Universidad de Concepción
Departamento de Ingeniería Civil

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N°A01-04 NUMERICAL STUDIES LEADING TO IMPROVED MICROTREMOR RECORDING AND ANALYSIS

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ABSTRACT

Numerical simulations are used to assess the effects of different geophone natural periods, and different seismograph digitizing resolutions, on the ability of microtremor methods to identify and characterize the shear wave velocities of surface materials. This is done by progressively downgrading high-quality actual microtremor recordings so that they correspond to the output of instruments of higher natural frequencies and/or lesser digitizing resolution. It is found that the combination of low-noise, high-resolution, gain-ranging recorders and lightweight high-frequency geophones allows useful data to be recorded.

Further numerical simulations show that in the case of a low-velocity near-surface layer, our ability to record low frequencies is not matched by an ability to make meaningful inversions of the resultant dispersion curves, because widely differing properties beneath the near-surface material may make little difference to a forward-modeled dispersion curve. This is exacerbated by the tendency of low-velocity layers to not support the propagation of low-frequency Rayleigh waves. Despite this limitation array methods offer a useful way to determine Vs30.

Keywords: Microtremor, coherency, inversion, geophone, array.

1 INTRODUCTION

The role of soft soils in modifying earthquake ground shaking is of crucial importance both in structural design, and in predicting future structural damage. Soil layers can change both the amplitude and duration of earthquake ground shaking, and this soil response can be frequency dependent, involving resonance effects. A knowledge of the ability of a particular site or region to amplify and prolong ground motion is therefore important, and methods to assess ground properties have long been sought after. Microtremors – the ever-present low-level ground vibrations caused by wind, surf, traffic, and other non-earthquake sources – have been used for many years as a component of such assessments. Japanese workers have been at the forefront of such work since Kanai et al. (1954) used a zero-crossing method to estimate the natural frequency of soft layered sites. Significant early work by Aki (1957) was largely unappreciated at the time, but it laid the foundations of later work by Asten (1978) using the azimuthally-averaged coherency of microtremors. More recently, since Akamatsu (1961) recognized the dominance of surface waves in microtremors, it has been recognized (e.g. by Horike (1985)) that seismograph arrays can be used to record microtremors, a dispersion curve for Rayleigh waves obtained, and the s-wave profile obtained by inversion.

Following another thread, Nogoshi and Igarashi (1971) computed horizontal-to-vertical spectral ratios of microtremors for single sites, and associated them with the site frequency. This approach was popularized by Nakamura (1989).

Interest in site evaluations by means of microtremors led to the establishment in 2001 of the SESAME (Site EffectS assessment using AMbient Excitations) group which studied both threads extensively. Their web site is located at http://sesame-fp5.obs.ujf-grenoble.fr/. The SESAME group was formed to investigate the horizontal-to-vertical spectral ratio approach, but later included array studies.

The horizontal-to-vertical spectral ratio approach has centered on issues of instrumentation, standardization of analysis software, and interpretation of results. Included in the SESAME recommendations for HVSR instrumentation is advice not to use accelerometers, and not to use geophones with natural frequencies greater than 1 Hz. However an array method which has found favor is the slant-stack (ReMi) method of Louie (2001), which allows the use of 4.5 Hz vertical-sensing geophones. Despite the different ways of analyzing the data, this anomaly deserves further study because both methods use microtremors and should be subject to the same restraints. If ReMi works with 4.5 Hz geophones, so should the method described by Nakamura (1989).

The matter of choosing the natural frequency of a sensor such as a geophone is not trivial, because the ease of deployment of sensors depends on their weight, which in turn is related to their natural frequency. Small, light 4.5 Hz geophones are much easier to deploy than even 1 Hz geophones, and so should be used if this can be done.

Array methods have addressed issues of different types of analysis, and different methods of inversion. It is not uncommon for investigators, e.g. Horike (1985), to report shear wave velocities to considerable depths irrespective of the analysis and inversion methods used. However taking a fundamental view of the wave propagation processes which operate, one arrives at a picture, certainly in the case of sites that have a surface layer having a shear wave velocity that contrasts with the deeper material, of waves trapped near the surface. If this is true, and energy does not penetrate to depth, the wave cannot "know" about the properties of the deeper material.

This issue came to light as a consequence of inviting several practitioners to use their favorite microtremor array method on three soft sites in the Lower Hutt area, New Zealand. These three sites were MCE (McEwan Park) which has estuarine soils over deep stiff gravels; BHP (Brian Heath Park) which has lacustrine soils; and PKW (Parkway) which has swamp deposits over lacustrine deposits, with a gravel layer interposed between the two softer layers. Shear wave velocity profiles of the three sites obtained using SCPT are given in Fig. 1. All the three sites had been well characterized by using SCPT (seismic cone penetration test) but the shear wave velocity profiles were not divulged to the participants, thus achieving true blind evaluations.

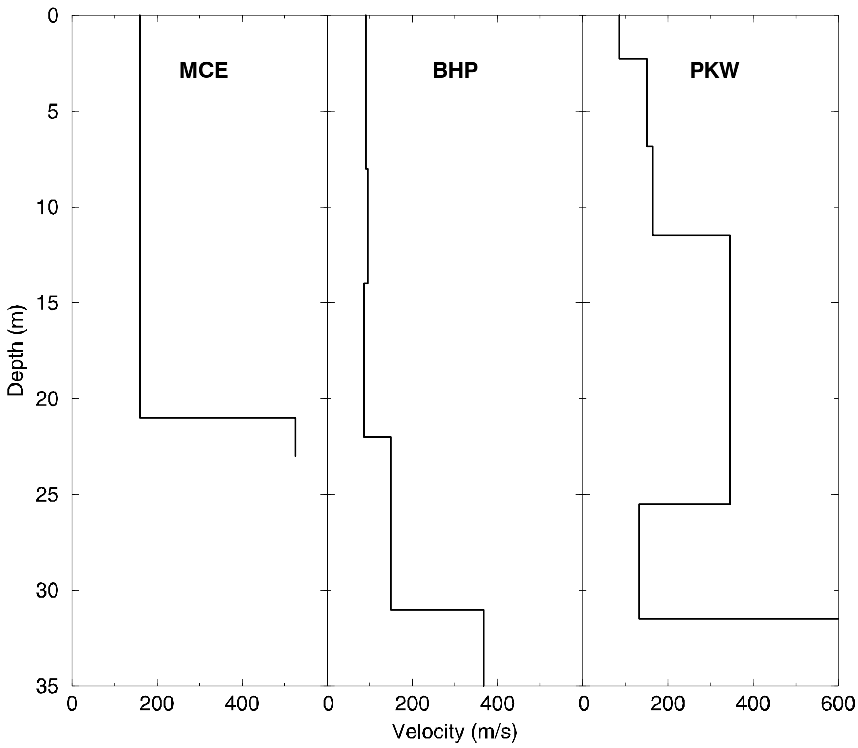

Fig. 1. Shear wave velocity profiles at the three sites discussed. MCE is McEwan Park, BHP is Brian Heath Park, and PKW is Parkway stream reserve.

Slant stack and azimuthally-averaged coherency approaches were used, the data processing details being left to individual preference. Comparing the results from the different techniques, it became obvious that they all returned values for the depth and shear wave velocity of the layer nearest the surface, which closely matched the SCPT values, but diverged on values for deeper layers. None of the methods detected the velocity inversion at the Parkway site.

2 SENSOR AND RECORDER CHARACTERISTICS

As previously mentioned, both SESAME recommendations and Louie (2001) practice are at odds regarding the choice of natural frequency for the sensors used. In a world of ideal sensors neither the parameter sensed nor the natural frequency of the sensor should matter because ratios or phase relationships are being studied, and as long as matched sensors are used there should be no problems. In the real world, the sensors introduce both instrumentation noise and digitizing noise. If these noise sources are important the data can be downgraded significantly. It has been the author’s unreported experience that a 12-bit strong motion recorder with a range of ±2g does not yield useful HVSR data even at a noisy urban site. This is presumably due to the one milli-g step size in digitizing.

A dataset which was recorded at the BHP site as described by Chávez-García et al. (2005) offers an opportunity to study the effects of sensor properties experimentally, because it was recorded on 24-bit, low-noise, gain-ranging recorders, and the ground motion was sensed by long-period three-component geophones. Each sensor was a Guralp model CMG-40T with a 30 sec natural period, and each recorder a Nanometrics ORION. At an urban site like BHP, such instrumentation will record the ground motion in the frequency range of interest faithfully, with negligible system noise or digitizing noise. This offers an opportunity to numerically simulate various other recorder/sensor arrangements to find out whether they are adequate to provide reliable HVSR curves.

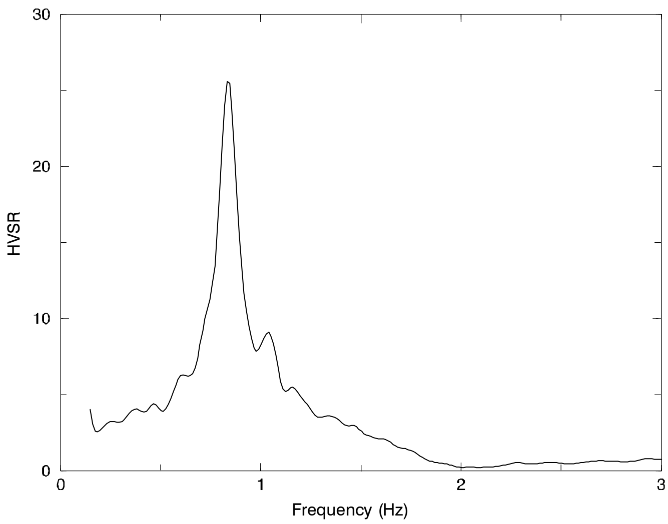

Fig. 2. Horizontal-to-vertical spectral ratio at the BHP site using original data. This curve corresponds to all cases for which high frequency geophones have been simulated, provided that low-noise, gain-ranging digitizers with 8-bit or over resolution, are used.

A selection of six instrument response types (30 sec, 5 sec, 1 sec, 4.5 Hz, and 20 Hz geophones, plus an accelerometer) was combined with a selection of seven digitizing resolutions (24-bit, 20-bit, 16-bit, 12-bit, 8-bit, 4-bit, 3-bit) and new records synthesised, corresponding to the 42 possibilities. In each case a gain-ranging digitizer with gain steps of a factor of two was simulated. The various geophone natural periods were simulated by applying an appropriate one-pole filter prior to re-digitizing. In the case of acceleration, the raw velocity record was differentiated. The synthesised records were processed to obtain HVSR values. This whole exercise was then repeated for gain-ranging digitizers with gain steps of a factor of 16, and then for a digitizer without gain-ranging, whose span was equal to the largest signal. Thus 126 simulations were performed.

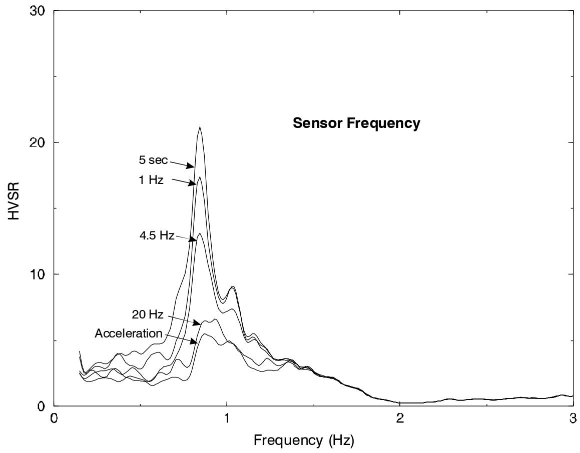

Fig.3. Horizontal-to-vertical spectral ratios at the BHP site for various sensors. A 4-bit digitizer is assumed, together with gain-ranging using 16× steps.

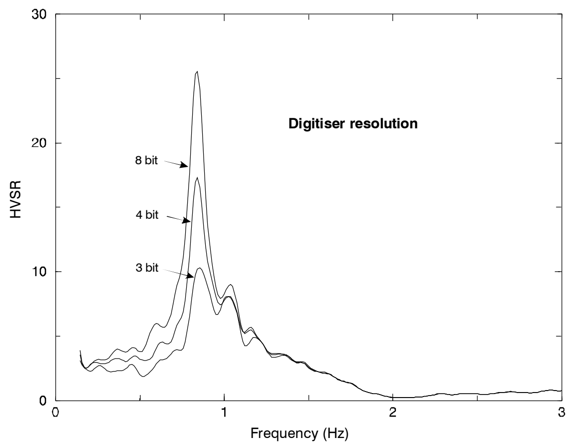

Fig 4. Horizontal-to-vertical spectral ratios at the BHP site for various digitizer resolutions. A 20 Hz geophone is assumed, together with gain-ranging using 2× steps.

In most cases the HVSR curve was unchanged from the curve of Fig. 2 which was obtained from the high quality raw data records, and only the exceptions will be illustrated from here on. HVSR curves essentially identical to the one in Fig. 2 were found for all sensor frequencies, provided that the digitizer was 8 bits or better, and that gain-ranging was employed. The exceptions are expressed in Fig. 3, which shows the effect of varying the geophone frequency, Fig. 4, which shows the effect of varying the digitizer resolution, and Fig. 5, which shows the effects of different gain-ranging steps. Note that in each case extremes were needed in some parameters in order to force a deviation from the ideal curve.

In Fig. 3 the effect of sensor frequency is examined. The digitizer resolution was restricted to 4 bits, and gain ranging with a factor of 16× adopted. As expected, higher frequency geophones with their attenuated response to low frequencies, progressively underestimated the HVSR. However the use of 8-bit or better digitizer resolution, and gain ranging with steps of 2× would have made the HVSR curves for all sensors the same.

In Fig. 4 the effect of digitizer resolution is examined. The sensor frequency was restricted to 20 Hz, and gain ranging with a factor of 2× adopted. As expected, lower digitizer resolutions with their increased digitizing noise, progressively underestimated the HVSR. However the use of 1 Hz or lower natural frequencies, and gain ranging with steps of 2× would have made the HVSR curves for all digitizer resolutions the same.

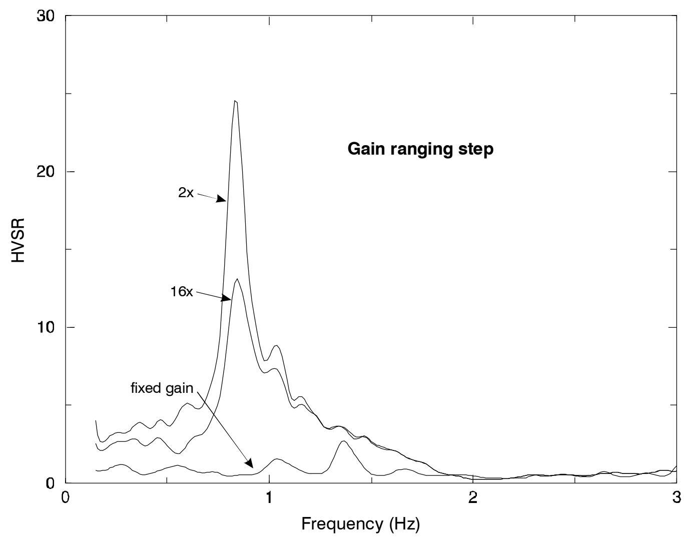

Fig 5. Horizontal-to-vertical spectral ratios at the BHP site for various gain ranging steps. A 4.5 Hz geophone is assumed, together with a 4-bit digitizer resolution.

In Fig. 5 the effect of gain ranging step size is examined. The sensor frequency was restricted to 4.5 Hz, and 4-bit digitizer resolution employed. As expected, larger gain steps progressively underestimated the

HVSR. However the use of 8-bit or better digitizer resolution, together with a 4.5 Hz geophone, would have made the HVSR curves for all gain ranging step sizes the same.

Figs 3, 4 and 5 select the few combinations of sensor and recorder which give inadequate results, and do not show the overwhelmingly great number of cases (associated with high-resolution, gain-ranging recorders) which give adequate results. Provided that the geophone and recorder have low noise, good results can be obtained from recorders with 24-bit gain-ranging analog-to-digital converters, irrespective of the sensor natural frequency.

In today's world of increasingly cheap and sophisticated electronics, 24-bit gain-ranging analog-to-digital converters are by no means unusual, and for microtremor recording they offer the prospect of miniaturized equipment. This is because the weight of a ground motion sensor is a function of its natural frequency, with higher frequencies being associated with smaller, lighter sensors. The simulations reported in this paper suggest that for typical urban sites, digitizing noise is only important when outmoded low-resolution, non-gain-ranging analog-to-digital conversion is employed in conjunction with high-frequency sensors.

3 INVERSION OF DATA

The concept that surface waves sample depths of soil according to their wavelength is common to all array methods. Such sampling is the origin of the dispersive nature of surface waves in layered materials. It follows that an inversion in some sense is necessary to obtain a shear wave velocity from microtremor data. In the cases of Louie (2001) and Roberts and Asten (2005) the inversion uses a manual iterative approach, with one curve being matched to another by eye. Such human intervention may unwittingly incorporate other information such as that velocity increases with depth. However, it should be possible to remove human influence by implementing a machine inversion. This was attempted in the case of microtremor array data recorded at the BHP site, by incorporating forward modeling of a layered site in order to derive a theoretical azimuthally-averaged coherency, in a simplex optimization routine. For this site there was no swift convergence to a single acceptable model, and each initial model chosen led to a different matched model – in a word, the inversion is pathological. However when the automatic simplex-based approach was restricted to optimizing a single layer over a half space, it swiftly obtained values of shear wave velocity and depth identical to the values given by the Louie (2001) and Roberts and Asten (2005) methods. This result is in accordance with the idea that, being surface waves, microtremors can be trapped within a surface layer, and thus be unable to yield information on the properties of deeper layers.

Even if the microtremors could penetrate below the surface layer there remains a doubt as to whether deeper layers could perturb a dispersion curve sufficiently to be observable through the uncertainties in the dispersion curve. The BHP and PKW sites have been investigated in this regard, by determining theoretical fundamental-mode Rayleigh wave dispersion curves. In the case of BHP, the approach was simply to replace the 9 m thick second layer with an extension of the top layer, this extension having the same vertical shear-wave propagation time as the 9 m thick layer. In the case of PKW, a trial and error approach was adopted, until a profile below 11.5 m, not having a velocity inversion, led to a dispersion curve that approximated the case with an inversion. In all trials the matrix propagator software described by Herrmann (1996) was used.

The results are displayed in Fig. 6 for BHP and in Fig. 7 for PKW. In each case a vertical dashed line marks the expected frequency of the uppermost layer. In each case the calculated dispersion curves for the alternative models lie very close to each other, and in the presence of noise it would be hard to distinguish between them.

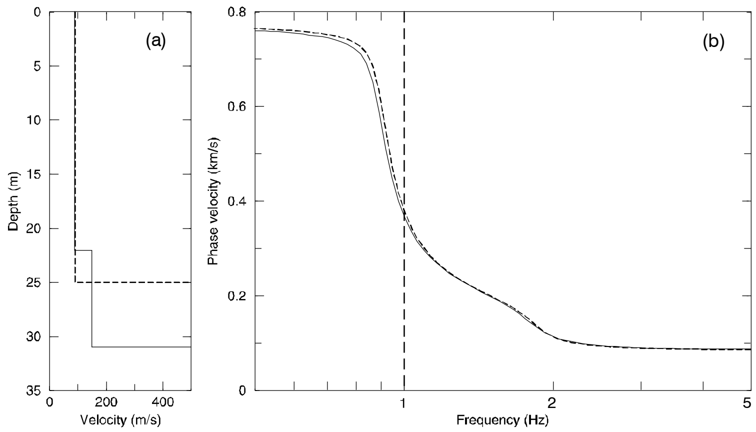

Fig. 6. (a) Alternative shear wave profiles assumed for the BHP site. (b) Dispersion curves corresponding to the profiles of (a). Dashed vertical line marks the frequency below which Rayleigh waves are thought to cease dominating.

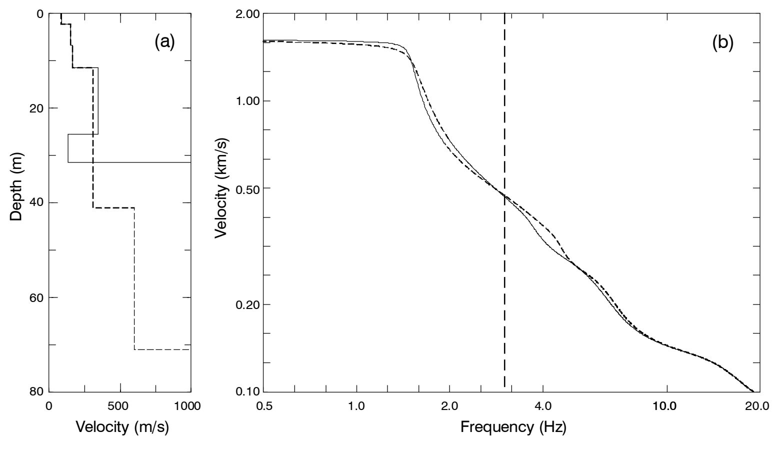

Fig. 7. (a) Alternative shear wave profiles assumed for the PKW site. (b) Dispersion curves corresponding to the profiles of (a). Dashed vertical line marks the frequency below which Rayleigh waves are thought to cease dominating.

3.1 Useful Frequency Range of Inversion

In the previous section it was shown that in certain cases two different soil models can have very similar dispersion characteristics. In the case of BHP (Fig. 6) the differences in dispersion are chiefly expressed below 1 Hz. If indeed the 22 m thick surface layer acts as a high pass filter to propagating waves, it would be expected that above about 1 Hz microtremors would consist mainly of Rayleigh waves crossing the basin, but that moving below 1 Hz there would be an increasing contribution from other non Rayleigh wave phenomena. The existence of the array recordings described by Asten et al. (2005) offers an opportunity to investigate this, because motion not corresponding to propagating waves will lower the coherency between network stations.

The result of a computation of azimuthally-averaged coherency for vertical motion at the BHP site is shown in Fig. 8. As shown in Asten et al. (2005) the array at BHP was hexagonal, the hexagon sides being 15 m in length, and a seventh station being at the centre of the hexagon. One station did not operate correctly, so data from four triangular arrays with 15 m sides were able to be averaged, albeit with only three unique inter-station azimuths. The azimuthally-averaged coherency for pure Rayleigh waves is expected to decrease monotonically with frequency from zero up to the first zero crossing (as shown conceptually by the dashed line in Fig. 8), because coherency decreases with increasing frequency and it also decreases for the lower propagation velocities associated with higher frequencies. Monotone decrease is not seen below 1 Hz for BHP, implying that the top 22 m thick layer indeed filters out lower frequency Rayleigh waves, and makes the inversion of dispersion data meaningless at the very frequencies required to distinguish the 1-layer and 2-layer cases.

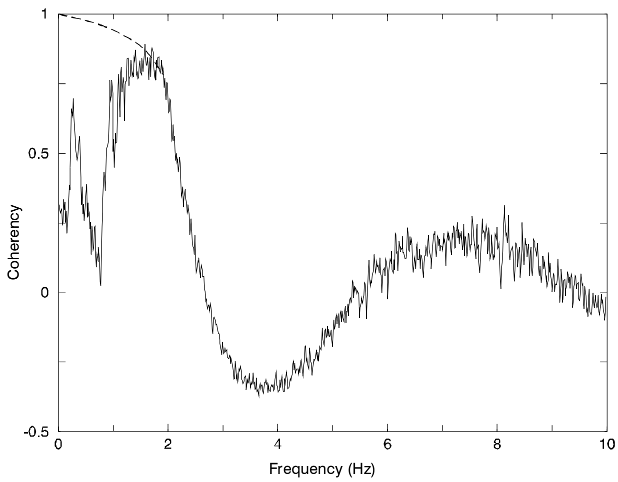

Fig. 8. Azimuthally-averaged coherencies for the BHP site, using triangular arrays with 15m sides. Dashed line shows the expected form of coherency if Rayleigh waves dominate the microtremors.

Similar reductions in azimuthally-averaged coherency for frequencies less than that associated with the top layer were also seen at the MCE and PKW sites, but are not shown here.

3.2 Array Layouts

In the work described by Asten et al. (2005), which provided the microtremor data described here, the array used at BHP comprised a regular hexagon of stations, plus one station at the centre of the hexagon. This layout is intended to provide a good approximation to azimuthal averaging of the inter-station coherencies. The hexagonal arrangement indeed provided useful data. However when azimuthal averaging is considered for an inter-station distance corresponding to one hexagon side it is seen that there are only three basic azimuths involved. For this inter-station distance a triangle of stations is equivalent to a hexagon of stations, except that averaging is improved with the hexagon due to more data being accumulated. Naturally a hexagon also offers a range of other inter-station distances. Given that the coherencies derived for this paper using triangles led to an adequate characterization of the top layer, and that it is only the top layer that can be well characterized, there is good reason to adopt a simpler triangular array layout for microtremor array studies.

4 COMBINING HVSR AND ARRAY APPROACHES

It is commonly believed that the natural frequency of a resonant site will be manifested by a peak in the HVSR. The MCE and BHP sites each have a significant velocity contrast at 20 to 30m depth, and should accordingly be resonant, and show the peak. This is indeed the case for BHP (see Fig. 2) but is not the case for MCE. Fig. 9 shows the HVSR curve derived from the data for MCE in Asten et al. (2005).

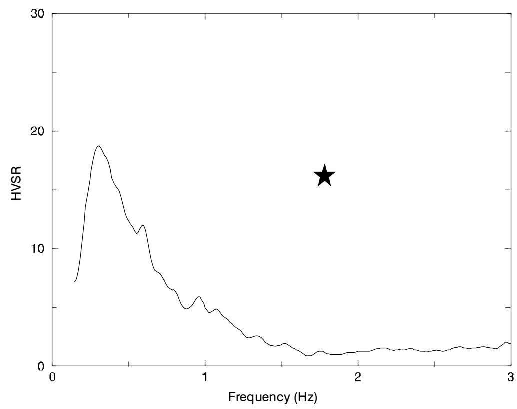

Fig. 9. Horizontal-to-vertical spectral ratio at the MCE site. Asterisk marks the frequency at which a peak is to be expected on the basis of resonance of the top, 21m thick, soil layer.

The 1.9 Hz site resonance peak is expected to appear where an asterisk is shown. The peak at 0.3 Hz does not have the narrow character of a site resonance such as in Fig. 2, and its origin is unknown. Other cases are known to the author where either a resonant site does not have a peak in microtremor HVSR, or a non-resonant site does show a peak in HVSR. As a matter of routine, a three-component sensor should be incorporated in all array layouts (or from a different perspective any HVSR instrumentation should be augmented with two other vertical-sensing geophones to make an equilateral triangle array). By taking this approach it should be easier to avoid pitfalls in what is still a maturing field.

Even though array methods may not deliver accurate shear wave velocities for deeper materials, their good characterization of the top layer will in many cases provide a useful approximation to Vs30 (the mean shear wave velocity based on travel time to a depth of 30 m). Vs30 is widely regarded as an important parameter in assessing the hazard at soft sites.

5 CONCLUSIONS

This study has found that in using microtremors to characterize a site with a highly contrasting surface layer, the sensor requirements are much less demanding than has been believed, and that any conclusions drawn about shear wave velocity profiles should be restricted to the top soft layer.

Useful contributions to site studies can be made by deploying equilateral triangular geophone arrays and then recording microtremors at the array stations using low-noise, 24-bit, gain-ranging recorders. The geophones may be high frequency, and at least one should sense three components of motion, the other two only needing to record the vertical component. The array side dimension may be as little as 20 m. The recordings should be analyzed using both azimuthally-averaged coherency to determine the shear wave velocity profile at the site, and the horizontal-to-vertical spectral ratio at one site in order to identify site resonances. The array-determined shear wave velocity profile at the site in turn can give a good approximation to Vs30.

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