SITE EFFECTS AND SPAC. RESULTS FOR THREE SITES IN WAINUIOMATA

Francisco J. Chávez-García[1], Miguel Rodríguez[1] and William R. Stephenson[2]

ABSTRACT

We apply the SPAC method to investigate site response at three sites in the Wainuiomata valley. At each site, square arrays with a fifth station at the centre were used to record 35 minutes of ambient noise. Distance between the stations on the square and the central one were 10, 20, 40, and 80 m. The data were analyzed through the computation of cross-correlation among stations. The resulting functions were inverted for the phase velocity dispersion curve of Rayleigh waves at each site. The results are reliable in the frequency band 1.1 to 3.7 Hz. The dispersion curves were inverted for the shear wave velocity profile at each site. We observe only marginal differences between sites FWP and BHP, where large amplification is given by very soft soil relative to a significantly stiffer bedrock. The third site, MCP, shows a velocity gradient with depth, without a pronounced contrast in the depth range investigated. We computed transfer functions for vertical incidence of shear waves on the inverted profiles, and compared the results with horizontal-to-vertical spectral ratios of microtremor records. The differences between the two shed some light on the complementary nature of both types of measurement and suggest that any single measurement may lead to erroneous interpretations.

INTRODUCTION

Site effects play a major role in destructive ground motion. The effects of local geology may modify in a very significant way observed ground motion on soft soils, the case of Mexico City earthquakes during 1985 being a foremost example. Ground motion was amplified by a factor of about 40 at the resonant frequency of the very soft soil layer covering the ancient lake bed zone. Site effects may be taken into account with relative ease when abundant records of ground motion exist for nearby stations on different soil conditions using for example spectral ratios *e.g.*, [6]. Usually, however, we must have recourse to exploration techniques to determine the subsoil structure and deduce from there the expected amplification.

More than 40 years ago, Aki [1, 2] proposed an innovative technique (the SPAC method) which used noise measurements from a pair of stations to determine the underlying subsoil structure. Assume that we record microtremors using an array of stations on the free surface, and that we compute the cross-correlation function between different pairs of stations, at the same interstation distance, sampling different orientations on the free surface. At this point, we require two hypotheses: ambient vibration is stationary in both time and space, and the wavefield consists of dispersive waves propagating along the free surface. Under these hypotheses, Aki [1] showed that the average of those different cross-correlation functions for the vertical component takes the special form of a zero order, first kind Bessel function. In the argument of that Bessel function appear the fixed interstation distance, the frequency, and the phase velocity of the propagating waves. It is then possible to obtain a phase velocity dispersion curve using the records filtered in a series of narrow frequency bands. In recent applications of the SPAC method *e.g.*, [8, 9, 12], the seismographs have been disposed on half a circle, with a central station, recording simultaneously. This array satisfies a requirement of the method, as it allows the sampling of different azimuths between pairs of stations at the same distance to compute the azimuthal average.

[1] *Instituto de Ingeniería, UNAM, Apdo. Postal 70-472, Coyoacán, 04510 México D.F., Mexico*

[2] *Institute of Geological and Nuclear Sciences Ltd., Gracefield Road, P.O. Box 30 368, Lower Hutt, New Zealand (Member)*

In this paper we present results of the application of the SPAC method to study site response at three different sites in the Wainuiomata valley. As described below, Wainuiomata valley has received considerable attention, with many experiments being performed. This allows us to judge the reliability of the results obtained with the SPAC method. Finally, we compare transfer functions computed from the shear wave velocity profile deduced from SPAC measurements with the estimates provided by horizontal-to-vertical spectral ratios of microtremor records. Our results indicate that, where site response is large and is due to large impedance contrast between sediments and basement, the amplification function due to site effects has a simple shape and there is a prominent resonant frequency that may be readily identified from any of the different measurements currently used in the field (say single station microtremor measurements). However, where site response becomes less simple, the use of a single measurement to characterize site effects may give a wrong answer.

GEOLOGICAL SETTING AND PREVIOUS STUDIES

Wainuiomata valley is located on the southern tip of the North Island, New Zealand (Figure 1). The flat urban area of Wainuiomata has been formed by the infill of two tributaries of the Wainuiomata River; the Fitzherbert Stream and the Black Stream. The infill process is thought to be due to a combination of the following three factors; tilting of the bedrock by tectonic action, a landslide blocking the drainage passage, and aggradation in the Wainuiomata Valley building up a gravel dam.

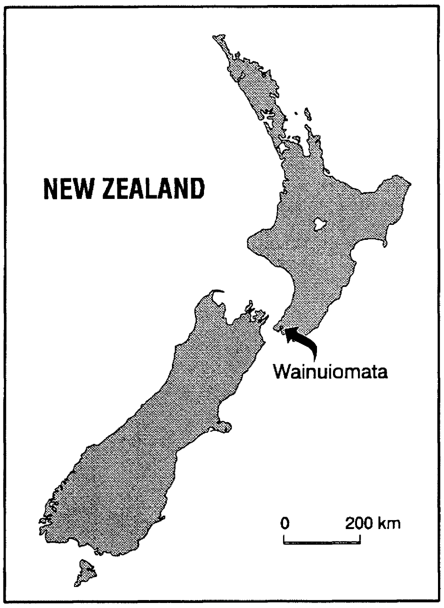

Figure 1. Map of New Zealand showing the location of Wainuiomata valley.

Pollen studies [5, 13] show that deposition of lake sediments commenced no earlier than 80,000 years ago and no later than 50,000 years ago. The presence of Kawakawa tephra of age 22,600 years near the top of the lake sediments shows that sedimentation ceased about that time.

Formation of a lake and sedimentation of the lake happened simultaneously, with the lake sometimes achieving depths of 10 metres. At 22,600 years ago, marked by a tephra layer four metres from the surface, the environment turned to a swamp. This swamp was drained in historical times and the area developed for housing. During the process of lake infilling, fan gravels partitioned the linear valleys into discreet pockets. The process of the deposition of the Wainuiomata deposits is described in [5]. The ex-lake areas of Wainuiomata have been investigated by means of CPT, seismic CPT (SCPT) and microtremor measurements as described in [3]. The microtremor measurements show how the valley systems are partitioned into discreet blocks and the SCPT probes suggest the accumulation of increasingly fine material with distance downstream. This is because decreasing shear wave velocities are observed the further downstream that the SCPT measurements are made. The ex-lake deposits have depths of up to 31 metres and they are associated with water contents (expressed as mass of water divided by mass of solids) of over 120% and shear wave velocities down to 90 metres per second.
Site response at Wainuiomata has been extensively studied. At the centre of one of the deepest deposits (WBFS of Figure 2) a vertical array of strong-motion accelerometers has been installed at depths of 0, 12 and 22 metres. These devices were installed using direct push (penetrometry) methods. In addition to that, during the year 2000, a temporary network of velocity seismographs with natural frequency 1 Hz, was deployed on the sediments of Wainuiomata, with three stations on the rock surrounding the ex-lake sediments [14]. The occurrence of 21 earthquakes during the period of temporary deployment of accelerographs has allowed the standard spectral ratios (SSR), to be determined for the 13 stations on ex-lake sediments. At the same time, long periods of microtremors were recorded at the 13 ex-lake stations, allowing HVSR values also to be determined.

A summary of all the Wainuiomata subsurface investigations has been produced [4]. Figure 2 shows the sites where SPAC was carried out (FWP, Frederick Wise Park; MCP, Mary Crowther Park; and BHP, Brian Heath Park). Site response in this area is characterized by resonant frequencies between 0.8 and 1.2 Hz, with amplification factors around 10. An additional constraint on the shear wave velocity profiles at those sites comes from Seismic Cone Penetration Tests. However, it is not planned to release these profiles until the completion of a series of microtremor-based investigations, so as not to influence the people interpreting the microtremors.

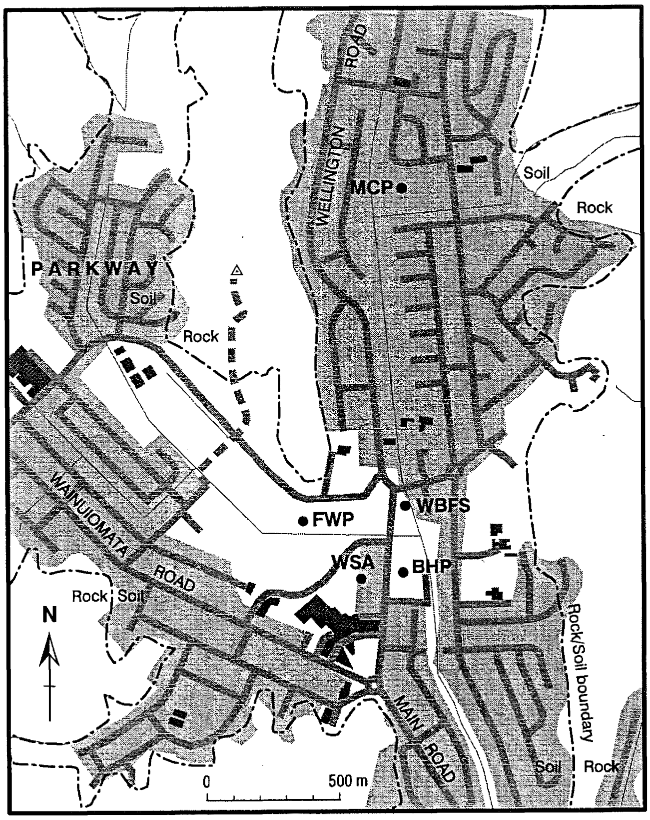

Figure 2. Map of Wainuoimata valley showing the locations of the three sites investigated: Frederic Wise Park (FWP), Brian Heath Park (BHP), and Mary Crowther Park (MCP). The gray shaded areas indicate the extent of the urbanized zone. The thick grey lines indicate roads. The dark grey polygons indicate large buildings. The thin lines indicate drains. WBFS indicates the location of the fire station where a stratigraphic drillhole was sited and where the vertical array of strong-motion accelerometers is installed.

THE FIELD EXPERIMENT AND ANALYSIS METHOD

The instruments used for the field experiment were 5 Orion 24-bit digital recorders from Nanometrics, coupled to CMG40 Guralp seismometers, with natural period of 60 seconds. Each station included a GPS receiver, for precise time keeping. The procedure used to make the measurements was the same for all three sites. We used a square array with one station at its centre. The distance between the central station and the others was initially taken as 10 m. With this configuration 35 minutes of ambient vibration were recorded. Then, we displaced the stations on the corners of the square successively to 20, 40, and 80 m distance from the centre, and repeated the measurement. Given the square shape of the array, we obtained data for two different interstation distances from each array. For example, from the first array (10 m distance to the centre, shown in Figure 3) we obtain data for cross-correlation computations at 10 m distance from pairs S2-S1, S3-S1, S4-S1, and S5-S1, and at 14.1 m from pairs S2-S3, S3-S4, S4-S5, and S5-S1. In addition, we also obtained data at 20 m interstation distance for pairs S2-S4 and S3-S5, which was included in the analysis of the data from the second array. From each of the 35 min measured windows we extracted simultaneous 1 minute length, non-overlapping windows, which were used for the computation of the cross-correlation.

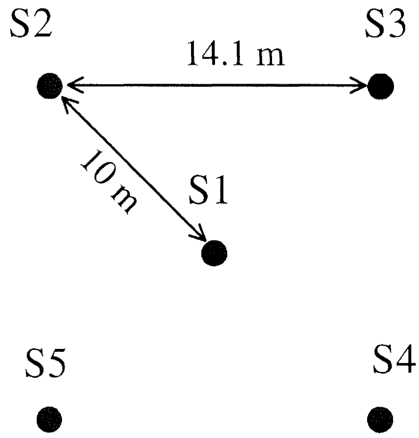

Figure 3. Example of the array configuration used. The diagram indicates the location of the stations for the 10 m aperture array. The same geometry was used for successive distances of 10, 20, 40 and 80 m from the central station.

The computation of the cross-correlation coefficients was done for all pairs of simultaneous recordings of ambient noise. The selected record windows were baseline corrected and cosine tapered. Then, they were bandpass filtered using a sequence of 30 Butterworth filters, 0.4 Hz wide. The average cross-correlation between each pair of traces was saved together with the central frequency value of the filter used. Finally, the average of all cross-correlations determined for any given distance between stations was computed. An example of the results is given in Figure 4. This figure shows the average cross-correlation computed for 4 different distances (from the arrays with 10 and 20 m distance recorded at Brian Heath Park). The theory of the SPAC method [1] requires these average curves to have the shape of a Bessel function of the first kind and zero order, J_0, of argument $\left(\frac{r\omega}{c(\omega)}\right)$, where ω is the circular frequency, r is the distance between stations, and $c(\omega)$ is the phase velocity of the medium at frequency ω.

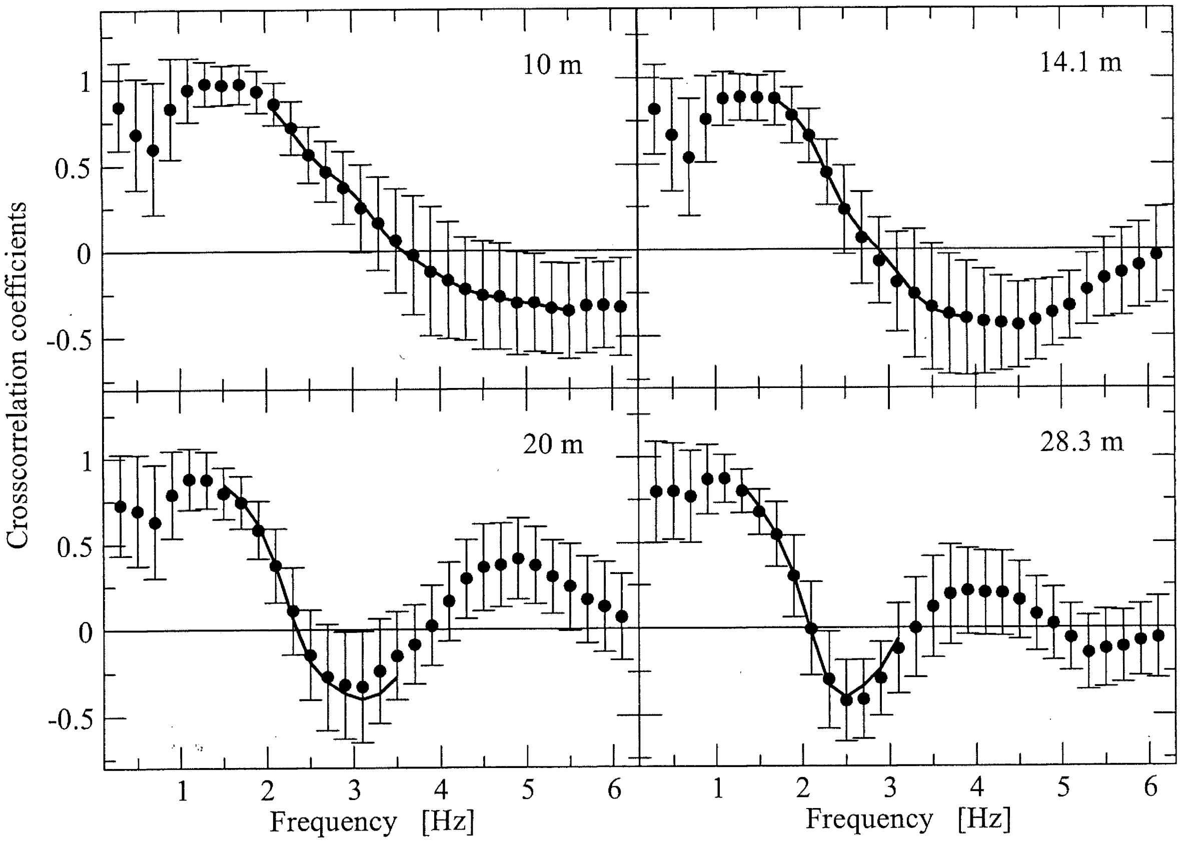

Figure 4. Example of the cross-correlation coefficients computed for 4 different interstation distances, taken from the first two arrays recorded at BHP. The solid line shows, for each distance, the function obtained from the inverted phase velocity dispersion curve. The solid line is only drawn in the frequency range that was considered reliable.

We have inverted these coefficients to obtain the function $c(\omega)$ that best fits these data. The frequency of the first zero crossing decreases with increasing distance between stations. The standard procedure for analysing these results is to invert the argument of a J_0 function that best fits the observed cross-correlation. The only unknown in the argument is the phase velocity dispersion curve. However, it is not theoretically sound to directly compute the value of the phase velocity because the cross-correlation coefficient provides an estimate of the real value, with an associated uncertainty. A standard inversion procedure allows us to use the estimate of the argument of the Bessel function to obtain an estimate of the phase velocity. Moreover, the inversion procedure also allows us to obtain an estimate of the uncertainty of the phase velocity. The theory of the SPAC method does not constrain the range of frequencies for which information is useful in the cross-correlation curves. That means that, theoretically at least, we could obtain the phase velocity dispersion curve from measurements at a single distance between receivers. In reality, however, we have observed that good results are obtained for a restricted frequency range for each interstation distance. The larger the interstation distance the lower the frequency at which results are useful. A more rigorous analysis of this issue will be presented in Rodríguez *et al.* (in preparation). For the purpose of this paper, we have accepted as reliable the cross-correlation coefficients in a region about their first zero crossing. The frequency range that was accepted was tentatively taken as going from 0.5 f_{zc} to 1.5 f_{zc}, where f_{zc} is the frequency of the first zero crossing of the cross-correlation function. The results of the inversion are shown in Figure 4 as solid lines, only for the frequency range that we considered reliable. A measure of the reliability of the results is that a single phase velocity dispersion curve was able to satisfy the measurements for all distances at any one array.

Once we obtain a phase velocity as a function of frequency, we can invert it for the shear wave velocity and thickness of the sedimentary layers below each site using standard procedures [10]. On the basis of the analysis of the errors and of the dependency of the results of the inversion on the initial model, the observed phase velocity was considered to be reliable in the frequency band from 1.1 to 3.7 Hz, in the case of BHP and FWP, and from 1.1 to 4.1 Hz in the case of MCP.

RESULTS

Figure 5 shows the final dispersion curve obtained from the data recorded at FWP. The inversion procedure requires an initial model for the phase velocity dispersion curve. We have tried several possibilities, using different functions to generate the initial model. The choice of these functions is not determinant in the results. Moreover, one of our criteria to judge the frequency range where the resulting phase velocity dispersion curve is reliable is that the results are independent of the initial model, as shown below. Figure 5 shows the results using two different initial models, $c = 200/f$ and $c = 500/f$, where c is the phase velocity of the initial model, and f is frequency. The results for the first initial model are shown with closed triangles, while those for the second initial model are shown with open triangles. We observe that, for frequencies lower than 3.5 Hz, the initial model does not influence the result. The final dispersion curve is the same for the two cases. In contrast, for frequencies higher than 3.5 Hz, SPAC measurements do not contribute significant information, and the inverted phase velocity dispersion curve tends steadily to the initial model. For frequencies lower than 1 Hz, the phase velocity tends to large values, without a bound. This indicates that measurements at low frequencies were unable to sample the phase velocity value of the underlying basement. Given that the sensors we used were sensitive at low frequencies, this suggests that the largest distances between stations were not large enough to include wavelengths related to the bedrock. The results of Figure 5 show that we can have confidence in the final phase velocity dispersion curve between 1 and 3.5 Hz.

Figure 6 shows the final dispersion curves obtained for the three sites investigated. We clearly observe that the results for FWP and BHP are very similar up to 3.5 Hz. At higher frequencies they may be different, but our results are not reliable at those frequencies. At low frequencies (about 2 Hz), the phase velocities at the two sites, FWP and BHP, go from velocities around 100 m/s to larger velocities, indicating the presence of a higher velocity substratum. The error in the estimate of phase velocity increases substantially with decreasing frequency, indicating that this substratum may not be reliably resolved. The results for MCP are significantly different from the other two sites. The phase velocity has similar values at higher frequencies, but goes to larger values at about 2.5 Hz. It reaches a plateau at 300 m/s between 1 and 2 Hz, and then goes to larger velocity values with decreasing frequency, but those points have larger errors. For frequencies higher than 3.5 (for FWP and BHP sites) to 4 Hz (for MCP site) the phase velocity dispersion curves tend to the initial model, again indicating that our SPAC measurements do not provide useful information for higher frequencies.

Figure 7 shows the inverted shear wave velocity profiles determined for the three sites. A P-wave velocity of 400 m/s was assumed for the alluvial material. As expected, the differences between FWP and BHP are marginal. Both sites show very low velocity sediments (about 100 m/s) overlying a more resistant basement. The thickness of the sediments at BHP could not be determined, but cannot be less than 30 m. At FWP, the thickness is better constrained and is about 45 m. The results for the MCP site are quite different, with a shear wave velocity gradient in the whole depth range that was investigated. No single impedance contrast could be identified. The good agreement that we obtained for all our measurements at each site indicates that the profiles given in

Figure 7 are reliable within the area covered by the arrays (a square of 80 m by 80 m) and represent the average of the subsoil structure under that square. A caveat applies, however. The phase velocity dispersion curves lack information at lower frequencies, as mentioned above. This limitation does not result from the instruments used, but rather from interstation distances that were not large enough to sample signals travelling through the underlying bedrock (see [7]). Thus, the resolution of our profiles decreases rapidly with depth, and the velocity of the halfspace is poorly constrained in all three cases.

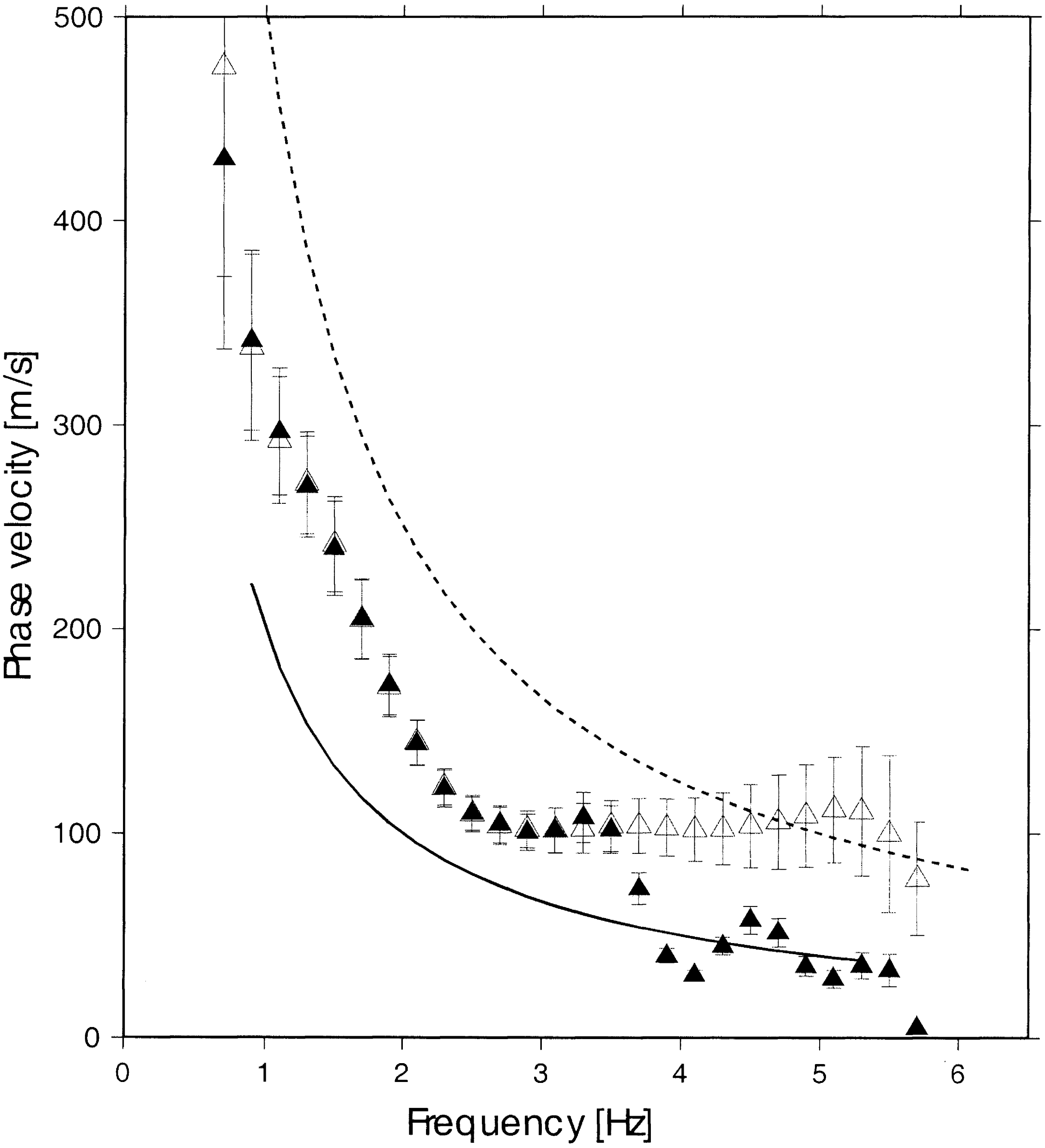

Figure 5. Inverted dispersion curve for FWP site. The solid triangles show the final phase velocity dispersion curve inverted from the cross-correlation coefficients using as initial model the curve c = 200/f (solid line). The open triangles show the final phase velocity dispersion curve when the initial model is takes as c = 500/f (dashed line). For frequencies larger than 3.5 Hz, the results of the inversion tend unashamedly to the initial model.

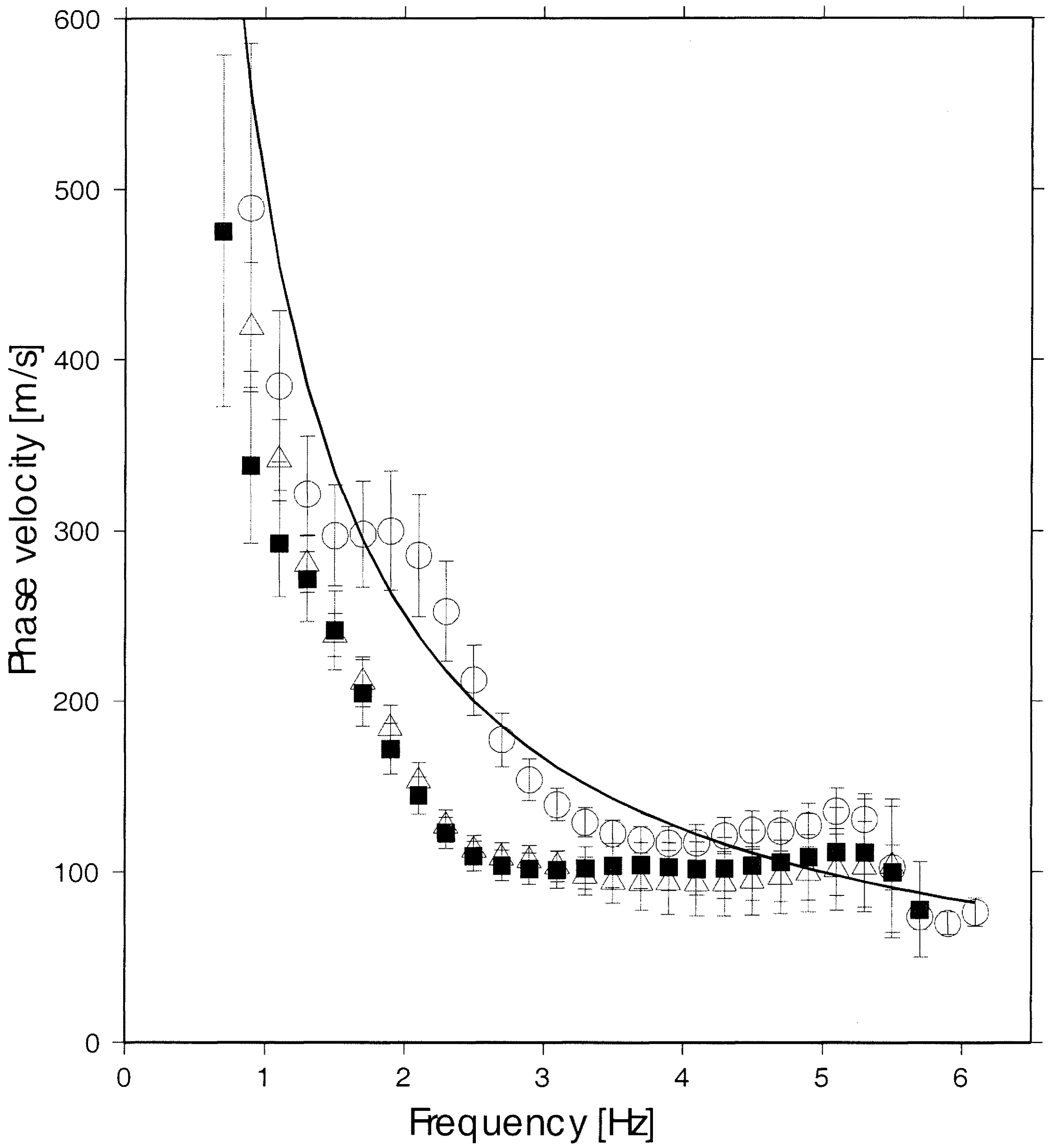

Figure 6. Inverted dispersion curves for the three sites that were investigated. The solid line shows the initial model, c = 500/f. Open triangles show the final dispersion curve obtained for BHP. Solid squares correspond to the phase velocity dispersion curve determined for FWP. Open circles show the phase velocity dispersion curve determined for the MCP site.

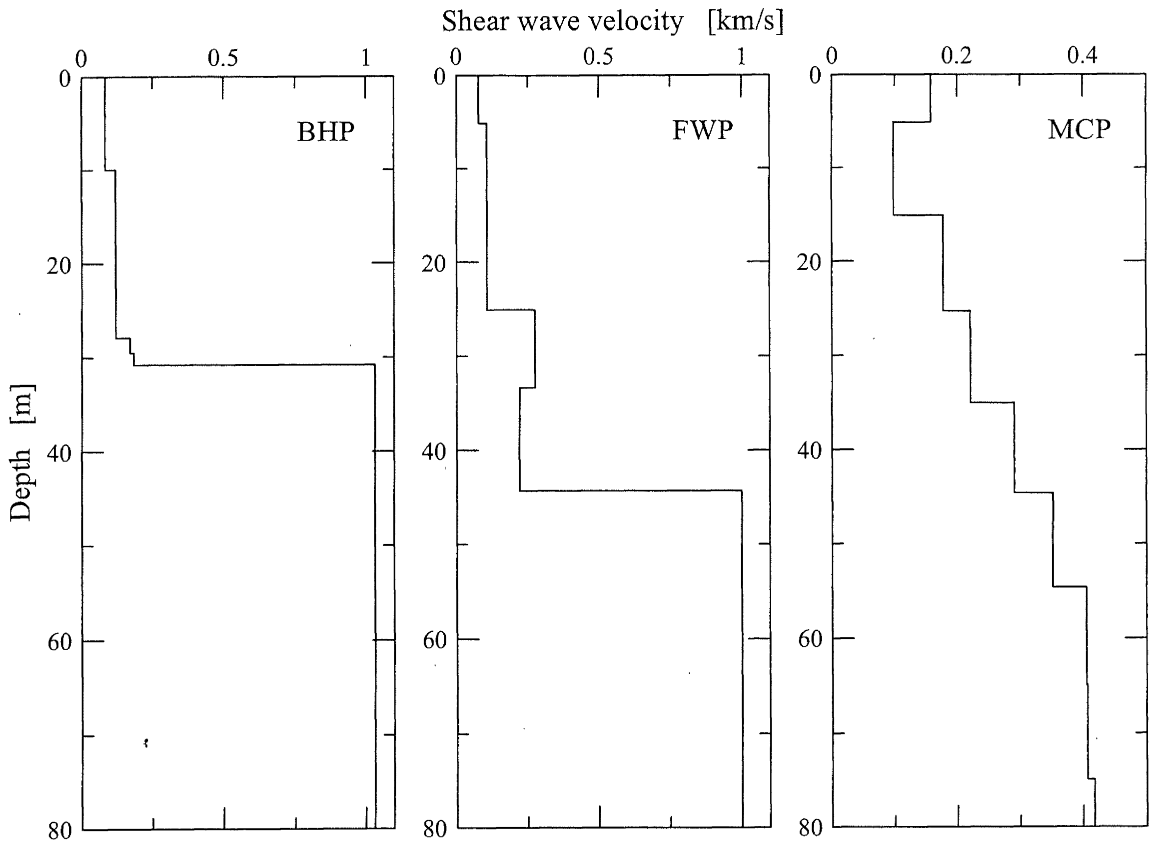

Figure 7. Soil profiles determined for the three sites investigated through the inversion of their phase velocity dispersion curves.

Finally, Figure 8 shows the expected transfer functions for vertically incident shear waves, computed for the soil profiles given in Figure 7 (solid lines). The large impedance contrast between sediments and bedrock results in large amplification at BHP (a factor 14) and at FWP (a factor of 12). The dashed lines in Figure 8 show the average of horizontal-to-vertical spectral ratios (HVSR) on noise windows recorded at one of the stations at each site [11]. We verified that the results do not depend on the particular station chosen. The two dashed lines correspond to the two horizontal components. We observe a good agreement between HVSR and the theoretical transfer functions at FWP, with only a small disagreement in the frequency of the main peak. For the BHP site, however, a large disagreement is shown in the dominant frequency of the first peak of the theoretical transfer function (at 1.0 Hz) and the peak obtained from the HVSR curves (at 0.84 Hz). This difference suggests that the thickness of the sediments was underestimated by the inversion of the phase velocity dispersion curve. Indeed, the resolution of the inversion was good only for the shallower layers. Thus, SPAC measurements could be overestimating the dominant frequency. The large amplification observed in the HVSR suggests that it gives a more reliable result (when large amplification is observed in HVSR, it usually means very reliable results, [11]). However, this discrepancy asks for additional independent estimates. The maximum amplitude of amplification at the BHP and FWP sites shows a very good agreement between HVSR and the results of SPAC suggesting that both methods are able to provide a correct estimate of the impedance contrast. The results for the MCP site are quite different from the previous two sites. The shear wave profile, without strong impedance discontinuities results in smaller amplification. The theoretical transfer function shows a peak at 1.3 Hz with amplitude 4. However, the HVSR curves suggest that the velocity gradient continues at depths greater than could be reached using our arrays. These results indicate that larger arrays are required to obtain a good estimate of the sediment thickness, which could otherwise lead to erroneous interpretations. Finally, HVSR seems to provide a reliable estimate of the transfer functions at each of the three sites for the fundamental resonance peak. For larger frequencies, the HVSR curves are flat and do not give any information. Our results show again the importance of using at least two independent estimates of site response, even if (as in this case) the same dataset is used.

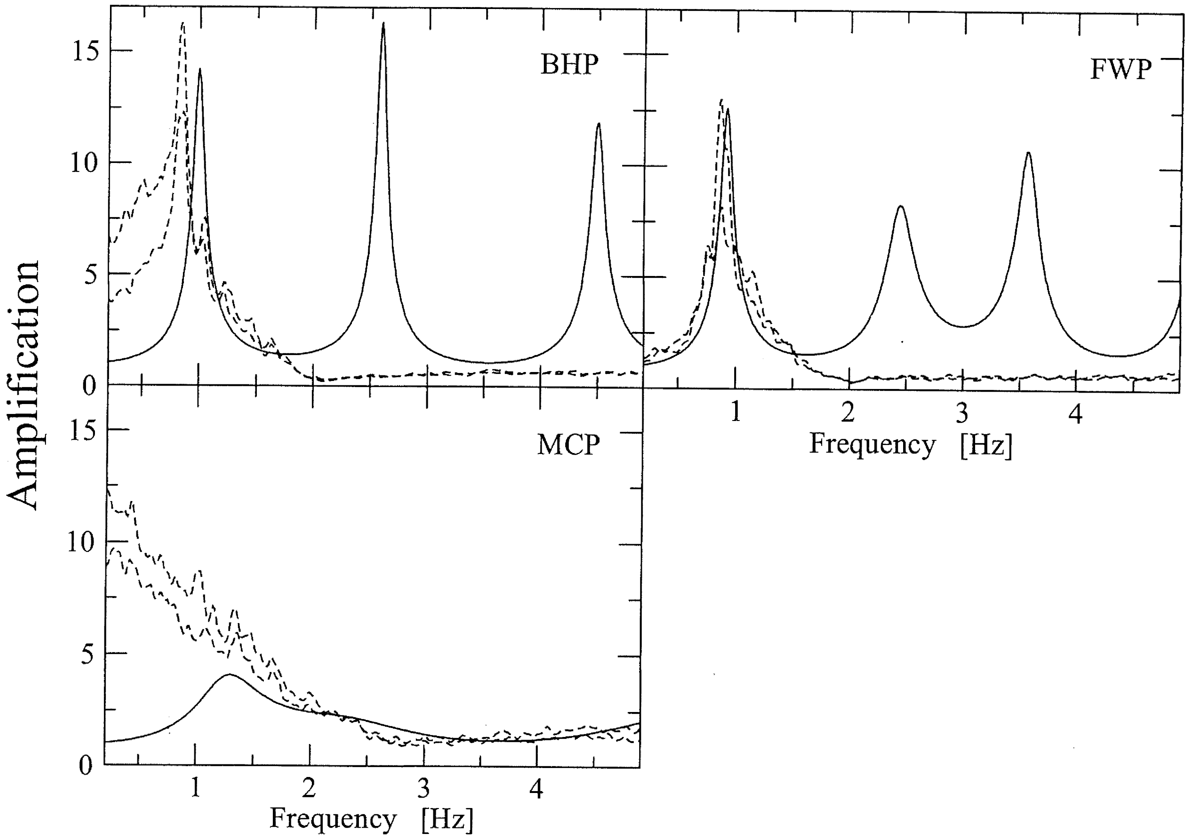

Figure 8. Solid lines: transfer functions computed for vertical incidence of shear waves on the soil profiles determined at each site investigated (BHP, FWP, and MCP). The dashed lines in each diagram show the transfer function determined using horizontal-to-vertical spectral ratios on ambient noise records at each site, one for each horizontal component.

CONCLUSIONS

We have presented an application of the SPAC method to investigate site response at three sites in Wainuiomata valley. At each site, five seismic stations were used in square arrays of different sizes to record ambient noise. Using the SPAC method, we computed the cross-correlation among records and inverted them to obtain a phase velocity dispersion curve. This curve was in turn inverted to obtain a shear wave velocity profile at each site. Finally, the theoretical transfer functions computed from these profiles were compared with HVSR of noise records. The conclusions that can be derived from our study are the following.

The SPAC method is a reliable tool for estimating a shear wave velocity profile. However, its resolution is limited to wavelengths that can be adequately sampled with the interstation distances used in the field. In our case, the larger arrays were still too small to obtain a reliable estimate of the sediment thickness in the case of BHP. Likewise, in the case of the MCP site, a shear wave velocity gradient was well identified, but not its vertical extent. With these caveats, the comparison between results using SPAC and results from HVSR was very useful for understanding the limitations of each method independently. In the case of MCP, for example, HVSR does not show a resonant peak, but this is understood in terms of the soil structure determined from SPAC. Finally, our results support the application of HVSR, which provided not only an estimate of the resonant frequency, but seems to give a good estimate of the maximum amplification factor. Our results also show (again) the importance of using at least two independent estimates of site response, even if (as in this case) the same dataset is used.

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