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Soil effects analysis in Cádiz Bay using ambient vibration measurements

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Abstract

In April 2008 an ambient vibration measurement campaign was conducted in Cádiz Bay (South of Spain) in the framework of the RISTE-COSTE project. Two different techniques were applied in order to study the site effects from predominant soil types in six nearby towns: Cádiz, Chiclana, Rota, Puerto Real, San Fernando and El Puerto de Santa María.

The first technique considered was the H/V method (also known as Nakamura's technique) to identify the natural frequency of the soil deposit. In order to apply this method, five sites were chosen from every town, all of them located in free field condition. The equipment used to obtain the records was a CityShark digitizer with two Lennartz, triaxial sensors of 5 s. Different time window lengths were used to obtain the records varying from 10 to 20 minutes depending on site conditions. The second technique was based on the set up of an array (array technique) consisting of 11 sensors (two concentric circles with 5 sensors each one plus one central sensor) with a maximum diameter of 100 m. The soil profile characteristics (Vs and thickness of each layer) for each site were obtained first using the FK and SPAC methods and then performing the inversion of the dispersion and autocorrelation curves using the "neighbor algorithm".

The results of H/V technique showed predominant high fundamental frequencies in the majority of sites (from 4 to 12 Hz), which is confirmed in some cases by the results of array technique. The array technique showed clear definition of Vs and thickness for the layer closer to the surface and this is used for the numerical simulations to characterize soil amplification.

Keywords: Cádiz Bay, ambient vibrations, fundamental frequency, soil effects.

1. Introduction

The evaluation of site effects associated to geological and geotechnical conditions represents a very important part of the seismic risk studies.

In general terms, soft soil layers of considerable thickness (non-consolidated deposits) tend to amplify, selectively, certain frequencies of seismic waves, and deamplify others. It is also usual to observe that movement duration and peak ground acceleration increases. This phenomenon can produce destructive effects on surface like the case of the Michoacán earthquake in Mexico in 1985. In this case, serious damages in Mexico City were caused to structures more than 400 km away from the epicenter (Sauter, 1999).

The studies oriented to the identification of local effects are also very important, to achieve more efficient seismic-resistant designs and for the establishment of criteria for improving urban planning.

These effects can be evaluated using different techniques, generally classified as empirical and numerical. In this study, two empirical techniques were applied: the H/V technique (also known as the Nakamura technique) and the Arrays technique. Both are based on the measurement of surface waves with the use of seismic sensors.

1.1. Study area

The Cádiz Bay is located in the Cádiz province, in the autonomous community of Andalucía (SW of Spain). It has an extension of 607 km^2 and a population of 417.924 habitants in 2006. It is formed by five towns: Cádiz, Puerto de Santa María, San Fernando, Puerto Real and Chiclana de la Frontera. Concerning this work, the town of Rota will also be considered part of the studied area. This bay has large extensions of salt marshes and mattings.

As a consequence of the collision between the tectonic plates of Eurasia and Africa, a wide area of deformation is present in the south of Iberian Peninsula. The region from south of the Iberian Peninsula and north of Morocco and Algeria will be named the Ibero-Maghrebian region in this study. This region extends from the Gulf of Cádiz on the west to the north of Algeria to the east. The seismicity of the Ibero-Maghrebian region is characterized by a continuous occurrence of shallow earthquakes (h <40 km) of magnitude lower than 5.0 and earthquakes of greater magnitude separated by long intervals of time (Figure 1). The two extremes of the Ibero-Maghrebian region (Gulf of Cádiz and north of Algeria) are characterized by the occurrence of large earthquakes: Lisbon (1755, Io=X), 1964 (Ms=6.4) and 1969 (Ms=8.1) in the Gulf of Cádiz and those of Orán (1790, 1887, Io=X), El Asnam (1980, Ms=7.1) or Boumerdes (2003, Mw=7.1) in Algeria.

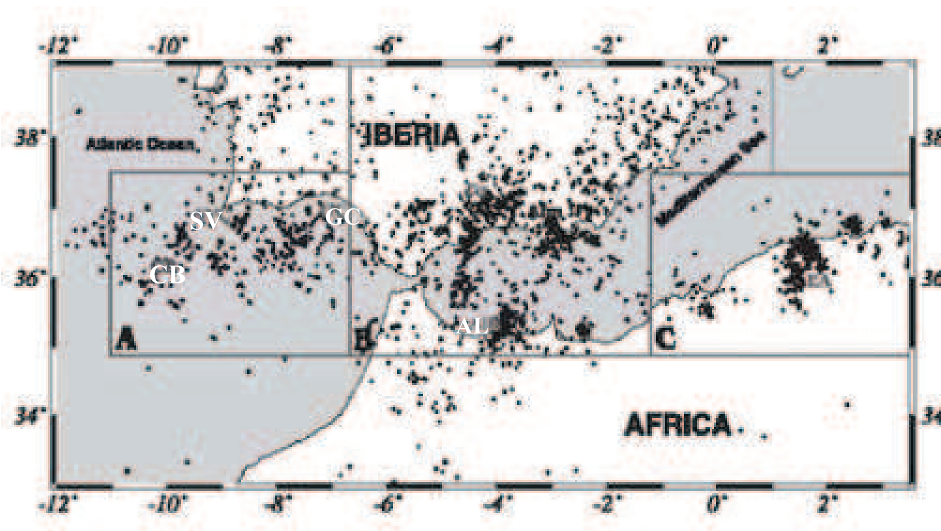

Figure 1. Distribution of epicenters along the borders of Iberia and Africa plates in the period of 1980-1999. CB Gorringe bank, SVC: San Vicente Cape, GC: Gulf of Cádiz, ALH: Alhoceima. Zones A, B and C were defined by Buforn et al., (2004).

The seismic hazard studies of the region propose, for a return period of 500 years, basic acceleration values between 0.05 and 0.07g for the six towns considered in this study. (NCSE-02)

Based on the lithological descriptions of papers 1061 (Baena et al., 1984), 1062 (Baena et al., 1984), 1068 (García et al., 1984) y 1069 (García et al., 1991), from the geological map correspondent to the Cádiz Bay, a geological map was obtained in which, following the criteria of Fleta et al. (1998), the classification of soils is simplified into four types: rock, A, B and C. The map obtained is shown in figure 2.

It can be seen that a large number of the towns resemble little islands, particularly Cádiz and San Fernando where ancient constructions are built. Nevertheless, the sedimentation and erosion processes, as well as human and tectonics interactions of the area, have contributed to an increase in the establishment of human settlements but usually where the soil condition is type C (natural or anthropogenic fillings, with low consolidated materials). The islands are constituted predominantly by conglomerates and sandstone rich in oyster from the Tertiary age (known as "*piedra ostionera*").

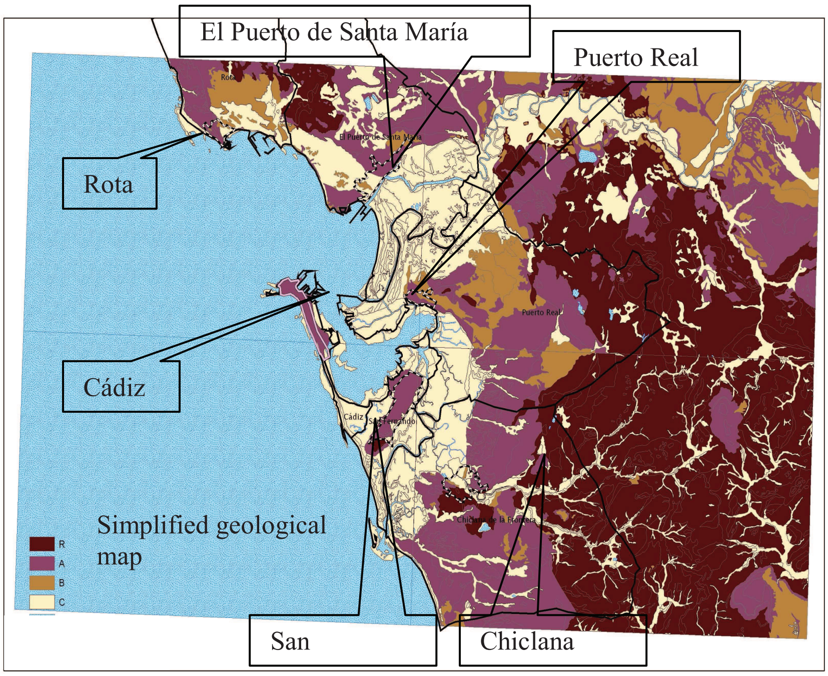

Figure 2: Simplified geological map of the Cádiz Bay. The legend in the map indicates the criteria adopted: R: rock, A: weathered rock, B: medium soil, C: soft soil.

2. Methods and data acquisition

2.1. H/V techniques for the determination of the fundamental frequency of the soil deposit

Proposed by Nakamura (1989), this method has proven to be useful for the identification of the fundamental period (or frequency) in soil deposits. The existence of previous information of local geology, as well as geotechnical and geophysical data will allow a better interpretation of the results.

The assumption in the H/V method is that ambient vibrations are composed by various types of waves and considers that they are similar horizontally and vertically in the bedrock. Spreading through the different layers of soil, the vibrations of the horizontal component are amplified due to multi-reflections of the S wave. This is valid if in these vibrations the Rayleigh waves prevail and its ellipticity is almost unitary. This is generally the case in stratified environments where there is a significant contrast between the impedance of the soil layers and the bedrock. The H/V method has been widely tested and an exhaustive list of recommendations for its application is available (Bard et al.,2004).

The instrumentation used to carry out the measurements in this work is composed by a CityShark digitizer and two Lennartz sensors, triaxials of five seconds. The software used for data processing was the GEOPSY (version 2.2.6, 20071130, designed in C++by Marc Wathlet, Grenoble, France). During the measurement campaign 41 sites were selected to apply this technique.

2.2. Arrays technique for the determination of layer thickness and shear wave velocities

The simultaneous record of microtremors by various sensors distributed in a determined geometry, known commonly as *arrays*, has been an attractive method for the determination of the velocities Vs and the thickness of the soil profile.

The main reason for the success of this method is that it is relatively simple. It uses passive seismic data which are the ambient vibrations. The method assumes that the ambient vibrations are composed by surface waves and that the structure of the subsoil is formed by horizontal layers.

In this type of medium, the surface waves are dispersive and show apparent velocity variations depending on frequency. The vertical components are affected only by the Rayleigh surface waves (Wathelet, 2007).

The processing of data for obtaining the Vs profiles from the series of noise measurements is divided in two main steps:

1- Derivation of the spectral curve characteristic of the wave propagation (also called dispersion curve or auto-correlation curve). The velocity of the waves that travel at a determined frequency is derived from the processing of microtremors acquired simultaneously on various stations. This can be obtained by three methods (Wathelet et al., 2007): The wavenumber vs. frequency method known as F-K, the high resolution of wavenumber vs. frequency method (F-K high resolution) and the spatial auto-correlation method (SPAC).
2- Inversion of the curve obtained in step 1 to obtain the structure of the soil. In this step, the resolution in depth is intrinsically related to the spectral amplitudes of the wavefield, as well as to the capacity and the distribution of the sensors. To conduct the inversion of the dispersion curves, the method that allows the determination of the Vs profiles consists in inverting the spectral curves, either dispersion or auto-correlation obtained in step1. Both techniques of number of wave vs. frequency provide the apparent dispersion curve which can be inverted using the classic linearized algorithm or a direct search technique like the “neighbor” algorithm, iterative methods or neural network. In this case, the neighbor method was used to perform the inversion of the dispersion curves and also the auto-correlation curves.

For the measurement of seismic noise using *arrays,* a data acquisition system developed by DMT (Deutsche Montan Technology) was used. It consists of one Compact Summit unit with a digitizer for 24 seismic channels. 11 Mark LC4 uniaxial (one vertical component) 1 Hz sensors were connected using a homemade adaptor and cables. The sensors were located in a concentric shape with respect to the central sensor, two concentric circles: one with a maximum radius of 50 m, in whose circumference five sensors were located, and another with a maximum radius of 25 m, where the other five sensors were located. To define their location in the measurement campaign, the simplified geological map from figure 2 was used. Microtremors were recorded by the different arrays in two separate 8 minutes windows and subsequently joined to obtain a total record length of 16 minutes. H/V measurements in the center of each array and 50 m away where also performed.

3. Results obtained and discussion

3.1. H/V Technique.

A total of 41 measurements were conducted in different sites in six towns of the Cádiz Bay, also in the arrays as we mentioned above. Figure 3 correspond to the H/V ratios of two of them: Chiclana and Puerto Real, since they represent two opposite cases: in Chiclana the identification of the peak corresponding to the maximum amplitude was very clear, with a natural frequency close to 1.5 Hz and with small differences between the two measuring locations distanced 50 m. In the case of Puerto Real, very low H/V ratios were obtained (amplitudes close to the unit in all the range of frequencies), which do not allow a clear identification of one unique peak and its maximum amplitude. Automatic peak identification performed by the software shows a wide frequency range and a high dispersion in the result.

Table 1 presents a description of the H/V ratios estimated for the six municipalities. Based on it, the results can be classified in three categories:

- Chiclana, El Puerto de Santa María y San Fernando: peak acceptably defined in high frequencies that define the contrast of the shallower layer. A second peak can be seen on low frequencies, poorly defined because of the large dispersion of the different H/V ratios. This second peak could show a second contrast between deeper layers.
- Cádiz y Rota: one unique peak in the high frequencies, clearly defined probably due to the fact that measurements were made in an area of thick artificial deposits.
- Puerto Real: it is not possible to define f_0 due to the large dispersion of the H/V ratios in the low frequencies and the low amplitudes (close to the unit) in the high frequency range.

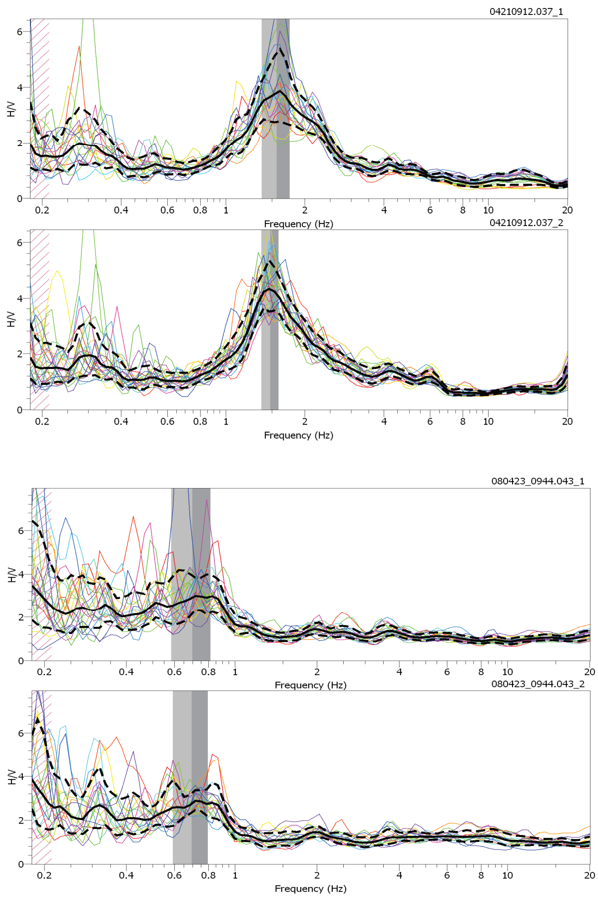

Figure 3. Left: H/V ratios in the array of Chiclana. Right: H/V ratios in the array of Puerto Real. Top: H/V at the center of the array and bottom: 50m away from the center. The average is shown in a continuous black line and the dotted lines correspond to the average ± a standard deviation. The grey vertical lines correspond to the median ± one standard deviation for the maximum H/V amplitudes.

Table 1. Results obtained from the application of the H/V technique for the six municipalities of the Cádiz Bay. All selected time windows were of 20 minutes.

3.2. Array technique. The results obtained were classified according to the quality of the data: error bands and frequency range.

- Chiclana and El Puerto de Santa María dispersion (FK) and autocorrelation (SPAC) curves show the best quality. This is shown in figure 4a which corresponds to the solution for Chiclana with the FK method, where the black one represents the dispersion curve, with the corresponding error bars for each frequency.
- In the case of Cádiz, the obtained dispersion curve is more limited in the range of frequencies and the results between the FK and SPAC methods do not match in terms of their tendency.
- For Puerto Real and Rota, the solution obtained is very limited in all the frequency ranges; also a gradual increase of slowness with respect to the frequency is not appreciated, which is expected in a theoretical dispersion curve. Being both curves almost horizontal (obtained by FK an SPAC), the dispersion phenomena is not clear, which lead us to consider that the medium behaves as a homogeneous layer (not stratified). Figure 4b shows the best solution obtained by the FK method for Puerto Real.
- Finally, San Fernando has the least clarity in the definition of the dispersion curve given by the FK method (the many peaks do not allow the definition of a smooth curve) and it becomes impossible to define the ranges in which the auto-correlation curve varies, for the application of the SPAC method.

Municipality	Location	Frequency f_0 (peak observed, Hz)	Amplitude	Observations
Chiclana	Recinto ferial	1,6	3,7	Possible second peak at 0.3 HZ, but high dispersion.
		1,5	4	
Rota	Base naval 1	9,8	2,9	Very high peak due to the presence of man-made landfills, rest low amplitudes.
		15,1	2,1	
	Base naval 2	9,8	4,3	
		13,0	2,5	
El Puerto Sta. María	Parking Valdelagrana	3,5	2,4	A second peak is defined at low frequencies, high dispersion.
		3,4	2,4	
San Fernando	Parking Bahía Sur	3,5	2,9	Peak probably defined for f_0, another appears a low frequencies, but large dispersion.
		3,5	2,9	
Puerto Real	Recinto ferial	0,8	3,1	Too much dispersion to define f_0.
		0,8	2,9	
Cádiz	Campo fútbol	5,2	5,4	Peak very defined in high frequencies due to man-made landfills
		5,5	6,4	

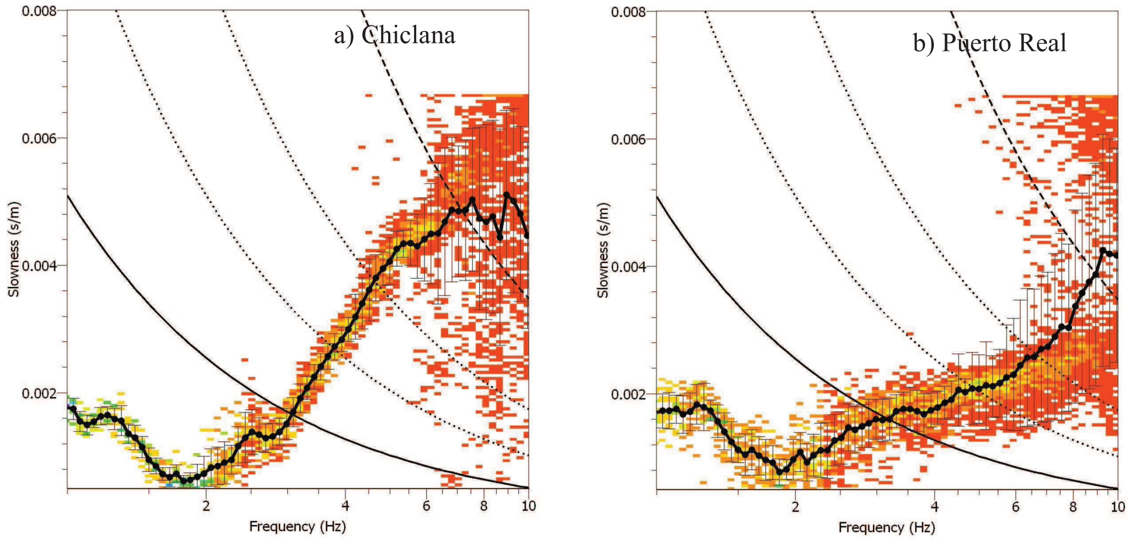

Figure 4. Two cases of the application of the *array* technique with the FK method after removing aliasing noise for each frequency band (the error bars have been diminished). Fig. 4a corresponds to Chiclana, where a gradual increment of slowness can be seen with the frequency. Fig. 4b represents the case of Puerto Real, where the dispersion curve show a less dispersive media turned out to be more irregular and horizontal. In both figures, the solid black lines correspond to wave numbers K min/2 and Kmax, respectively, while the dotted lines represent the highest security range of results, according to the capacity of the array resolution (Kmín and Kmáx/2, respectively, Wathelet, 2007).

Figures 5a and 5b present the profiles obtained from the best solutions (less dispersion of the results) from the application of the FK method for the locations of Chiclana and Puerto Real. For Chiclana, a good definition of the Vs can be seen in the first layer, in which practically all the models generated by the inversion algorithm match. The depth of this first layer is defined moderately well (minor coincidence of the methods) and a larger dispersion of the results in terms of the Vs value is obtained for the second layer. For Puerto Real, the different models coincide in defining a very similar value for the first layer, but not so for the layer's depth nor the Vs of the second layer. It is worth mentioning that the Vs for first and second layers are very similar, which agrees with the fact that for this location, the dispersion curve was very horizontal. This reinforces the idea that the medium is homogeneous and contradicts one of the main hypotheses for the application of this method.

Table 2 shows comparisons between the f_0 (fundamental frequency) obtained from the different methods. In the second column, f was obtained from the velocities and the depth of the profiles chosen as the best solution from each array and using the relationship: f_H = ¼*(Vs/H), where Vs represents the shear velocity of the layer with thickness H. In the third column, the f_0 was read directly from the spectral ratios. With these comparisons we find or not the contrast that produces the fundamental resonance mode in the soil column. Chiclana, El Puerto Santa María and Cádiz were the places in which the results showed best coincidence. The other three cases require complementary information, like data coming from NSPT tests to define in a more precise way the profiles for these locations.

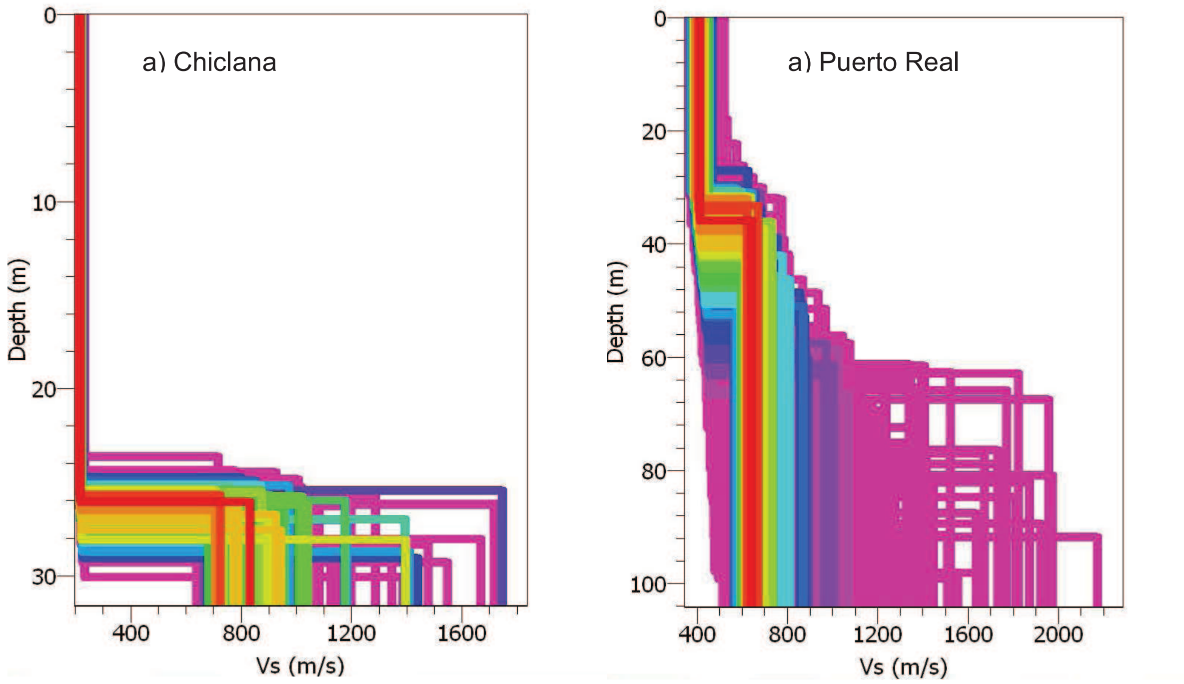

Figure 5. Solutions of Vs vs. depth for the locations of Chiclana and Puerto Real with the application of the FK method. The different colors correspond to different models generated by the neighbor algorithm. The purple colored lines correspond to the models with highest error and the red ones to the ones with the less error.

Tabla 2. Frequencies f_H and fundamental frecuencies f_0 obtained from profiles (arrays results) and H/V technique, respectively.

Town	f_H according to profile (Hz)	f_0 according to H/V (Hz)
Cádiz	3,8	5,5
Chiclana	2,1	1,6
Puerto Real	2,9	0,8
Rota	2,4	9,8
San Fernando	3,4	3,7
Santa María	3,9	3,4

4. Conclusions

In this work, a microtremor measurement field campaign was conducted in different towns of Cádiz Bay. H/V and array techniques where applied in order to characterize site effects.
The results obtained after applying those techniques show a clear definition of shear wave velocity and thickness for the first layer of soil for the sites of Chiclana, El Puerto de Santa María y Cádíz. The remaining three cases require complementary data for the determination of the Vs vs. depth profiles.
The fundamental period and Vs profiles obtained will be useful for the soil structure characterization in order to perform numerical simulation to characterize soil amplification.

Acknowledgments

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