SPAC: An alternative method to estimate earthquake site effects in Mexico City

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RESUMEN

Debido a la sencillez de su registro y a la facilidad relativa de su análisis, los microtremores se han convertido en una herramienta de gran utilidad para los estudios de microzonificación sísmica.

El método SPAC propuesto por Aki (1957) permite obtener información sobre la estratigrafía del sitio en estudio, a partir de registros de microtremores obtenidos con un arreglo instrumental. El efecto de sitio, caracterizado por el periodo dominante y la amplificación, se estima con la estratigrafía obtenida.

En este artículo se presentan las generalidades del método SPAC, su aplicación a registros de un arreglo instrumental en Ciudad Universitaria, México, y se realiza una comparación con los resultados obtenidos con el método de F-K por Kagawa (1996). La estructura de velocidades obtenida en este trabajo es consistente con la obtenida por Kagawa (1996). También se concluye que el método SPAC es más eficiente que el método F-K, pues requiere menor número de arreglos y menor número de estaciones por arreglo para obtener los mismos resultados.

También se presenta la función de transferencia del modelo de velocidades obtenido, y se compara con la función de transferencia del modelo de velocidades de Kagawa, y también con la obtenida con cocientes espectrales de datos de terremotos.

Este ejemplo muestra que a partir de registros de microtremores y el método SPAC es posible realizar una estimación confiable de la estructura de velocidades.

PALABRAS CLAVE: Microtremores, arreglo de microtremores, arreglo instrumental, estructura de velocidades, efecto de sitio.

ABSTRACT

Microtremor recordings are a very useful tool for microzonation studies because of simple data acquisition and analysis. The Spatial Autocorrelation Method (SPAC) proposed by Aki (1957), may be used to constrain the velocity structure underlying the site with microtremor array measurements, and the site effect (dominant period and amplification) can be calculated. In this paper the SPAC method is applied to Ciudad Universitaria, Mexico City. Results are compared with those obtained by Kagawa (1996) with the F-K method. The velocity structure inferred using SPAC method is consistent with Kagawa´s results.

We compare the transfer function obtained from the velocity model estimated by SPAC method with the transfer function from Kagawa´s velocity model, and from spectral ratios of earthquake data.

We conclude that the velocity structure of a site can be estimated from microtremor recordings by the SPAC method.

KEY WORDS: Microtremors, microtremor array, SPAC method, velocity structure, site effect.

INTRODUCTION

The use of environmental vibration recordings (microtremors) to produce microzonation maps is becoming very popular throughout the world. After the September 19, 1985 earthquake, the role of site effects in inducing damage in Mexico City has become evident.

Nakamura (1989) has proposed a practical and inexpensive procedure for estimating information about the fundamental frequency of a site using microtremor recordings. However, this method has generated some reservations by other authors (see Kudo, 1995).

Other methods using microtremor recordings are less popular because they are more expensive and more complicated both for observation and analysis. These methods are based on microtremor at several stations located at fixed distances, forming arrays.

In this work we briefly comment on the history of microtremor techniques. We describe the SPAC method and we apply it to an example in Mexico City. We also discuss possible applications in other cities, where subsoil conditions are different from those of Mexico City.

MICROTREMORS

Kanai *et al.* (1954) was the first to use microtremor recordings with the objective of studying site effects. However Kanai and his coauthors thought that the source of microtremors was white noise, and that they were mostly body waves. Bard (1998) showed that microtremors are about 70% surface waves At long periods, below 0.3 to 0.5 Hz, they are caused by oceanic waves at large distances. It is possible to find good correlation of microtremors in those periods with large scale meteorological conditions at sea. For intermediate periods, between 0.3-0.5 Hz and 1 Hz or less, microtremors are generated by waves near coast and their stability is significantly smaller than at long periods. For short periods, at frequencies larger than 1 Hz, microtremors are due to human activities. The microtremor spectrum will have several peaks related to different frequencies.

Traditionally, noise of natural origin at frequencies smaller than 1 Hz, is called microseisms. It is different from the noise caused by human activity called microtremors. In Mexico City, as in other larger urban areas, the boundary between these two types of noise is about 0.5 Hz. We consider microtremors to be produced by environmental vibrations caused by natural sources or by human activity.

In the early years most microtremor observations and investigations were carried out in Japan. It was not until the eighties when microtremors were used in other countries, such as United States, Mexico, Chile and China.

Over the last decade at least two-thirds of the papers on microtremors in these countries used the H/V method, or Nakamura method (Nakamura, 1989). This technique assumes that the spectral ratio of horizontal to vertical components, called quasi-transfer spectrum (QTE) yields an estimation of site effects. Nakamura reformulated his original method by making slight modifications (Nakamura, 1996). While his semi-qualitative theoretical explanation remains questionable to many scientists, the method has been widely used in practical applications. It has been found that this method is successful in finding the fundamental frequency though the amplitudes often show significant inconsistencies (Bard, 1998).

Prior to Nakamura's work, Nogoshi and Igarashi (1971) had proposed a similar method relating the H/V ratio with a measure of the ellipticity of Rayleigh waves as an indicator of the fundamental resonance frequency of a structure. The method proposed by Nogoshi and Igarashi is more accurate, but Nakamura's procedure is attractive by its simplicity.

Assuming that microtremors contain surface waves, Aki (1957) proposed the Spatial Autocorrelation Method (SPAC). This method began to be used in the last decade. A similar method is the F-K method (Horike, 1985). Both methods require microtremor measurements at several stations, at least seven for F-K and four for SPAC, located at fixed distances, accordingly with the research characteristics, forming an array. These methods can estimate the velocity structure from dispersion curves of Rayleigh waves, but do not determine the fundamental frequency directly, which can be obtained by Haskell-Thomson method.

Microtremor arrays have rarely been used in Mexico. In one case a Japanese team jointly with Mexican researchers from CENAPRED and from Instituto de Ingeniería of the National University of Mexico (UNAM), applied the F-K method to data obtained in arrays at three sites of Mexico City: Presa Madín, Central de Abasto and Ciudad Universitaria (CU). The results obtained in the present paper will be compared with those obtained in 1991 for CU in the latter study.

SPAC

The purpose of the SPAC method is to obtain a velocity structure from microtremor recordings. It is necessary to simultaneously record microtremors at several stations to conform an instrumental array. The method requires at least three stations. Following the process described below, the dispersion curve for the Rayleigh waves is obtained and used to determine the velocity structure.

Aki (1957) considered a circular array of stations for microtremor observation. Let us represent harmonic waves of frequency ω of microtremors by the velocity wave forms $u(0,0,\omega,t)$ and $u(r,\theta,\omega,t)$, observed at the center of the array $C(0,0)$ and at point $X(r,\theta)$ of the array. The spatial autocorrelation function is defined as

$$\phi(r,\theta,\omega) = \overline{u(0,0,\omega,t)\cdot u(r,\theta,\omega,t)}, \tag{1}$$

where $\overline{u(t)}$ is the average velocity of the wave form in the time domain. The spatial autocorrelation coefficient ρ is defined as the average of the autocorrelation function ϕ in all directions over the circular array:

$$\rho(r,\omega) = \frac{1}{2\pi\cdot\phi(0,\omega)}\int_0^{2\pi}\phi(r,\theta,\omega)d\theta, \tag{2}$$

where $\phi(0,w)$ is the SPAC function at the center $C(0,0)$ of the circular array. By integration of equation (2) we find

$$\rho(r,\omega) = J_0\left(\frac{\omega r}{c(\omega)}\right), \tag{3}$$

where $J_0(x)$ is the zero-order Bessel function of first kind of x and $c(\omega)$ is the phase velocity at frequency ω. The SPAC coefficient $\rho(r,\omega)$ may be obtained in the frequency domain using the Fourier Transform of the observed microtremors:

$$\rho(r,\omega)=\frac{1}{2\pi}\int_0^{2\pi}\frac{Re\left[S_{CX}(\omega,r,\theta)\right]}{\sqrt{S_C(\omega)\cdot S_X(\omega,r,\theta)}}d\theta, \qquad (4)$$

where $S_C(\omega)$ and $S_X(\omega; r,\theta)$ are the power spectral densities of microtremors at sites C and X respectively, and $S_{CX}(\omega, r,\theta)$ is the cross spectrum between ground motions at these two sites. Thus the SPAC coefficients may be obtained from averaging normalized coherence function defined as the co-spectrum between points C and X in the direction θ. From the SPAC coefficients $\rho(r,\omega)$, the phase velocity is obtained for every frequency from the Bessel function argument of equation (3), and the velocity model can be inverted.

AN APPLICATION IN MEXICO CITY

Microtremor array measurements were carried out in several sites of Mexico City. Here we present the results for the university campus (CU), and we compare them with the results obtained by Kagawa (1996) from the F-K analysis of records obtained during the campaign of 1991.

The CU array consisted of four REFTEK instruments with Guralp broadband sensors. Three instruments were deployed in the vertices of an equilateral triangle with 1 Km sides and the fourth instrument was plced at the center of the triangle. The records are 40 minutes long with 100 samples per second. Figure 1 shows the location of the array in CU. Figure 2 shows all the elements that compose a station. Figure 3 displays a sample of measured microtremors at the four stations. The records are adjusted to the same reference time, using the GPS initial time for each station. Six windows were selected for stationarity, and their power spectral densities were calculated (Figure 4). Using equation (4), the autocorrelation coefficients were calculated for the internal array comprising the central station and each station at the vertices of the triangle; and the external array comprising the three stations at the vertices of the triangle. The autocorrelation coefficients for the external array are more stable (Figure 5). Using equation (3) we obtain the dispersion curves for the internal array and the external array including the uncertainty associated to the dispersion of the coefficients in each direction. Figure 6 shows the dispersion curves obtained from the autocorrelation coefficients of Figure 5. Straight lines define the reliability range according to Miyakoshi (1995). Using the dispersion curve within the interval of confidence the stratigraphy was obtained as shown in Figure 7 (see Table 1). The dispersion curve for this stratigraphic model is shown as a solid line in Figure 6. Notice the well-constrained density of data points.

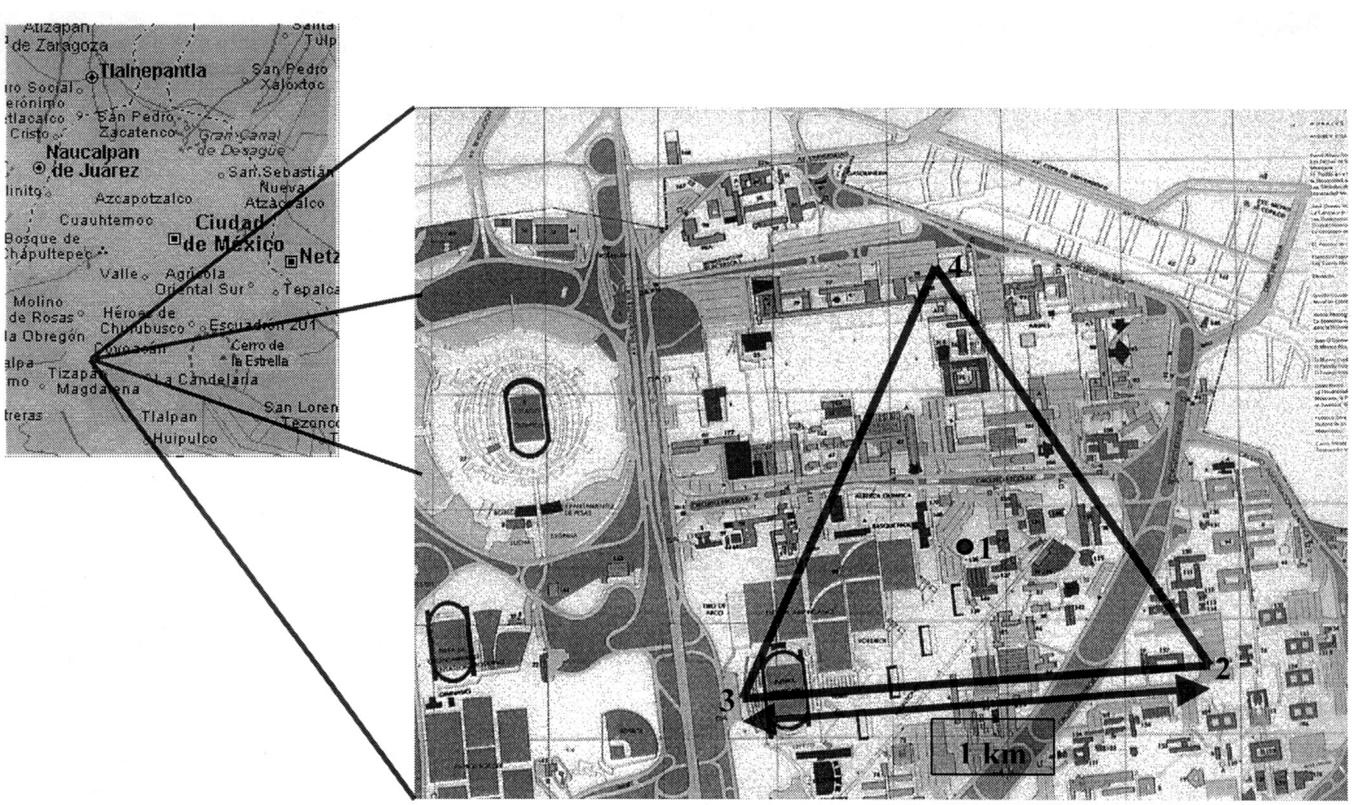

Fig. 1. CU array location.

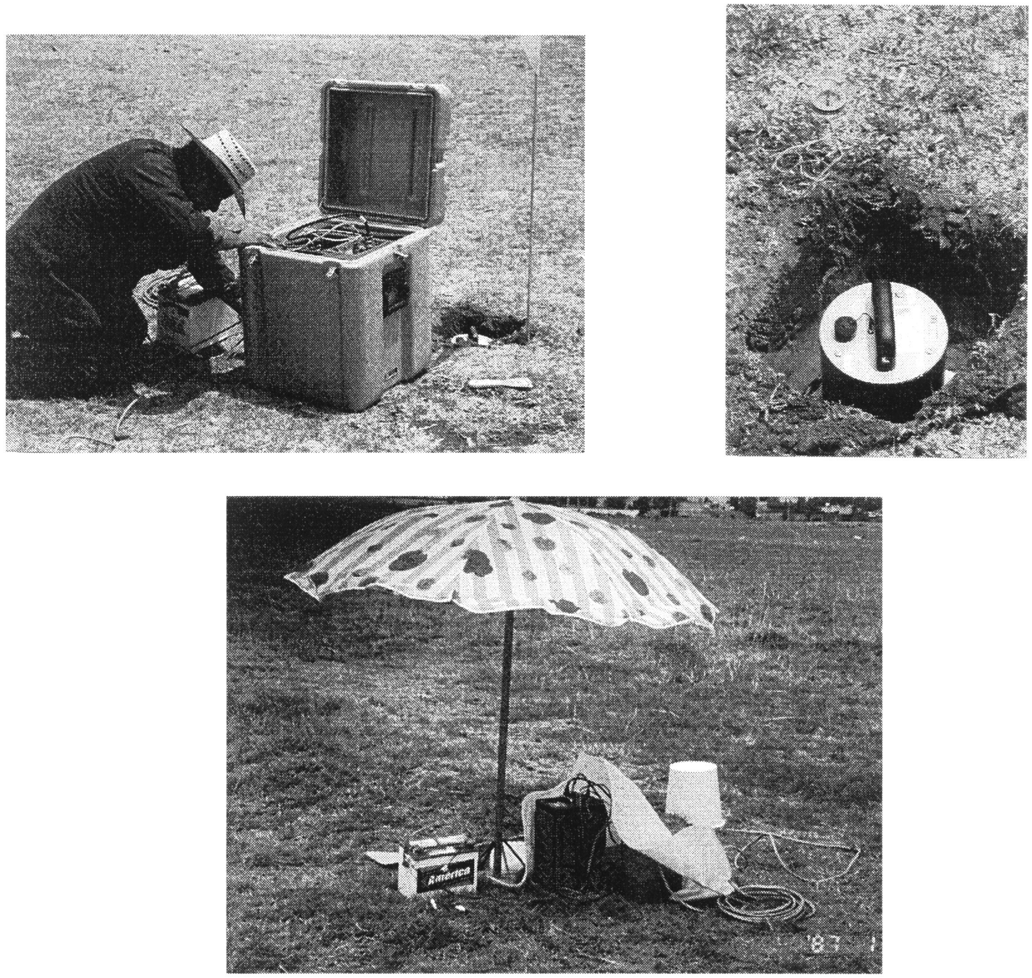

Fig. 2. Used equipment. Digitalizer and recording equipment REFTEK, GURALP sensor and a view of a station.

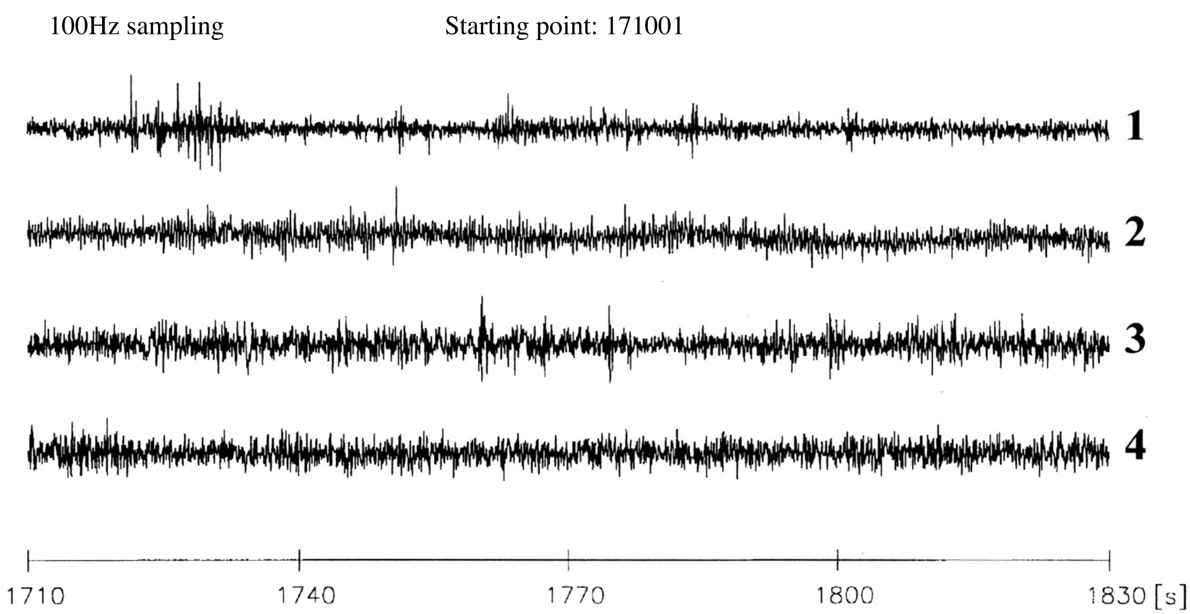

Fig. 3. Example of microtremor recording from CU array. The numbers correspond to the stations from one to four, from top to bottom respectively.

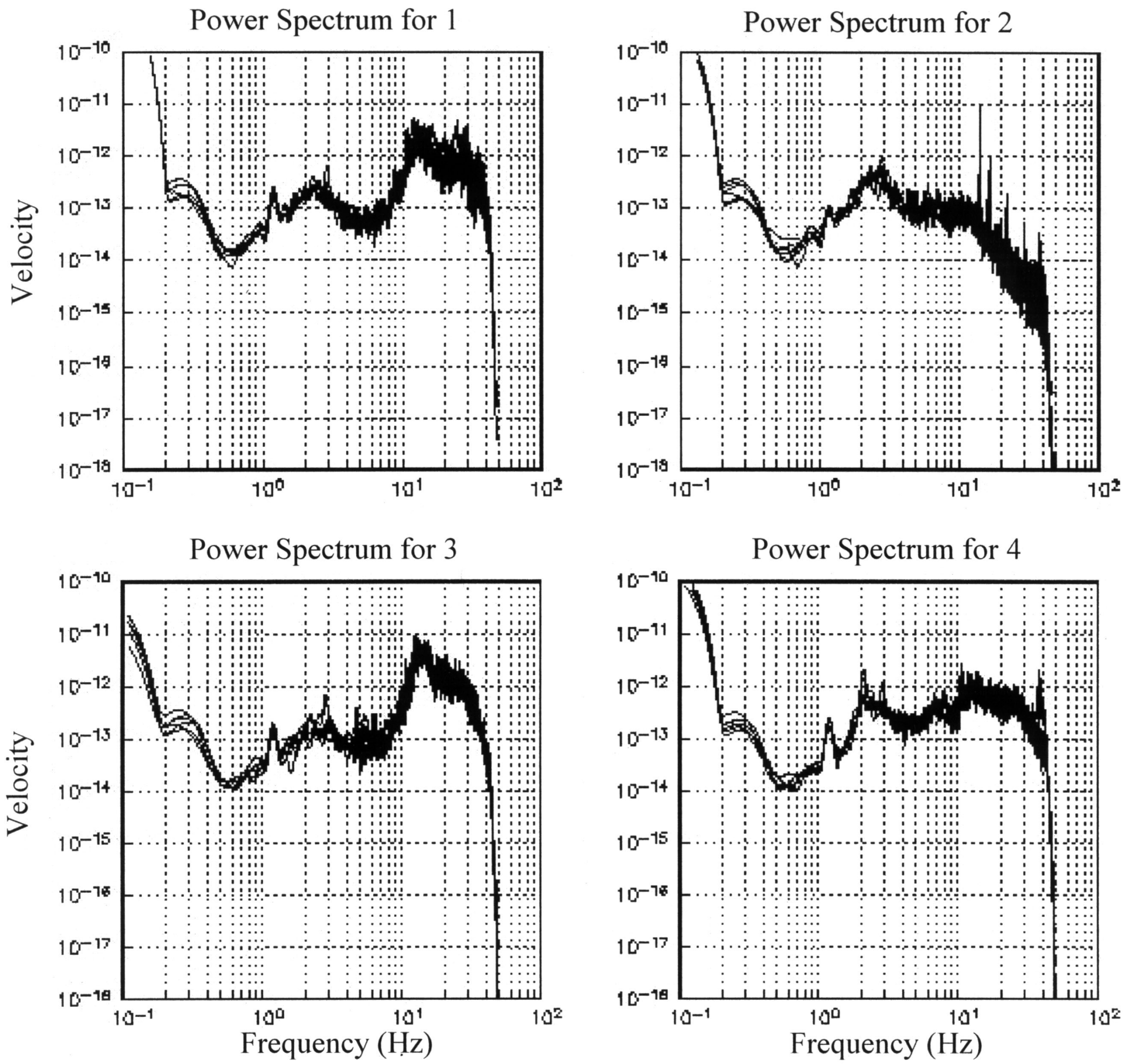

Fig. 4. Power spectrum for 6 windows for each station.

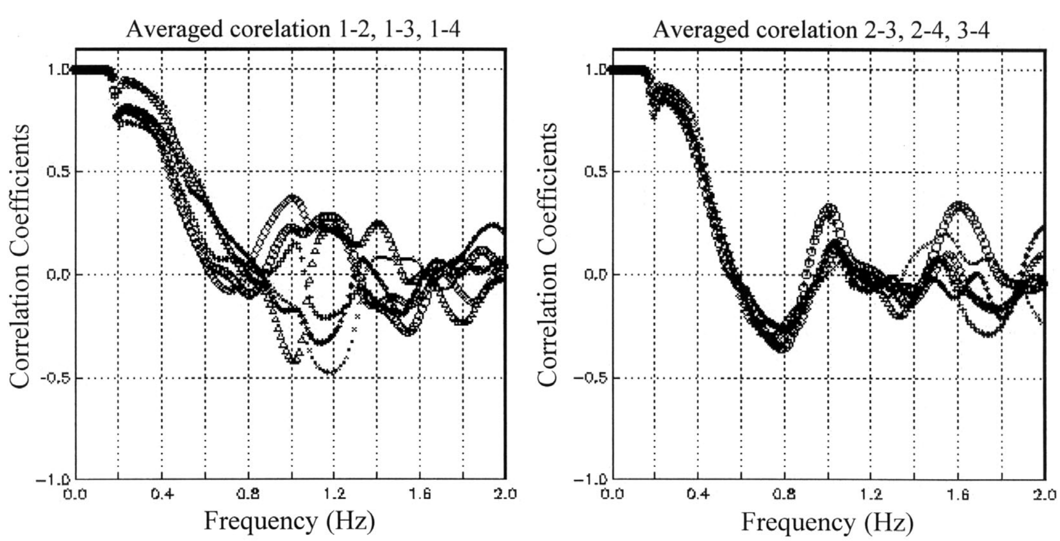

Fig. 5. Averaged Correlation Coefficient for internal stations (left) and for external stations (right).

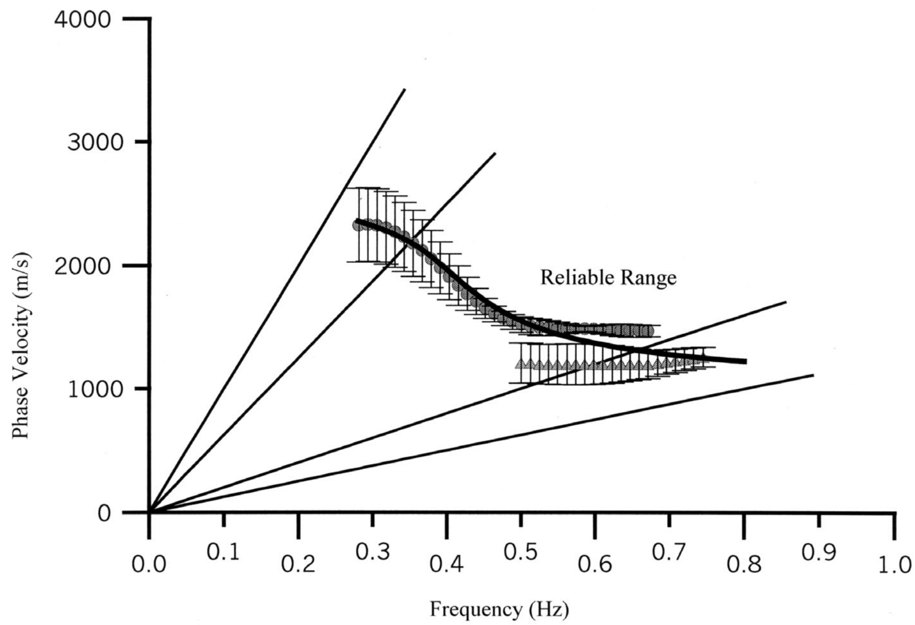

Fig. 6. Dispersion curves obtained from the correlation coefficients of external (circles) and internal (triangles) average. The right lines indicate the reliable range from Miyakoshi (1995) that depends on the maximum and minimum distance between stations. The continues line is the inverted velocity model.

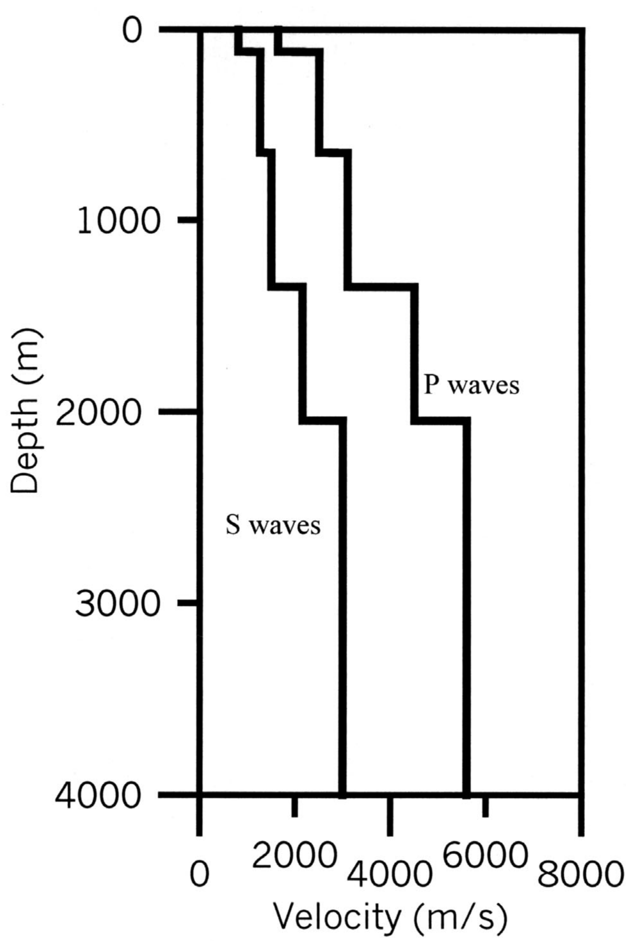

Fig. 7. Velocity model inverted from the dispersion curve of Fig. 6.

Let us compare the dispersion curve obtained with this method with the one obtained by Kagawa (1996) using the F-K method. In Figure 9 the stratigraphic models are compared for P and S waves. Solid lines refer to the SPAC method, and dashed lines show the model obtained by Kagawa. The difference is basically the thickness of the layers. We are not confident of the information from the array at frequencies larger than 0.8 Hz. A smaller array would allow us to achieve a better definition of shallower layers. For the same range of frequencies obtained with a single SPAC array, it was necessary to use three arrays in the F-K method. The transfer function for each model was calculated by the Haskell-Thompson method. The results are shown in Table 2 for SPAC results, and Table 3 for the F-K method. QS values are as obtained by Singh *et al.* (1995) and QP values were obtained from the relationship (Lay and Wallace, 1995):

$$Q_P = \frac{9}{4} Q_S \, .$$

This assumes that Qp is more than twice Qs. These two transfer functions are compared with the empirical transfer function based on the spectral ratio between CU and Estanzuela stations for the Tehuacan earthquake (June 15, 1999) as calculated by Montalvo *et al.* (2002).

The solid line in Figure 10 shows the transfer function for the SPAC method, while the dotted line shows the transfer function for the Kagawa model (F-K method). A dashed

Table 1

Inverted model from the dispersion curve of Figure 6. This values are also plotted in Figure 7

Thickness (m)	Density (t/m^3)	P wave velocity (m/s)	S wave velocity (m/s)
116	2.0	1630	804
530	2.0	2500	1263
700	2.2	3100	1500
700	2.2	4500	2153
∞	2.5	5600	3000

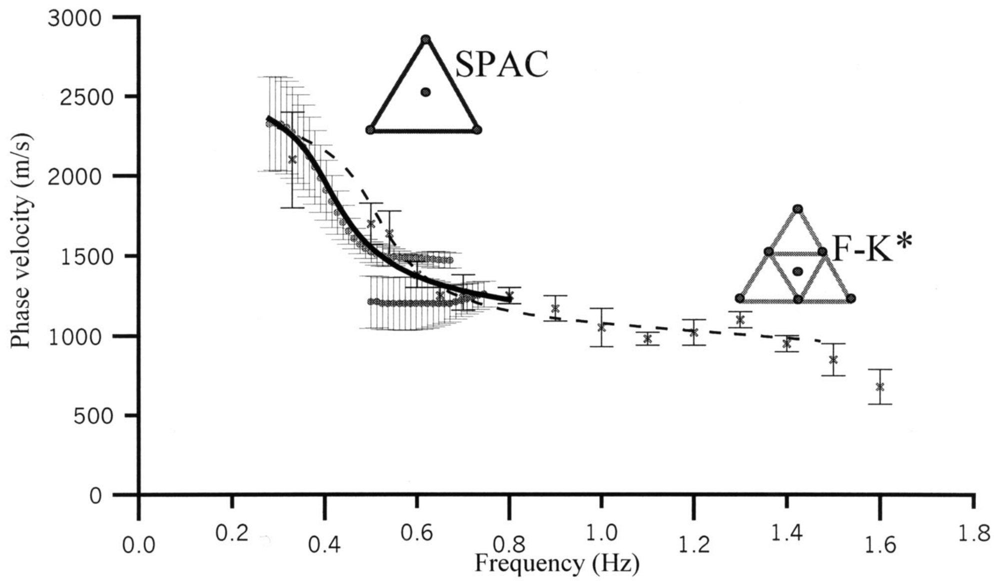

Fig. 8. Comparison between the results obtained in this study (continuous line and points) and those obtained by Kagawa *et al.* (1996) using the F-K method (dashed line).

line shows the empirical transfer function by Montalvo *et al.* (2002). The transfer function for Kagawa´s model leads to very high amplifications relative to the hill zone. It appears out of range for this kind of geotechnical zone. However, the empirical transfer function by Montalvo *et al.* (2002) compares well with the SPAC model, particularly for frequencies 1.25, 1.75, 2.25 and 3.2 Hz. The amplitude differences can be explained by the fact that the transfer function by Montalvo *et al.* (2002) does not consider local characteristics of CU. These authors found a clear site effect at CU for frequencies between 1 to 4 Hz; this effect is also found in the transfer function of the SPAC model.

CONCLUSIONS

It appears that the SPAC method is more efficient and more economic than the F-K method, as it requires at most four stations. It produces a larger density of samples per frequency interval, for a better adjustment of the dispersion curve. For a given interval of frequencies the SPAC method requires fewer instrumental arrays than the F-K method.

Transfer functions calculated for the SPAC model were compared with the empirical transfer function calculated by Montalvo *et al.* (2002). We conclude that the SPAC method is useful to estimate a structure that yields information about the amplification interval from microtremors recordings. Note that the computed amplifications are very similar to those calculated from spectral ratios of earthquake recordings.

A smaller array is required for the shallow velocity structure. Also, the possible relation between distance among stations and the quality of the correlation coefficients needs further study.

Table 2

Structure model obtained with SPAC method

Thickness (m)	Density (t/m3)	P wave velocity (m/s)	S wave velocity (m/s)	QP	QS
116	2.0	1630	804	562	250
530	2.0	2500	1263	562	250
700	2.2	3100	1500	562	250
700	2.2	4500	2153	675	300
∞	2.5	5600	3000	5000	5000

Table 3

Structure model obtained by Kagawa *et al*. (1996) using F-K method

Thickness (m)	Density (t/m3)	P wave velocity (m/s)	S wave velocity (m/s)	QP	QS
15	1.8	1500	205	562	250
10	1.8	900	402	562	250
9	1.9	1250	506	562	250
10	1.9	1500	714	675	300
10	1.9	1400	432	675	300
116	2.0	1630	804	675	300
330	2.0	2500	1263	675	300
500	2.2	2900	1294	675	300
600	2.5	4500	2153	675	300
∞	2.5	5600	2841	5000	5000

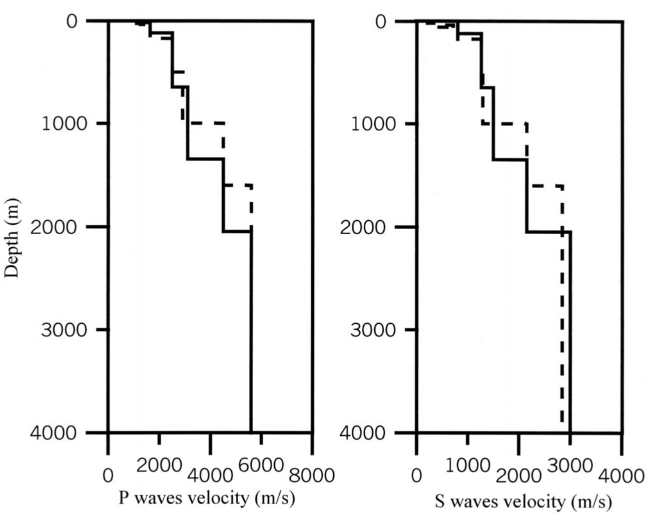

Fig. 9. Comparison between the velocity structure for P and S wave propagation obtained in this study (continuous line) and the one obtained by Kagawa *et al*. (1996) (dashed line).

The SPAC method requires a good time control, and simultaneous recordings at least for two instruments. This may be a disadvantage in comparison with Nakamura's technique, which uses recordings from a single instrument and does not require a common time base. However, the information obtained with the SPAC method is more complete than that obtained by Nakamura's method.

In conclusion SPAC may be a valuable alternative method to estimate site effects in Mexico City. It is worth testing in other lake zone sites where a more complicated velocity structure exists, and where the amplification of the ground motions is larger.

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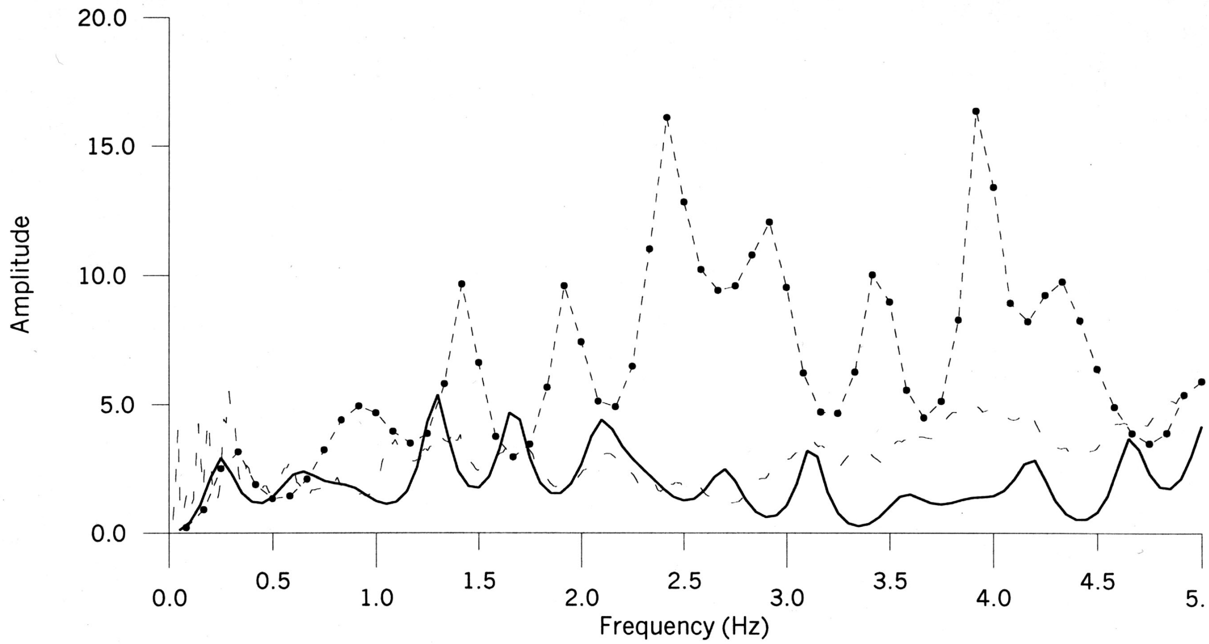

Fig. 10. Comparison between transfer functions for the model obtained in this work with SPAC method (continuous line); for the model by Kagawa *et al.* (1996) using F-K method; and empirical transfer function obtained by Montalvo *et al.* (2002) using spectral ratios for the Tehuacan earthquake (June 15, 1999).

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