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ESTIMATION OF S-WAVE VELOCITY STRUCTURE USING ARRAYS OF LONG PERIOD MICROTREMORS.

By

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SUMMARY

Assessment of local site effects is one of the most important subjects in engineering seismology. In order to perform the assessment, it is necessary to determine the S-wave velocity structure of the site. Additionally, in some basins, it is very important to know the deep sedimentary structure, due to the amplification phenomena of low frequency waves. There are several techniques to achieve this purpose; probably the most inexpensive technique is using vertical component of microtremors measured by array. The phase velocity of Rayleigh waves is inverted to an S-wave velocity (Vs) profile using optimization techniques. Most of the time, least square methods have been applied in the inversion. Recently, heuristic methods are also been used in inverting phase velocity from microtremor exploration.

In this study we performed seven arrays of microtremors in Tsukuba city, located at North-Eastern edge of Kanto Basin, in order to estimate the deep S-wave velocity structure. The spatial autocorrelation method SPAC was used to determine phase velocity dispersion curves in the frequency range from 0.3-2.5 Hz. The determination of Vs profiles reached a depth of 750 m. Comparisons with Vs from the existent results of PS-logging test at the center of the array proved the reliability of the method. Vs profiles, the ability to reach large penetration depths in populated urban areas and its low cost compared to conventional geophysical prospecting, make Microtremor Array Exploration Method very attractive and useful for microzonation and site effects studies in developing countries.

Key words: Microtremors, Array Measurement, Kanto basin, Tsukuba, SPAC, shear wave velocity.

1. INTRODUCTION

The geometry of the subsoil structure, the soil types and the variation of their properties with depth, the lateral discontinuities and the surface topography can produce large amplifications of ground motion and increase the damage during destructive earthquakes. For this reason the accurate knowledge of the geometry and the *Vs* structure of alluvial–diluvial deposits and the basement are very important in microzonation studies.

Vs is usually determined in the field by using conventional seismic prospecting techniques (reflection, refraction, boreholes) and in the laboratory through dynamic tests on soil samples. The use of conventional seismic exploration methods presents some difficulties

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when deep sedimentary structures needs to be determined. For example, in reflection and refraction surveys, the use of artificial sources such as explosives or vibrators is necessary, which sometimes is not easy in urban areas. Furthermore, the dimensions of the required arrays are large according to the desired penetration depth and therefore it is difficult to be deployed in populated areas. Additionally, the cost of large scale deep geophysical prospecting is high, and therefore, in most cases in site effect studies, the depth of the seismic basement is limited to a layer with *Vs* larger than 400 m/s (Engineering bedrock) and not the real very deep underground reflector of the incident waves (*Vs* > 3000 m/s, Seismic bedrock). Additionally, the cost for implementing deep borehole is also high and the results are valid only for a single site.

Microtremors techniques have been consolidating during last decades as a really good tool in reconnaissance and research of shallow and deep soil structures (Alfaro, 2005 [1]). There are several techniques using microtremors, during last years Horizontal Vertical Spectral Ratio (HVSR) have been used all over the world after Nakamura's paper (1989) [2] in order to determine soil's predominant periods and dynamical soil's classification (Alfaro *et al.* ,2001 [3]; Bhattarai, 2005 [4]); HVSR has generated several discussions due to the lack of robustness in the theory(Horike *et al.*, 2001 [5]) , however Arai and Tokimatsu (2000 [6], 2004 [7]) developed a technique that allow the determination of *Vs* Structure means inversion of HVSR. They developed a complete formulation assembling surface waves in order to make the inversion. However, in this research, microtremor array technique was used, because it has a robust theory and it has been used all over the world, mainly in Japan, additionally to apply the method proposed by Morikawa *et al.* (2004) [8], two sites SPAC method, which could provide results with similar quality by using only two stations instead of 4, 7 or 10 stations, that the conventional SPAC method requires.

In the present report the microtremor array technique is applied to assess the *Vs* Structure. The method uses the microtremor records obtained at stations deployed in a triangular array. The measurements are taken simultaneously at all stations, which are operating for a short duration of time. The analysis of the microtremor records is performed through the spatial autocorrelation coefficient method (SPAC method) introduced by Aki (1957, 1965 [9-10]) and established by Okada (2003) [11]. It is important to mention another technique for arrays analysis, Frequency-wavenumber spectrum method (F-K), developed by Capon (1969) [12] and applied to microtremors by Horike (1985 [13]) and Okada (2003 [11]). F-K method is used to estimate dispersion curve of Rayleigh wave and velocity structure. The weak point of this method is the necessity of simultaneous measurement with several stations.

The SPAC method is based on the theory of the Stationary Random Functions, according to which, microtremor is considered as a stationary stochastic process both temporally and spatially. In the present study, microtremor measurements were performed at one site, representative from geological point of view, in the city of Tsukuba, where information of a deep borehole of 1300 meters is available (Hayashi, 2005[14]; Hayashi *et al.*, 2005 [15]). The practical aim of this study is to estimate a Vs profile, especially for depths larger than 500 m, reaching that of the bedrock. To examine the efficiency and the accuracy of the method the results are compared with bore-hole Vs profile at the site.

2. THEORETICAL BACKGROUND

2.1. CONVENTIONAL SPAC METHOD

Aki (1957, 1965 [9-10]) presented a theoretical background for estimating phase velocities by means of the SPAC method. In this section the SPAC method is summarized according with Okada (2003) [11] and Morikawa *et al.* (2004) [8].

Let us consider a circular array with a radius r for observing microtremors. The harmonic waves at angular frequency ω of the vertical component of the microtremors are represented by $u(t;\omega,0,0)$ and $u(t;\omega,r,\theta)$, which are observed at the center $C(0,0)$ of the array and a site $X(r,\theta)$ of the circle, respectively. It is thought that the vertical component of the microtremors mainly consists of Rayleigh waves with a fundamental mode. A schematic description of these symbols is shown in Figure 1.

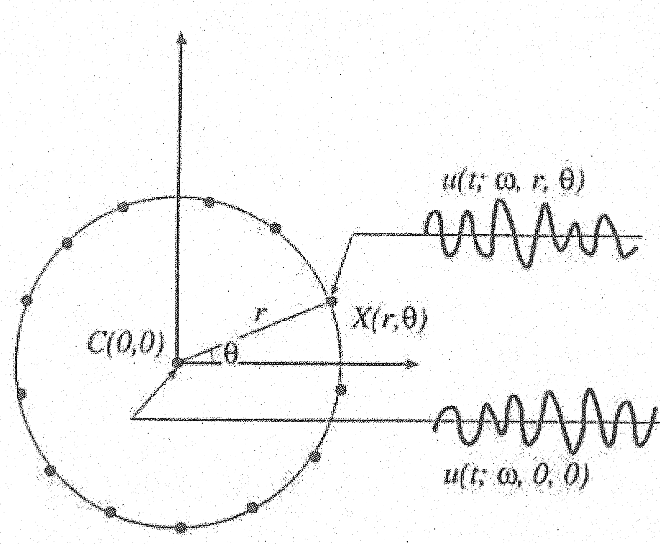


Figure 1. A schematic description of the symbols for the observation sites and the vertical component of the microtremors. $u(t;\omega,0,0)$ and $u(t;\omega,r,\theta)$ denote the harmonic waves at frequency w, which are obtained at the center $C(0,0)$ of the array and a site $X(r,\theta)$ of the circle shown by dots [8].

The spatial autocorrelation function is defined as

$$\phi(\omega;r,\theta)=\langle u(t;\omega,0,0)\cdot u(t;\omega,r,\theta)\rangle \qquad (1)$$

Where $<z(t)>$ stands for the mean value of $z(t)$ in a time domain with duration T defined as follows:

$$\langle z(t)\rangle=\frac{1}{T}\int_0^T z(t)dt \qquad (2)$$

The spatial autocorrelation coefficients are defined as the average SPAC function at all the observation sites on the circular array, in other words,

$$\rho(\omega;r) = \frac{1}{2\pi \cdot \phi(\omega;0,0)} \int_0^{2\pi} \phi(\omega;r,\theta)d\theta \qquad (3)$$

where $\phi(\omega;0,0)$ is the autocorrelation function at center C(0,0). After a mathematical reduction, the integral of equation (3) is rewritten as

$$\rho(\omega;r) = J_0\left(\frac{\omega r}{c(\omega)}\right) \qquad (4)$$

where J_o is the Bessel function of the first kind with the zeroth order and c(ω) is the phase velocity at frequency ω for the Rayleigh waves with the fundamental mode.

The SPAC coefficients denoted by equation (3) can be directly calculated in a frequency domain using the Fourier transform of the observed microtremors, that is,

$$\rho(\omega;r) = \frac{1}{2\pi} \int_0^{2\pi} \frac{real[S_{CX}(\omega;r,\theta)]}{\sqrt{S_C(\omega;0,0) \cdot S_X(\omega;r,\theta)}} d\theta \qquad (5)$$

Where *real* [.] stands for the real part of the complex value, and $S_C(\omega;0,0)$ and $S_X(\omega;r,\theta)$ are the power spectra of the microtremors at two sites, *C(0,0)* and $X(r,\theta)$ respectively. $S_{CX}(\omega;r,\theta)$ is the cross spectrum between $u(t;\omega,0,0)$ and $u(t;\omega,r,\theta)$.

It can be seen in both equations (3) and (5) that the SPAC coefficients are obtained by averaging the complex coherence functions with regard to azimuth from site to source θ, where the complex coherence functions are defined as the real part of cross spectrum $S_{CX}(\omega;r,\theta)$ and normalized by the power spectrum *C(0,0)*.

The SPAC coefficients, $\rho(\omega,r)$, can be directly calculated from the observed data on the microtremors using equation (5). It is easy to complete this calculation by applying a numerical technique such as the Fast Fourier Transform (FFT) method. Furthermore, the phase velocity at frequency ω will be obtained as the argument of the Bessel function in equation (4). In this study it was used a software *b_fit* developed by Yokoi (2005a [16]) to find the optimum value for phase velocity. That program uses Levenberg-Marquardt method and some subroutines from Press *et al.* (2002 [17]). On the other hand, to perform the inversion it two programs were used: *disp_smal*(Yokoi, 2005b[18 - 19]) and *surf96* (Herrmann and Ammon (2004) [20]).*disp_smal* is a program to obtain the optimum underground velocity structure for the given dispersion curve of Rayleigh wave based on the down hill simplex method combined with the simulated annealing approach.

2.2. TWO SITES SPAC METHOD – 2sSPAC METHOD

Following Morikawa *et al.* (2004)[8] the 2sSPAC method was also applied, in which it is possible to obtain the SPAC coefficients through simultaneous observations at the various pairs $C(0,0)$ and $X(r, \theta)$ instead of through simultaneous observations at all sites of the array. The only modification to equation (5) is that the integrand is formed separately for each θ. Thus, the 2sSPAC method does not require as many instruments or operators, which are indispensable for the conventional method. Instead, a longer duration is needed for the observations.

3. -OBSERVATION OF MICROTREMORS

The microtremors were observed in the North-Eastern part of the Kanto Basin, in the city of Tsukuba (Japan), where the depth to bedrock was found to be about 600 m by a deep borehole. These observations were performed on 27 and 28 July 2005, which included seven arrays: one with 29 m radius (largest side within 50m); two with 115 m radius (largest side of 200m); two with 290 m radius (largest side of 500m) and two with 520 m radius (within largest side 900m). A detailed explanation about the array of short period microtremors can be seen in Almasani (2005 [21]). The arrangement of the arrays is shown in figure 2. Hereafter, these observations are called R and B arrays.

We have made simultaneous observations at four sites, with vertical-component velocity type seismographs, with a long natural period of To= 10 sec. The microtremors were recorded by digital recorders with a resolution of 24 bits converted with an analog band pass filter, the pass band of which is from 0.1 seconds to 5.0 seconds. The records were synchronized with the time code generated by Global Position System (GPS) clocks. We gathered 3 sets of data on 200m array, 10 sets of data with 500 m array (total duration 2 hours) and 10 sets of data with 900 m array (total duration 2 hours); because of two arrays (B and R) the total of data available is 52 sets, coordinates of stations can be seen in Table 1.

On the other hand, quality of data depends on the amount of interferences due to anthropogenic sources like cars and other kind of vehicles; in this case 500 m arrays presented the highest interference due to the location of B5 and R5 stations, which were located in an Avenue with intense traffic of trucks. An example of waveforms can be observed in Figure 3, which corresponds to microtremors of 900 m array. Also it was gathered data to apply the two sites SPAC technique 2sSPAC (Morikawa *et al.*, 2004 [8]) for the array B of 200 m, we gathered data for six pairs, as follows: B1-B2, B1-B3, B1-B4, B1-B5, B2-B6 and B1-B7, that means that there were two distances r (57.7 m and 115.4 m). For the conventional SPAC method there were 5 distances between stations (57.7, 100.0, 115.4, 173.2 and 200m).

Using equation (5) it is possible to assess SPAC coefficients, as shown in Figure 4, which are functions of distance and frequency. For low frequencies, SPAC coefficients have maximum values. Because the aim in this individual study is large period microtremors, SPAC coefficients are shown from 0.3 to 5 Hz. Concerning 2sSPAC Figure 5 shows a comparison between SPAC coefficients obtained for B array with conventional SPAC method and using 2sSPAC method, there is a good agreement in shape and trends, however, in spite of the fact that there are stability, there are variations in values, even for the conventional

SPAC method assessed by different data sets. SPAC coefficients of 2sSPAC seem to be a smoothed and averaged version of the conventional SPAC coefficients.

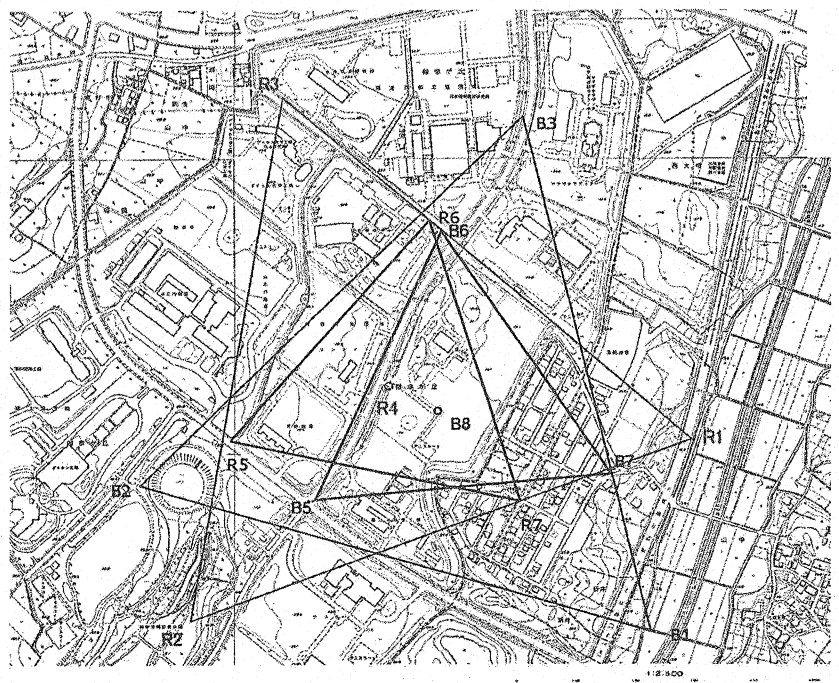


Figure 2. Location of the observation sites. The observation sites are located in the northern part of the Kanto Basin, Japan, in Tsukuba city, where the depth of bedrock is known to be about 600 m by a deep borehole (Hayashi *et al.*, 2005[15]). B8 is the center of the B Arrays and R4 is the center of the R arrays. R1-R2 length is 900m; B5-B6 length is 500m. Observations were carried out during workdays. Note that B5 and R5 are located in an Avenue with intense traffic.

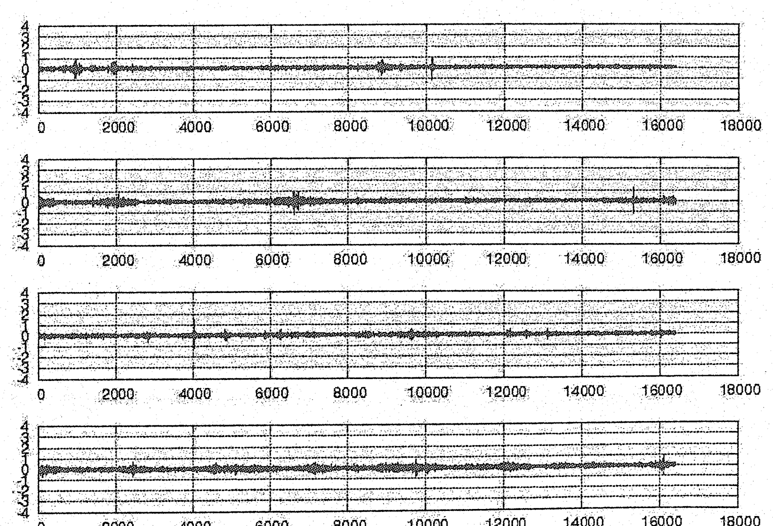


Figure 3. An example of the microtremor records for 900 m array; stations R4, R1, R2 and R3 respectively. Each trace indicates vertical ground velocity component.

Table 1 Coordinates of station for 500 m and 900 m arrays in Japanese Geodetic Datum 2000

900m Array

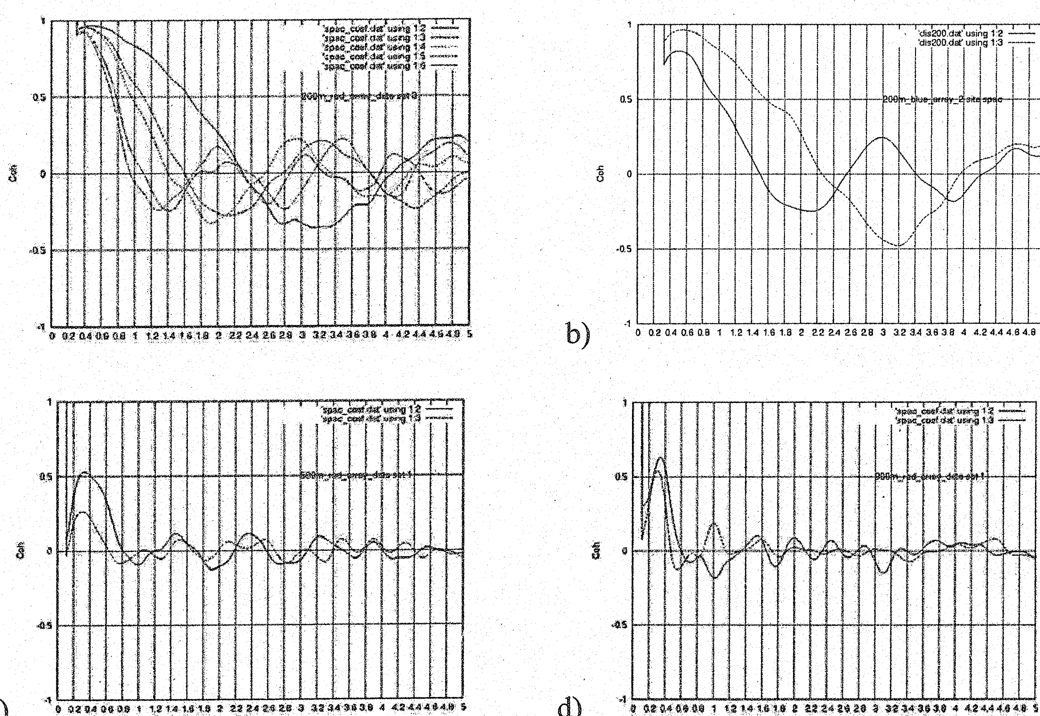
Station	X	Y
R1	1538.8	574.8
R2	691.8	266.0
R3	848.3	1153.8
R4	1026.3	665.0
B1	1470.8	247.8
B2	604.3	496.3
B3	1252.3	1122.0
B4	1109.0	622.0

Distances		
	R1-R2	901.52m
	R1-R4	520.39m
	B1-B2	901.43m
	B1-B4	520.51m

500m Array

Station	X	Y
R5	758.0	572.0
R6	1093.3	944.8
R7	1248.8	468.0
R8	1035.0	660.0
B5	902.0	471.8
B6	1114.0	926.3
B7	1402.0	515.8
B8	1141.3	636.3

R6-R7	501.33m
R5-R6	290.64m
B6-B7	501.51m
B5-B6	290.35m



a) b) c) d)

Figure 4. SPAC Coefficients obtained from simultaneous observations, a) 200 m array, b) 2sSPAC 200m array; c) 500m array and d) 900m array.

The next step in the analysis is to fit Bessel function of the first kind of zero order for every frequency according with equation (4), this procedure implies the verification about the values that could be used for the fitting. Figure 6 shows some examples of fitting Bessel functions. For certain frequencies it is possible to use data from various distances, however, in the case of low frequencies it is possible to use only data from largest array. It was used the program *b_fit* by Yokoi (2005a) [16]. By means of inversion of equation (4) it is possible to assess the dispersion curve; examples are shown in Figure 7.

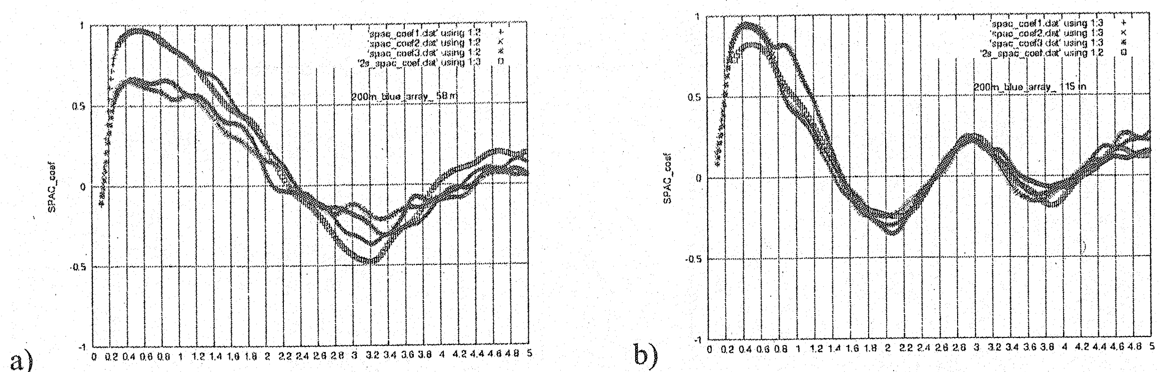


Figure 5. SPAC Coefficients obtained from simultaneous observations and using 2sSPAC method in B200m arrays, a) r= 58 m , b) r=115m. Open squares correspond to 2sSPAC.

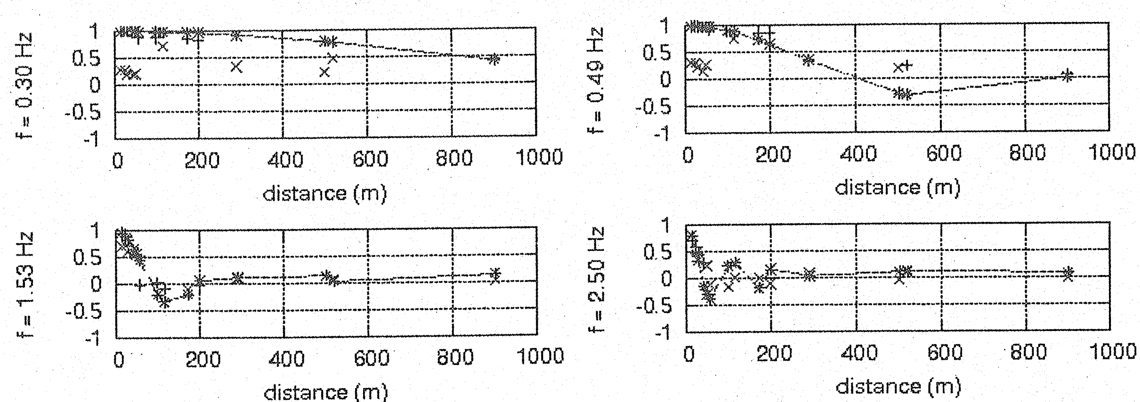


Figure 6. An example of fitting the Bessel functions of the first kind of zero order for several frequencies (0.30 Hz, 0.49, 1.53 and 2.50 Hz) Note that 'x' denotes the dots not used for fitting the Bessel function, where as '+' denotes those used.

4.- DETERMINATION OF Vs STRUCTURE

The phase velocity was inverted to *Vs* structure using two methods: the least squares method (Herrmann and Ammon, 2004[20]) and the combination of Down Hill Simplex Algorithm with Very Fast Simulated Annealing Method (Ingber, 1989 [22]; Yokoi, 2005c [19]). Following Yamanaka (2005) [23] the Simulated Annealing Method is based on the idea of thermodynamics where melted metal reaches to low-energy state with gradual decrease of temperature (Metropolis and Rosenbluth, 1953 [24]). Afterwards Kirkpartrick *et al.*(1983) [25] applied the idea to optimization problems with an analogy between both subjects. The misfit to be minimized in inversion corresponds to energy in thermodynamics, and parameter change does to move of material state. This move of parameters is controlled by cooling schedule of the system with temperature decrease.

Table 2 shows several examples of results obtained using the Very Fast Simulated Annealing Method. These show a good agreement with the existing PS-logging. Figure 7a corresponds to the dispersion curve obtained with the first R200 m data array plus a set of R900 m array; figure 7b corresponds to the second set of R200 m data plus a set of R900 m and so on. In the table 2 Vs structures correspond to the dispersion curves of figure 7.

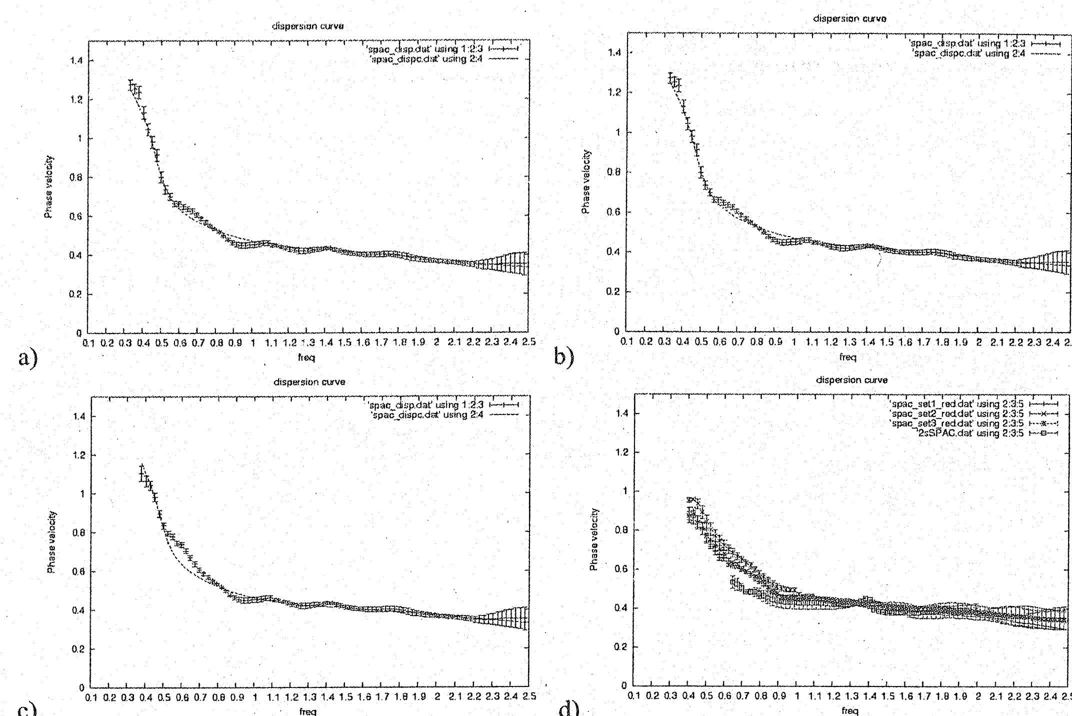


Figure 7. Phase Velocities of Rayleigh waves obtained from vertical component of microtremors. The continuous line shows the theoretical dispersion curve. a) first R200 m data array plus a set of R900 m array; b) second set of R200 m data plus a set of R900 m. a) third R200 m data array plus a set of R900 m array; d) Shows the comparison of three sets of 200m dispersion curve with 2sSPAC.

Table 2. Velocity Structure at the Observation sites of Microtremors estimated from the Phase Velocities and the Thickness of Each Layer Obtained from nearby deep PS-logging. Set 1 corresponds to figure 7a, set 2 corresponds to 7b; set corresponds to 7c.

set 1

H(KM)	VP(KM/S)	VS(KM/S)	RHO(GM/CC)
0.060	1.62	0.30	1.82
0.190	1.81	0.46	1.88
0.426	2.04	0.68	1.95
999.000	3.11	1.64	2.23

set 2

H(KM)	VP(KM/S)	VS(KM/S)	RHO(GM/CC)
0.055	1.63	0.30	1.82
0.186	1.79	0.45	1.87
0.433	2.05	0.68	1.95
999.000	3.19	1.71	2.25

set 3

H(KM)	VP(KM/S)	VS(KM/S)	RHO(GM/CC)
0.055	1.61	0.28	1.82
0.189	1.79	0.45	1.88
0.432	2.04	0.67	1.95
999.000	3.32	1.82	2.28

Real - Simplified

H(KM)	VP(KM/S)	VS(KM/S)	RHO(GM/CC)
0.050	1.50	0.25	1.80
0.170	1.60	0.40	1.90
0.430	1.70	0.65	2.00
0.000	4.80	2.50	2.50

On the other hand, Figure 8 shows some examples of results using *surf96* (Herrmann and Ammon, 2004[20]), Figure 9 shows the comparison of the results with the information from borehole data. Results using both methods are suitable, however one advantage of the method proposed by Yokoi (2005c) [19] is that is possible to assess thickness and *Vs*, meanwhile in Herrmann and Ammon (2004) [20] it is necessary to fix the thickness or the *Vs* of each layer. However, *surfer96* presents standard error (km/s); mean residual (km/s); average residual (km/s) and percent of signal power fit in percentage.

It was performed two tests using two sites SPAC technique (Morikawa *et al.*, 2004 [8]) , the first one for the B200 m array and for the B900m and R900m arrays, in these two cases taking advantage on the two hours records. Results for B200m can be seen in Figure 7. Obtained trend is similar to the conventional SPAC method, but in a narrower band of frequencies; however it seems to be an unfair comparison between the two methods SPAC and 2sSPAC, because only two distances were used in 2sSPAC for fitting the Bessel function. For 900m arrays results were not suitable; as a result further research is needed.

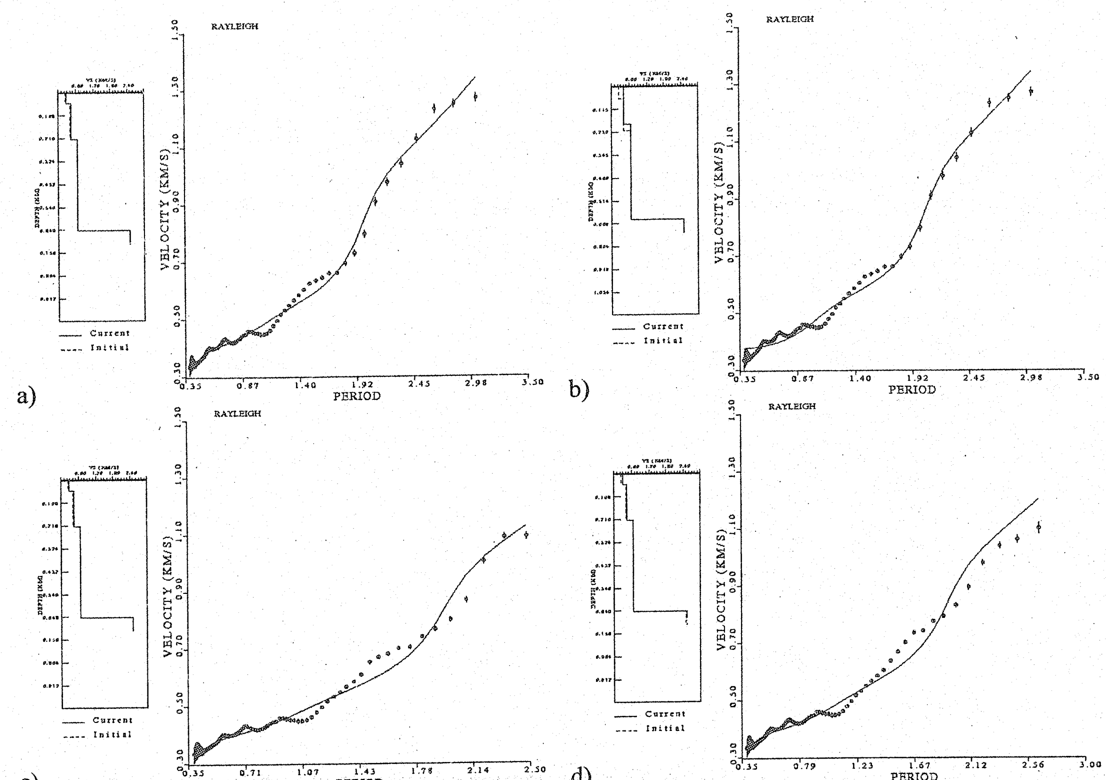


Figure 8. Several Vs soil structures using *surf96* (Herrmann and Ammon, 2004[20] a) and b) used the same dispersion curve as input data, a) with fixed thickness and b) with fixed Vs, c) and d) are the results using other dispersion curves. The 900 m arrays allowed observing long periods as 3 seconds.

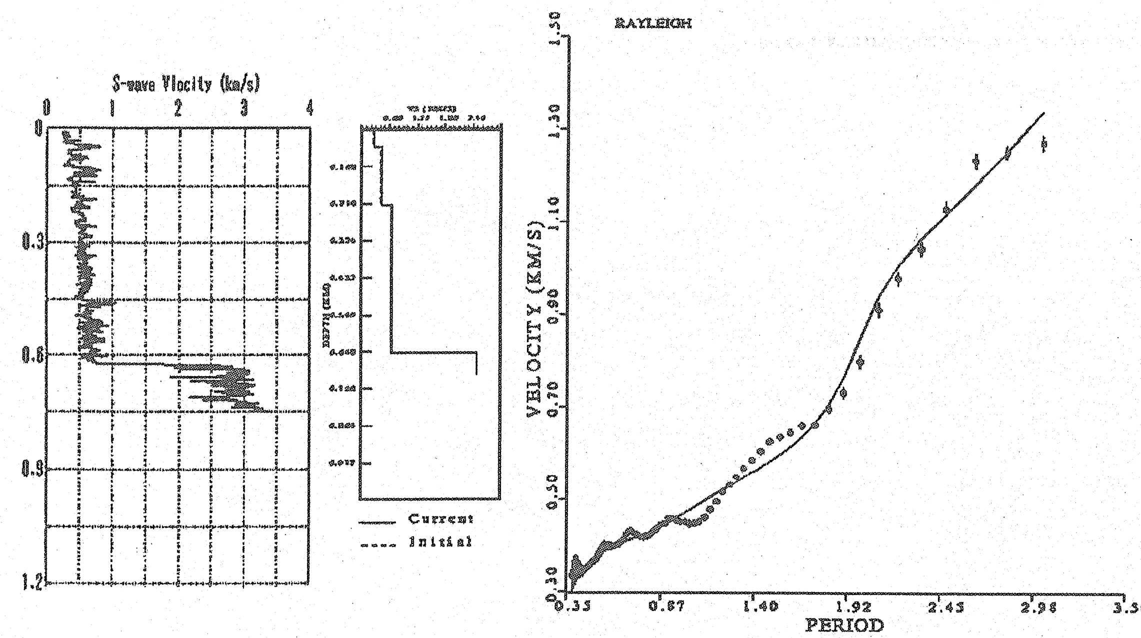


Figure 9. Comparison of the obtained Vs structure with the information from PS-logging data.

5. DISCUSSION AND CONCLUSIONS

Among several geophysical prospecting methods, passive methods have the advantage that these do not need artificial sources that can disturb the people or expensive drills. Microtremors techniques have been consolidating during last decades as a really good tool in reconnaissance and research of shallow and deep soil structures (Alfaro, 2005 [1]).

Results obtained using SPAC and 2sSPAC methods were suitable and could reflect the main features of the *Vs* Structure at the site. 2sSPAC results were good for 200 m arrays, however, in a narrower band of frequencies, which was due to the fact that it was used two distances for fitting Bessel functions, instead of five distances used for standard SPAC method. On the other hand, as results for 900 m using 2sSPAC were not good, further research is needed.

According with the waveforms obtained, mainly for station R5 and B5 in 500 m arrays, it is advisable to avoid large avenues or roads, because waveforms could be plenty of interferences and results could be not suitable. Also, could be advisable to perform the measurements during such hours with minimum interferences due to punctual loads, like heavy trucks, or follow the recommendation of Apostolidis *et al.* (2004)[26] to locate the stations at least 50m far from avenues or roads.

The most significant advantage, of estimation of Shear Wave Velocity structure, using arrays of long period microtremors, is that it allows the reliable determination of *Vs* profiles down to large depths (about 600 m) with relatively small apertures of the deployed arrays (900 m). This is significant for accurate soil response studies regarding large cities, where open free spaces suitable for the deployment of large conventional arrays are difficult to be found and high energy sources cannot be easily used.

Then, the long period microtremors array can be considered as a valuable technique for determining shear velocity structure and play an important role in the Disaster Prevention Tasks.

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