COMPARISON OF SITE RESPONSE DETERMININATION TECHNIQUES IN THE WELLINGTON REGION, NEW ZEALAND

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SUMMARY

Microseismic data from short-period and broadband seismographs have been used to compare the site response determined from sediment/rock site spectral ratios and horizontal to vertical component (H/V) spectral ratios (Nakamura's technique). The H/V ratios were calculated using both microseismic noise and microearthquakes. In the Hutt Valley, Wellington, an alluvial valley with up to 300 m of sediment, the broadband H/V ratios showed both a whole basin resonance (0.5-0.6 Hz) and a 1.5-2 Hz resonance in the top 20-30 m of soft sediment. The frequencies of the H/V ratios agreed with the sediment/rock ratios but the H/V ratios generally underestimated the sediment/rock amplitudes. The difference in the amplitudes between the two techniques was not consistent and thus the H/V ratio would not be effective in determining the ground shaking hazard over a region of varying geology.

INTRODUCTION

One goal of microzonation studies is to find the easiest and most cost effective way to identify the areas in cities that are most at risk from amplified ground shaking, particularly in areas where there is limited geotechnical information from boreholes or shear wave velocity studies. A common technique is to use short-period (1 Hz) sensors to record seismic noise at many sites and then to calculate the approximate response using a ratio of the spectra of the horizontal to vertical components of the noise (HVNR)[Nakamura, 1989]. Ratios of the horizontal to vertical spectra of the S waves of earthquakes (HVSR) have also been used to estimate the site response without the need for a reference site [Lermo and Chavez-Garcia, 1993]. There is general agreement that HVSR and HVNR give a good approximation of the fundamental period of resonance of a site [*eg*. Field and Jacob, 1995], but much less agreement as to whether the HVSR and HVNR amplitudes are of any practical use. In general the HVSR and HVNR underestimate the amplitude determined from sediment/reference site ratios (SRR) [*eg*. Lachet *et al*., 1996]. However some authors have found the relative levels to be similar to modelled amplitudes, particularly in areas where the subsurface can be approximated by a 1D model [Konno and Ohmachi, 1998]. The purpose of this study has been to compare HVSR and HVNR to SRR for a range of geologic conditions using both short period and broadband sensors.

This study considers only amplifications due to small ground motions where no non-linear effects would be expected. While non-linear effects are likely in a damaging earthquake, areas of greater damage have been well correlated with areas of high linear amplifications [Boatwright *et al*., 1991; Hartzell *et al*., 1996]. The degree of non-linearity in both amplification and resonant period to be expected is still an area of debate [eg. Field *et al*., 1998], and thus the goal of weak motion studies is to estimate the relative, not absolute levels of ground shaking.

Much of the focus in the classification of sediments has been on the top 30 m, because the shallow sediments appear to have the greatest influence on the surface shaking [Hartzell *et al*., 1997]. However some studies have shown that some of the variability in surface response can be due to focusing effects from structures at 1-2 km depth [Hartzell *et al*., 1997; Gao *et al*., 1996] and the long period shaking can depend on the total thickness of a

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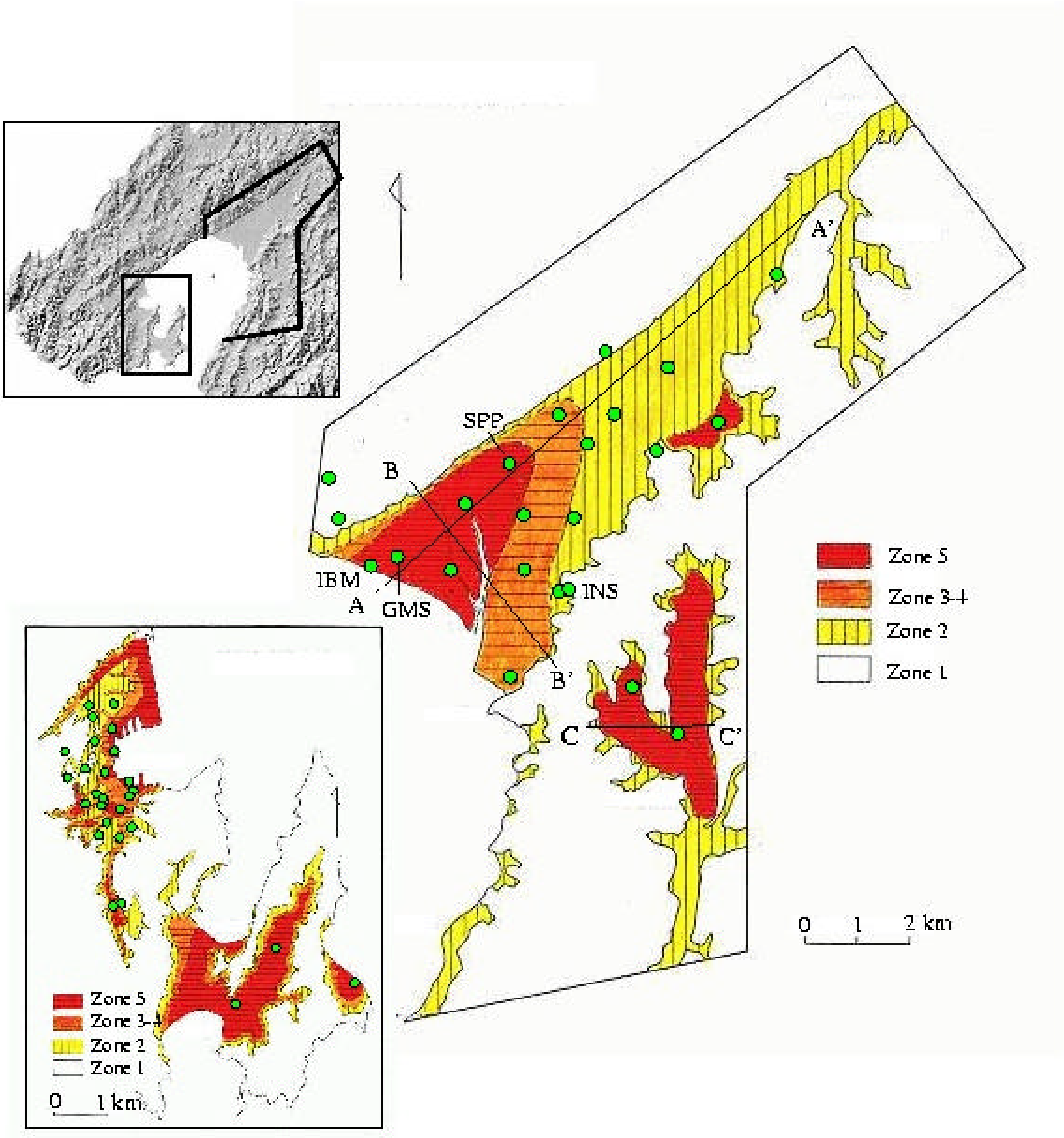

Figure 1. Ground shaking hazard maps for Lower Hutt and Wellington [Van Dissen *et al*., 1992a,b]. Inset shows relative location in the Wellington region. Circles are temporary seismograph stations used in the Lower Hutt (right) and Wellington (left) studies, with the named sites also used in the broadband deployment. Zone definitions: Zone 1: bedrock, Zone 2: compact alluvial and fan gravel, up to 200 m (LH) or 120 m (Well) thick, Zone 3-4: up to 20 m of interfingered layers of soft sediment (fine sand, silt, clay, peat), and compact gravel and sand with not more than 10 m of soft sediment, Zone 5: more than 10 m of soft sediment with shear wave velocities on the order of 200 m/s or less, underlain by up to 270 (LH) or 150 (Well) m stiff sediment.

basin [Ibs-von Sent and Wohlenberg, 1999]. In this study we compare the resonant frequencies determined from short period and broad band recordings to a recent 2D finite-element model [Adams *et al*., 2000].

DATA

Three primary weak-motion data sets have been used in this study. The first two were collected for regional ground shaking hazard assessments of Lower Hutt and Wellington, New Zealand in 1991-1992 [Taber and Smith, 1992; Van Dissen *et al*., 1992a; Taber and Richardson, 1992; Van Dissen *et al*., 1992b]. The site responses were presented as SSR, using single rock sites on the edge of each region. The result of the studies, which also included analyses of strong motion records and borehole information [McVerry and Sritharan, 1992; Stephenson and Barker, 1992] were ground shaking hazard maps divided into four shaking zones (Fig. 1). There were 23 seismograph sites in Lower Hutt and 27 sites in Wellington. These studies used 1 Hz Kinemetrics L4C-3D. The third dataset, consisting of broadband seismograms, was collected in Lower Hutt in 1998.

The Lower Hutt Valley runs approximately NE-SW and is 12 km long with a maximum width of 4.5 km (Fig. 2). The alluvial and marine sediments extend to a maximum depth of 300m at the coastline. The soft sediment (post-glacial sands, silts and minor gravels) gradually thickens to the southwest and reaches a maximum depth of 30 m near the current shoreline [Dellow *et al*., 1992].

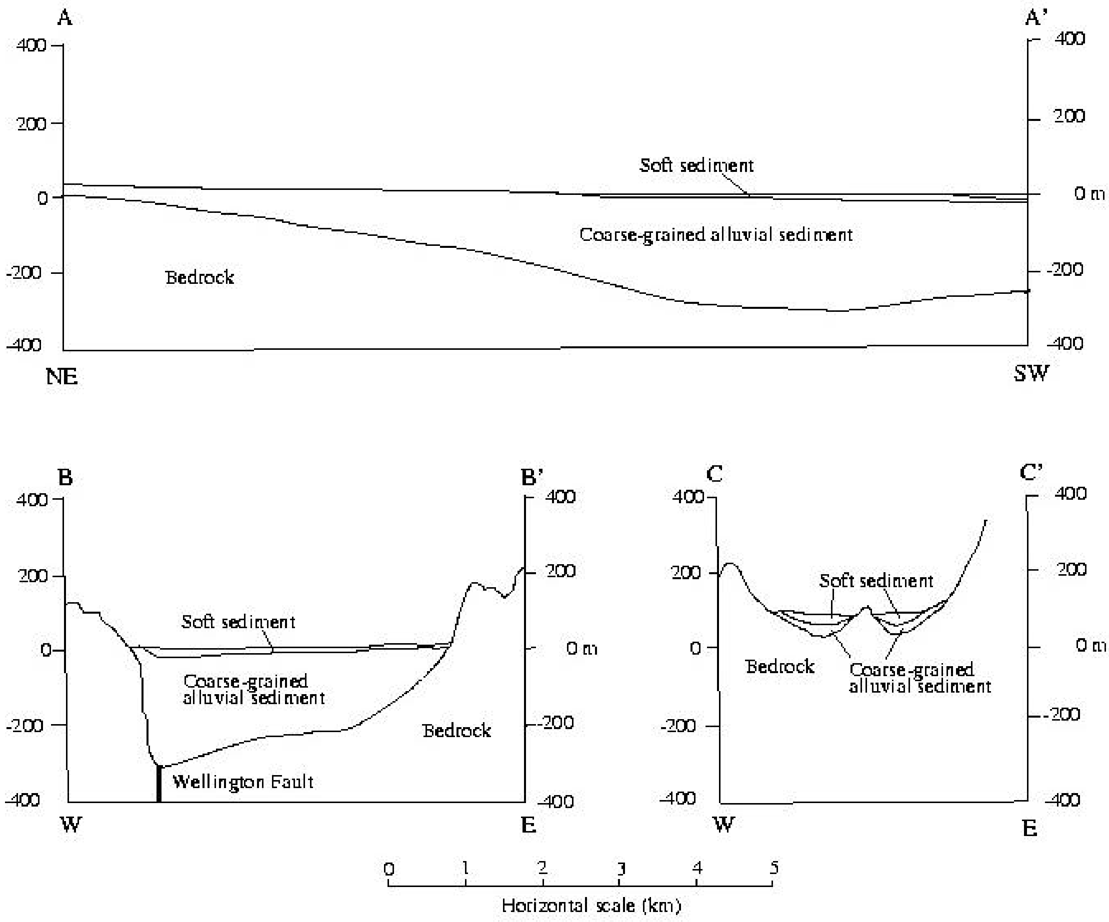

Figure 2. Lower Hutt cross sections [Dellow et al., 1992]. Locations shown in Figure 1.

Four of the sites used in the Lower Hutt survey were reoccupied for a 3 week period in January 1998 using broadband seismographs to examine the longer period response of the valley. The reference sensor (station INS) was buried in highly weathered greywacke at the edge of the valley and the other three were placed on concrete floors in low buildings on the valley floor. Three of the four sites were in exactly the same position as in the earlier short-period study and the fourth was sited about 100 m from the short period sensor location. The seismographs consisted of Guralp CMG40T sensors and Nanometrics Orion recorders, using 100 Hz sampling.

Six local earthquakes that were clearly recorded at all sites were chosen for analysis. The earthquakes ranged in magnitude from 2.8 to 4.3 and occurred 20 to 125 km from the array. None were large enough to be felt in the Lower Hutt area. Twenty seconds of data were selected from each trace, starting 0.5 seconds before the S wave arrival. For each trace the mean was removed and a 2% Hanning taper was applied before calculating the Fourier amplitude spectra. The spectra were then smoothed with a 0.2 Hz triangular window. Ratios were taken using individual horizontal components as well as the RMS of the north and east components. As there were only minor differences between the north and east components, only the RMS results are shown here. Each noise record used in the HVNR analysis was also twenty seconds long. The noise segments were individually selected to avoid large local noise sources.

BROADBAND SITE RESPONSE

The response at the broadband sites was examined using all three ratio techniques. The HVSR and HVNR are compared in Figure 3 along with the short period HVSR determined from recording made during the previous deployment. The frequencies of the fundamental and secondary resonances are nearly the same for both techniques, though the amplitude of the secondary resonance is lower for the HVSR and all higher frequencies.

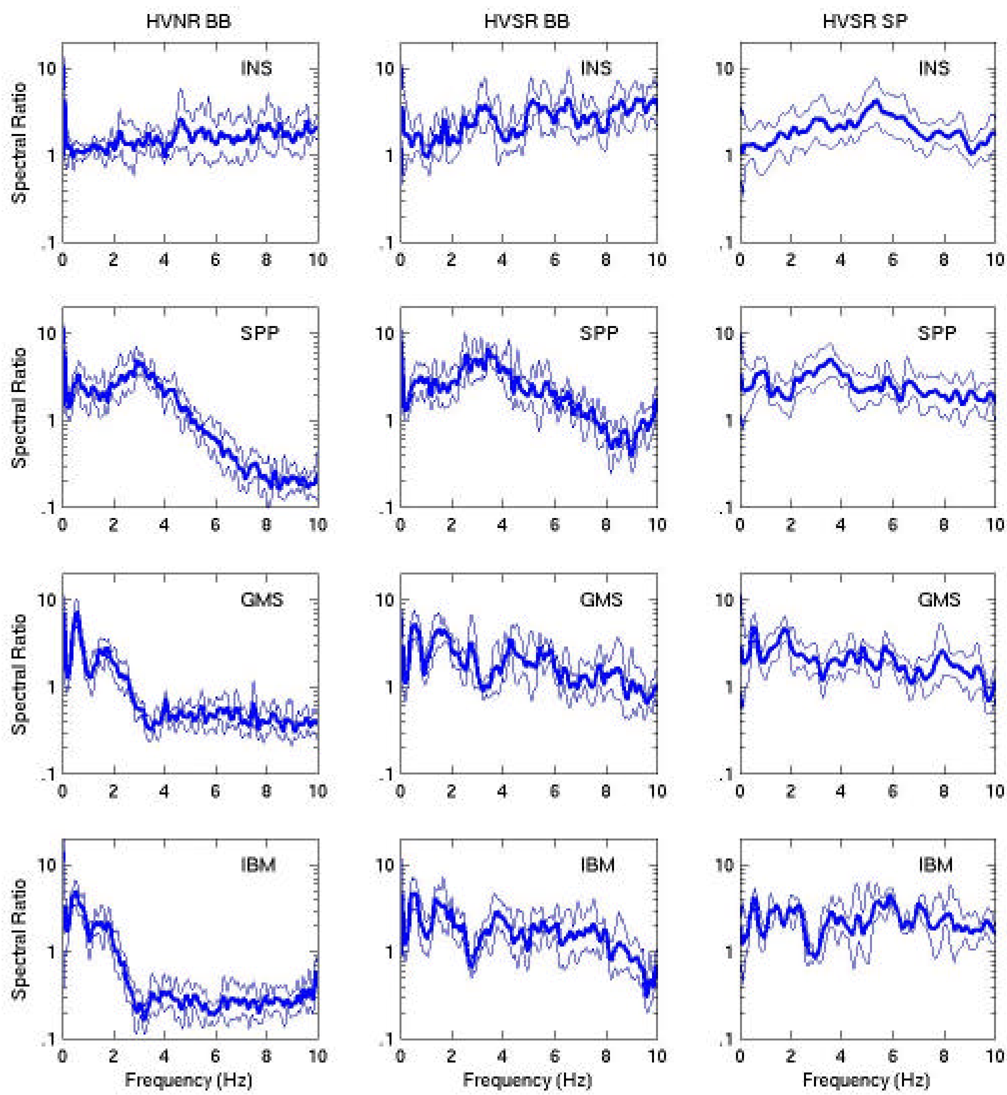

Figure 3. Lower Hutt spectral ratios for the four broadband sites. The mean (dark line) and +/- 1 standard deviation (light lines) are shown for each site. Left and centre columns show the broadband HVNR and HVSR broadband ratios and the right column shows the short period HVSR. The RMS of the north and east component is shown in each case. INS is the reference site.

The scatter in the HVNR appear to be about the same as the HVSR. The short period HVSR are also shown in the figure and are similar to the broadband response, though a different set of earthquakes has been used (3 to 26 events per site) and the short period sensor response decreases rapidly below 1 Hz. Both the HVSR and HVNR show resonances at 2 frequencies for all three basin sites. All three sites have one peak in the range of 0.5-0.6 Hz and a second peak near either 1.5 or 3 Hz. The strong low frequency resonance is most evident at IBM and

GMS. This frequency is consistent with the fundamental basin frequency predicted by recent 2D finite element modelling [Adams *et al*., 2000] and is also consistent with the longer period response evident in several strong motion records [McVerry and Sritharan, 1992]. There is a small increase in the fundamental frequency (0.5 to 0.6 Hz) as the depth to basement decreases from 300 to 275 from IBM to SPP. Thus the broadband HVSR might be effective in mapping the depth to basement as suggested by Ibs-von Seht and Wohlenberg [1999], who found a close correlation between resonant frequency and basin depth as determined from boreholes.

While the fundamental frequency and the next higher resonance are separate in the HVSR, the separation is less clear in the SSR (Fig 4). The SRR at site SPP is lower than at GMS or IBM from the fundamental frequency to about 2 Hz. Above 2 Hz the amplification is higher at SPP. This is similar to the short period results [Taber and Smith, 1992]. The higher frequency resonance, which varies from 1.5 to 3 Hz, is consistent with a simple 1D ¼ wavelength resonance estimate for the soft sediment thickness, which increases from approximately 15 to 30 m from SPP to IBM.

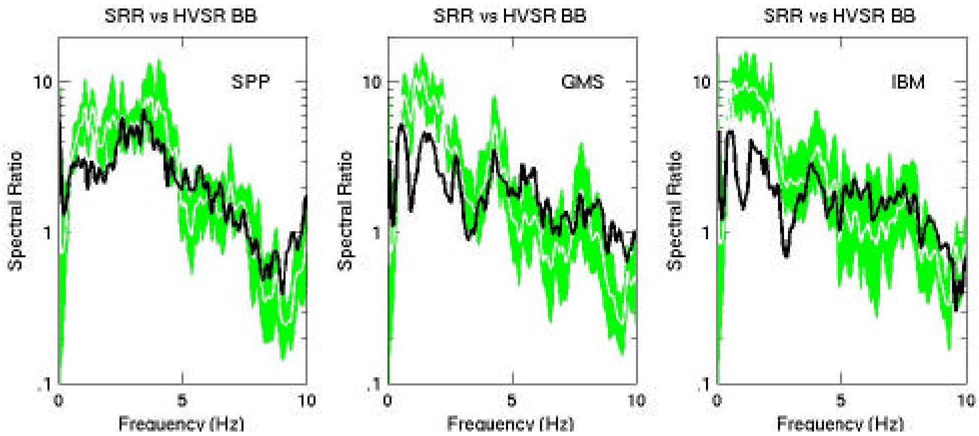

Figure 4. Comparison of broadband SRR (mean +/- 1 standard deviation) and HVSR (dark line) for three Lower Hutt sites.

It has been suggested that whole basin resonances might not be excited by the small earthquakes recorded in the original hazard study, and that is why a longer period response was observed in the strong motion data but not the weak motion data at L05 [Sritharan and McVerry, 1992]. However, the fundamental does appear to be excited by both microseismic noise and the small earthquakes used to calculate the HVSR in Figure 3. The same earthquakes show the fundamental resonance to be of no greater amplitude than the shallow resonance in the SRR. The fundamental resonance might become more important in a large earthquake as non-linear effects are more likely in the soft sediment surface layer than in the deeper layers which are primarily gravels and stiff sediment.

HVSR SHORT PERIOD RATIOS

The earlier SRR and ground shaking hazard zoning [Taber and Smith, 1992; Van Dissen *et al*., 1992a] was used as the basis for evaluating the HVSR in Lower Hutt. Figure 5a compares the peak amplitude of the SRR and HVSR in terms of the ground shaking hazard zones (defined in Fig. 1). In addition sites in the highest hazard zone were split into sites which exhibited a strong resonance at a particular frequency and those that did not. The maximum amplitudes of the HVSR were slightly lower than the SSR for sites in Zones one to four, but for Zone five sites, especially those with resonant characteristics, the HVSR were much lower than the SSR. In the extreme case, at a site with 30-35 m of soft sediment with a shear wave velocity of 90-150 m/s [Stephenson and Barker, 1992], the maximum of the HVSR was around six while the SRR was about 20. In general, the more narrowly peaked the resonance, the greater the underestimation. The narrowly peaked resonance generally corresponds to a high impedance contrast between the soft sediment and the next layer.

The maximum amplitudes of the HVSR demonstrated no clear distinction between zones. For example, a Zone 1 site (rock) had a maximum ratio of five, while four of the Zone 5 sites had maximum ratios less than five. In contrast, the SRR agreed with the ordering of the zones as expected, since they were one of the elements used to determine the original zones. However there was some overlap, since the final map boundaries were based primarily on the soft sediment thickness contours. In addition, the Zone 5 boundary was based on the high amplitude long period response seen in limited strong motion records near site SPP [Sritharan and McVerry, 1992]. A comparison of the ratio amplitudes using the average horizontal spectral amplification (the average of the amplitude over the 0.5-2.5 Hz frequency band) suggested by Borcherdt [1991] produced similar results to the peak ratio comparison.

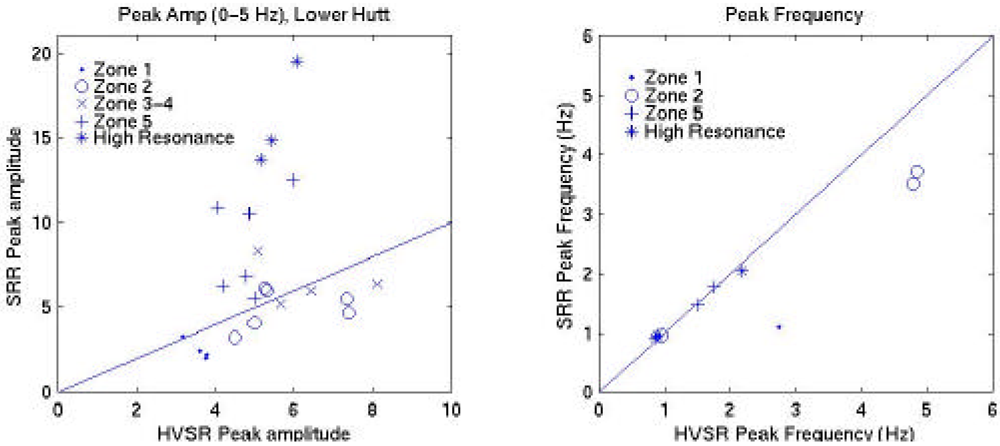

Figure 5. Lower Hutt short period SSR vs HVSR, with symbol type showing the ground shaking hazard zone. a.(left): peak amplitude ratio, b.(right): Frequency at peak amplitude ratio.

As has been observed in other studies, in cases were there was a clear resonant peak in the SRR, the frequency of the HVSR peak generally coincided with it (Fig 5b). When the resonance was less clear, for example at the Zone 1 and Zone 2 sites, the difference in frequency at which the peak amplitude occurs could be greater.

In contrast to the Lower Hutt sites and two other sedimentary basins in the Wellington region (McLauchlan and Taber, 1999; Winthrop, 1998), the HVSR for the Wellington City array are in general of greater amplitude than the corresponding SRR (Fig 6a). The Wellington reference site in this case was defined as the average of two separate rock sites. A similar result was found using HVNR and only one of the two rock sites (Taber and Clitheroe, 1996). As different reference sites were used in the Wellington and Lower Hutt studies, it was suspected that the Wellington reference site must have a higher amplification than the Lower Hutt reference site, perhaps due to topographic effects as it was located near the top of a steep hill.

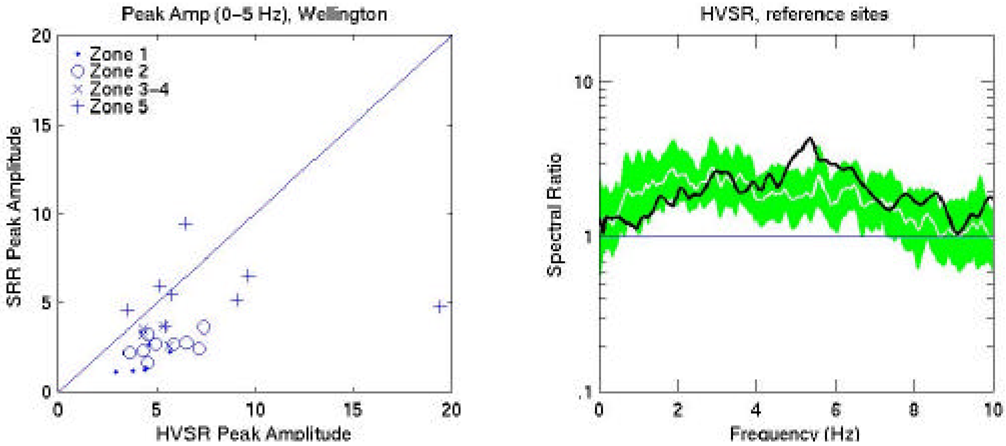

Figure 6. a.(left): Comparison of the peak sediment/reference site spectral ratio to the earthquake horizontal to vertical spectral ratio in Wellington. b.(right): Comparison of the Wellington reference site HVSR (mean +/- one standard deviation) to the Lower Hutt reference site HVSR (dark line).

The HVSR for the Wellington reference site is not significantly higher than for Lower Hutt (Fig 6b), but both reference sites for both surveys are significantly above 1 at some frequencies. Even if the other Wellington SRR ratios are multiplied by the average reference site HVSR value (about 1.5), the Wellington HVSR still overestimate the SRR. The difference in the relative HVSR values may be due in part to the difference in the geology of the two areas. The subsurface geology of Wellington City, with numerous infilled streams producing an irregular soft sediment thickness, is far more complicated than the simple subsiding basin of Lower Hutt. Thus a 1D approximation, which has been shown to match HVSR results far better than 2D models [Coutel and Mora, 1998], may be more appropriate for Lower Hutt. The Wellington sites are also generally stiffer and have a lower level of amplification.

CONCLUSIONS

Microseismic data from short-period and broadband seismographs have been used to compare the site response determined from sediment/rock site spectral ratios with horizontal to vertical component (H/V) spectral ratios. As also shown in a number of other studies, the H/V ratios successfully estimated the resonant frequency. In the case of Lower Hutt, both the HVNR and HVSR showed the both the fundamental frequency of the basin (0.5-0.6 Hz) (as determined from the finite element modelling of Adams *et al*., [2000]), as well as a 1.5-2 Hz resonance in the near-surface soft sediments. Thus both small earthquakes and microseismic noise can excite whole basin resonances.

In Lower Hutt the H/V ratios generally underestimated the sediment/rock amplitudes while in Wellington the reverse was true. The difference in the amplitudes between the H/V and sediment/rock techniques was not consistent and the H/V amplitudes did not discriminate between previously determined ground shaking hazard zones. The match of amplitudes was best in stiff sediments and worst at highly resonant sites. Thus H/V ratios would not be effective in estimating the ground shaking hazard over a region of widely varying geology. However the H/V ratios can be useful for separating regions with different resonances and determining the lateral extent of resonant sediments.

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