crossing decreases with increasing distance between stations.

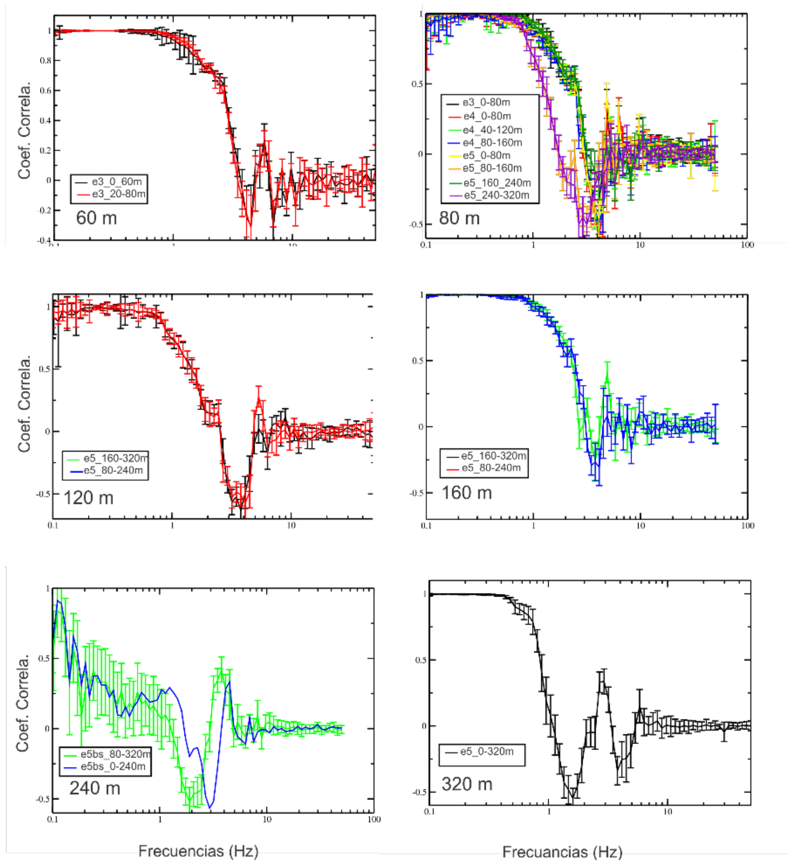

Figure 8. Spatial autocorrelation curves obtained for linear array configuration, distance between stations 60 m, 80 m, 120 m, 160 m, 240 m and 320 m.

5.2 Dispersion curves

Phase velocities *c(ω)* of the dispersion curve are calculated for each frequency using equation 2. From spatial autocorrelation coefficients, the dispersion curves of phase velocity (Figures 9 and 10) for all distances between stations for each linear array configurations were calculated. Dispersion curves of phase velocity are averaged to obtain a single curve for all the linear array shown in Figure 11.

5.3 Shear wave velocity profile

The dispersion curve is defined for the case of one-dimensional models, vertically heterogeneous and inversion are resolved by a classic problem (Hermann, 1994). In current work Wathelet et al., (2004) proposes the use of neighborhood algorithm ("neighborhood algorithm"), to determine the spatial parameters in an appropriate way.

In the inversion process, randomly generated velocity profiles through the neighborhood algorithm. Theoretical dispersion curves are compared with those obtained from arrays microtremors records in the field, and a value of mismatch ("misfit") is determined for each of the calculated profiles. Several independent execution of the program to show that the calculated results are reliable profiles are required (Wathelet et al., 2005). The inversion process of dispersion curves of phase velocity has limitations as the non-uniqueness in the solutions and loss of resolution with depth.

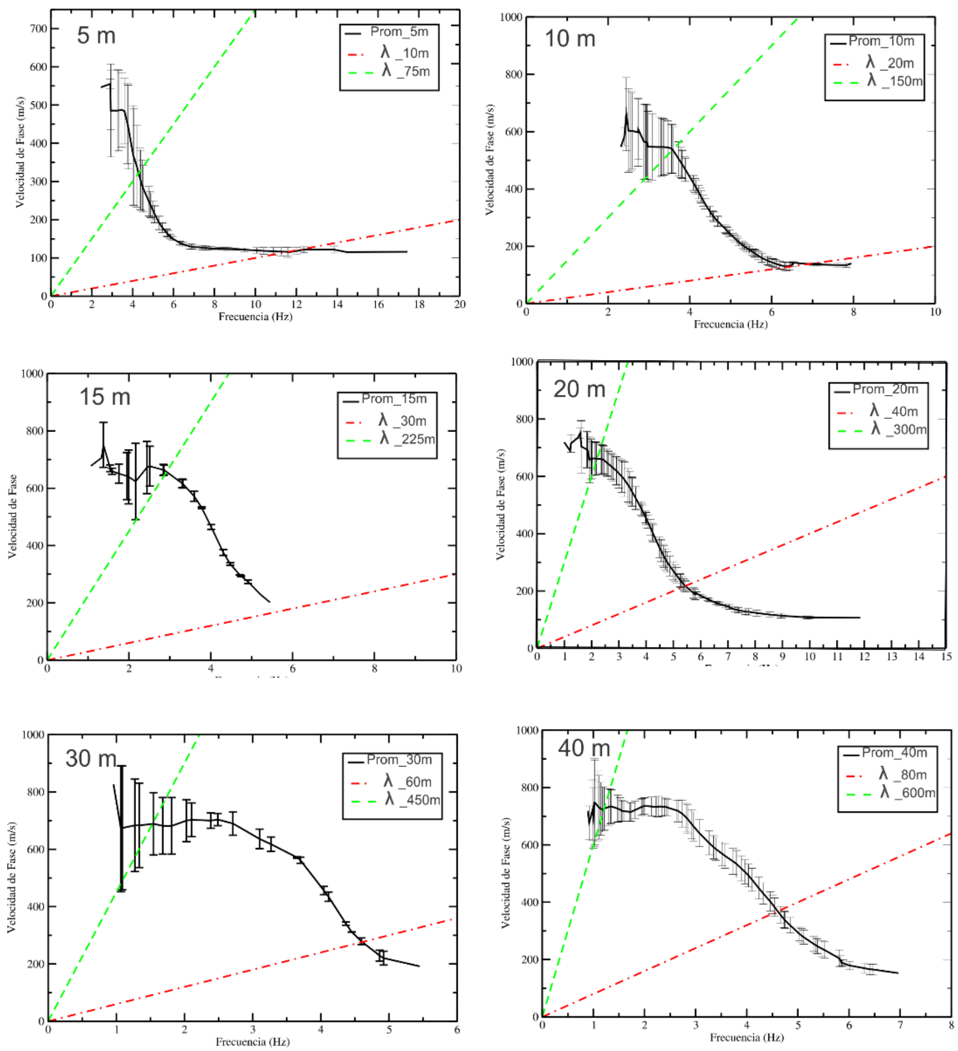

Figure 9. Dispersion curves obtained for linear array configuration, distance between stations 5 m, 10 m, 15 m, 20 m, 30 m and 40 m.

The shear wave velocity profile for the given linear array was determined from spatial autocorrelation curves, shown in Figure 12. It was calculated from an initial model of a layer of soft soil on a halfspace (Table 1). A practical manner this model is introduced in the program Dinver (Wathelet et al., 2004), the outermost divided into four layers with velocity *Vs* and variable thickness.

Table 1 – Initial parameters for calculating the shear wave velocity profile

Layer	*Vs* (m/s) range	Depth range (m)
1	100 – 150	1 – 20
2	300 - 350	20 – 30
3	700 - 800	30 – 500
4	1000 - 3000	500 - 4000
halfspace		

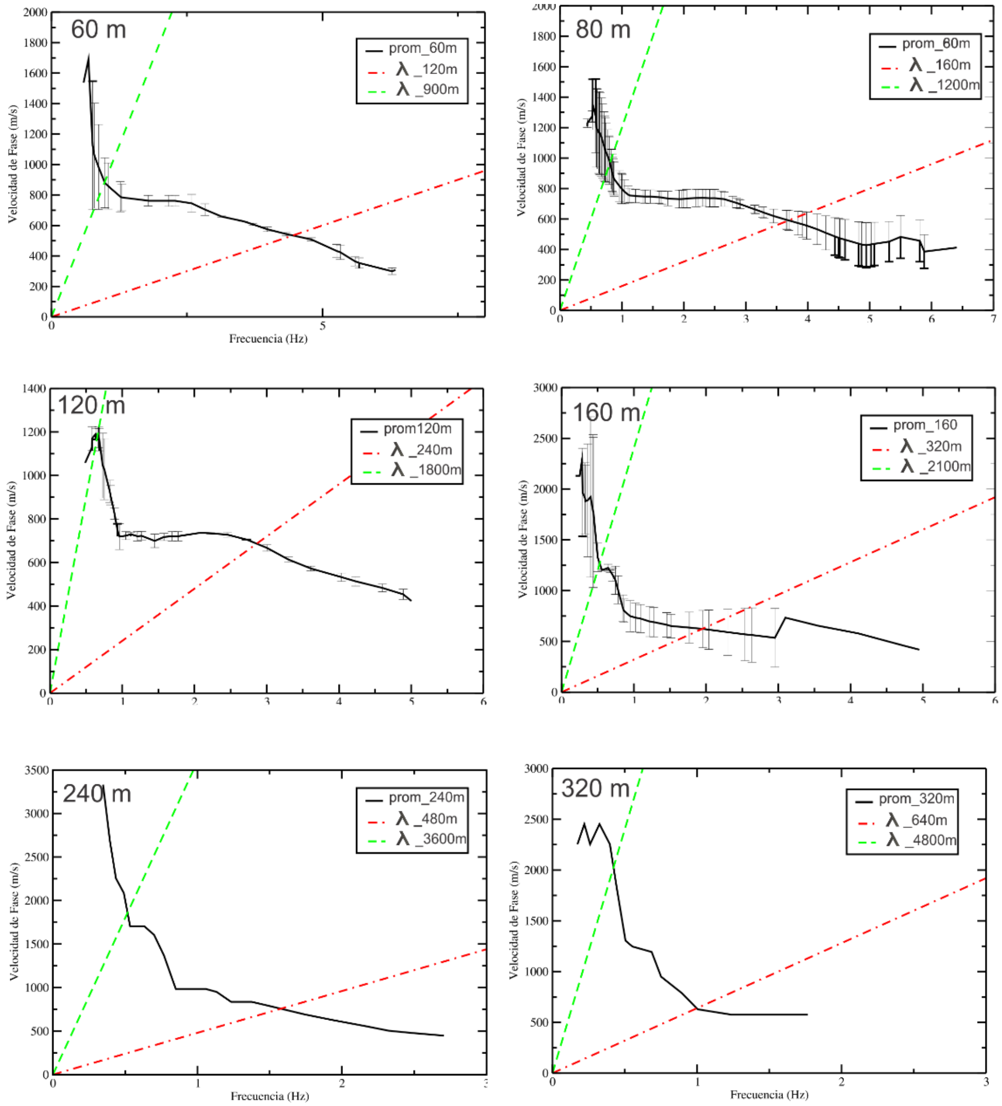

Figure 10. Dispersion curves obtained for linear array configuration, distance between stations 60 m, 80 m, 120 m, 160 m, 240 m and 320 m.

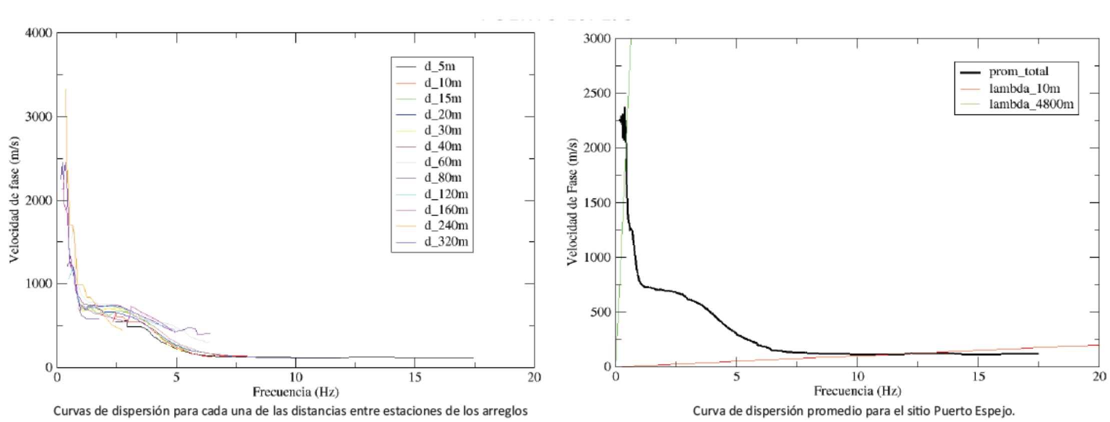

Figure 11. Dispersion curve for the total length of the linear array.

Figure 12 shows the different solutions for the velocity profiles of shear waves in the first 30 meters. The surface model with the lowest mismatch value is composed of two layers with varying speeds in a range between 100 m/s and 350 m/s. It can be observed that there is a good relationship between the depth and the thickness of the surface layers of soil deposit that were reported in a study of downhole type (DH) conducted on site Puerto Espejo (Figure 12).

The shear wave velocity profile on site Puerto Espejo, with the best fit is composed of three layers on a half-space, with depths of 7.5 m, 24.5 and 400 m. In Figure 13, a zone contrast with shear wave velocities > 800 m/s, under these considerations corresponds to basement. In Figure 14 the dispersion curve of phase velocity obtained from microtremor arrays and the different solutions in the inversion process is presented. Table 2 summarizes the results of the calculated profile Puerto Espejo site.

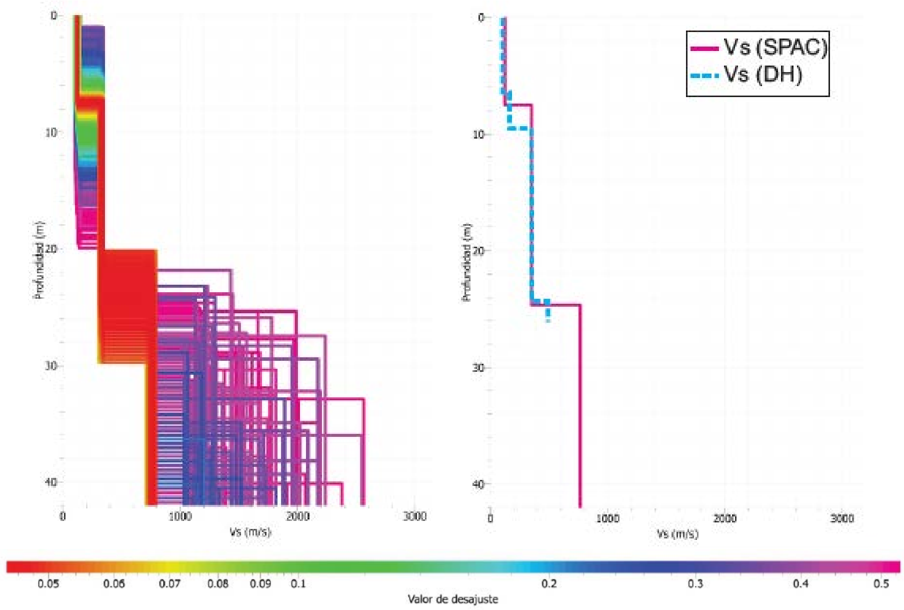

Figure 12. Shear wave velocity profile obtained for the line array 30 meters deep. In blue shows the profile obtained from studies downhole (DH)

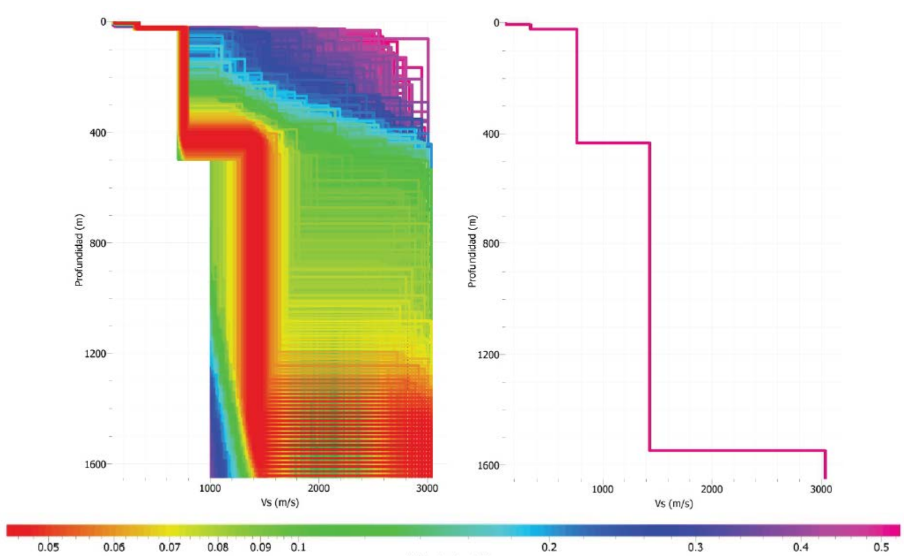

Figure 13. Shear wave velocity profile obtained for the line array.

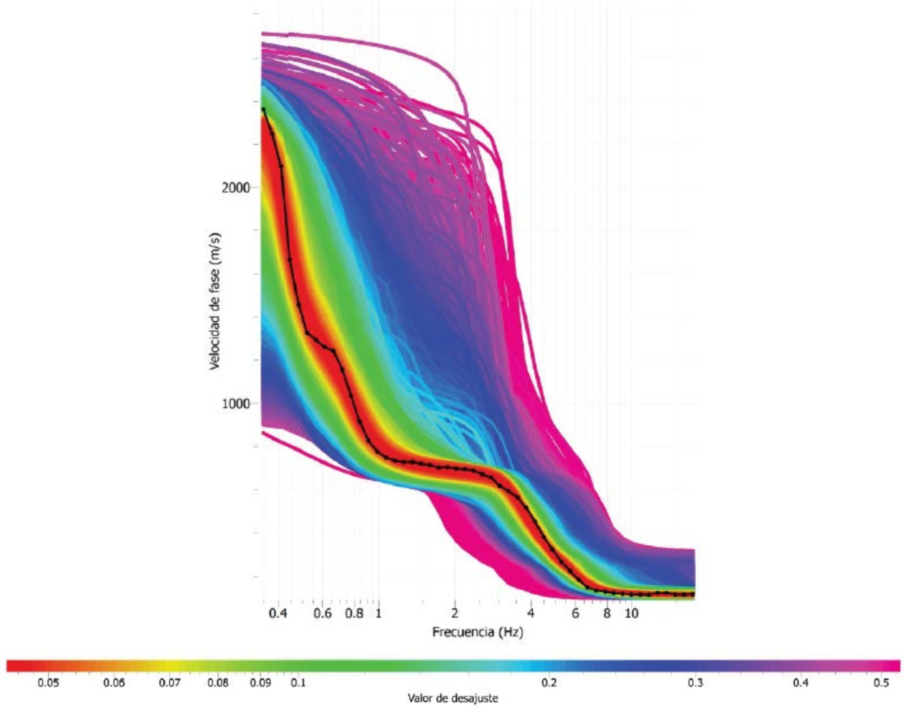

Figure 14. Dispersion curve of phase velocity obtained from microtremor arrays and the different solutions in the inversion process.

Table 2. Final model in Puerto Espejo

Layer	Vs	Depth (m)	Density (kg/m3)
1	100-150	7.5	2000
2	300-350	24.5	2000
3	700-800	400	
semiespacio			

6. Conclusions

In this paper microtremor records that are presented in a wave field under a linear array in the city of Armenia were studied; to achieve this objective the information recorded during the operation of a linear array with five seismological stations and accelerographic covering a length of 320 m was used.

In the analysis of arrays microtremor by the method of spatial autocorrelation, must make a number of assumptions, for example, the waves are stationary and isotropic and that the autocorrelation coefficient is the average of all waves coming from all directions in space. Like all methods of surface waves, the geometry obtained is unidimensional, implying that this technique is not suitable when strong lateral variations in subsurface are presented.

For the lineal array, the inversion process of curves spatial autocorrelation adjusted to a Bessel function, allowed to obtain a velocity model shear wave composed of three layers on a half-space with speeds varying in a range between 100 m/s 800 m/s to a maximum depth of 400 m. Comparing this model with the surface layers that are reported in the downhole study in Puerto Espejo site, can see that there is a good relationship between the depth and the thickness of the surface layers of soil deposit.

Although the SPAC method has limitations in determining shear wave velocity models, such as: The horizontality of the layers to infinity, alleged that the microtremor are stationary in time and space, and are composed of Rayleigh waves dominate the vertical component, the presence of sources of non correlatable noise culture; the technique is easy to apply in urban areas and becomes a tool to determine shear wave velocity profiles in areas of difficult access and additionally is a good contribution to site effects analysis and studies of seismic micro-zoning of cities.

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