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CONSTRUCTION OF 3D S-WAVE VELOCITY STRUCTURE OF CDMX, MEXICO USING OBSERVED MICROTREMORS

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Abstract

In Mexico City (CDMX), Mexico, microtremor recording campaigns have been carried out, using simultaneously 18 velocity type seismographs whose flat response is up to 30 s and has three components. In total, environmental noise has been recorded at almost 500 points in the city, with an array of 18 seismographs. CDMX can be divided into mainly three zones, basin zone, transition zone and hill zone, and the size of arrays and number of seismographs were determined according to the assumed basin depth in each zone. In each array, the distances between sensors range from 350 to 3500 m and the simultaneous recording duration is around 69 hours with a sampling rate of 100 samples per second. These records provide ample possibilities to conduct velocity structure profile inversions from the surface waves dispersion curves that can be extracted from microtremor data through various methods. In this work we explore the ability of commonly used survey methods, such as spatial autocorrelation (SPAC) [1], frequency-wavenumber (F-K) [2] and seismic interferometry [3] methods, to provide us with a clear image of the surface wave dispersion curves. In addition, the relevance of the use of horizontal and/or vertical components is explored, when the method allows to use Rayleigh and/or Love waves. After determining the best way to obtain the dispersion curves, dispersion curves from all the microtremor data at every array point are estimated. Then the dispersion curves are inverted in combination with microtremor horizontal-to-vertical spectral ratios (MHVRs), in order to obtain the S-wave velocity structure profiles at each point in CDMX. The theoretical MHVRs are calculated based on the diffuse field theory [4]. These profiles form the basis of the 3D S-wave velocity model that we propose for CDMX.

Keywords: Microtremor; Array measurements; S-wave velocity profile; Spac method; CDMX.

1. Introduction

Mexico City is the most populated city in Mexico and one of the most populated in the world. Since the occurrence of the Michoacán earthquake in 1985, it has been an example of the important participation of site effects in seismic wave amplification. Ordaz y Singh [1] have shown that in the Mexican basin an amplification of about 50 times has been observed. The modeling of the amplification of these waves in Mexico City has been the subject of many works. The one-dimensional models have served to explain the amplification in some places, but they have not allowed to fully explain the recorded wave field. Three-dimensional models have sought to explain it. Some of them have used symmetric models to approximate the shape of the basin [2]. Others have considered the irregular shape of the basin but have approximated the thickness of the soft strata based on the dominant period of the site with a fixed or gradually increasing S wave velocity [3][4]. On the other hand, there are some estimates of the S wave velocity structure in some places of the city. Some of them are based on information from deep wells made after the 1985 earthquake

[5]. Others based on estimates have been made through microtremor arrays [6][7][8][9][10]. Although these estimates provide adequate models, they have not been sufficient to form a three-dimensional model of the basin. In this work we use the records of an extensive campaign of microtremors measurements in Mexico City carried out between 2017 and 2019. During that time itinerant arrays of 18 broadband velocity type sensor stations (up to 30 s) were installed. Each array was recording microtremors for approximately 3 days. With this information, methods such as H/V and MSPAC method are explored in order to form velocity profiles that together allows to determine a three-dimensional model of the basin of Mexico.

2. Data

The extensive campaign of microtremor measurements included the installation, in most cases of arrays of 18 broadband velocity type sensor stations with flat response up to 30 s (Guralp CMG6TD). In total, 29 arrays were deployed and the total number of measurement points was 500. These covered the southern part of the Mexico city where the Chalco sub-basin and the Xochimilco sub-basin are located (fig 1). The equipment was installed facing magnetic north and in the majority of cases, as far as possible, buried in holes of approximately 50 cm (as shown in fig. 2) in order to reduce the effects of wind and thermal variations on the recorded motions. The equipment typically remained continuously recording for three days with a cadence of 100 samples per second for the three components. All equipment was provided with a GPS antenna that ensures to have the GMT common time of the records.

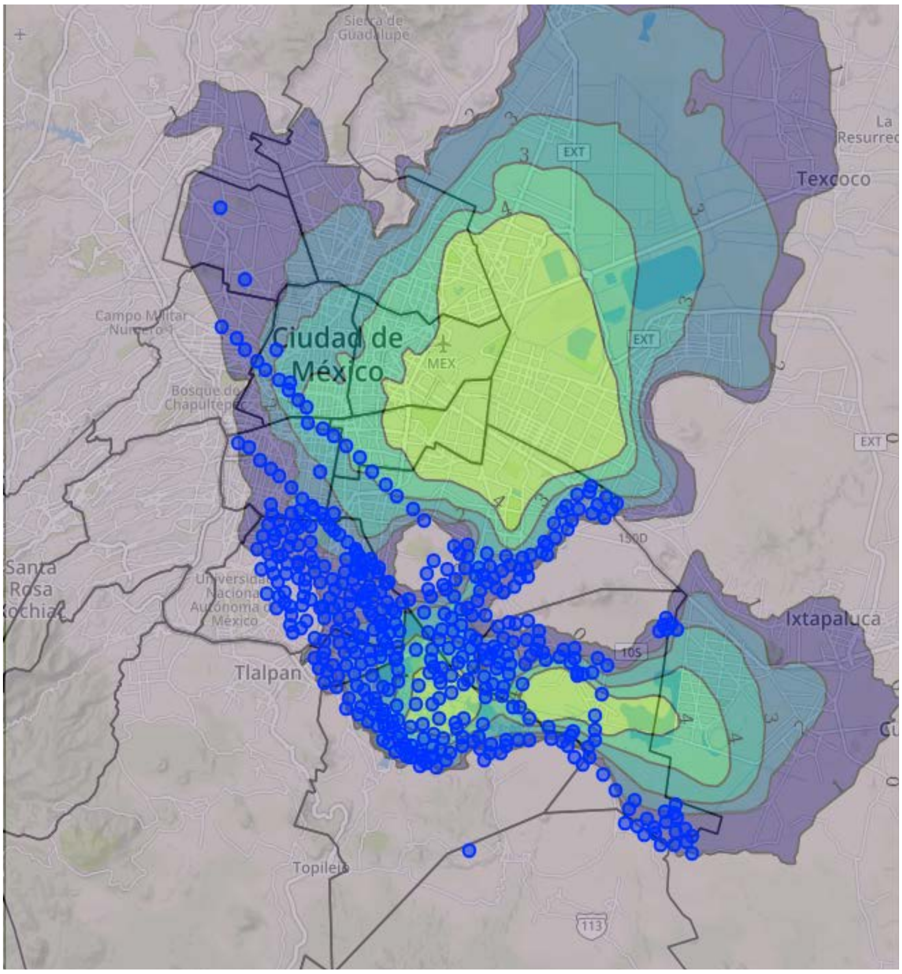

Fig. 1 – Map of Mexico City, showing the measured points or sites. The color scale indicates the different periods used in the Complementary Technical Standard for Design by Earthquake 2004.

Initially the installation was planned in a regular grid. However, when installing the different arrays, some planned points could not be installed due to the presence of water bodies or the lack of authorization to perform the installation at points that offered the necessary security. Three of the arrays were on a line trying to record aftershocks of two major earthquakes that occurred during the campaigns. The lines were oriented in the direction of the epicenters of these earthquakes. Two of the lines were oriented with respect to the epicenter of the Mw 8.2 earthquake that occurred on September 8, 2017 and the other with respect to the Mw 7.2 earthquake occurred on September 19, 2017. The first two lines were recording for approximately 6 hours while the last line was recording continuously for 7 to 12 days depending of the station.

The arrays were identified with the letter A, so we have A1, A2, etc., while each station was identified with a consecutive three-digit number after the letters CM, so we have the stations CM001, CM002, etc.

Fig. 2 – Example of the typical installation of the stations.

3. Data análisis

The data has been processed using different methods such as H/V, f-k analysis, the mspac method and correlations between pairs of stations. While the first method is applicable to a single station, the other three methods require the simultaneous measurement of records in an array of stations synchronized with common time. The results of the spectral quotients have an important value since they have been carried out with the same type of equipment with a good distribution of points and with a long enough time duration of the record to consider the day and night variations and the effects of nearby transient sources. Moreover, the long-time duration of the records also allows a statistical analysis. This analysis is in preparation [11], but here we will highlight some of the points of the H/V analysis based on these data. We will focus our attention more on the results based on analysis of array methods especially in the MSPAC.

3.1 H/V method

The microtremor spectral ratio method H/V was initially proposed by Nakamura, who thought that this ratio allowed to isolate the site effect. However, it has been shown that this ratio does not correspond to the transfer function that characterizes the structure of site velocities. Bard [12] discusses the weaknesses of the theoretical background of the method. However, it has been shown that it is very good for characterizing the dominant period of a site but that it generally underestimates the amplification of the seismic waves. This method has been widely applied to characterize the dominant period and to construct the isoperiod maps. Such has been the case of Mexico where it has been used to prepare the isoperiod map that has been used in the construction regulations (fig. 1).

The method consists in compute the ratio of the Fourier spectra amplitude of the horizontal components between that of the vertical component. These ratios are averaged for a number of windows that allow a statistically significant estimate.

On the light of diffuse field theory Sánchez-Sesma et al. [13] presented an explanation of the theoretical basis of the spectral ratio. Unlike the traditional procedure of calculating the H/V as an average of ratios, SS et al. calculate the H/V as a ratio of averages. The differences with the Nakamura H/V are small and mostly present in the amplitude. The powerful thing about this idea is that it allows to relate the H/V to the imaginary part of Green's function and consider in it the presence of both surface waves and body waves. This allows to estimate the velocity structure from the inversion of the spectral ratio considering also the amplitude.

From the geotechnical point of view, Mexico City has been divided into 1) lake zone, 2) transition zone and 3) hill zone. Since this zoning is related to the thickness of the sedimentary layer there is a relationship between this geotechnical zoning and the natural periods of the land. Thus the boundary between the hill zone and the transition zone is delimited by the 0.5 s isoperiod curve, and the boundary between the transition zone and the lake zone by the 1 s isoperiod curve. Although the objective of the project is to characterize the response of the basin, especially in the part of the lake deposits, some arrays were installed in mixed zones or in transitional or hills zones.

In fig. 3 we show some of the ratios that we have obtained for 15 stations of the campaign that were located in different zones. Some ratios (b, i, o) show sharp and well marked peaks with great amplitude. With them it is possible to clearly obtain the fundamental period of the site. They also show qualitatively the great amplification that is generated in the lake area. Other ratios (a, b, m) do not show substantial amplification. Others (d, g, h, k, n) show the presence of two peaks and it is difficult to determine clearly which of them represents the fundamental period or will play an important role in seismic amplification. It is clear that the fundamental period is not enough to characterize the ground response. Other of them have more peaks or peaks not very well marked. We could seek to characterize the site response using more than one peak. But the best way is to determine the structure of velocity and through it, estimate the site response in the band of interest instead of just looking for the dominant periods. In addition to determining the dominant period, the ratios help to restrict the inversion of wave velocity structure models as demonstrated by Piña [14], when is used in conjunction with the dispersion curve. Later we will show how we will use the ratios in this way.

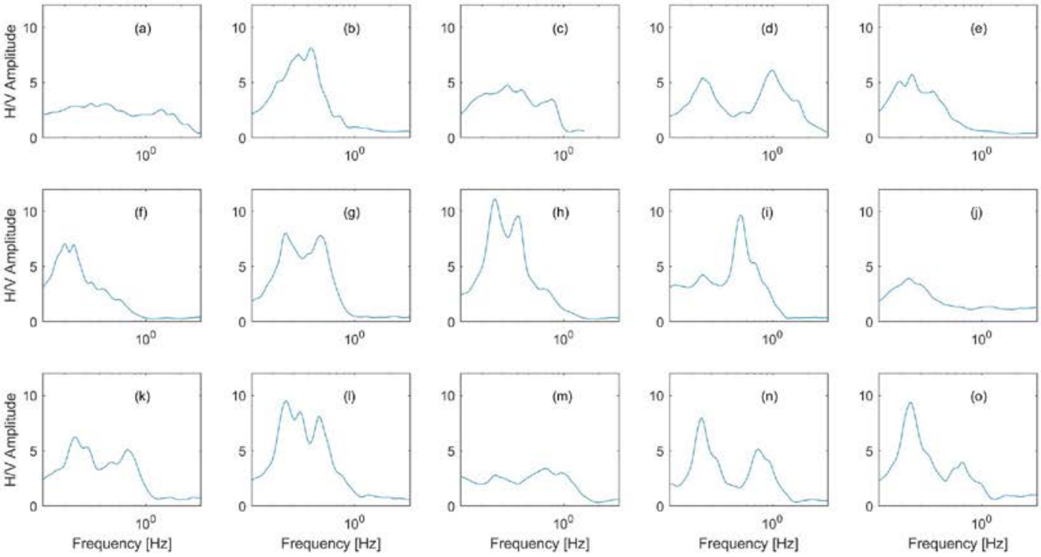

Fig. 3 – Examples of the spectral ratios H/V of 15 stations of the measurement campaign. The graphs are logarithmic on the horizontal scale and comprise the frequencies of 0.13 to 3 Hz.

3.2 MSPAC method

The MSPAC method [15] is a variation of the SPAC method initially proposed by Aki [16]. The SPAC method considers arrays of stations placed in different directions on a circle of radius r. The MSPAC method makes an adaptation considering the stations located in a ring between two radii defined by r1 and r2. Both, SPAC and MSPSAC seek to estimate the phase velocity dispersion curve of Rayleigh waves by performing a statistical analysis with several seismic noise windows. As an intermediate step, the autocorrelation coefficient is sought through the averaged and correlated cross correlation assembly for different azimuths. It is expected that these correlation coefficients will be in the form of a zero-order, first-order Bessel function. In its argument, this Bessel function involves the phase velocity dependent on the frequency we seek.

In this work we apply this method to 10 arrays: A1, A2, A3, A4, A5, A7, A8, A9, A12 and A20. The distribution of the stations and the location of the arrays can be seen in fig. 3. We use time vertical component records at 10 samples per second. In Table 1 we show the location and recording time we use in the analysis for each array.

We use the MSPAC analysis module within the Geopsy software [17]. For the MSPAC analysis, frequency dependent windows were used considering 200 wavelengths for each period of interest. The analysis was performed between 0.05 and 5 Hz. For this analysis we used only the vertical components. Several rings were considered for each array. The number of rings per array appears in Table 1. Although there is an array where there were only 7 rings, the average number of rings per array is larger than 27. The radii of the rings varied within a smaller radius of 180 m in A12 and the largest radius of 6096 m in A3. The smallest and largest radius for each array is also listed in Table 1.

In fig. 4 we show the location of the arrays that appear in Table 1. Of the 10 arrays analyzed 6 of them correspond to zone III. Of the remaining arrays, 2 of them correspond to mixed zones and the other two were located in zone I and zone II.

The standard analysis provided by Geopsy is quite useful and friendly to define the dispersion curve when the data allows it. In our case, for several of the arrays, the data did not allow a clear definition of Bessel's function or of the dispersion curves in the corresponding histogram. However, zero crossings of Bessel's function could be determined in many of the rings of each array. Considering also that we have a large number of rings for each array, we use those values to define the dispersion curve. In fig. 5 we show the dispersion curves defined by means of those points for the 10 arrays that we analyzed here.

Table 1 – Arrays analyzed in this work and their characteristics.

Array	Zone	Time used for analysis [hrs]	Number of stations used	Number of rings used	Smaller radii [m]	Larger radii [m]
A1	I, II, III	67	18	32	296	3831
A2	III	86.5	18	27	259	2642
A3	II, III	87	18	45	277	6096
A4	III	88	18	34	249	5106
A5	III	88	18	29	210	2326
A7	III	10	6	7	343	1297
A8	III	31.5	17	32	462	4184
A9	III	87	17	19	306	2884
A12	II	91	18	24	180	3377
A20	I	97	18	25	352	3451

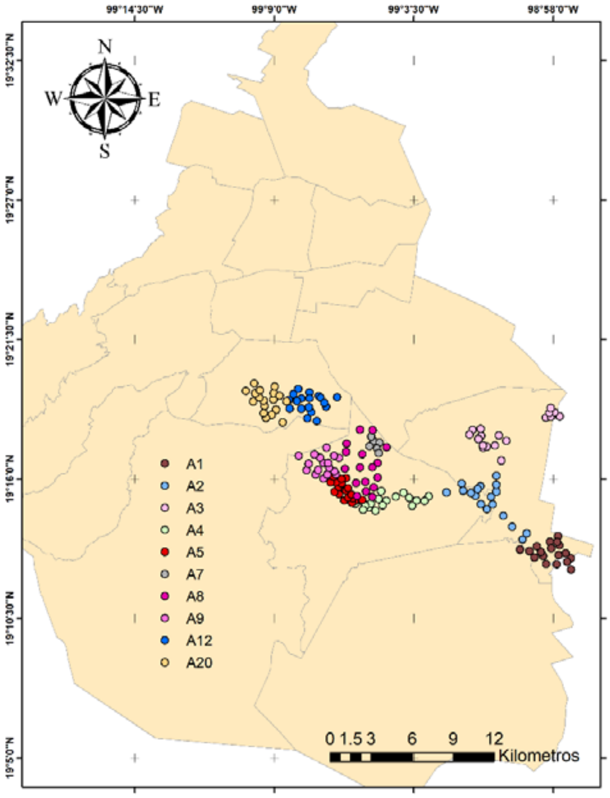

Fig. 4 – Location of stations and array used in the present study. The dots represent stations while each color represents an array.

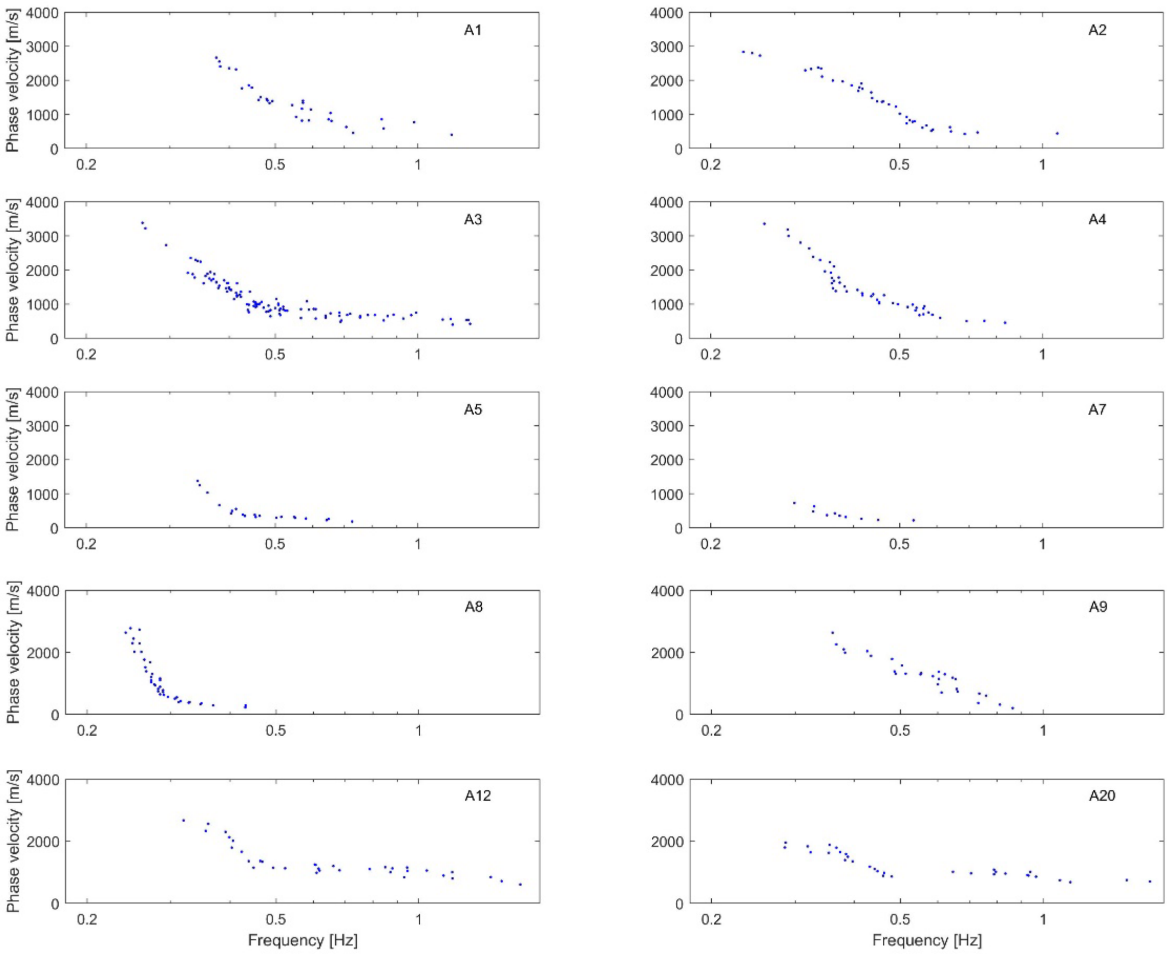

Fig. 5 – Phase dispersion curves obtained by MSPAC analysis for 10 arrays in Mexico City.

We can observe differences between the dispersion curves found. Arrays A5, A7 and A8 show low phase velocities. For the A8, this low-velocity plateau appears from 0.3 Hz, while in the A5 array it occurs from 0.4 Hz. In the A7 array, this plateau seems to start around 0.35 Hz, but it is difficult to know by the limited number of points. It should be remembered that this array only had 6 stations and these only have 10 hours of records. Systematically, arrays A1, A12 and A20 also have a plateau but with higher phase velocity values. Array A3 also has a plateau with intermediate values below those presented by Arrays A1 and A 12 but above those of Array A5. In general, these plateaus are consistent with the zones where each array is located. However, we can observe that before the plateaus the dispersion curves present different behaviors that range from vertiginous descents with large variations of the phase velocity as presented by the A8 array, or smooth and extended descents such as that presented by the A2 array, for instance.

4. Discussion of results

We make an approximate and very preliminary adjustment of three of these dispersion curves. The results of the curves adjusted with the models are shown in fig. 6. The three adjustments have been made with very simple and gross models, all of them consider only one layer in a half space. We consider the arrays A1, A4 and A7. The model for the two arrays A1 and A4, considered a layer of 545 m/s of S wave velocity with thicknesses of 385 and 420 m respectively. For the A7 array, a layer of 100 m/s with a thickness of 80 was used. In contrast to the high values used for the half space of the first two models, the value of the half space for the A7 array has a velocity of S wave of only 1100 m/s and the tendency of the dispersion curve in low frequencies is not well constrained. Although these models are very rough, they show us that the depth of the engineering bed rock considered in Mexico (Vs> 720 m / s) can be more than a few hundred meters. That justifies the need to characterize the stratigraphy up to a few hundred meters to reach that S wave velocity.

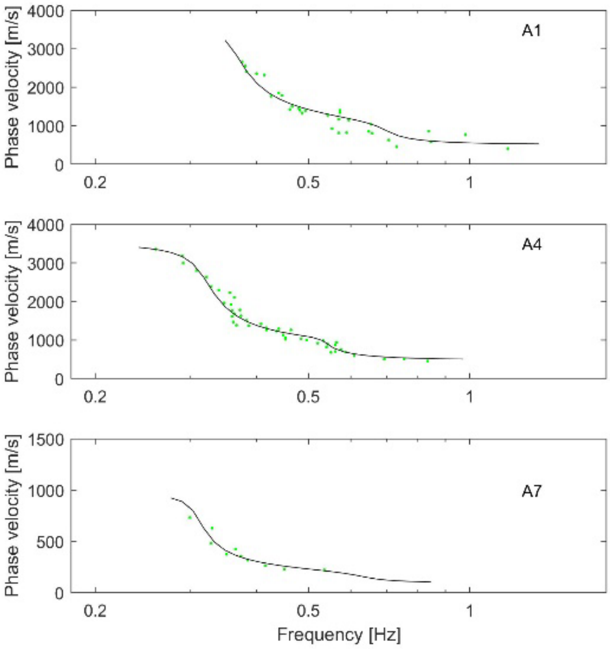

Fig. 6 – Adjustment of three phase velocity dispersion curves using preliminary and rough models for the arrays A1, A4 and A7.

In general, the velocidades shown by the curves appear to be within the range of speeds estimated by Chavez-García and Quintanar [18] for a period of 5 seconds.

The dispersion curve corresponding to array A20 is the only one obtained for zone I. This curve is compatible with the results reported by Flores-Estrella and Aguirre [7] and Kagawa[6] for the CU site located in the western part of array A20.

Although the dispersion curves found here are not sufficient to constrain the velocity model, they are useful for use in conjunction with other results to generate a more complete velocity model. In a previous study conducted to the east of Mexico City, Chavez-García and Aguirre [8] obtained dispersion curves for frequencies above 1 Hz with velocities of the surface layer that vary between 57 and 209 m/s using triangular arrays of up to 45 m. Arrays like that can be complemented with the results obtained here to constrain and complete the information of the superficial part. They are also useful for use as an initial model in determining dispersion curves based on other methods. For example, Hernandez-Hernandez [19] obtained good results using data from the A1 array and using the correlation of the radial components. In his work he also makes the joint invertion with the spectral ratios H/V. Vergara-Huerta and Aguirre [9] using smaller microtremor arrays obtained the velocity structure of a site close to A1 and A2 arrays, so that the model can be completed by combining both results.

5. Conclusions

In Mexico City, an extensive campaign of microtremor array recording has been carried out. This paper presents preliminary results of the analysis of these data.

The results of the average H/V analysis are exemplified for 15 stations with more than 60 hours of continuous recording. Some stations showed significant amplification, as was known, and a well-defined dominant frequency. In other stations they presented more than one peak and, on some occasions, the peaks had similar amplitudes.

From the MSPAC analysis, phase velocity dispersion curves were estimated for 10 arrays. In general, the dispersion curves obtained in this work are consistent with the geotechnical zones where each array was located. The curves in general coincide with the works published about the study sites. The gross and preliminary models used to adjust the dispersion curves suggest that the engineering bed rock may reach a few hundred meters in zone III.

These results along with the need to know quantitatively the subsoil of Mexico City are an incentive to continue this line of research.

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