QUANTIFICATION OF SEISMIC SHAKING VARATIONS DUE TO SOURCE EFFECTS AT SOFT SOIL SITES IN THE WELLINGTON REGION

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CONTENTS

SUMMARY

Microearthquakes have recently been used in the Wellington region to estimate relative site responses for the purpose of defining the ground shaking hazard. In these studies, the amplifications of ground motion at individual flexible sediment sites have varied by up to a factor of 5 depending on the earthquake. The purpose of this project has been to systematically examine the causes of the variation. Much of this variation in ground motion amplification has been found to be to due to random scattering effects, and not to be simply related to earthquake location or mechanism.

The importance of random scattering means that while the average response of a site can be determined by measuring the response of a range of earthquakes, there will always be a degree of uncertainty in the actual response of a site in a particular earthquake.

INTRODUCTION

Local site response in urban areas has been a major factor contributing to damage from earthquakes in the past decade, particularly in such cities as Mexico City in 1985 and San Francisco in 1989. Much effort has been devoted to quantifying site responses and relating the responses to subsurface structure, particularly the thickness and shear wave velocity of flexible sediments [3]. Both strong motion and weak motion recordings have been used to measure site response, and these measured responses have been compared with non-linear and linear response models [9,6].

When recordings from a number of different earthquakes are available at an individual site, the relative response of the flexible sediment site to a reference site, referred to here as the amplification, varies from earthquake to earthquake [*eg.* 5]. Some sites show a characteristic frequency response, though the amplification can vary by up to a factor of 5 [14]. At other sites, the frequency response, as well as the maximum amplification, varies from earthquake to earthquake. This uncertainty in site response needs to be considered when determining design parameters. The variability from earthquake to earthquake also makes it difficult to compare a limited number of strong and weak motion records to determine the extent to which ground motion at a particular site remains linear. The purpose of this project has been to examine this variability and to discuss possible causes. Weak motions were used in this study because there are more recordings of weak motion at more closely spaced sites than are available for strong-motion data.

DATA PROCESSING

The data used for this project were collected during ground shaking hazard studies conducted for the Wellington Regional Council. For each survey, earthquakes were digitally recorded using 1 Hz, 3-component seismometers for periods of 1-3 months. Each experiment consisted of 10-20 seismographs deployed over areas ranging from 50 to 200 km^2. In each case a bedrock site was chosen as the reference site. Up to 30 earthquakes were recorded at each site. An example of one of the survey areas (Porirua) is shown in Figure 1.

Fourier and response spectra were calculated from the recorded seismograms to determine the frequency response of each site. Spectral ratios were then calculated to determine site responses relative to a nearby rock site. The spectral ratios are a

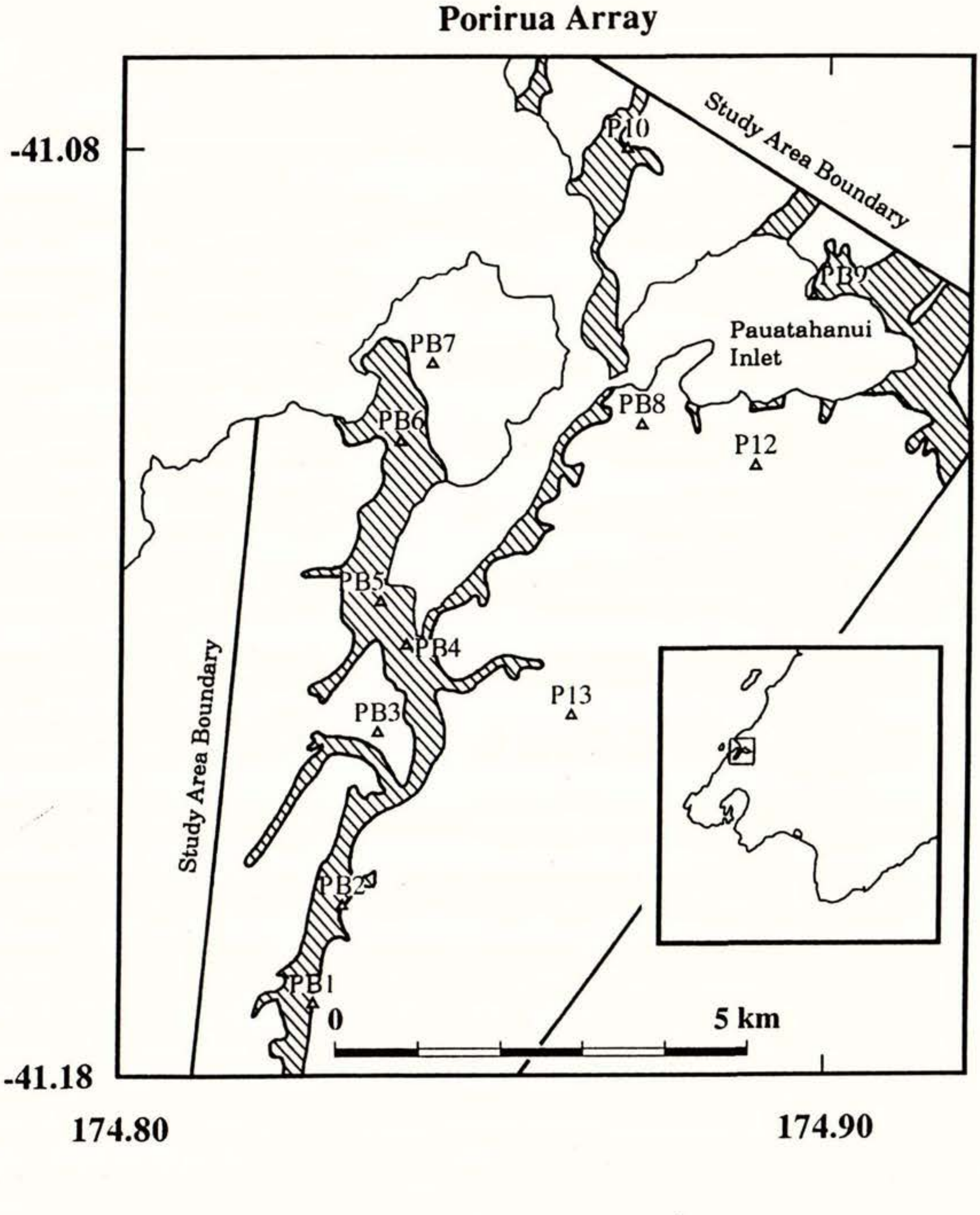

Figure 1. Site location map for the Porirua survey. Cross-hatched area is underlain by Quaternary-aged sediment. Boxed area in inset shows location of survey.

means of separating site effects from source and path effects [*eg*. 2]. It is particularly important to remove the source effects because the frequency content of small earthquakes is very different from frequency content of large, damaging earthquakes. A major assumption in the use of spectral ratios to estimate site response is that the relative excitation of different frequencies between sites will remain the same no matter what the input spectrum.

Response spectra were calculated for the data in the following manner. The instrument response was first removed from the signal and then the resulting ground displacement was converted to either velocity or acceleration, after appropriate filtering and tapering of the signal. The 5% damped response spectra were calculated using the longest S wave sample that could be extracted from all the sites for a particular event. Thus each response spectral ratio was calculated from two equal length records, but the length of accelerograms could be different for different events. The length ranged from 10 to 35 seconds.

The Fourier spectra were treated slightly differently. A 10 second window, starting 0.5 second before the S wave arrival, was selected from the horizontal components of each seismogram. In the original analysis, the spectra were smoothed with a 0.5 Hz triangular moving window. This heavy smoothing was used because the goal of the microzoning project was to find the average site response. In later, more detailed analysis, the rock site spectra were smoothed using a 1 Hz triangular moving window, but no smoothing was applied to the flexible sediment sites. The rock site spectra were heavily smoothed in an attempt to remove random variations due to scattering of the incoming seismic wave. The sediment site spectra were not smoothed so that any sharp resonances could be examined.

The horizontal components were considered separately, as well as combining the components into an average horizontal amplitude spectrum. Spectral ratios were then calculated by dividing each spectrum by the spectrum for the reference site. A distance factor (the distance from the reference station to the earthquake divided by the distance from the soft site to the earthquake) was then applied.

Sites where amplifications occur can be divided into three classes based on the frequency response: 1. strong resonance at a single frequency, 2. multiple, but well defined resonances, and 3. broadband amplification. The type of amplification is dependent on the site geology. A conclusion based on the surveys is that resonance at a single frequency occurs when there is a uniform soft layer over bedrock. Multiple resonances occur when there are a small number of well defined layers over bedrock while broadband amplification occurs when there is a gradual increase of shear wave velocity with depth. In all three cases the standard deviation of the mean ratio is about 1/2 the value of the mean.

The simplest case, strong resonance at a single frequency, was examined using sites from two different surveys in the Wellington region. The use of resonant sites, where there is little change in the shape of the response spectrum, means that the variability is defined primarily by the maximum of the spectral ratio. The variability will be presented in two ways. First selected spectra will be discussed, so that sediment and rock site spectra can be examined separately. Second, spectral ratios will be examined to look for possible causes of the variability.

SPECTRA

The 5% damped response spectra for flexible sediment site PB4 and rock site PB8 (Figure 1) are plotted in Figure 2 for two earthquakes. As expected, the spectra of the flexible sediment site, PB4, are very different from the rock site spectra. In

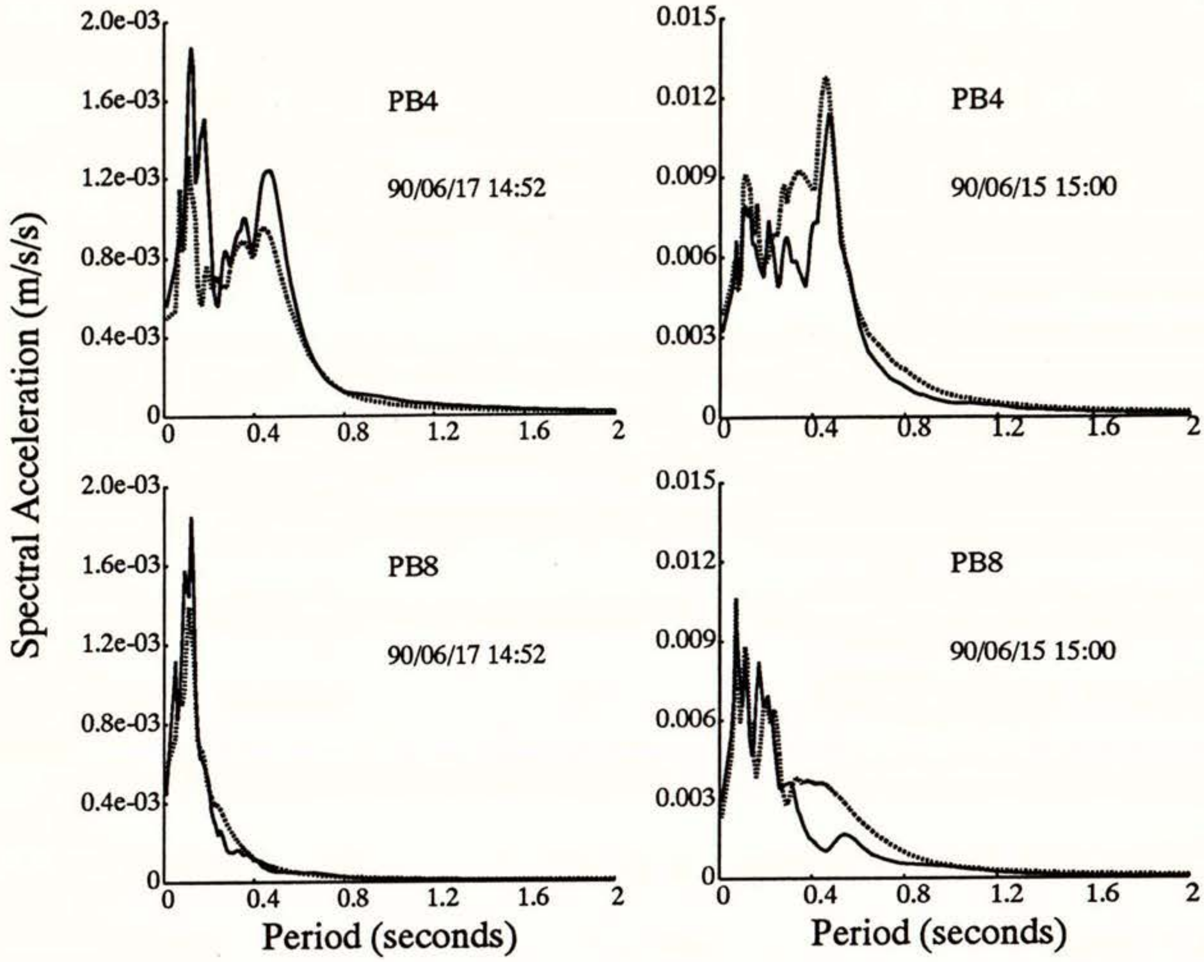

Figure 2. Damped (5%) acceleration response spectra for 2 earthquakes recorded at a flexible sediment site (PB4) and a rock site (PB8) in Porirua (see Figure 1 for location). Site PB4 is underlain by 12 m of soft sediments (fill, interbedded sand and silt) with a shear wave velocity of approximately 110 m/s [12]. Site PB8 is underlain by weathered greywacke. Left: A magnitude 2.7 event centred 30 km from Porirua. Right: A magnitude 3.7 event centred 39 km from Porirua. Note vertical scale change. Solid line is N-S component. Dotted line is E-W component.

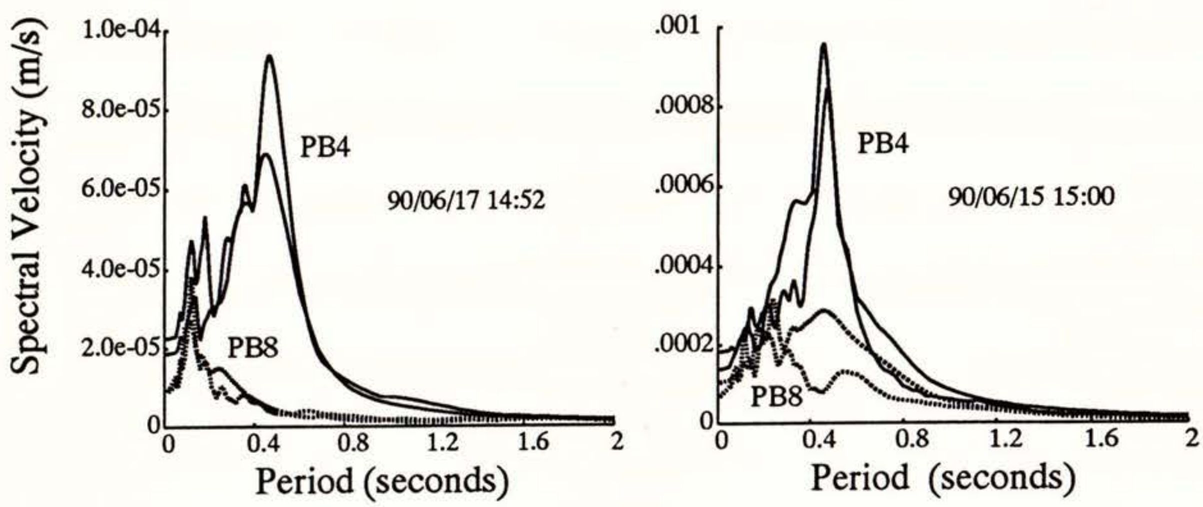

Figure 3. Damped (5%) velocity response spectra for the same events and sites as in previous figure. Solid lines are N-S and E-W components of site PB4. Dotted lines are N-S and E-W components of site PB8.

both events there is a peak near 0.5 seconds on the flexible sediment site record, even though the rock spectral amplitude is very low at that period. The spectral shapes of the sediment site differ only at very short period. The short period is relatively more pronounced in the smaller earthquake due to the shorter period source. The importance of the 0.5 second peak is much more pronounced in the velocity response (Figure 3). Since the site resonance is clearer in the velocity response, the variability analysis was carried out on the velocity time series.

An analysis of the smoothed Fourier spectra showed that the maxima of the spectral curves are tightly bunched at 2.15±.13 Hz for site PB4, while the spectral amplitudes range over nearly 2 orders of magnitude. An example of Fourier spectra for 3 earthquakes is shown in Figure 4. In contrast, the spectra of the rock site show different patterns for each earthquake. The peak frequencies determined on the north and east components are similar. It was found that the peak frequency at the soil sites varies within a very narrow range regardless of the amplitude of the ground response, earthquake magnitude, ray path or azimuth.

The source mechanism of an earthquake also appears not to affect the resonant frequency significantly. The earthquakes used in this study are distributed in a range of depths which include both subducted and overlying plates. The earthquakes on the two sides of the subduction interface have different focal mechanisms [10] and therefore there should be a range of source functions in the Porirua data set.

The frequency variation appears to be normally distributed and thus is likely to be caused by random errors such as environmental noise at survey sites. A possible non-random cause for the frequency variations may be the length of the smoothing window. Variations in sediment thickness near the site may also have a second order effect.

SPECTRAL RATIOS

The amplitudes of the response spectral ratios (Figure 5) and Fourier spectral ratios (Figure 6) show a much larger variation than do the frequencies at resonant sites. Note the lack of any amplification at the short periods of the source maximum seen in Figure 2. The variation of the peak amplitude ratio is about the same for the response and Fourier spectral ratios. The Fourier spectral ratios particularly show that in all cases there was a strong resonance in a very narrow frequency band (1.8-2.3 Hz), though in a few cases there was an additional resonance near 2.6 Hz.

In an attempt to determine the cause of the amplification variability, the Fourier spectral ratios were analysed against six different parameters at 6 resonant sites. The parameters considered were: distance to epicentre, azimuth to epicentre, angle of incidence of shear wave at basin interface, earthquake depth, earthquake magnitude, and maximum spectral amplitude at the rock site. No significant correlation was found for any of the parameters. For some earthquakes recorded in Porirua a high ratio at one flexible sediment site correlates with high ratios at the other flexible sediment sites (Figure 7). However in other cases the correlation is poor, which shows that while nearly the same frequency is excited each time in the basin, the relative amplitudes in different parts of the basin will vary with each earthquake. This may be explained by the modelling of Saikia *et al.* [11] who have shown that an irregular basin structure is needed to match the long duration of shaking in Los Angeles. An irregular structure means there will be significant differences in amplifications between sites and these differences will vary with each earthquake.

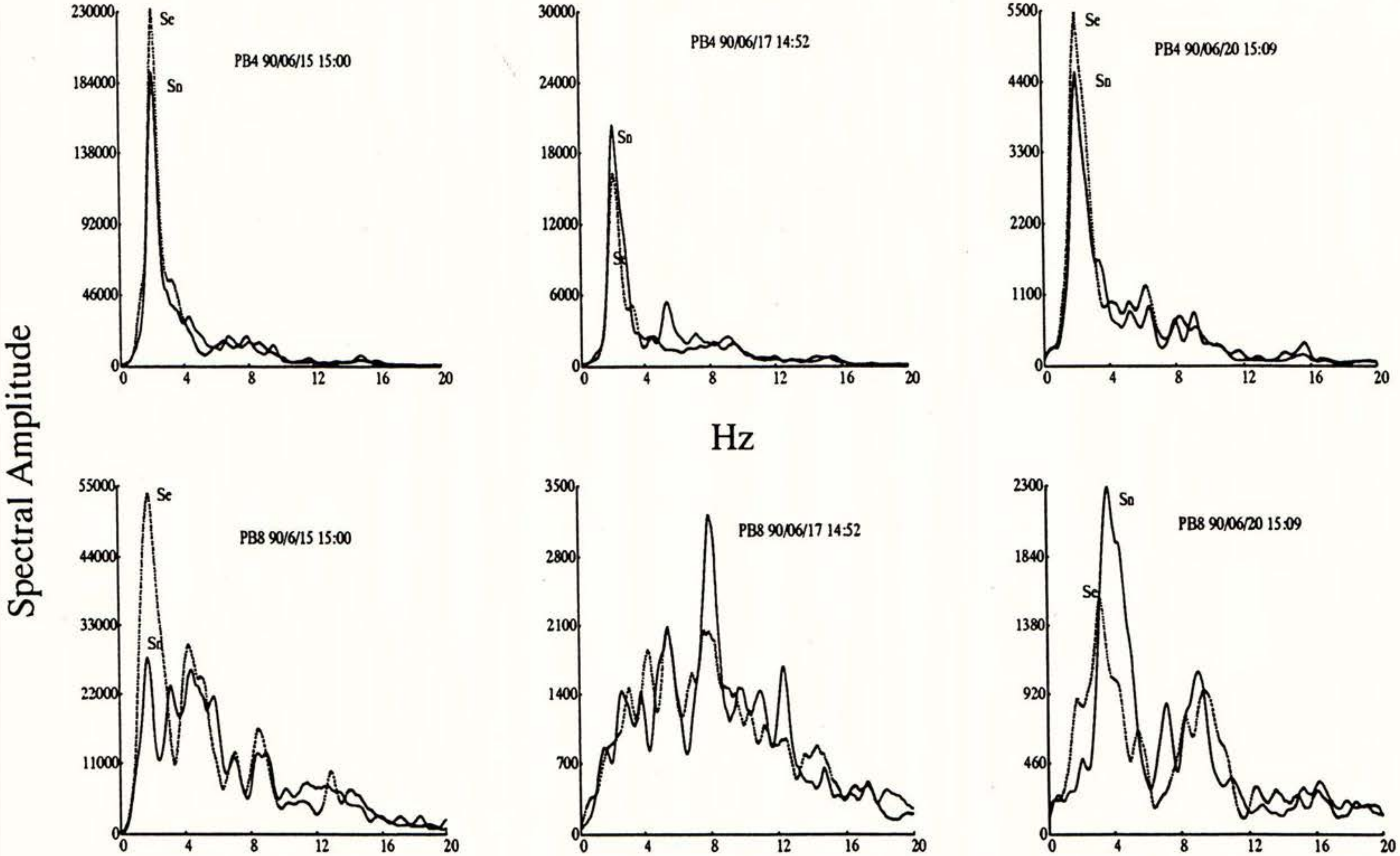

Figure 4. Fourier velocity spectra for a flexible sediment site (PB4) and the rock reference site (PB8) for three earthquakes. Both the north (solid) and east (dotted) components are shown. The instrument response has not been removed from the spectra.

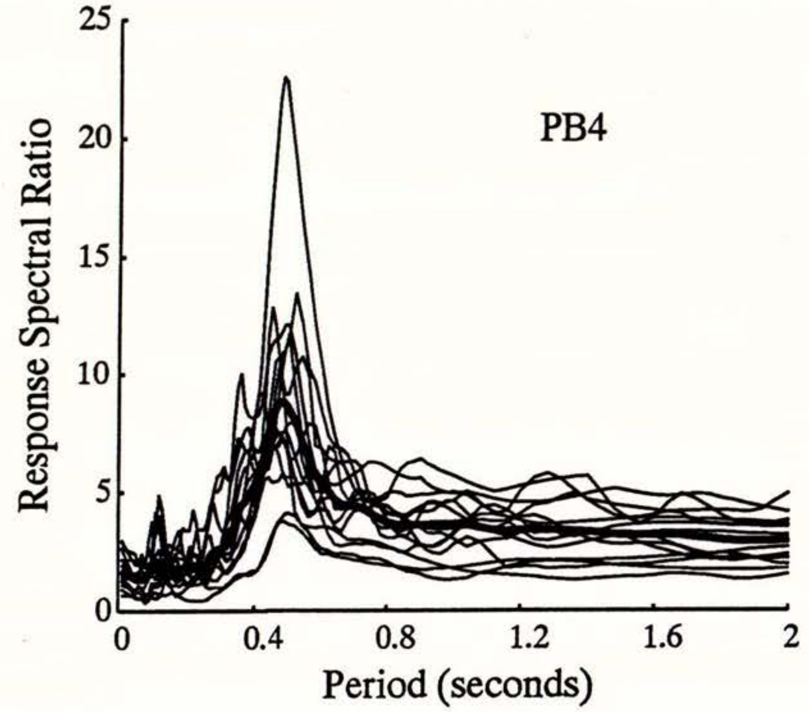

Figure 5. Acceleration response spectral ratios (PB4 divided by PB8) for 14 earthquakes recorded at flexible sediment site PB4. The ratio of the N-S horizontal component is shown. The dark line is the mean of the ratios.

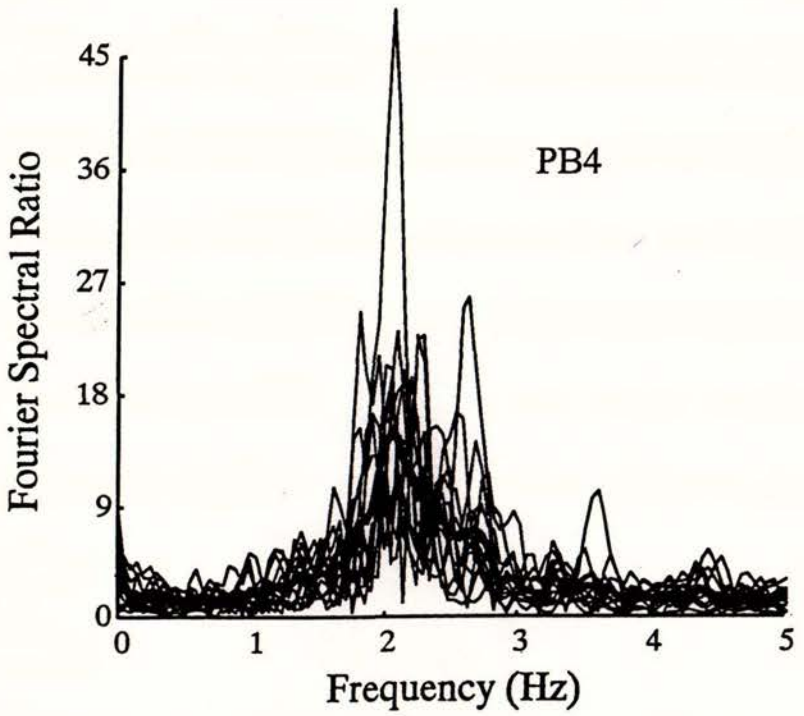

Figure 6. Fourier spectral ratios (PB4 divided by PB8) of 14 earthquakes recorded at flexible sediment site PB4. The ratio of the N-S horizontal component is shown. The dark line is the mean of the ratios. No smoothing applied to the PB4 spectra. PB8 spectra smoothed with a 1 Hz moving triangular window.

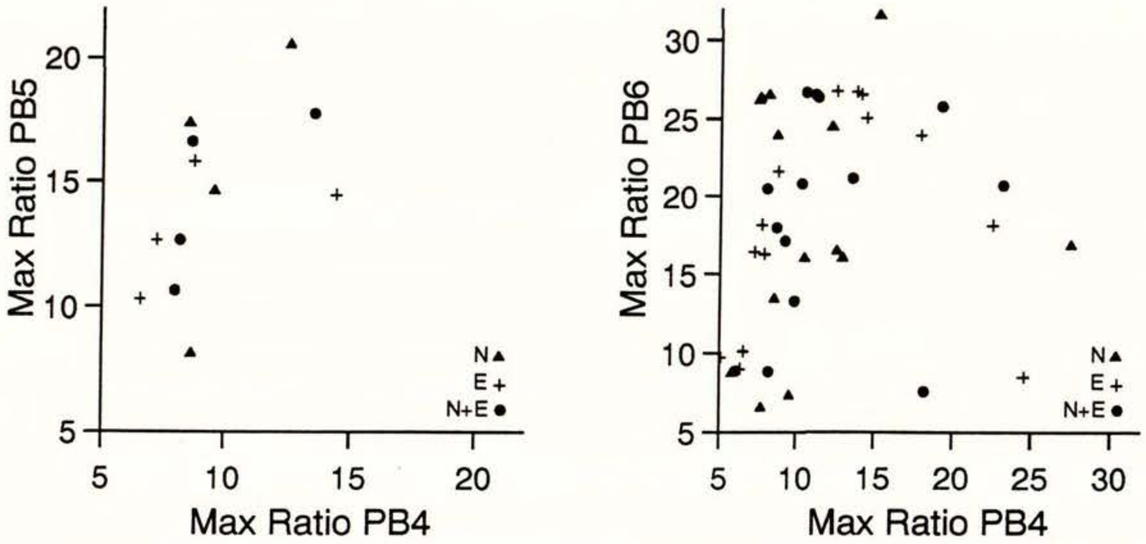

Figure 7. Comparison of the maximum Fourier spectral ratio at sediment sites in Porirua for individual earthquakes. North, East, and the average of the two components is shown for each event. Left: site PB4 vs site PB5, Right: site PB4 vs site PB6.

The earthquakes recorded on the Porirua array were also grouped by location and the properties of each group compared. It was found that if the range of hypocentres was small enough within a group there was a correlation between events for both rock site and soft site spectra. For groups with a larger separation in either depth or epicentre, there was little or no correlation.

One dimensional modeling of the Porirua basin showed that the angle of incidence of the incoming wave should vary uniformly with spectral ratio in agreement other 1D modelling [5]. Since this is not evident for the real data, the 1D model must be too great a simplification of the Porirua basin. However the resonant frequency predicted by the one dimensional modeling based on the geotechnical information matches the frequency observed in the data.

The computer modelling was limited to one dimension in this project because much more time was spent on the analysis of the recorded data than was anticipated. The extra data analysis time was needed because of the unexpected importance of random scattering. To understand this effect, significant time was spent analysing the raw spectra, instead of using only the smoothed spectral ratios as anticipated.

Uneven basement topography and complex local structure may be the cause of considerable variability in the spectral ratios [7,8]. If a model is sufficiently complex, the variation in amplitude will appear random as shown in recent three dimensional modelling of Christchurch by Haines *et al* [7], where small variations in incident angle produced large variations in amplitude. The variability modelled by Haines *et al* was in good agreement with the measured weak-motion response in Christchurch [13]. Thus in a detailed 3D model, amplitude variations which are due strictly to azimuth and angle of incidence, can appear almost random. If 5-10 widely-spaced azimuths and angles of incidence were chosen (as in the case of the recorded data) no simple relationship between either azimuth or angle of incidence with amplitude could be determined.

The only clear correlation of spectral ratio with location occurs for very close earthquakes (less than about 25 km away). Earthquakes within this distance produced spectral ratios significantly higher than the average at a number of sites. Figure 8 shows examples for a flexible sediment site and a stiff soil site in Lower Hutt. This increased shaking is probably due to the greater coherence (and thus less random scattering) of the incoming wavefield [15]. The implication of this result is that nearby small earthquakes should not be used when determining the average site response, because these events are not representative of the amplifications to be expected from earthquakes in the distance range of 50-100 km, which is the range where site effects are most likely to be important in large earthquakes [1].

The relationship of spectral ratio to maximum ground motion amplitude was also examined. It was found that there was no correlation between the two parameters. Thus the variability is not a non-linear effect, ie. the larger amplifications do not correlate with the smaller rock motions. This was the expected result because the recorded motions were below the level where non-linearity has been observed elsewhere.

The conclusion from the above analysis is that much of the variation in ground motion amplification cannot be simply related to earthquake location or mechanism. Thus seismic waves from earthquakes in the same location and with the same mechanism will generate nearly the same amplifications, but only small changes in location can cause large changes in amplification. The local site geology may determine the average response at the site but large variations must be expected. This also implies that one-dimensional models will always underestimate the variability of the amplification.

DISCUSSION

In addition to the "apparent" randomness due to structural causes, there are several other factors which may contribute to the variability. These can be divided into physical effects including random scattering, bedrock site response, and seismic source, and processing effects, particularly the smoothing of the Fourier spectra. Smoothing is not a variable in the response spectral ratio calculations but it still is a factor. It is assumed that the incoming wave at the flexible sediment site is the same as the measured ground response at the reference site. This is probably where there is the largest deviation from the assumptions in the use of spectral ratios. In most cases the reference site and flexible sediment site are far enough apart that random scattering of the incoming seismic wave can cause random differences between the rock spectra and the spectra of the input to the sediment site. Increasing the smoothing of the rock site spectra to reduce the effect of random variations did not reduce the standard deviation of the spectral ratios in this study (Figure 6, for example). However, averaging of several rock sites together has been shown to decrease the variability [15]. This averaging creates a reference spectrum that is closer to the average input spectrum across the array.

The smoothed spectrum depends heavily on the length of the smoothing window. Equal length smoothing windows may distort spectra with large amplitudes in narrower frequency ranges than the smoothing window. If the smoothing procedure is applied before taking the ratio, source and path effects will not be completely removed. Therefore, the spectral ratios obtained from the conventional processing procedure always contain errors contributed from source and path effects.

It is difficult to separate the effects of each of the factors in the variability but a rough estimate can be made. Comparison of the current study using one reference site to the multiple reference site approach of Yu and Haines [15] suggests that less

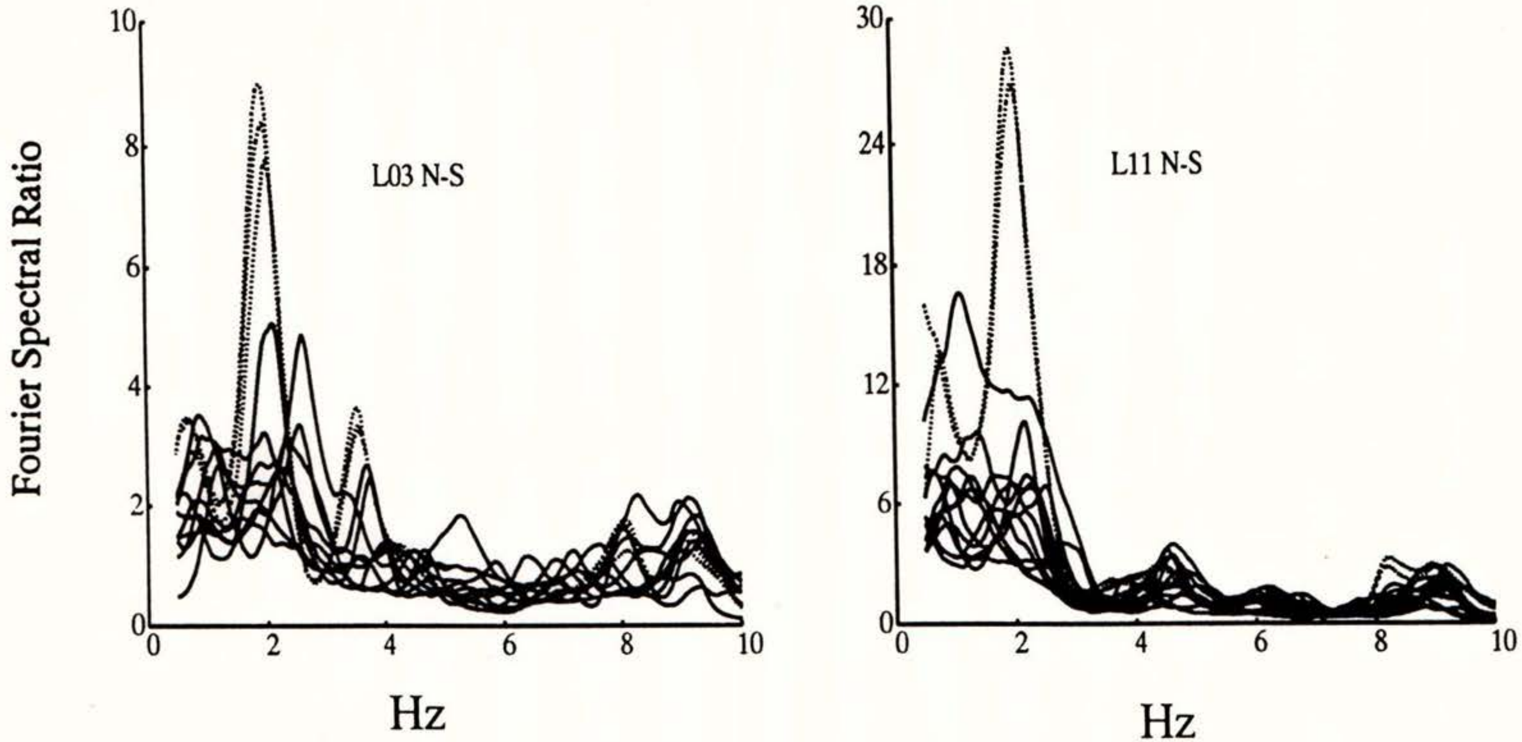

Figure 8. Plot of all Fourier spectral ratios at two Lower Hutt sites showing the high amplitudes generated by a very local (10 km distance) earthquake swarm. The ratios for the nearby earthquakes are shown by dotted lines. Site L03 is on very stiff soil on the edge of the valley and site L11 is on approx. 20 m of soft sediment on 200 m of gravels.

than half of the variability is due to random variations in the rock site spectra. Smoothing appears to have an even smaller effect. Thus probably over half of the FSR variability where a single reference site is used is a real effect due to structural and source mechanism variations.

Borcherdt and Glassmoyer [4] suggested that averages of spectral ratios over specified frequency bands (average horizontal spectral amplitude or AHSA) provide estimates of ground response useful for summarising variations on a regional scale and variations pertinent to various types of structures. They found that the correlation of average spectral ratio to shear wave velocity was nearly the same for strong and weak motions, when a broadband average from 0.5 to 2.5 Hz was considered. This is the frequency range most important for larger engineered structures. Averaging over a range of frequencies reduces the effect of narrow resonance peaks and enhances the importance of low frequency shaking.

The amplifications from some earthquakes are higher or lower than the average at most sites (for example, the nearby earthquakes shown in Figure 8) while the pattern of amplifications is significantly different than the average for some events. For example, consider two sites in Lower Hutt. The higher amplitude site has a peak Fourier spectral ratio that is twice the ratio of the lower amplitude site. However the relative shaking for individual earthquakes can vary from one site having 1 to 4 times the Fourier spectral ratio of the other. There is much less variation in the AHSA. For the same earthquakes, the ratio of AHSAs for the two sites only varies from 2 to 2.8. Thus the AHSA is much less variable and is a better estimate of the average relative shaking but the much larger variation in peak spectral ratios must be considered when expressing the variations from the average.

CONCLUSIONS

Much of the variation in ground motion amplification has been found to be to due to random scattering effects, and not to be simply related to earthquake location or mechanism. For nearly coincident hypocentres there was a correlation between earthquakes for both rock site and flexible sediment site spectra. For larger separations in either depth or epicentre, there was little or no correlation. Larger amplifications do not correlate with the smaller rock motions implying that the variability is not a non-linear effect.

In contrast, the resonant frequency for strongly resonant sites showed little variation while the spectral ratio at that frequency varied by up to 50%. Thus the resonant frequency is a very stable quantity that is not effected by the frequency spectra of the incoming wave or the angle of approach of the wave.

The only clear correlation of spectral ratio with location occurs for very close earthquakes (less than 25 km away). Earthquakes within this distance produced spectral ratios significantly higher than the average. This implies that nearby small earthquakes should not be used when determining the average site response, because these events may not be representative of the amplifications to be expected from earthquakes in the distance range of 50-100 km, which is the range where amplification effects are most likely to be important. Thus while an average response can be determined for each site, the response due to a particular earthquake may vary significantly from the average.

ACKNOWLEDGEMENTS

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APPENDIX

Papers and Presentations Relating to this Project

1. Local Variations in Seismic Shaking in the Wellington region, New Zealand, J.J. Taber and R.J. Van Dissen, *EOS, Trans. AGU, 74*, 435, presented at December 1993 AGU meeting, San Francisco.
2. Variations in Ground Shaking due to Micro-earthquakes in Wellington City, New Zealand, J.J. Taber, presented at the IASPEI conference in Wellington in January 1994.
3. Limits to microzonation due to real variability in site response, J.J. Taber, Proceedings of the 5th International Conf. on Seismic Zonation, Nice, France, October, 1995, in press.
4. Uncertainties in site response estimates, J.J. Taber and X. Luo, Proceedings of the Pacific Conference of Earthquake Engineering, Melbourne, Aus., November, 1995, in press.