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SASW MEASUREMENT FOR THE CALCULATION OF SITE AMPLIFICATION EQC RESEARCH PROJECT 97/276

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Opus: *an accomplished work, a creation, an achievement*

ABSTRACT

Calculations of the site amplification effects of soft sediments were made at two locations in the Wellington region, Parkway in Wainuiomata and Wi-neera Drive in Porirua. At each location the soil shearwave velocity profile was measured using the Spectral Analysis of Surface Waves method (SASW). The shearwave velocities were combined with geotechnical data to formulate a soil model for each site which was used as an input to the computer program SHAKE, which calculates the seismic response spectrum for each soil layer.

The ratio of the response spectrum at the rock to the response spectrum at the surface provides a measure of the site amplification. This spectral ratio, determined using the SASW data, was compared with spectral ratios for the same locations determined using earthquakes records from the soft soil sites and from the closest rock sites.

TECHNICAL ABSTRACT

This project has evaluated the Spectral Analysis of Surface Waves (SASW) method as a means of economically obtaining soil strength information in order to derive an estimate of seismic site amplification. Response spectral ratios were calculated at two sites in the Wellington region at which earthquake monitoring has been carried out by the Institute of Geological and Nuclear Sciences (GNS). The ratios of response spectra were calculated using SHAKE a modelling method in which non-linear soil behaviour is approximated by a damped linear elastic model.

The input data to SHAKE consisted of shearwave profiles measured using the Spectral Analysis of Surface Waves method (SASW), geotechnical data and time histories of historical earthquakes. The SASW testing provided profiles of shearwave velocities as deep as 40 metres which compared well with the SCPT profiles which were available for the top 14 metres.

The reliability of the results have been assessed by comparing the computed site amplification with equivalent estimates made using earthquake record data. The assessment has been based on comparisons of:

- Average Fourier spectral ratios calculated from more than 10 local earthquakes and 12 earthquake input records for the SHAKE model,
- Response spectra for a single local earthquake and a SHAKE input best approximating the spectrum of the base motion of that earthquake. The model input was scaled to have the same peak acceleration as the rock site record.
- Peak spectral ratios for the single local earthquake and the scaled SHAKE input, as well as for 15 unscaled SHAKE inputs.

The SASW results are in good agreement with the observed ground motion at the Parkway, Wainuiomata site both in terms of period and magnitude. At Wi-neera Drive in Porirua the correlation between the SASW results and observed ground motion is not as good. This may reflect the fact that the rock site at this location is approximately 4km from the soft soil site, whereas at Parkway the base motion is recorded at four rock sites within 400m of the soft soil test site. The shearwave profile obtained from the SASW testing was also a better match with the SCPT profiles at Parkway than at Wi-neera Drive. A firmer conclusion on the correlation at Wi-neera Drive will be possible when data becomes available from downhole instruments to be installed at the site by GNS during 1998.

The peak spectral ratios when plotted against the maximum acceleration at the rock level appear consistent within the expected non-linear behaviour of the soil.

CONTENTS

1.0 INTRODUCTION

This project has evaluated the use of the Spectral analysis of Surface waves (SASW) technique as an economical means of estimating the seismic site amplification.

Shearwave profiles were measured using SASW, at Parkway, Wainuiomata and Wi-neera Drive in Porirua, where the site amplification has been previously determined by the Institute of Geological and Nuclear Sciences (GNS) and Victoria University of Wellington (VUW). Their studies involved calculating the ratios of the Fourier spectra of earthquakes recorded at the site and at nearby rock sites.

The shearwave profiles obtained from the SASW testing have been used to calculate the site amplifications using SHAKE. The resulting amplifications have then been compared to the amplifications measured by GNS and VUW.

2.0 SASW TEST METHOD

Spectral Analysis of Surface Waves (SASW) is a method for determining the shearwave profile of a layered soil system by measuring the surface waves (Rayleigh waves) at two points on the ground surface. During data analysis, the waveforms at the surface are separated into their component frequencies and the Rayleigh wave velocities for each wave frequency are determined. Longer wavelengths travel deeper in the soil and so their velocities are influenced by the Rayleigh velocities of these deeper layers.

The SASW method relies on the dispersive nature of Rayleigh waves. In a homogeneous, isotropic, elastic half-space Rayleigh wave velocity is independent of frequency. However in a layered half-space, such as a layered sedimentary basin, the longer wavelength components will penetrate deeper and be influenced by the properties of deeper soil layers. The Rayleigh wave velocity is thus dependent on wavelength and a profile of soil shearwave velocity may be acquired by measuring the Rayleigh wave velocity for a range of wavelengths. Typically, data is obtained for wavelengths ranging from less than one metre and up to 100m or more.

Waveforms measured over a range of sensor spacings are combined to produce a dispersion curve of Rayleigh wave velocity versus wavelength. A soil model, comprising shearwave velocity, poissons ratio and density is formulated and used to produce a theoretical dispersion curve which is then compared with the experimental data. The soil model is iteratively adjusted to achieve a best fit with the field data. The in-situ soil shearwave velocity profile is interpreted as the velocity profile belonging to the best fit model.

Using Rayleigh waves for soil investigation has the advantage that they attenuate at a lower rate than other types of wave. Whereas body waves radiate in all directions and attenuate in proportion to the square of the distance from the source, Rayleigh waves are confined to the surface and attenuate with the square root of the distance. As a result, beyond a short distance from the wave source, the majority of the energy at the surface is Rayleigh wave energy. Waves of measurable amplitude and a broad range of frequencies can be economically generated using simple hammer sources or dropped weights, though mechanical or electromagnetic shakers may also be used.

The basic technique of using the dispersion characteristics of surface waves for measuring the properties of layers below the surface has been under development since the 1950's, when it was used to study the earths crust (Haskell, 1953). Recent advances in data acquisition and the use of portable computers has meant that the technique can now be routinely applied using relatively inexpensive equipment, rather than being restricted to a time consuming and costly research exercise.

2.1 DATA COLLECTION AND PROCESSING

The SASW testing utilised a Toshiba T4700CS laptop computer with a docking station, a National Instruments AT2150 Dynamic Signal Acquisition board and LabVIEW software. Two Mark L4 1Hz seismometers were used as sensors.

For each sensor spacing used for the testing, surface wave time histories from several hammer blows were converted to the frequency domain and then stacked. This allows the cross power and coherence spectra to be calculated and recorded. The coherence and cross power spectra are subsequently used as criteria for the rejection of poor quality data. The coherence function provides a measurement of the quality of the data over the range of calculated frequencies. It is a measure of the ratio of the power of the signal which is common to both sensors to the total power.

Therefore at a particular frequency if the signal is common to both sensors (ie a useful signal) the coherence function will be close to unity. If there is a signal due to noise at one sensor which is not present at the other sensor the coherence function will be significantly less that unity, signalling that the data should be rejected.

The cross power spectrum is a complex function defined as the Fourier transform of the cross-correlation function between the two signals. The real and imaginary components of this function can be represented by the magnitude and phase angle of a rotating phasor in the complex plane.

While the magnitude of the cross power spectrum gives some information on frequencies which are common to both sensors, the phase angle is of most significance, since it can be used to determine the phase velocity. The phase angle is only relative (i.e. between 0 and 360°) and before it is used to calculate the velocity it must be unwrapped to compensate for waves which have multiple cycles within the sensor spacing.

Using software written in Matlab the coherence function for each spacing was examined and data with low coherence (generally below 0.95) was rejected, at the same time the phase velocity was unwrapped and the phase velocities calculated.

Forward modeling, to find soil models with theoretical dispersion curves closely approximating the experimental dispersion curves, was carried out using the programme WinSASW. This programme utilises an initial model based on estimates of layer thickness, shear wave velocity, density and poisson's ratio. The model is insensitive to slight variations in the assumed values of density and poisson's ratio. In subsequent iterations to achieve a match with the experimental data, only the shearwave velocity and depth values in the theoretical model are adjusted.

2.2 LOW FREQUENCY SURFACE WAVE SOURCES

The depth of penetration for the SASW test depends on the velocity of the soil and the range of wavelengths that can be generated with sufficient energy and coherence to be usefully recorded. A low frequency source is required to generate long wavelength Rayleigh waves and maximise the depth of investigation. Two low frequency sources were evaluated.

Firstly a mechanical shaker was used consisting of two sets of counter-rotating weights driven by a 5 hp DC motor, controlled by a 24A rectifier was utilised. The rotating weights can be positioned to apply the force in either the vertical or horizontal plane. The frequency range available in the vertical plane is 2 to 4 Hz whereas in the horizontal plane the shaker can be used at frequencies below 2Hz. The shaker was first used in the vertical configuration with frequencies ranging from 2.1 to 3.7 Hz, and then in the horizontal configuration at 1.9 and 2.2 Hz. The rotation speed is controlled by an input voltage.

Four concrete piles approximately 600 mm deep were poured to couple the shaker to the ground. Threaded rods were set into the piles and the shaker was bolted down, giving a positive coupling to the ground.

The second method of producing low frequency surface waves comprised a 1000kg concrete block which was dropped onto the ground using a mobile crane. This has the advantage of requiring less site preparation but does require a site with access and where a small amount of soil compaction is acceptable. A dropped weight is a practical option for testing on a routine basis because of the simplicity of the technique and the ready availability of machinery such as cranes or backhoes to lift the weight.

3.0 SITE SELECTION

The Parkway and Wi-neera Drive sites were selected after consultation with GNS. The criteria for selecting the sites included the accessibility for machinery used to generate low frequency surface waves, the depth to bedrock, the amount of other geotechnical information available at the site and proximity to Central Laboratories.

The two sites chosen were sites at which GNS has carried out extensive geotechnical and geophysical investigations. The approximate locations of the two sites are shown on the location map in Figure 1.

The sites are described below, based on information supplied by GNS and VUW. This includes cone penetrometer tests and seismic cone penetrometer tests, borehole logs, laboratory test results and geophysical data.

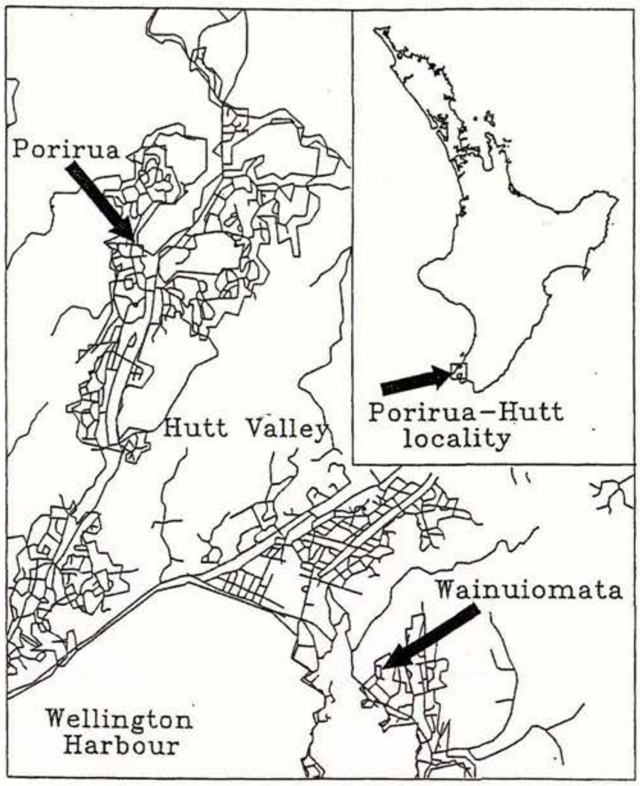


Figure 1. Location of study areas.
(Courtesy of Stephenson and Barker, 1992)

3.1 PARKWAY, WAINUIOMATA

The upper Parkway area has been investigated by GNS as part of a Microzoning project funded by the Public Good Science Fund. The GNS investigations included eleven Cone Penetrometer Tests (CPT), three Seismic Cone Penetrometer Tests (SCPT) and 25 seismometer locations four of which were rock sites. In addition, Victoria University has conducted seismic refraction and reflection surveys, p and s wave measurements and a microgravity survey at the site.

The upper Parkway area is located to the north - west of the main Wainuiomata township, in a north - south aligned valley between two greywacke spurs. The floor of the valley is 400 to 500 m wide and the area which has been investigated by GNS is 600 m in the north - south direction.

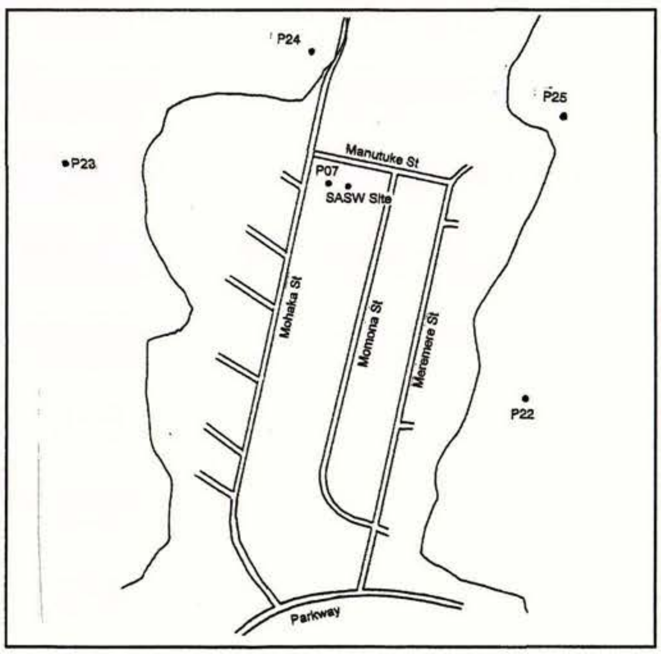


Figure 2. Plan of Parkway site

Parkway is a fully developed residential area filling most of the valley floor. The location of the SASW test is approximately in the centre of the valley adjacent to Black Stream. The stream runs along the centre of a reserve area which is bordered by the back yards of houses in Mohaka Street and Momona Street. The test site was on the eastern side of the stream starting five metres south of Manutuke Street, with the furthest sensor location 60 metres further south. A site plan with the location of the SASW test and the closest GNS seismic monitoring stations, CPT and SCPT sites, is shown in Figure 2.

Permission to carry out the SASW testing was granted by the Hutt City Council Leisure Services Division who maintain the reserve. The only buried services in the reserve are stormwater outlets from the back of some of the houses. The only one of these which crosses the test site would not have affected the test data because it was 30 metres from the centre of the SASW accelerometer layout.

3.2 WI-NEERA DRIVE, PORIRUA

The Porirua basin is a study area for GNS and was used in a joint GNS, VUW study for the Wellington Regional Council. After CPT tests at Tawa and Linden showed only shallow deposits of soft soil, the study was focused on the harbour area near the mouth of the Porirua Stream. Work in this area comprised six CPT tests and one investigation drillhole. Samples from the drillhole have been tested for water content, bulk and dry density, particle distribution and atterburg limits.

The drillhole (dating back to 1990) was on land presently occupied by the Whitireia Community Polytechnic. This land is mostly reclaimed over tidal and near-shore swamp sediments. The drillhole shows more than four metres of made ground overlaying eight metres of sands and silts.

The SASW testing was done close to the drillhole site, along the grass verge at the edge of Wi-neera Drive on the eastern side of the Polytech campus. A site plan, including the location of the SASW test and GNS drillhole, CPT and seismic monitoring stations, is shown in Figure 3.

Permission to carry out the SASW testing was granted by Porirua City Council, Leisure and Recreation Division who maintain the reserve area on the seaward side of Wi-neera Drive. It was found that there are no buried services on the northern side of Wi-neera Drive that might have affected the propagation of shallow waves in the soil.

Figure 3. Wi-neera Drive Site Map

4.0 TEST RESULTS

The following sections discuss the SASW data collected on site and the processed results. Dispersion curves output from WinSASW are shown in Figures 4 and 5 and the interpreted shear wave velocity profiles are shown in Figure 6.

4.1 PARKWAY SITE, WAINUIOMATA

The Parkway site is located on reserve land along the side of Black Stream. Seismometers were arranged in a line parallel to the stream with spacings of 1, 3, 6, 10 and 30 metres. A variety of energy sources were used, including hand held hammers ranging from 0.5 to 4 kg for the close sensor spacings and the two alternative low frequency sources for the larger spacings of 10m and 30 metres (refer to section 2.2).

In the first stage of testing the shaker was used for a low frequency source. However the data obtained exhibited poor coherence and only the data recorded for the 10 metre sensor spacing was useful. It appeared that the energy of the source was insufficient. The use of an electromagnetic shaker was not pursued because the maximum energy of two commercial alternatives, sold for surface wave investigations, are both less than 500N.

The 1000kg dropped weight was then used, producing enough energy to record data at the 30 metre seismometer spacing. Surface waves with good coherence were generated for wavelengths of up to 100 metres, corresponding to a penetration depth of 30 to 40 metres (depending on the wave velocity).

All data collected at the site was processed using our Matlab and WinSASW software to produce dispersion curves which were combined to provide a compact dispersion curve. An estimated model of the shearwave profile was then used to produce a theoretical dispersion curve. The initial model was iteratively adjusted until the theoretical curve fitted closely with the experimental dispersion curve. The final soil model is shown in Table 1.

The closeness of the fit between the theoretical dispersion curve associated with the final model and the experimental dispersion curve is illustrated in Figure 4.

Table 1. Parkway Site: Final soil model from WinSASW

Depth Range (m)	Shearwave Velocity (m/s)	Density (t/m^3)
0 - 0.23	98	1.7
0.23 - 0.75	138	1.8
0.75 - 1.95	90	1.7
1.95 - 9.45	155	1.9
9.45 - 17.5	250	1.9
17.5 - 21.0	420	2.0
Below 21.0	2000 (est)	2.4

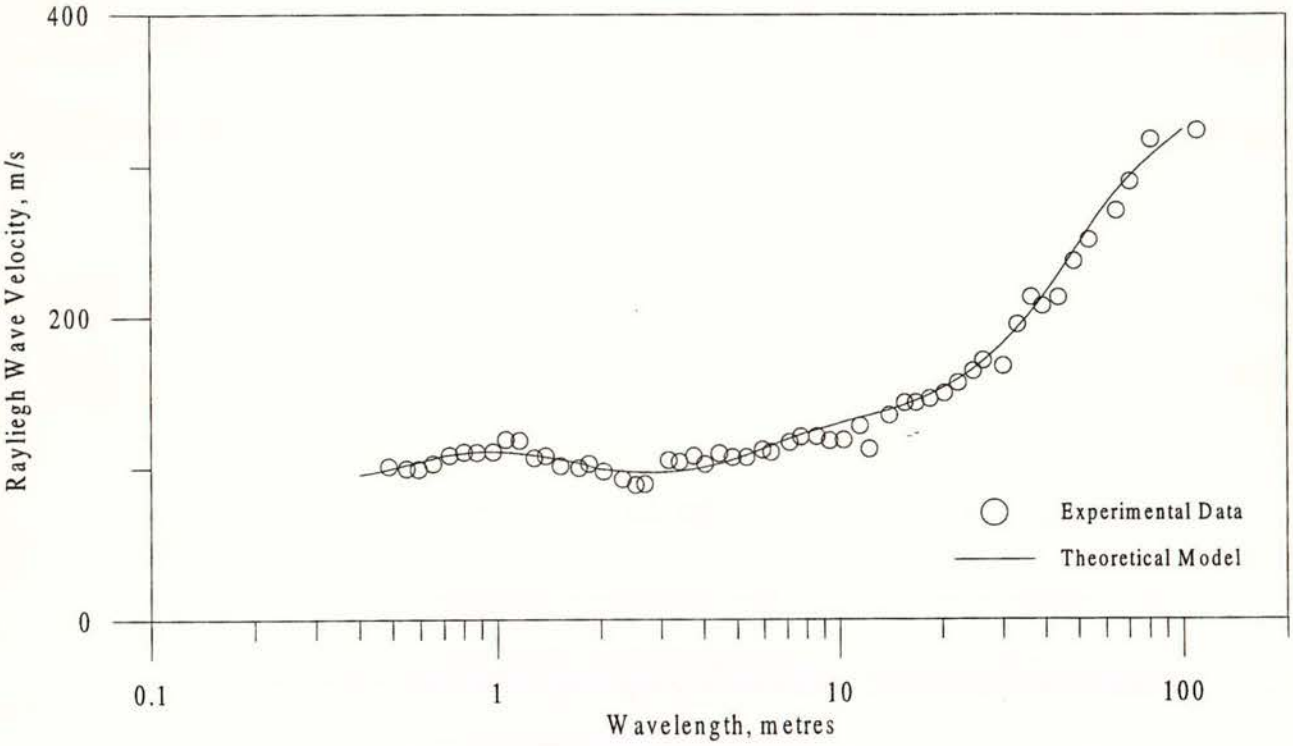


Figure 4. Dispersion curves for Parkway site

4.2 WI-NEERA DRIVE SITE, PORIRUA

The Wi-Neera Drive site is located along the boundary of the Whitireia Community Polytechnic. The seismometers were arranged in a line parallel to Wi-neera drive with spacings of 1, 3, 6, 10, 35 and 50 metres. A variety of energy sources was utilised. For the 1 metre sensor spacing, hammers ranging from 0.25 to 0.5 kg were used. For sensor spacings of 3 to 10 metres larger hammers from 1.3 to 4 kg were used while for the 35 and 50 metre spacings the 1000kg drop weight was used.

The mechanical shaker was not employed because the earlier testing at Parkway had demonstrated that it had insufficient energy to generate long wavelength surface waves of adequate amplitude.

The weight was dropped on a area of broken ground in the reserve land on the northern side of Wi-neera Drive, with the resulting depression filled with top soil on completion of the testing. The 1000kg weight was dropped by a mobile crane from a height of about 2 metres. The surface waves produced included usable wavelengths of up to 70 metres corresponding to penetration depths of 20 to 30 metres.

All data collected at the site was processed using our Matlab and WinSASW software to produce dispersion curves which were combined to form the compact dispersion curve shown in Figure 5. As for the Parkway site, an model of the shearwave profile was estimated and used to produce a theoretical dispersion curve. The model was then iteratively adjusted until the theoretical curve was a close fit with the experimental data. The final soil model is shown in Table 2.

The closeness of the fit between the theoretical dispersion curve associated with the final model and the experimental dispersion curve is illustrated in Figure 5.

Table 2. **Wi-neera Drive Site: Final soil Model from WinSASW**

Depth Range m	Shearwave Velocity m/s	Density t/m^3
0 - 0.33	190	2.0
0.33 - 2.5	270	2.3
2.5 - 3.3	175	1.8
3.3 - 11.3	125	1.7
11.3 - 17.8	160	1.8
17.8 - 41.0	900	2.3
Below 41.0	2000 (est)	2.4

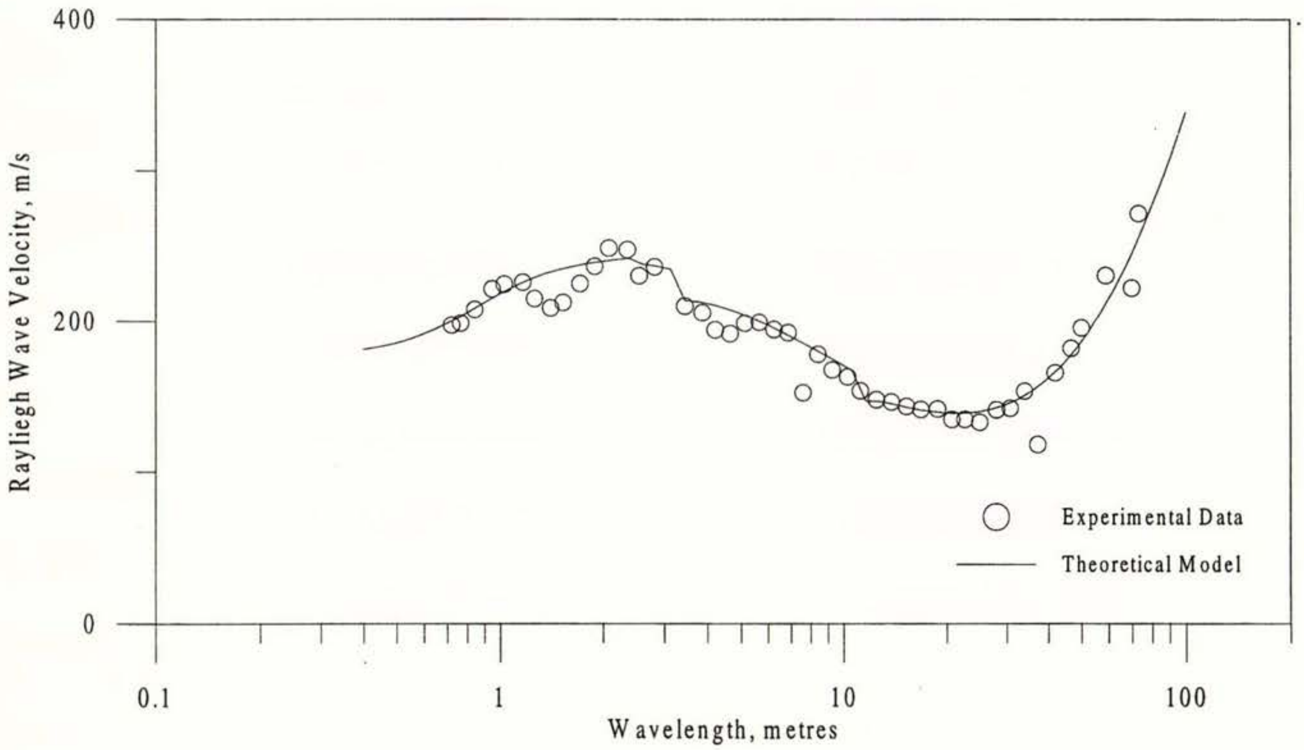


Figure 5. **Dispersion curves for Wi-neera Drive site**

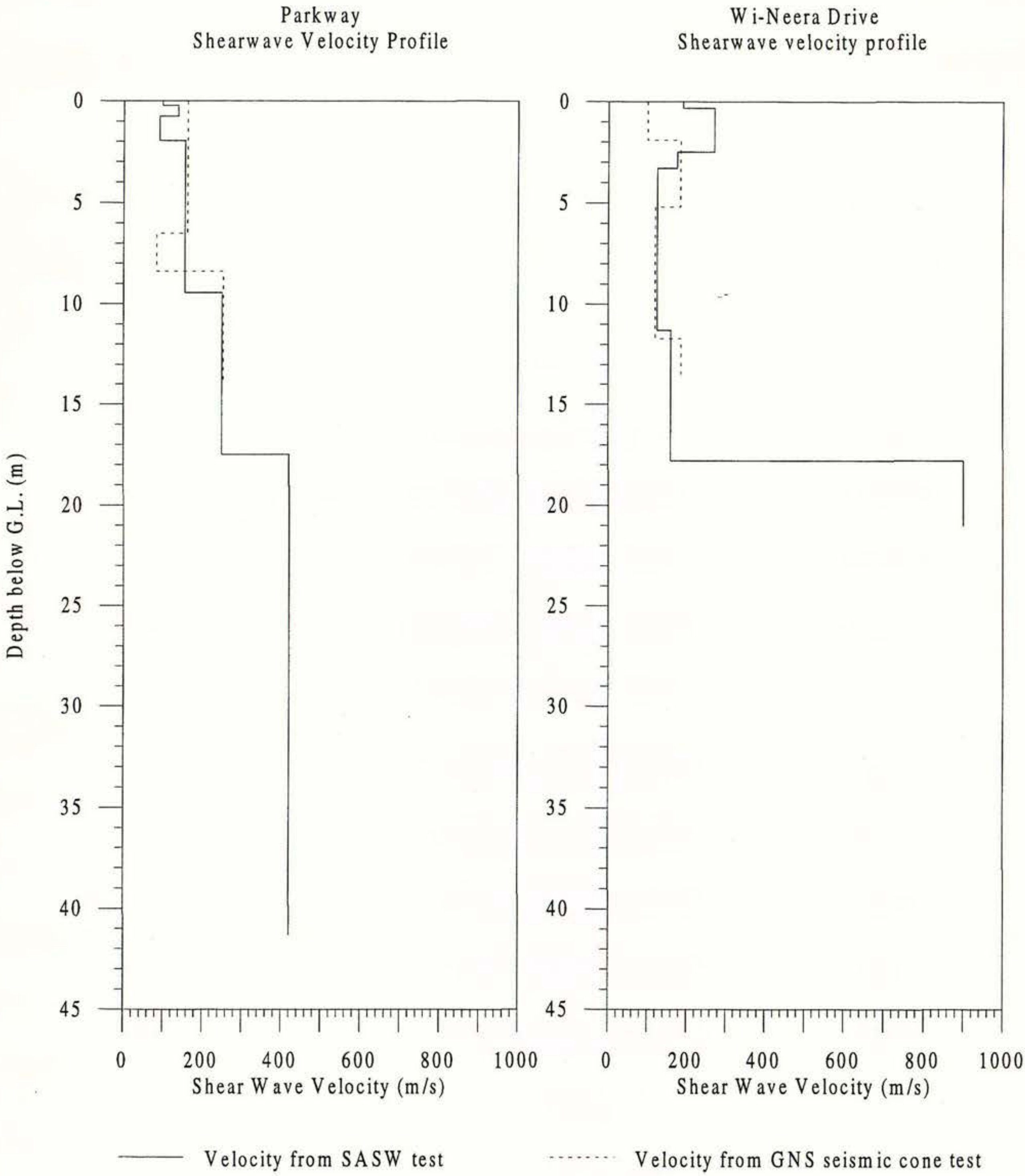


Figure 6. **Shearwave profiles for Parkway and Wi-neera Drive sites**

5.0 SITE AMPLIFICATION CALCULATIONS

Site amplifications were calculated as spectral ratios using the computer program SHAKE. The input models for SHAKE comprise the shearwave profiles calculated for each site from the SASW data, estimates of soil density poissons ratio and damping, and drillhole information on soil type. The input earthquakes were records of fifteen actual earthquakes held on file at Central Laboratories.

SHAKE is a computer program which utilises an equivalent linear procedure to calculate the non-linear behaviour of a horizontally layered soil/rock system subjected to transient vertically travelling shearwaves. SHAKE allows for the input earthquake to be applied to any layer and the response spectra of the input layer and any other layer to be estimated. Although our input models comprised seven layers, including the base rock, the thicker layers were divided into sublayers to make a 20 layer model which is the maximum capacity of the program. All of the fifteen earthquake records available are from rock (or very stiff soil) sites and so in each case the input record was applied to the base rock layer.

The response spectra for the base rock layer and for the surface layer were used to produce a plot of spectral ratio versus period. The maximum value of this spectral ratio and the period at which it occurs are referred to as the peak spectral amplification.

For each site SHAKE was run with each of the earthquake records without scaling. The peak acceleration at the surface, peak spectral amplifications, and their corresponding frequencies are plotted against the peak acceleration at the base rock layer (input earthquake) in Figures 7 and 8. The stain dependent nature of soil response, particularly at the large values of PGA associated with some of these earthquakes, is illustrated in these graphs.

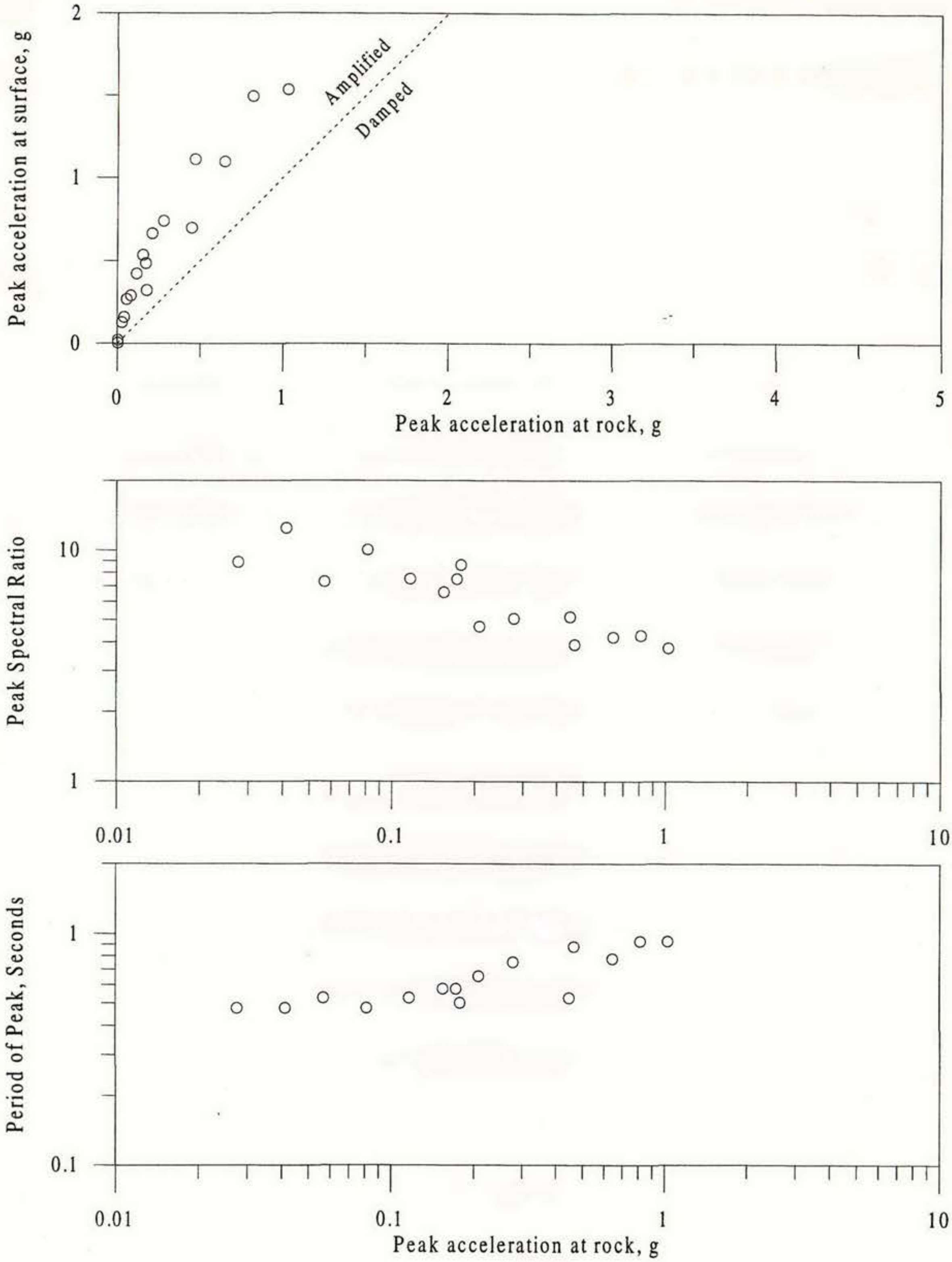


Figure 7. Peak Spectral Accelerations for Unscaled Earthquakes - Parkway

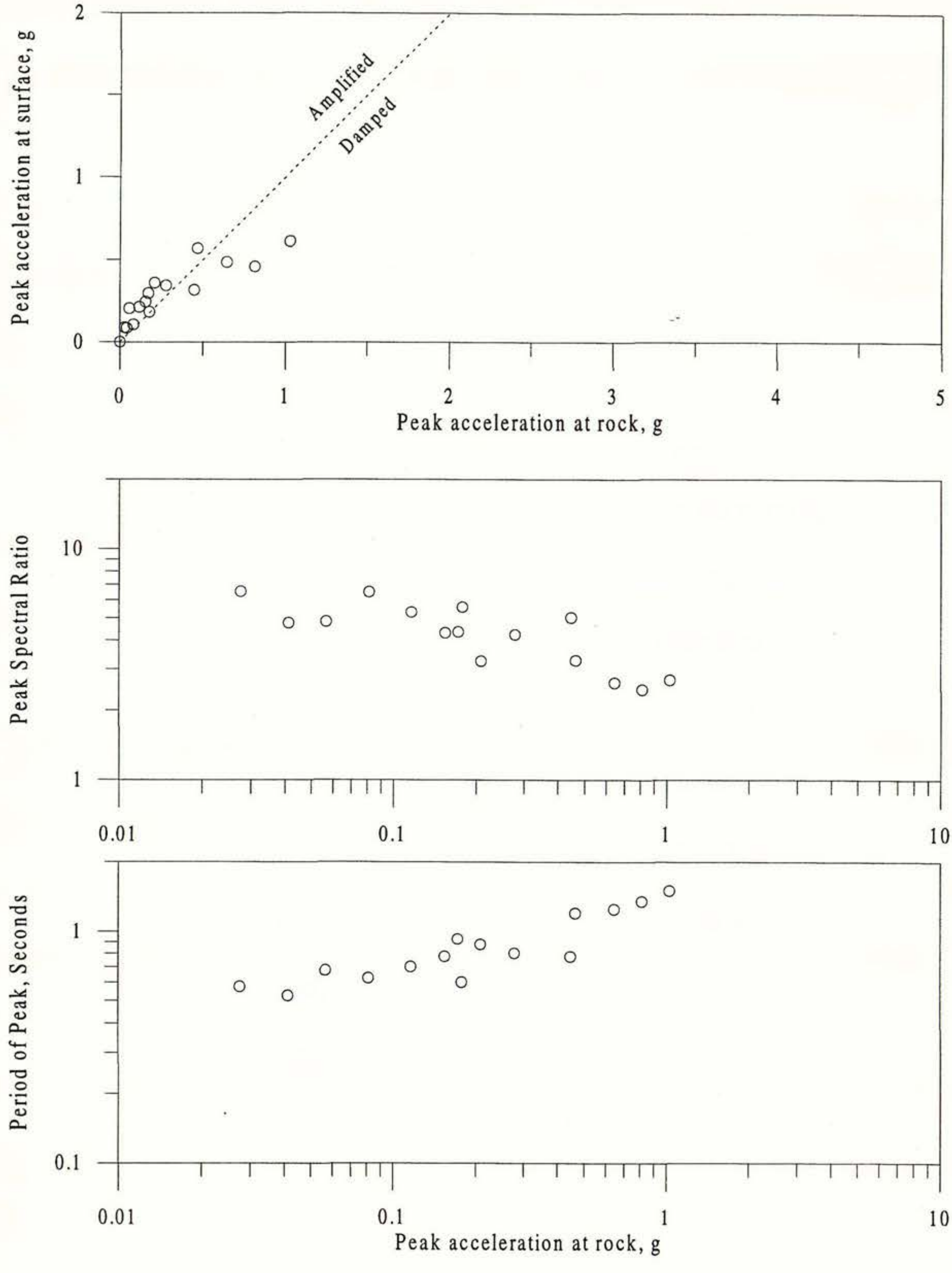


Figure 8. Peak Spectral Accelerations for Unscaled Earthquakes - Wi-neera Drive

6.0 SITE AMPLIFICATION COMPARISONS

For the two sites the Institute of Geological and Nuclear Science (GNS) have provided records of earthquakes from monitoring stations on rock and at the surface of soft soil deposits within the basin. GNS and Victoria University of Wellington have previously calculated the Fourier spectra and spectral ratios using earthquake records from these sites.

The spectra initially supplied by GNS were Fourier spectra of the uncorrected instrument signal. This is essentially a velocity signal whereas the Fourier spectra output by SHAKE are for acceleration. While the spectral ratios for velocity and acceleration are equivalent the individual rock and surface spectra are not directly comparable.

Furthermore, it was found that when the SHAKE input earthquake was scaled down to a similar magnitude to the recorded earthquakes, there was insufficient resolution to accurately define the Fourier spectra. However it is possible to calculate response spectra using SHAKE with better resolution for both acceleration and velocity. Therefore, at our request, GNS calculated response spectra for the selected earthquakes so that direct comparisons of rock and surface spectra could be made.

The evaluation of the modeling based on SASW data therefore utilises both Fourier spectra and response spectra. Other aspects related to the evaluation methods are discussed below.

- Mean Fourier spectra - the primary evaluation was based on mean spectral ratios due to the reported variation in spectral ratios determined for single earthquakes (Taber and Smith). For each site, the mean Fourier spectral ratios for between ten and twenty earthquakes, supplied by GNS, were compared to mean Fourier spectral ratios from SHAKE modeling using twelve unscaled earthquake inputs.

- Single earthquake response spectra - in this evaluation method the SHAKE derived response spectral ratios were compared with the spectral ratios for a single earthquake. The SHAKE base motion input was an earthquake record selected because it had a similar frequency spectrum to earthquakes recorded at the rock site

  The earthquakes used as input to SHAKE are all larger than those recorded by GNS and consequently are associated with lower amplification levels (because of the strain dependant behaviour of the soil). The earthquake records used in SHAKE are all large magnitude earthquakes in the range 5.5 to 8.0, recorded at a variety of distances from the epicenter, whereas the earthquakes recorded at the site were in the range of 2.0 to 5.5 with relatively small epicentral distances. It was therefore necessary to scale the input earthquake to the same size as the rock site earthquake. This was done by scaling to give the same peak acceleration.

- Peak spectral ratios - the peak values of response spectral ratio were plotted against the peak acceleration at the rock level. The peak values of response spectral ratios for the scaled earthquake input and associated surface record are plotted together with the equivalent data for all fifteen unscaled input earthquakes. These peak values are plotted against peak acceleration at the rock to illustrate the strain dependence of the amplification. The curve drawn through these points demonstrates this but is not a mathematical fit of the data.

6.1 COMPARISONS AT PARKWAY SITE

Fourier spectra for the monitoring station P23 on rock, and for station P07 which is the closest station to the SASW site, were provided by GNS. Mean Fourier spectral ratios and response spectra were also provided for P07 and P23. The locations of these stations is shown in Figure 2. Station P07 is closest to the SASW site, being approximately 20 metres to the west, and therefore was used for the initial comparison. Response spectra were also supplied for stations P07 and P23.

The earthquake for which individual response spectra were supplied was magnitude 5.5 and occurred on 22 August 1995. It was located at a depth of 81 km and had an epicentral distance from the monitoring station of 85 km. The earthquake from our files which gave the closest match when compared to the rock spectra was at Inangahua in the upper South Island, it was a magnitude 5.5 recorded on 25 May 1968. It was at a depth of 12 km and an epicentral distance of 12 km. The Inangahua earthquake was scaled by a factor of 0.0454 to give the same maximum acceleration as the record supplied by GNS.

6.1.1 Mean Fourier Spectra

The mean Fourier spectral ratios for stations P07 over P23 combine both the north-south and east west components. This is compared, in Figure 9, with the mean Fourier spectral ratios of the unscaled earthquakes.

The peaks for each of these spectral ratios both occur at a period of 0.60 seconds and both have a distinct plateau leading up to the peak, starting at a period of 0.25 seconds. The spectral ratios are in very good agreement, given the inherent uncertainties of the estimation procedures.

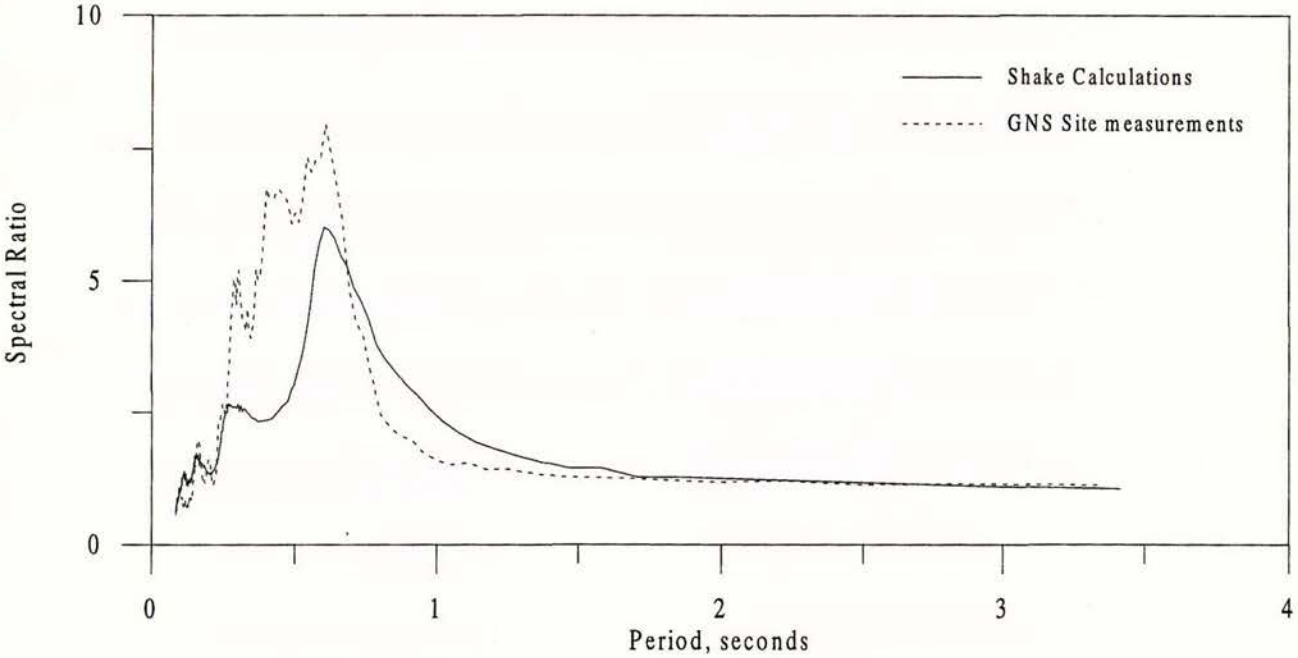


Figure 9. Comparison of mean Fourier spectral ratios at the Parkway site.

6.1.2 Single Earthquake Response Spectra

The resulting response spectra and spectral ratios, produced by SHAKE with the scaled earthquake, are shown in Figure 10 together with the data from GNS.

Although the input earthquake was scaled to have the same maximum acceleration the rock spectra have significant differences at periods above 0.1 seconds. The surface spectra show a similar pattern although there in much more energy in the computed spectrum. This translates through to a much larger peak on the computed spectral ratio than for the measured ratio.

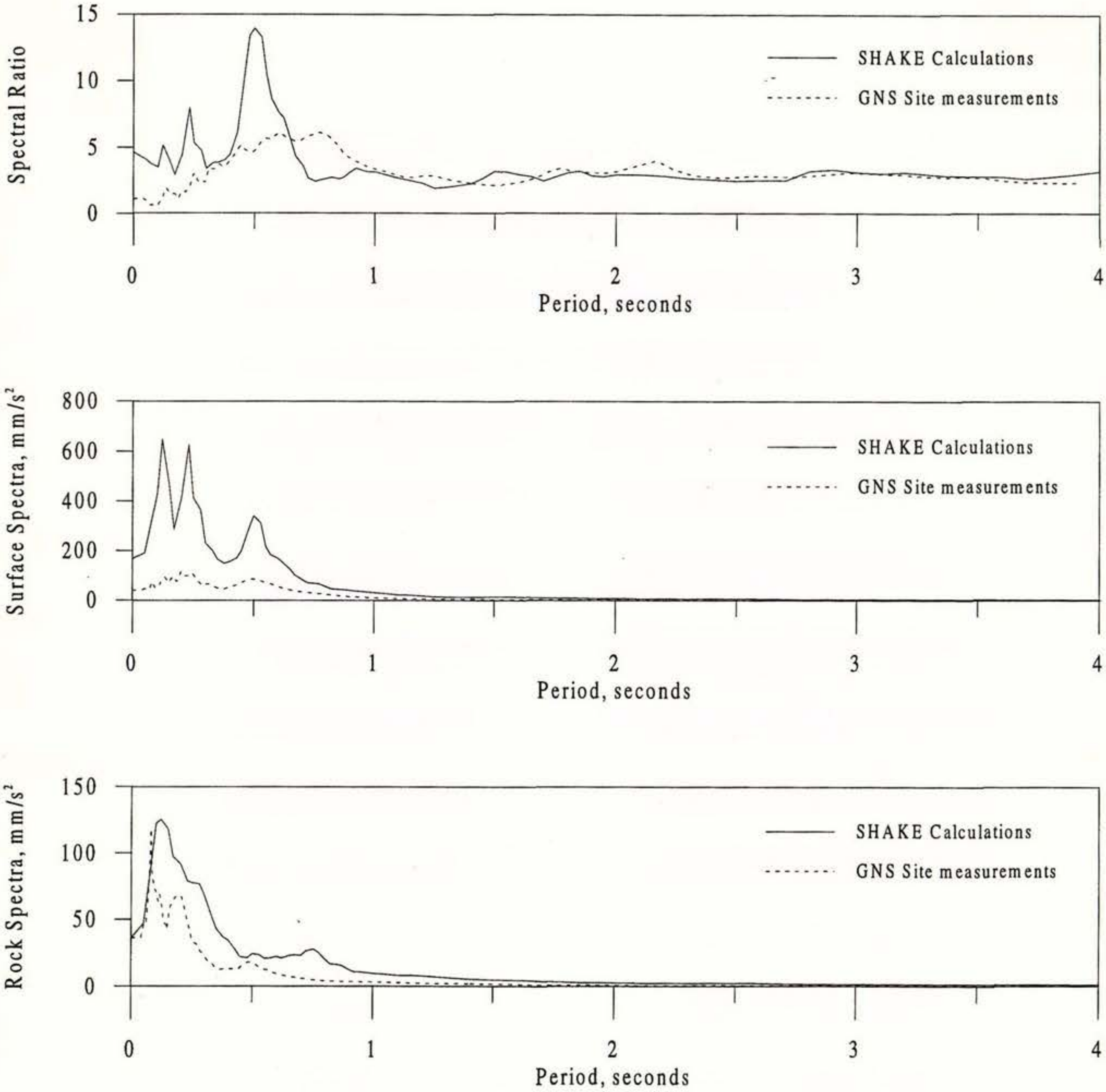


Figure 10. Comparison of response spectral ratios for a single event at the Parkway site.

6.1.3 Peak Spectral Ratios

The peak values of response spectral ratios from Figure 9 have been plotted together with the peak values for the unscaled earthquakes in Figure 11. The site earthquake shows a much lower value than the value calculated with the scaled earthquake. The peak of the mean Fourier spectral ratio is also shown, as a grey line. Because there is no peak acceleration value to plot the mean against, the line has been drawn up to the acceleration value of the selected earthquake which was the largest available.

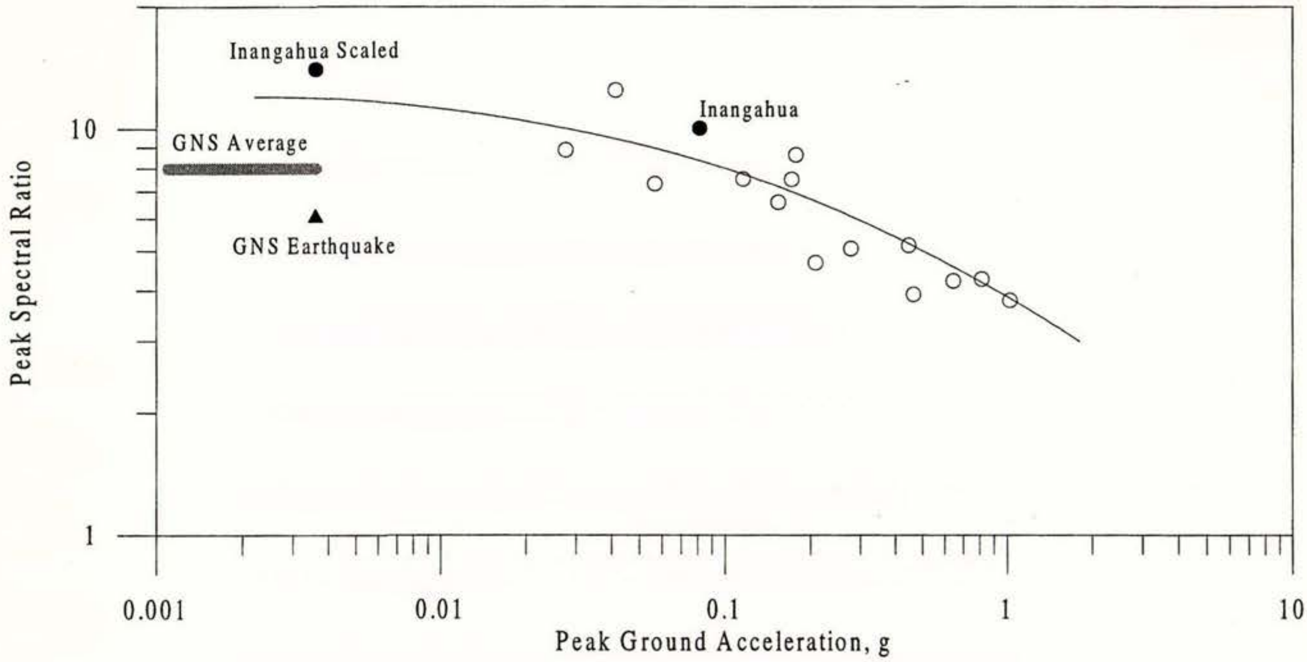


Figure 11. Peak spectral ratios at Parkway site

6.2 COMPARISONS AT WI-NEERA DRIVE SITE

Fourier spectra for records from the GNS monitoring stations PB5 and PB8 have been used for the comparison at the Wi-Neera Drive site. The locations of these stations is shown in Figure 2. Station PB5 is closest to the SASW site, being approximately 100 metres to the Southwest, while station PB8 is a rock site approximately 4 km to the Northeast.

The earthquake used for this comparison was magnitude 4.1 and occurred on 4 June 1990. It was located at a depth of 35 km and had an epicentral distance from the monitoring station of 30 km. The earthquake from our files which gave the closest match with the rock record spectra was at Te Kuha, it was a magnitude 5.7 earthquake recorded on 28 January 1983. It was at a depth of 8 km and an epicentral distance of 8 km from the recording station.

The Te Kuha earthquake was scaled by a factor of 0.0044 to give the same maximum acceleration as the earthquake recorded by GNS.

6.2.1 Mean Fourier Spectra

The mean Fourier spectral ratios for stations PB5 over PB8 combine both the north-south and east-west components. This is compared with the mean Fourier spectral ratios of the unscaled earthquakes in Figure 12. These two mean spectral ratios are quite different. Neither the peak value or the period of the peak are similar.

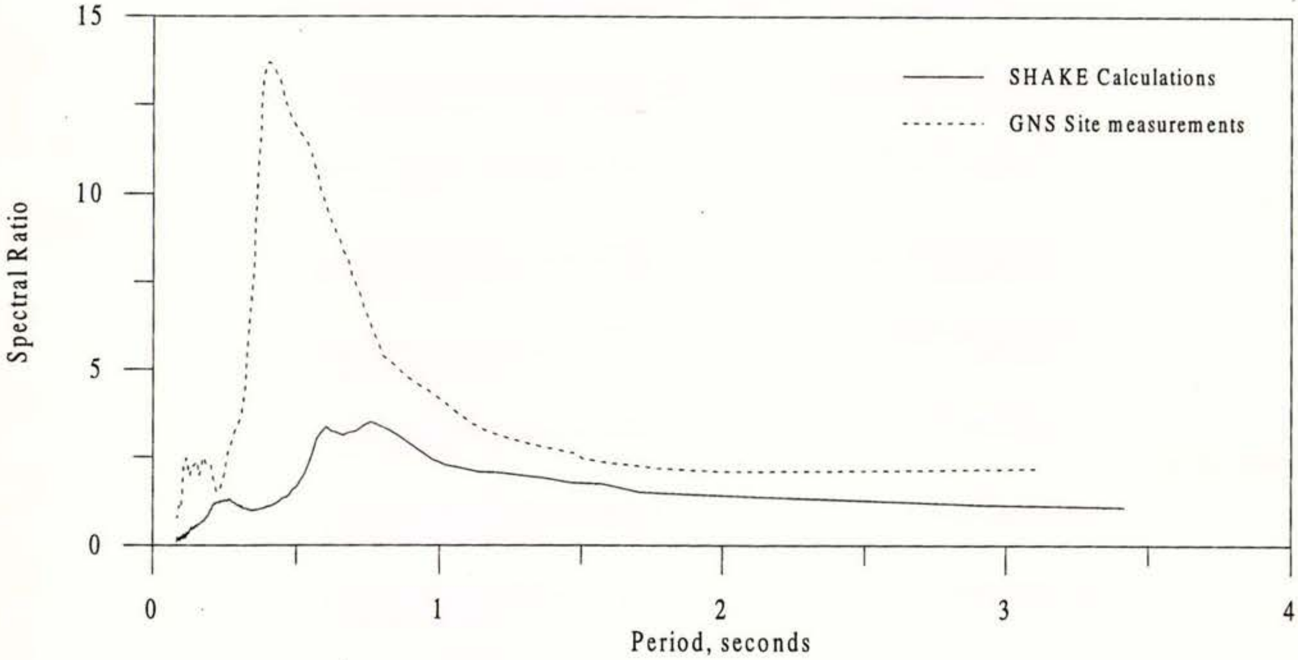


Figure 12. Comparison of mean Fourier spectral ratios at the Wi-neera Drive site.

6.2.2 Single Earthquake Response Spectra

The response spectra and spectral ratios produced by SHAKE with the scaled earthquake are compared with site data from GNS in Figure 13.

There are differences in the response spectra for both the rock and surface layer, although there is less difference than at Parkway. The main difference is in the frequency of the peaks for the surface spectra. Although the peaks for the spectral ratios are of a similar magnitude, there is a significant difference in the period at which the peaks occur.

Factors which may have influenced these results include:

- separation of approximately 100m between the GNS monitoring station and SASW test site,
- the small magnitude of the earthquakes recorded at the site requiring excessive scaling of the SHAKE input,
- the distance of 4km from the rock site to the soft soil site and sub-surface topography or source direction effects (Harmsen 1997).

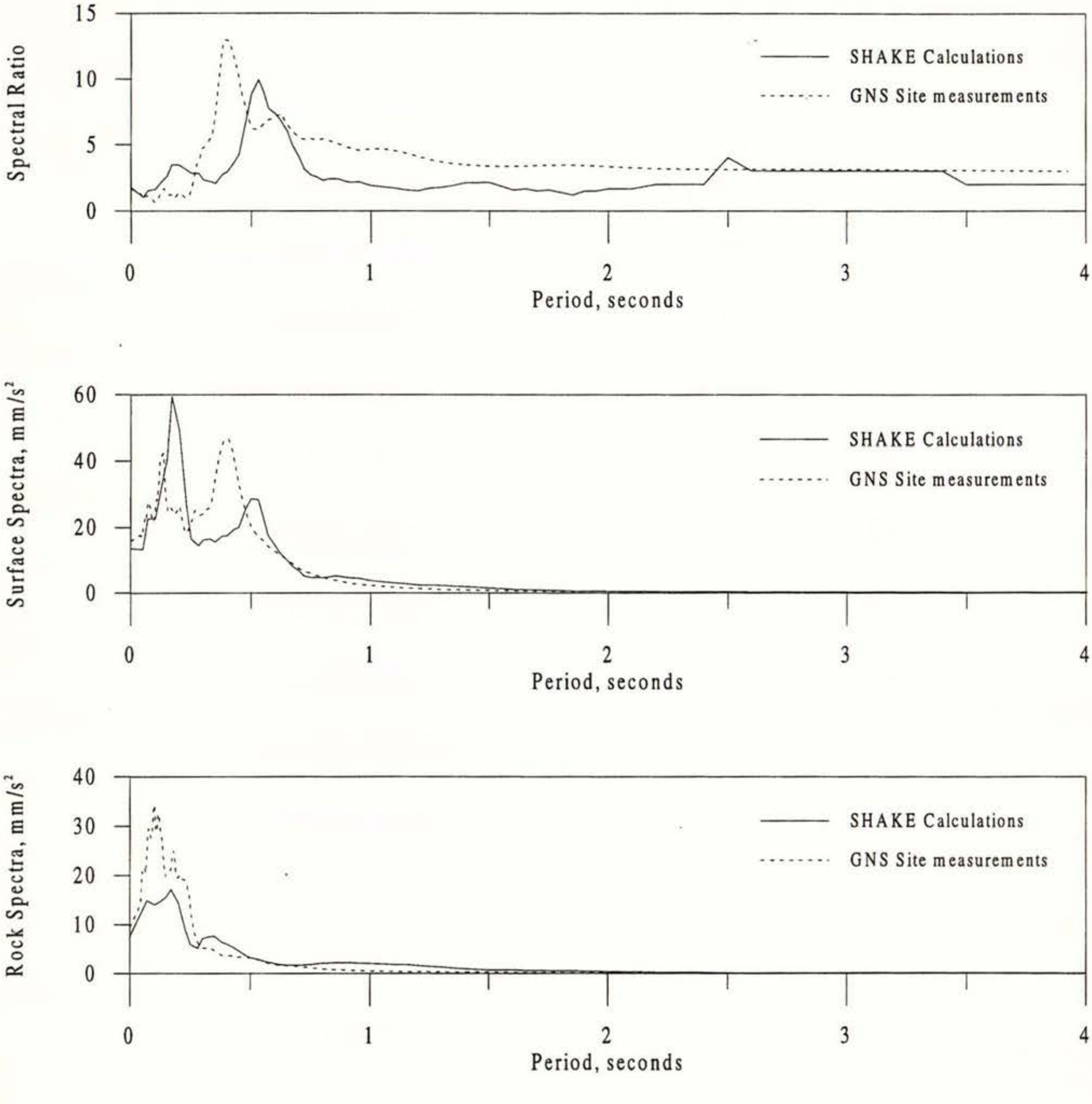


Figure 13. Comparison of response spectral ratios for a single event at the Wi-neera Drive site.

6.2.3 Peak Spectral Ratios

The peak values of response spectral ratios from Figure 12 have been plotted together with the peak values for the unscaled earthquakes in Figure 14. Both the selected site earthquake and the scaled earthquake are within the expected range for their size. The peak of the mean Fourier spectral ratio is also shown, as a grey line. Again the selected earthquake was the largest available so this line has been drawn up to the acceleration value of the selected earthquake. This mean data also falls within the scatter of data.

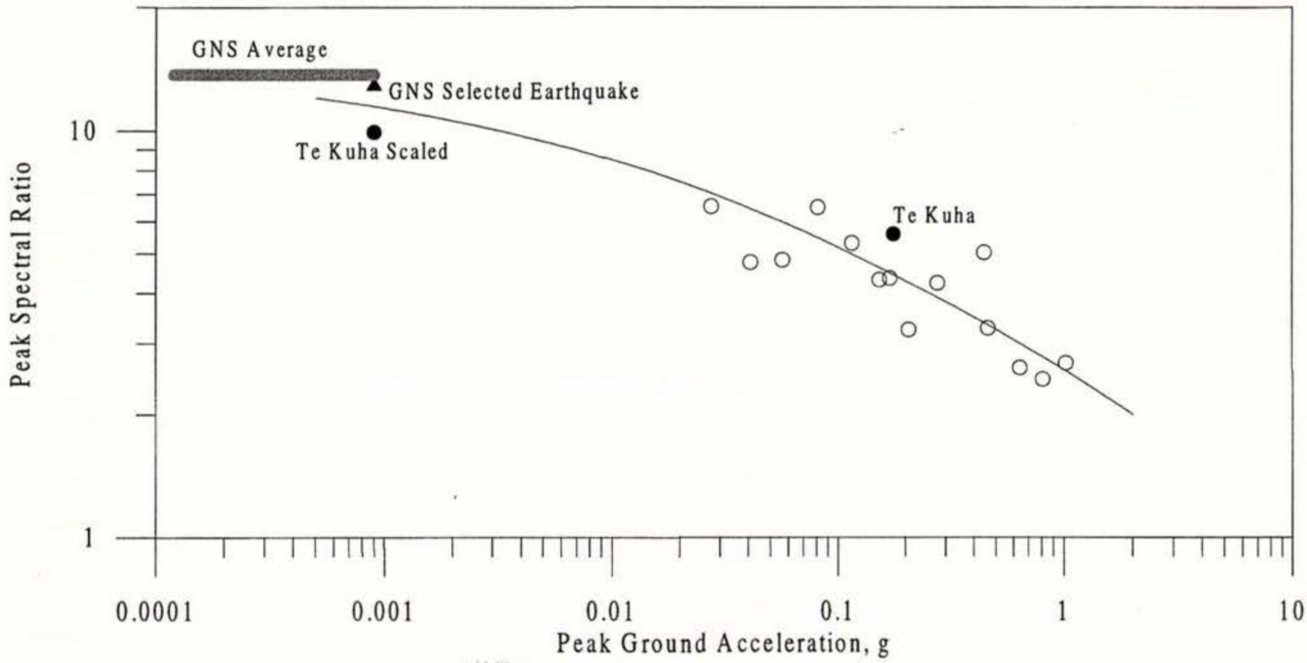


Figure 14. Peak spectral ratios at Wi-neera Drive site.

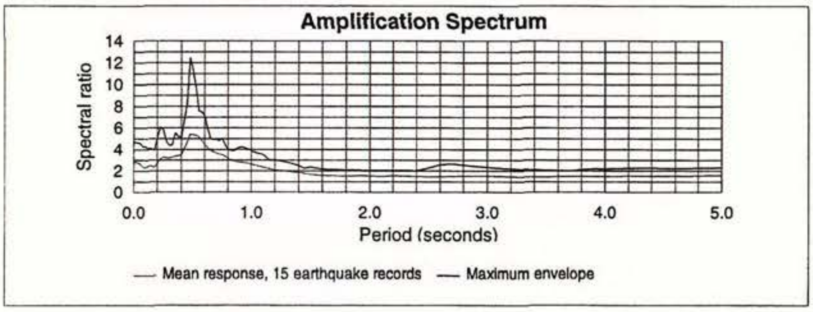
7.0 FUTURE UTILISATION OF SASW TESTING

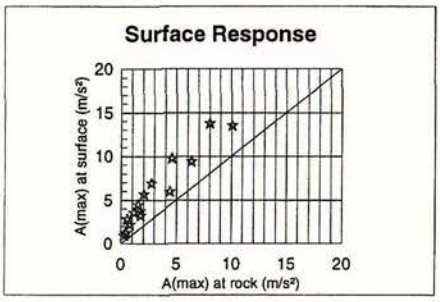
To utilise SASW as a standard test to determine site amplification it is preferable to adopt a standardised approach to reporting that conveys information in the format most useful to the engineering community. A suggested report form, based on data from the Parkway site, is shown in Figure 15.

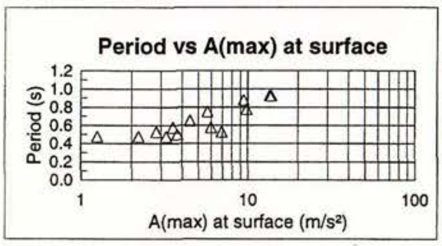
The suggested report form includes provision for soil liquefaction assessments based on shear wave velocity methods, for example those of Robertson (1990) and Tokimatsu and Uchida (1990).

SEISMIC EVALUATION
Site Amplification

Project Name:	**Parkway**	**Report No:**	522422.01
Test location:	**Manutuke St / Black Creek**	**Test date:**	02.02.98
Client:	**Earthquake Commission**	**Tested by:**	A Sutherland
Client ref:	**77/297**		T Logan







Soil Profile

Depth (m below GL)	Vs (m/s)	Soil type	Liquefaction (refer below)
0 - 0.23	98	fill	n/a
0.23-0.75	138	fill	n/a
0.75 - 1.95	90		
1.95 - 9.45	155	clayey silt	n/a
9.45 - 17.5	250		
17.5 - 40appro	420	sand	

Note: Vs profile measured using SASW method
Soil types inferred from CPT test

Response data based on "Shake" modelling using 15 earthquake records
Liquefaction assessment based on: (a) Tokimatsu & Uchida (1990) method
(b) Robertson (1990) method

Figure 15. Draft report form for site amplification.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from the results of this project.

1. The primary objective of this study, to assess the use of the SASW as a low cost method for determining site amplification has been validated . The method has significant potential but results must be carefully considered in the context of the characteristics of local earthquakes and the ground motion inputs used in the site response modeling.

2. At Parkway, the predicted and actual site amplification estimated using the mean spectral ratio are in very good agreement both in magnitude and period.

   There is a poor match at Parkway between predicted and actual amplification for the single earthquake response spectra, despite attempts to closely matching records based on their Fourier spectra, illustrating the degree of variation in site response for particular earthquakes.

3. At the Wi-Neera Drive site the predicted amplification using the mean spectral ratio and calculations based on earthquake records are in poor agreement

   For a single selected earthquake the results from the alternative methods showed a good match in magnitude but mismatch in period, suggesting issues of earthquake magnitude characteristics, monitoring station location and factors such as source direction and sub surface topography.

4. It is recommended that the comparison of site response at the Wi-neera Drive site be reassessed when additional site data becomes available from the sub-surface array, to allow the mean spectral ratio to be calculated using soft soil and rock motion records from instruments in close proximity..

   At the time the sites were selected, it was planned that comparative data would be available from a new sub-surface array to be installed by GNS at the Wi-neera Drive site. In fact an array at the position of PB5 is now due for installation in the next few months (i.e. May - June 1998). The array will have three seismometers at different levels and so future estimation of the spectral ratio will not be influenced by the present uncertainties arising from the assumption that earthquake records at the rock site several kilometers away accurately represent the motion of the rock at Wi-neera Drive.

5. We recommend that future evaluation of the SASW method should utilise data only from sites where the rock and surface monitoring stations are in close proximity and the SASW test site can be located at the same position. Testing of additional sites meeting these criteria is recommended to more firmly establish the use of the SASW method.

6. The following refinements to the SASW method are recommended:

   - Site performance estimates should be based on the mean spectral ratio calculated from modeling results for at least five earthquakes.
   - Evaluation of comparative site performance associated with higher strain events should be investigated using sites where recordings of large magnitude earthquakes have been made.

- If possible, time histories recorded at a rock monitoring station should be used as the input to SHAKE to avoid the need for excessive scaling down of larger magnitude earthquakes to amplitudes comparable with the weak motion records typical of site monitoring.

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REFERENCES

Addo, K. O. and Robertson, P. K. (1992), "Shearwave Velocity Measurements of Soils using Rayleigh Waves."

Barker, P. R. (1996), "A report on Cone Penetrometer and Seismic Cone Penetrometer Testing at Parkway - Wainuiomata", Prepared for Dr G McVerry & Dr R Beetham, Institute of Geological and Nuclear Sciences.

Duggan, E. B. (1997), "Shallow Seismic Structure of Parkway Basin, Wainuiomata, New Zealand."

Harmsen, S. C. (1997), "Determination of Site Amplification in the Los Angeles Urban Area from Inversion of Strong-Motion Records" Bulletin of the Seismological Society of America, Vol. 87, No4, pp 866-887, August 1997.

Heisey, J. S., Stokoe, K. H. II, Hudson, W. R. and Meyer, A. H. (1982), "Determination of In Situ Shear Wave Velocities from Spectral Analysis of Surface Waves." Research Report 256-2, Center for Transportation Research, The University of Texas at Austin.

Miller, M. D., Pullan, S. E., Waldner, J. S. and Haeni, F. P. (1986), "Field Comparison of Shallow Seismic Sources" Geophysics, Vol. 51 No. 11, November 1986, pp 2067-2092.

Nazarian, S. and Stokoe, K. H. II, (1986), "In Situ Determination of Elastic Moduli of Pavement Systems by Spectral-Analysis-of-Surface-Waves Method (Theoretical Aspects)" Research Report No 437-2, Center for Transportation Research. The University of Texas at Austin, November 1986.

Robertson P.K., (1990), "Seismic Cone Penetration Testing for Evaluating Liquefaction Potential", Proceedings of a Seminar on Recent Advances in earthquake Engineering Design using Laboratory and In-situ Tests, Sponsored by ConeTec Investigations Ltd, Vancouver, Canada.

Schnabel, P. B. and Lysmer, J. (1972), "SHAKE, A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites." Report EERC 71-12, Earthquake Research Centre, Univ of California, Berkeley.

Sritharan, S. and McVerry, G. H. (1992), "Microzone Effects in the Hutt Valley in Records from a Strong-motion Accelerograph Array", Bulletin of the New Zealand National Society of Earthquake Engineering, Vol. 25, No. 4, December 1992, pp 246-263.

Stephenson, W. R. and Barker, P. R. (1992), "Evaluation of Sedimentary Properties in the Lower Hutt and Porirua Areas by means of Cone and Seismic Cone Penetration Tests", Bulletin of the New Zealand National Society of Earthquake Engineering, Vol. 25, No. 4, December 1992, pp 265-285.

Stokoe, K. H. II, Rix, G. J. and Nazarian, S. (1989), "In Situ Seismic Testing with Surface Waves." 12th International Conference on Soil Mechanics and Foundation Engineering. 1989: Rio de Janeiro. Proceedings Rotterdam: Balkena, 1989 Volume 1.

Sutherland, A. J. (1993), "Pavement Properties Using Spectral Analysis of Surface Waves" Central Laboratories report 93-22128.

Taber, J. J, and Smith, E. G. C (1992), "Frequency Dependent Amplification of Weak Ground

Motions in Porirua and Lower Hutt, New Zealand", Bulletin of the New Zealand National Society of Earthquake Engineering, Vol. 25, No. 4, December 1992, pp 303-331.

Tokimatsu, K. and Uchida A., (1990), "Correlation Between Liquefaction Resistiance and Shearwave Velocity", Soils and Foundations 30, 2: 33-42.

Tokimatsu, K., Kuwayama, S. Tamura, S. and Miyadera, Y. (1991), "V_s Determination from Steady State Rayleigh Wave Method." Soils and Foundations Vol. 31, No 2, June 1991, pp 153-163.