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DEFINITION OF S-WAVE VELOCITY STRUCTURE USING MICROTREMORS AND SPAC METHOD APPLIED IN CHILPANCINGO, GUERRERO, MEXICO

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ABSTRACT

The geological structure of the deep sedimentary deposits in the valley of Chilpancingo and the variation of the shear wave velocity with depth were determined. Simultaneous measurements of microtremors from arrangements of seismometers were taken in two sites in Chilpancingo, the capital of the State of Guerrero, Mexico. The Spatial Autocorrelation Method, SPAC, was used to determine the dispersion curves of the phase velocity of the surface waves in the frequency range from 0.3 to 8.0 Hz. The determination of V_s profiles reached a depth of 350 m. In addition site effects using the spectral ratio technique in sedimentary soil/rock as well as the H/V spectral ratio were estimated using earthquake recorded data. The defined subsoil structure offered the possibility for its correlation with estimated site effects, in terms of transfer functions. In order to associate the empirical transfer functions with the geologic structure, the 1D estimates were computed. The results indicate a suitable correlation between the site response and soil model.

Introduction

The subsoil structure of the valley of Chilpancingo has been of great interest because a significant amplification of the ground has been observed during earthquakes. Duke and Leeds (1959), observed that the nature of the geological structure of the valley of Chilpancingo, which consist of deep deposits of sediments with low rigidity, was the cause of the severe damages suffered by the structures in the earthquake of the 28th of July 1957. After analyzing the records of accelerograms of intensive earthquakes from 1981 till date, Gomez Bernal *et al*. (1999), identified high amplifications in a band of long periods between 1 and 3 s. At the moment, there is no model of the subsoil at such depths that can suitably define the site effects in the valley.

In order to accurately estimate the site effects it is important to determine the geological structure of the subsoil, that is, the variation of the shear wave velocity with depth. In valleys where the thicknesses of sediments extend to great depths, as is the case of the city of

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Chilpancingo, it is necessary to know with greater details the deep deposit characteristics, due to the amplification of seismic waves of high periods (between 1 and 3 s). There are several methods to this end, generally, when using any of them, it is possible to perform the inversion of the phase velocities of the waves Rayleigh and then the velocity profile of shear waves is obtained. One technique that can be applied with much speed and ease is the one that uses the vertical components of the recorded microtremors simultaneously by an array of seismographs.

There are several methods that use simultaneous observations of microtremores; for example, Nakamura (1989) used the spectral relation Horizontal-Vertical (HVSR) to determine the dominant periods; other researchers have used a technique based on the inversion of the relation H/V which helps to estimate the variation of the shear wave velocity (Arai and Tokimatsu, 2004). Although this procedure has been questioned due to its lack of theoretical framework (Horike et al., 2001), nevertheless at present its application has extended to every parts, and it is use as a very versatile tool to determine the site characteristics in the seismographic station (e.g. Lozano et al., 2009).

The works of Aki (1957), have demonstrated that the techniques based on measurements of arrays of microtremors are reliable in establishing the subsoil profiles. The conventional SPAC method, which needs at least 4 stations, is based on the theory of stationary random functions, in such a way that microtremors are considered stationary within a given time and space. Aki (1957) established the theoretical framework to estimate the phase velocities from SPAC method, and he demonstrated theoretically that an autocorrelation space function between two stations is a Bessel function of first type and order zero, in terms of the wave number, assuming a random distribution of the direction of propagation with a constant velocity. Then, it is possible to obtain a dispersion curve of surface waves from microtremor array data.

Currently exists some knowledge about the characteristics of the subsoil of Chilpancingo, thanks to some geological sections which were defined in past decades. There are also some very superficial down-hole data, but the deeper only achieves 52 meters. With the aim of having additional information and be able to build a detailed stratigraphic model, in this work environmental noise field measurements was recorded. Data registered with triangular arrangements in two sites were analyzed with the SPAC method to set the rate of shear wave velocity, Vs, with depth. In addition, the site effects in the Valley of Chilpancingo were estimated using a subsoil model defined here, and then compared with amplifications calculated from strong ground motion records of earthquakes.

Array Observation of Microtremors

Aki (1957) established the theoretical basis of the spatial autocorrelation coefficient (SPAC) defined for microtremors and developed a method to estimate the phase velocity dispersion of surface waves contained in microtremors using a specially designed circular array. This SPAC method has been employed throughout the present study. In the method SPAC it is possible get direct results through trial and error process when comparing the curve of synthetic dispersion against the observed values, and then the final curve is set when there is convergence or when the differences are minimal.

Geologic setting

According with a geophysical exploration (Geoservicios, 1988), Chilpancingo city is located in a basin where the depth to the bedrock is supposed to be about 300 to 500 m. The sediments consist mainly of three layers (Fig. 1), a first layer formed of old and recent alluvial deposits (Qc) with thickness of 70 m; next the Chilpancingo group (Tpc) with a thickness about of 200 m; and finally the Balsas group (Teob) with a thickness about of 100 m, deposited in the Morelos group (Kim), which consists of limestone deposits.

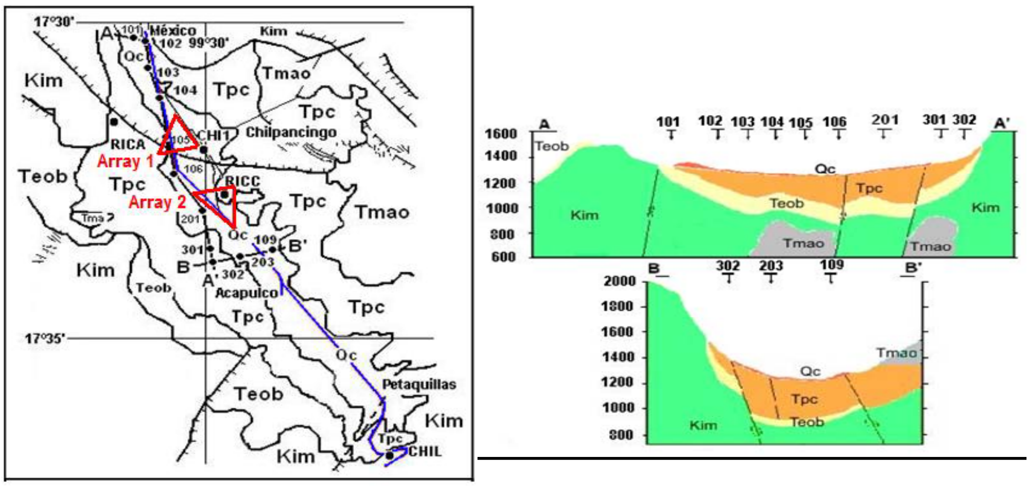


Figure 1. Geologic map and cross sections of the subsoil of Chilpancingo valley. The map shows locations of the observation sites, which are situated in the urban area.

Noise Measurement

Array measurements of microtremors were carried out at two sites within the city of Chilpancingo. These two sites were selected where it is expected that the unconsolidated sedimentary subsoil thicknesses are majors. The location and orientation of the stations are shown in Figures 1 and 2. The first array was located in the Institute of Juventud (Array 1), and the second in the University of Guerrero (Array 2). The stations were installed in such a way that one station was fixed in one of the vertices, while the another two were moved in order to cover each one of the vertices with five different equilateral triangle shapes of 10, 20, 40, 60 and 75 m. Whereas in the equilateral triangle shapes of 500 and of 1000 m, three fixed stations were used. Plural arrays were deployed by changing their sizes at different times, to cover wide wavelength or phase velocity changes as a function of frequency. This procedure was performed both for Array 1 and for Array 2.

We took records over 30 minutes in stations with triangle shapes until 500 m; but in stations with triangles of 1000 m were recorded about 10 hours. The measurements were recorded at 100 samples per second in both arrays. In station from array 1 with triangle shape of 75 m of side, and in station from array 2 of 95 m, vertical sensors with velocity of 5 seconds of period were used, and placed in the center, a 3D accelerometer K2 Kinemetrics. In the 500 m and 1000 m triangles, broadband velocity sensors Guralp of 30 s of period were used, and connected to data acquisition system K2 Kinemetrics (3D accelerometer).

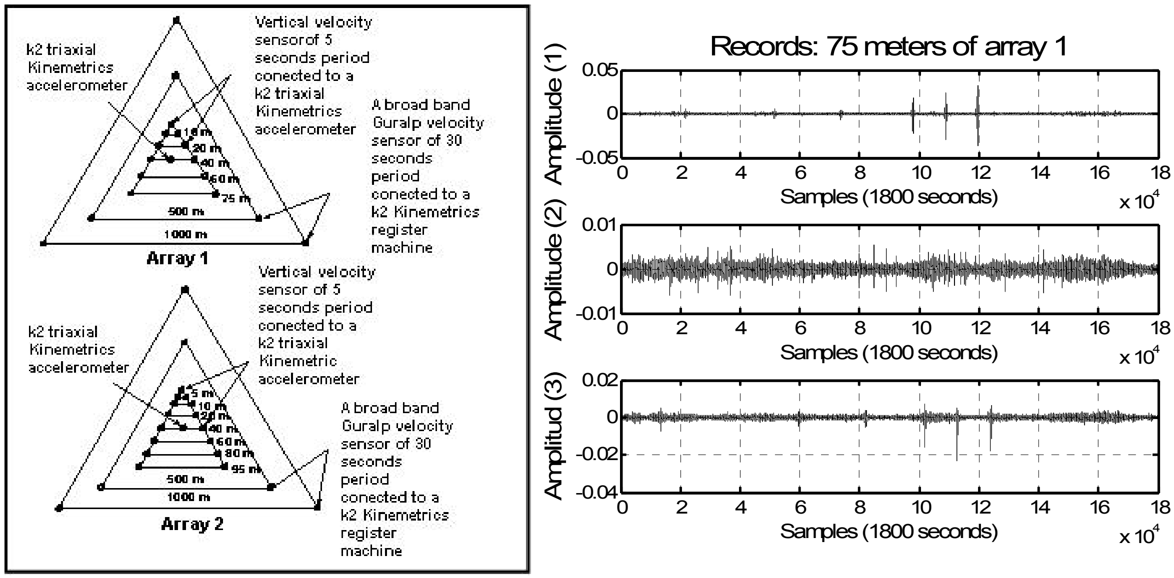


Figure 2. Geometry of triangular arrays in stations for microtremors detection in the SPAC method. And, one example of microtremor recording in station AR1-75.

Analysis and Results

We use only the vertical motion of microtremors to extract Rayleigh waves. Figure 2 shows an example of the time histories of microtremors that were simultaneously recorded at station AR175. The three traces correspond with three triangle vertices.

Figure 3 shows one example of the power spectra of simultaneous measurements in three vertices for two triangle shapes. Power spectra correspond to 21 windows taken from records with duration of 30 minutes in each station. A good agreement is observed both in form and amplitude when the curves are compared between 0.35 Hz and 10 Hz in the triangle of 75 m of Array 1; while in triangle of 95 m of Array 2 is observed good correlation between 0.1 and 7 Hz.

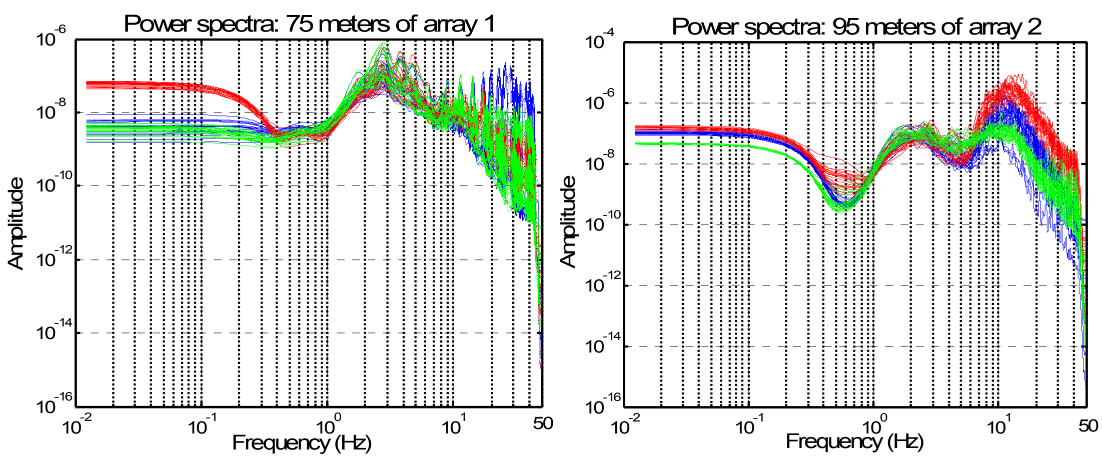


Figure 3. Power spectra for triangle of 75 meters of array 1 (AR1-75), and for triangle of 95 meters of array 2 (AR2-90).

Correlations between the three stations of each triangle are obtained. In Figure 4 are shown the correlations of triangle AR1-75 and those of the triangle AR2-95 in the 21 windows of 81.92 seconds of recorded simultaneous measurements. It is interesting to emphasize that the form of the observed correlation functions are resemble to the Bessel functions of first species and order zero, which is adequate and advisable in order to have more reliable results. In each triangle, a very good correlation among their three stations is observed.

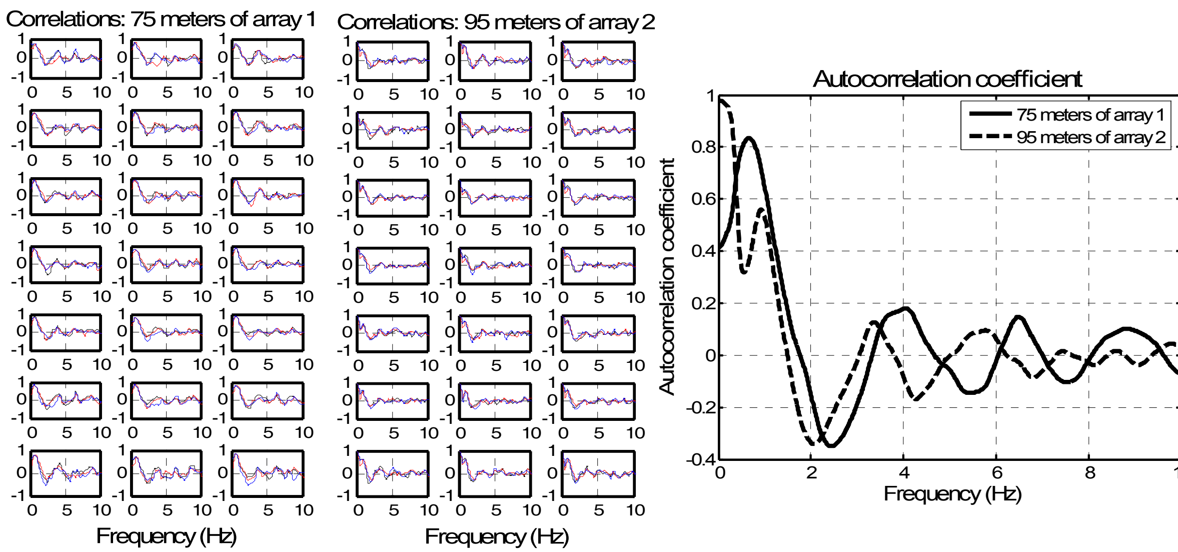


Figure 4. ***Left:*** Calculated correlations for triangles AR1-75 and AR2-95 in 21 windows with 81.92 sec of simultaneous recorded measurements. ***Right***: Autocorrelation Coefficients for triangles AR1-75 and AR2-95 in SPAC method.

The average of the correlations of 21 windows of each triangle leads to the autocorrelation coefficient of each one of the triangles. In Figure 4 (Right) these coefficients for each one of the two mentioned triangles appear. As can be observed in each, the first crossing by zero appears approximately in 1.75 Hz and in 1.50 Hz. These frequencies are those of interest in each triangle.

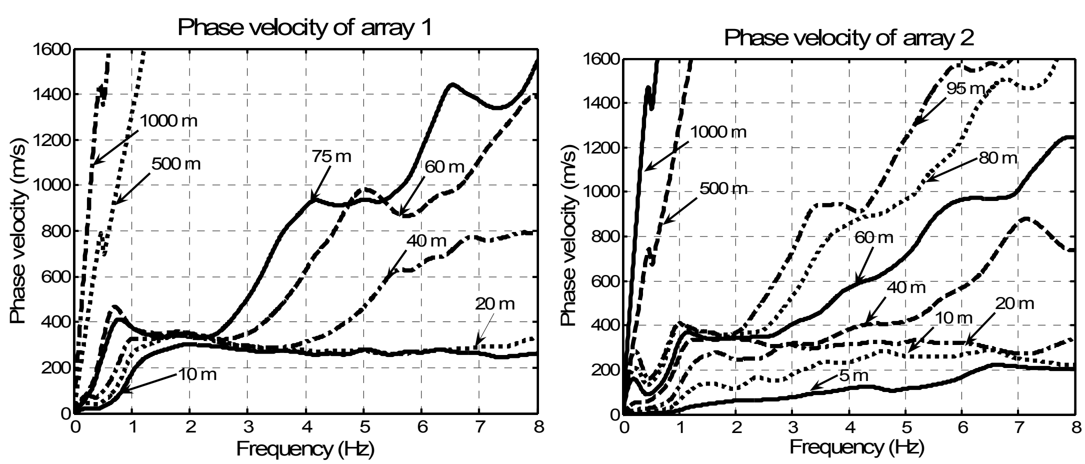


Figure 5. Phase velocity of Rayleigh waves observed in all triangles from arrays 1 and 2.

Measured or observed dispersion curves are obtained from observed phase velocities of Rayleigh waves of each array (Fig. 5). In each case, it is possible identifying a frequencies range close to the zero cross over frequency in the autocorrelation coefficient graphic. Subsequently theoretical dispersion curve of an assumed subsoil model is obtained, and that curve is compared with the observed. When do not match both curves, must prove other models until to achieve the convergence. Figure 6 shows observed and theoretical dispersion curves, for the array 1 (left) and array 2 (right). They were three curves for each triangle, which represent the average and their corresponding standard deviation. It is possible to observe the typical trend of Rayleigh waves speed dispersion curves: decreasing when the frequency grows.

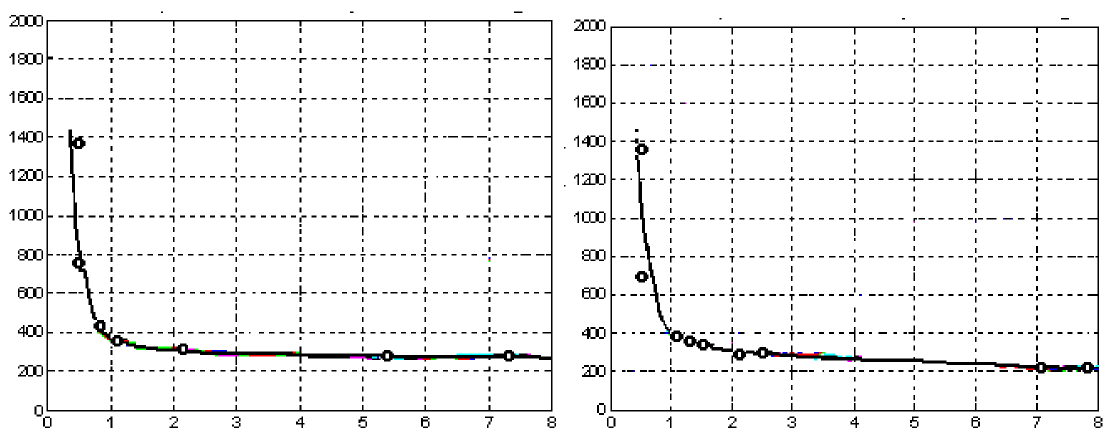


Figure 6. Dispersion of phase velocities obtained with SPAC. Observed velocities are shown with each symbol for each array size. Theoretical values for fundamental mode of Rayleigh waves are calculated for models shown in Table 1.

Table 1. Structure models at array sites.

Model M1. Array 1				Model M2. Array 2			
Thickness (m)	p (t/m^3)	V_s (m/s)	V_p (m/s)	Thickness (m)	P (t/m^3)	V_s (m/s)	V_p (m/s)
10.0	1.20	248.0	427.0	11.0	1.20	195.0	330.0
65.0	1.40	325.0	560.0	35.0	1.40	325.0	500.0
70.0	1.60	375.0	645.0	53.0	1.60	385.0	600.0
110.0	1.80	450.0	774.0	90.0	1.80	410.0	700.0
100.0	1.90	750.0	1100.0	125.0	1.90	715.0	1200.0
30.0	2.10	1440.0	2400.0	20.0	2.10	1410.0	2200.0
∞	2.30	2000.0	3400.0	∞	2.30	2200.0	3400.0

Final inverted Vs profiles are presented in Table 1 and Figure 7. The velocity structures at observation sites of microseisms were inferred from the dispersion of phase velocities. In array 1, information about subsoil was defined until a depth of 385 meters, where a smooth variation of shear wave velocities is observed until the fourth layer, but in the two deeper sublayers the resistance is stronger. Whereas for array 2, stratigraphic model was defined until a depth of 334 meters, displaying a tendency very similar with the first array.

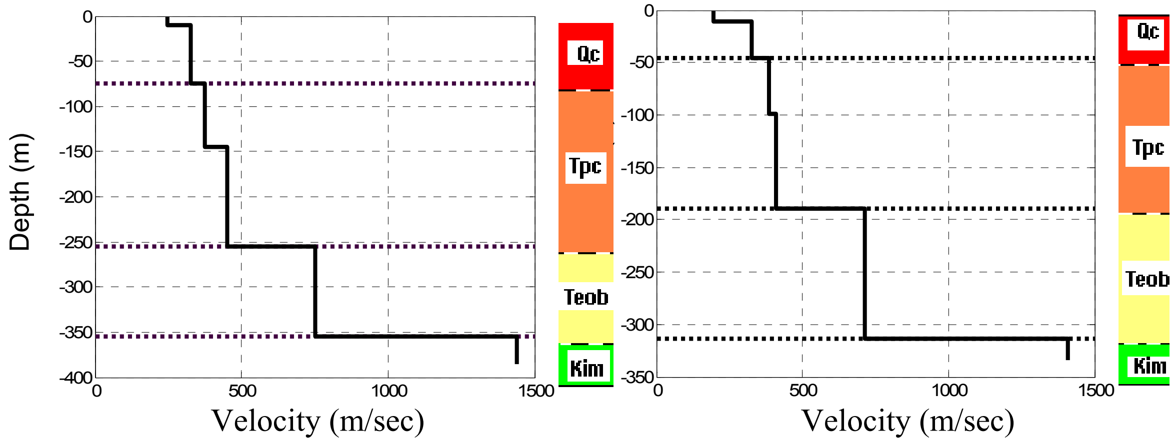


Figure 7. Shear wave velocity model, Vs, inferred from the SPAC method at two sites.

Preliminary estimation of site effects in Chilpancingo

The determination of the site effects using earthquake data was carried out by applying the sediment-to-bedrock spectral ratios (SR). In addition to that, the horizontal to vertical spectral ratio (HVSR) was used in order to compare the spectral peaks. We select the nine earthquakes with the larger intensities observed in Chilpancingo, such that accelerograms in rock at station CHIL, and in soil at station RICC were registered simultaneously. These events have moment magnitude between 5.9 and 7.5. All earthquake records were corrected by zero base-line.

The Fourier amplitude spectrum was calculated for three components, north-south (NS), east-west (EW) and vertical (VR). Following the work of Huang (1983), and after smoothing, we calculated the resultant or vectorial summation of the horizontal components (unique component, UC), which can be defined as:

$$|F_{UC}(f)| = \sqrt{(|F_x(f)|^2 + |F_y(f)|^2)/2} \qquad (1)$$

F_{UC}, represents the spectra of amplitude of Fourier in all the horizontal directions. Of course this average is not the arithmetic average of |Fx (f)| and |Fy (f)|.

The site effect of a sediment site station can be estimated by dividing its spectrum by that of the rock site, as far as both stations have recorded the same earthquake. Spectral ratios or transfer functions (TF) were calculated for the three components, north-south (TF-OBS-NS), east-west (TF-OBS-EW), and vertical (TF-OBS-VR). In order to get the maximum horizontal amplitude relation, which is independent of the instrument's orientation, the spectral ratio was calculated for the unique component UC. This transfer function (TF-OBS-UR) can be defined as:

$$TF - UR(f) = \frac{|F_{UC}(f)|_{RICC}}{|F_{UC}(f)|_{CHIL}} \qquad (2)$$

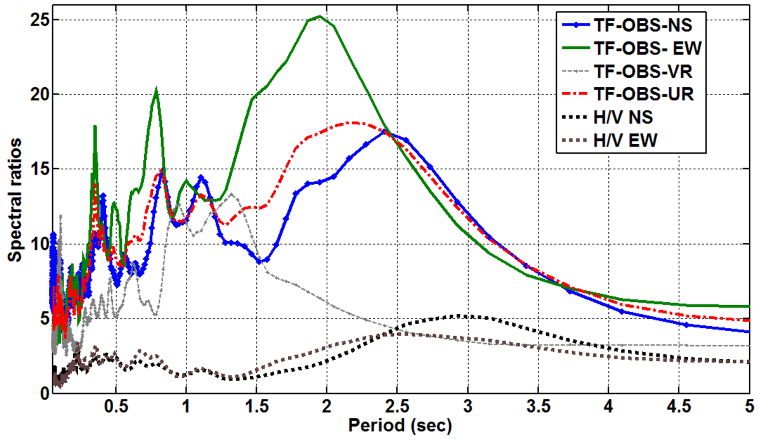


Figure 8. Average of soil/rock spectral ratios obtained from recorded data of nine intense earthquakes ($5.9<M_w<7.5$). Nakamura's spectral ratios in station RICC are included.

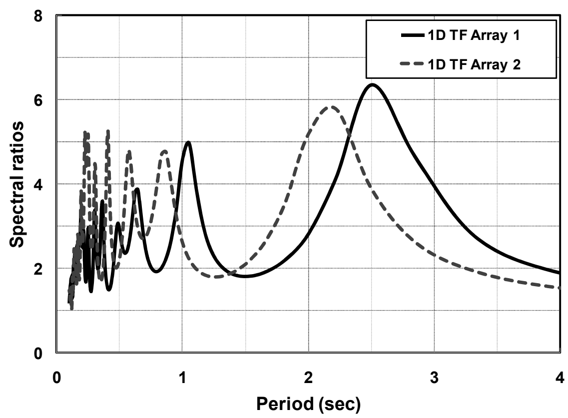
Figure 8 shows the average transfer functions, TF, or spectral ratios obtained from recorded data of the nine events mentioned above. Significant differences in the observed transfer functions TF of the two horizontal components (FT-OBS-NS and FT-OBS-EW) are evident as much in amplitude as in period. Although the characteristics in the source of the earthquake and the path have influence in the form, the dominant periods in each direction (where occur the maximum amplification) are clearly defined, such as it is illustrated in Figure 3. The difference in amplification indicates a strong polarization of the ground motion that is independent of the characteristics of the earthquake, and that is caused by the strong irregularity of 2D local geology.

1D numerical transfer functions calculated at two locations for incident S waves

In order to investigate the response due to vertical propagation of shear waves for each array model, we applied the 1D model and the SHAKE-91 (Idriss and Sun, 1992). The response was calculated by applying as input the outcrop accelerations recorded at station CHIL (rock) during the earthquake of September 14, 1995 (Mw = 7. 2). The horizontal peak ground acceleration of 0.026 g is the major value recorded in the firm soil of the Chilpancingo Valley.

Calculated Transfer functions for models M1 and M2 (1D TF Array 1 and 1D TF Array 2) of Table 1 are presented in Figure 9. In the first case (M1), the fundamental mode is 2.5 s and amplifies approximately 6.3 times, while the second, third and fourth mode are 1.0, 0.65 and 0.5 s respectively and have amplifications between 2.5 to 4 times. Meanwhile the TF calculated in model M2 indicates that the fundamental mode is 2.28 s and amplifies almost 6 times, while the second, third and fourth mode are 0.85, 0.58 and 0.4 s with amplifications between 3 and 4.

Figure 9 (right), compares numerical transfer function of M1 model obtained using 1D estimates, with the observed transfer functions (TF-OBS), during the September 14, 1995. It is very important to note that the theoretical curve match in shape with the observed curve in the fundamental mode range (2.3-2.5 s). However, there is a strong discrepancy regarding to the amplifications, because there are differences larger than a factor of 1.5 between the observed and the theoretical (1D TF Array 1) in NS direction, a factor of 4 in EW, and a factor of 2.5 in UR. In the same figure also appear as reference relationships H/V at RICC station.



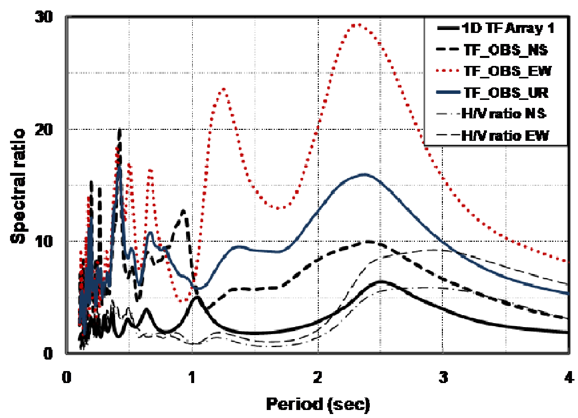


Figure 9. ***Left***: 1D numerical transfer functions for the models M1 and M2. ***Right***: Comparison among average spectral ratios observed during the September 14, 1995 earthquake, and 1D numerical transfer function.

Conclusions

In basis to the results from the present study we conclude that the arrangements observations of microtremors are a very promising method for determining S-wave velocity structures in intermediate depths. The SPAC method allows the reliable determination of Vs velocity profiles down to large depths (100-400 m), with relatively small arrangements. According to the two geological models proposed in this study, the layer deposits in Chilpancingo that contributes meaningfully to the amplification of the ground motion have thicknesses between 314 and 355 meters. The average velocity in these soil layers is ranging from 200 m/s in the most superficial sub layers, until 750 m/s in the interface with the limestone (Morelos group). These results are agree to a greater extent, with the existing geologic data of this section of the valley.

We have examined the site effects for the city of Chilpancingo Guerrero using an empirical technique, and 1D estimates. Based on the analysis used in this study, when both methods are compared, a significant difference in spectral amplifications was encountered in the period range between 2-4 s. The transfer functions are quite different in orthogonal directions, due to that a simplified 1D model predicts no difference between the transfer function of individual components in the horizontal direction. The change of ray paths of seismic wave, resulting from the complex 3D local geology in the valley might have caused this contrast. When the fundamental periods obtained from both methods are compared within the range from 2.5 to 2.9 sec, we found not much difference from site to site.

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