Client Report 2000/47

CONFIDENTIAL

Seismic CPT in strong soils

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Seismic CPT in strong soils

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ABSTRACT

The Seismic Cone Penetration Test involves pushing a sensor directly into the ground. The sensor measures seismic wave speeds in order to characterise the site. Such information is useful both for computer modelling, and for empirical understanding of soil-induced amplification of ground motion. Currently this technique is limited to relatively soft materials because it is not possible to penetrate harder ground. The new method is to drill a hole into the hard material and to backfill it with soft material, then to proceed as usual.

Although some problems were experienced with ground water flow, the new technique was shown to be feasible, and vital additional information about the Parkway site was obtained.

TECHNICAL ABSTRACT

A modified Seismic Cone Penetration Test was used to determine the shear-wave velocity profile at Parkway, Wainuiomata, to a depth of 31.5m. A 100mm diameter hole was drilled in the hard-to-penetrate soils of the site, and backfilled with a cement/bentonite/water grout so that an SCPT probe could be pushed into the ground and still remain in physical contact with the soil.

Mixing of ground water with the grout resulted in both a thinner grout than envisaged, and a consequent noisy set of seismic traces. Shear wave arrivals were picked and these arrivals enabled a shear-wave velocity profile to be assigned. This profile had a Rayleigh-wave dispersion character in good agreement with pre-existing experimental results and consistent with resonant frequencies of the Parkway basin determined by a seismograph array.

EQC PROPOSAL OBJECTIVES

1. To directly determine a shear wave velocity profile for the Parkway basin, particularly below 14m where impenetrable materials are encountered.
2. To demonstrate that the Seismic Cone Penetration Test can simply be adapted to allow the economical determination of shear wave velocity profiles in difficult materials.
3. To compare shear wave velocity profiles for Parkway, determined by direct (SCPT) and indirect (SASW) techniques.

1.0 INTRODUCTION

The Seismic Cone Penetration Test (SCPT), devised by Robertson et al (1986), provides an extremely rapid, reliable, and economic means of determining stratigraphic strength and modulus information of soils in one sounding. It was introduced to New Zealand in a primitive form as described by Stephenson and Barker (1988), then refined and used successfully to predict site resonant frequencies as described by Barker and Stephenson (1991).

SCPT is uniquely suited to investigating the seismic response of soft soil sites because in general a site which will amplify shaking is also one which offers little resistance to a penetrometer probe. However there are some sites for which this does not hold; at Miramar, Wellington, dilatant sands "locked up" under the shear stress induced by the cone, preventing penetration; at Gisborne, penetrometry was limited by accumulated side friction along the penetrometer rods; at Parkway, a presumed layer of gravels stopped penetration.

In circumstances such as these, other techniques are required if the shear wave velocity profile of the site is to be determined. Two possible techniques are; shear wave reflection/refraction (described in many books treating geophysical investigations), and Spectral Analysis of Surface Waves (SASW), (Nazarian and Stockoe, 1984). However both these methods are indirect in the sense that more than one shear wave velocity profile is capable of generating the arrivals (reflection/refraction) or dispersion curve (SASW) observed for a site. Moreover, in the case of SASW, Boore and Brown (1998), and Wills (1998) have cast doubts on this inversion process. In addition, shear wave reflection/refraction studies are bedevilled by the fact that p-wave arrivals (which are always earlier) can mask s-wave arrivals, and the fact that high velocity layers reflect incident energy, often making it difficult to characterise properly, deeper materials.

What is needed is a direct method similar to SCPT, and one such method exists - the conventional Vertical Seismic Profile (VSP) method, in which a geophone is lowered down a pre-drilled, cased hole, and the arrival of surface-generated s-waves is logged as a function of depth. Unfortunately this is an expensive procedure.

What we envisaged was a hybrid method which combined the directness of VSP and SCPT with drilling technology. Instead of casing a pre-drilled hole we proposed to backfill a pre-drilled hole with a bentonite/cement slurry, and to carry out an SCPT test in this filled hole.

2.0 THE CHOICE OF THE PARKWAY SITE

The Parkway basin has been the object of considerable study since Taber and Smith (1992) discovered that it had a large resonant amplification at around 1.5Hz. Following that discovery, a temporary network of seismographs was operated on and around the basin as described by Stephenson and Chávez-García (1998) and by Chávez-García et al (1999), in order to study the roles of normal modes and of propagating waves in controlling the resonant response. In addition, a series of seismic CPT probes was carried out by Barker (1996) in order to obtain shear wave velocity profiles at various locations within the basin. These SCPT tests were frustrated by an impenetrable layer at a depth of around 12m at all the locations tested, such that the 1.5Hz fundamental frequency of the basin could not be explained unless a 62 millisecond deficit in vertical shear wave propagation time could be accounted for, in and below the impenetrable material.

While it is relatively easy to invent distance-velocity pairs that supply the missing 62 milliseconds, it is less easy to ensure simultaneously that the postulated profile has a region of high velocity contrast, and that the postulated profile is reasonable (i.e. velocity generally increases with depth). Yet for a sharp resonance to be observed, there must be a high contrast in shear wave velocity at some depth.

The combination of a hard-to-penetrate site, a hard-to-envisage shear wave velocity profile, and a technically important site, made Parkway a prime candidate for testing the new technique. Having a good shear-wave velocity profile will enable accurate computer modelling of the response of the basin, and such modelling will be able to be compared with the seismograph array results, thus advancing our understanding of how to model such small local basins.

3.0 PREVIOUS GEOTECHNICAL INVESTIGATIONS AT PARKWAY

From the inception of the Parkway project there has been a series of geotechnical investigations carried out. These are all described by Beetham (1999). They commenced with the recording and analysis of microtremors in the area, in order to confirm that a site resonance observed by Taber and Smith (1992), was pervasive over a wide area. Following that confirmation, various other investigations were carried out as follows:

Cone Penetration Tests were carried out at 11 sites, and Seismic Cone Penetration Tests at three of these. The results are presented in Barker (1996), and are reproduced in an appendix to Beetham (1999). It should be noted that a misprint has occurred in the caption of Figures 4 and 5 of that report, where "Moana" should read "Momona". In brief the profiles show shear wave velocities of around 80m/s at the surface, increasing to 250m/s at 12-15m depth. These tests were all frustrated by encountering an impenetrable layer at 12-15m.

Gravity and seismic reflection/refraction surveys were carried out along two lines by Duggan (1997). They were interpreted as showing a 70m thick sedimentary layer with a shear-wave velocity of 140m/s, over greywacke basement.

An SASW test was carried out at site G02 (see Beetham, 1999) by Sutherland and Logan (1998). G02 corresponds to site 2 of Barker (1996). The SASW test results are presented in an ambiguous fashion, in that the tabulated and graphed velocity profiles for the site do not agree. However it is noted that waves with "wavelengths ... corresponding to a penetration depth of 30 to 40 metres" were generated. It seems more likely that the bottom Parkway layer extends from 17.5m to 41m as graphed, rather than from 17.5m to 21m as tabulated. This is consistent with the quoted shallower wave penetration at Wineera Drive, Porirua (the other site investigated by Sutherland and Logan (1998), and the measured and calculated frequencies for the two sites. We assume the graph of Figure 6 from Sutherland and Logan (1998) to define their characterisation of the site, rather than their table 1.

4.0 DRILLING AT PARKWAY

A 39m deep borehole was drilled at site G02 (see Beetham, 1999) by a contractor, under our supervision. The hole was made by wash drilling, using a stream of water to flush the cuttings to the surface. The colour and grain size of the cuttings give some indication of the materials encountered. The top 12m of the hole was 150mm in diameter, and was supported by a steel casing. This depth had already been investigated by SCPT, and although it had been intended to withdraw the casing, the presence of artesian water led us to leave the casing in place in order better to seal the flow. The bottom 27m of the borehole was 100mm in diameter, and was cased to 21m. Below this depth the hole was supported by a polymer gel being added to the drilling water. Six core samples were obtained during the drilling. These were from the following depths:

Open barrel	12.30m to 12.55m
HQ3 triple tube	16.00m to 17.00m
HQ3 triple tube	20.00m to 20.60m
HQ3 triple tube	23.50m to 25.00m
HQ3 triple tube	29.50m to 31.00m
HQ3 triple tube	37.00m to 38.60m

Detailed descriptions are given in appendix 2

The drilling was interrupted at times to measure water flow and/or pressure. An artesian flow of 30 litres/minute flowed from between 20.7m and 39m, and heads of 2.5m, 3.0m and 6.5m above ground level were measured at various stages of drilling, the head increasing with hole depth.

At the end of drilling the hole was backfilled with a bentonite/cement slurry. The slurry was made up of 3 parts bentonite and 1 part Portland cement. The hole was backfilled to about 20m and then left overnight. The following day the rest of the hole was backfilled. It was necessary to add barites to the slurry in order to provide sufficient load to overcome the hydrostatic pressure. The 100mm diameter casing was withdrawn at the same time as the backfilling operation.

5.0 THE SCPT PROBING PROCESS

Our usual procedure when carrying out SCPT probing, is first to push the probe to the full depth required, and then to withdraw the penetrometer rods, stopping every 20cm to generate a shear wave at the surface and detect it at depth. On this occasion the unusual nature of the site caused us to modify the routine.

Penetration was normal for the first 0.5m, with the probe being pushed by the rig, but below that depth a copious amount of discoloured water flowed up outside the rods. We think that the bentonite/cement/water slurry may have become diluted by the natural flow of ground water during emplacement, and that the slurry was therefore not nearly as stiff as expected. Below 0.5m, the penetrometer hydraulic system was used, not to push the penetrometer rods down, but to restrain them from falling under their own weight. At 31m we paused to ascertain whether surface-generated shear waves could still be detected. They could, but only when the truck motor (which drives the hydraulics) was stopped. This caused us to reconsider our procedure, and as a result we worked down from 31m to 37m (where the signal was lost) carrying out a shear wave propagation test at every 20cm. The truck motor was not needed because the weight of the rods carried them down.

The interval from 11.4m to 31m was evaluated over 1m intervals with each interval being dealt with by using the hydraulics to raise the probe 1m, then letting the probe fall back that 1m in 20cm increments, carrying out a shear wave propagation test at each depth.

This meant that the (seismically noisy) truck motor needed to be started only once per metre.

The fact that a copious flow of discoloured water was able to flow around the push rods implies that the cone (which contains the geophone) could not be in intimate contact with the borehole walls. This must have contributed to the poor quality of the data which we recorded. Had we understood the situation more quickly we would have carried out the probe working down from the surface, rather than by the somewhat hybrid method described above.

When probing was complete and the penetrometer rods had been withdrawn, the high artesian pressure caused water to flow up the probe hole, transporting infill material as it did so. This constituted a major problem, because the high pressure pushed out any device we tried to use as a plug. It became necessary to check the flow, and at the same time to achieve a permanent seal while the temporary bung was held in place. Our eventual solution to this problem was to use a "Cherne" pneumatic plug to stop the water flow. This plug was held down by a spacer, which was pushed down by the CPT rig through a threaded hole in a steel plate. In turn, this plate was welded to the 150mm diameter casing. Finally, the hole in the steel plate was sealed by screwing a steel plug into it.

6.0 SCPT RESULTS

The results of the SCPT probing are plotted in our usual format in Figure 1. We have appended the early (0 – 12.4m) SCPT results recorded by Barker (1996) in order to provide information for the top 12.4m without the influence of the borehole and casing. The new traces leave a lot to be desired, with arrivals prior to the main shear wave making a shear wave profile hard to determine. These early arrivals are clearly a result of the technique used, because they are not present in the early, non-drilled test for depths where the two tests overlapped. We suspect that conversions of p-waves to s-waves lie at the root of this problem, and that these converted waves could have been partially eliminated in the usual way by generating and subtracting two opposed traces at each depth, with a reversal of the exciting force cancelling the converted phases. None of our previous field experience had shown this problem, so we were not easily able to do this (our s-wave generator is intrinsically single-ended).

In making our evaluation of the SCPT traces we carried with us an awareness that visual appearances as reflected by drillhole logs, are no indicator of shear modulus, but that on the other hand it would be unwise to neglect the role of geologic process. At Parkway, we were aware of the existence of the ancient lake reported by Begg et al (1993), and of the likelihood that the resultant lake deposits could form part of the Parkway profile. Knowing that the foot of the Parkway gully marks the edge of the lake deposits, we determined the relative height of our test site by considering the gradient (1 in 69) of the gully as measured with an Abney level, and the distance (500m) from the test site to the lake deposits. Accordingly, if the stratigraphy of the test site is one of lake deposits overlain by stream deposits, we would expect the lake deposits to lie about 7m below the surface at the test site.

In order to obtain a realistic shear wave velocity profile from the traces in Figure 1 we kept in mind the frequency at which microtremor horizontal-to-vertical spectral ratios for the site reached a maximum, as documented by Rodríguez et al (2000), and the Rayleigh wave dispersion curve for the site presented by Sutherland and Logan (1998). We considered that a Rayleigh wave dispersion analysis of our final model should have high ellipticity near the HVSR peak frequency (1.5Hz), and should not depart too far from the dispersion curve measured by Sutherland and Logan (1998).

Our initial impression, as shown in Figure 2, was that between 12m and 20m a lot of energy is reflected back towards the surface, with velocities of the order of 100m/s being involved. An alternative perspective is shown in Figure 3, which shows a possible line of first arrivals which is evident upon a careful inspection of the traces. Other credible lines of first arrivals could also have been chosen. Deeper than about 20m it is noted that signals arrive early on the traces. We interpreted these as converted p-waves, which increase in relative strength because much of the s-wave energy has been reflected back towards the surface. A shallow model as follows (Model 1) was evaluated, giving expression to the structure implied by the arrivals of Figure 2. We assumed an arbitrary s-wave velocity of 1650m/s, p-wave velocity of 3500m/s and density of 2.6 T/m^3 for the substrate, on the basis that it was likely to be weathered rock. The values for rock are required only in order to model the Rayleigh wave dispersion characteristics of the site, and should not be taken as our view of reality. They make little difference to the dispersion in the range measured.

Model 1

Layer 1 is 2.24m thick,	s 85m/s,	p 1650m/s,	rho 1.8 T/m^3
Layer 2 is 4.56m thick,	s 149m/s,	p 1650m/s,	rho 1.8 T/m^3
Layer 3 is 4.7m thick,	s 164m/s,	p 1650m/s,	rho 1.8 T/m^3
Layer 4 is 8.5m thick,	s 110m/s,	p 1650m/s,	rho 1.8 T/m^3
Layer 5 is 4.0m thick,	s 500m/s,	p 1650m/s,	rho 1.8 T/m^3
Layer 6 is 16m thick,	s 1500m/s,	p 2600m/s,	rho 2.2 T/m^3
Half space is	s 1750m/s,	p 3500m/s,	rho 2.6 T/m^3

Modelling was performed using the suite of surface-wave analysis programs provided by Herrmann (1996). Although the ellipticity maximum for the model occurred at 1.40Hz, the match with the measured Rayleigh wave dispersion curve, as shown in Figure 4, was poor.

Figure 4 shows the measured dispersion results as circles, and gives two versions of dispersion calculated from the parameters given by Sutherland and Logan (1998) in their table 1. One version takes the p-wave velocity values given by Duggan (1997), and the other assumes a Poisson solid (Lamé's constants $\lambda=\mu$; Poisson's ratio = 0.25) as is often done. Sutherland and Logan (1998) do not state their assumed p-wave velocities, and we take it that they assumed a Poisson solid because that assumption makes their s-wave velocity model a better fit to the observed dispersion values. We note that as Sutherland and Logan (1998) write, "The model is insensitive to slight variations in the assumed values of density and Poisson's ratio", but we point out that these slight variations can have far-reaching consequences when inversion is attempted.

In making our comparisons of modelled and measured dispersions we have plotted the data as phase velocity versus frequency, on a linear scale. This differs from the approach of Sutherland and Logan (1998), who plotted phase velocity versus wavelength, on a logarithmic scale. We believe that the Sutherland and Logan practise emphasises the small-scale, near-surface properties in an unrealistic manner.

Six other arrival lines for Figure 1 were picked, models constructed, and dispersion curves calculated. In no case were we able to pick arrivals at depths greater than 31.5m. The most satisfactory model was our model 3, which gives expression to the lines in Figure 3 as follows. We assumed p-wave velocity values of 1650m/s for the material above basement, which reasonably represents water-saturated sediments.

Model 3

Layer 1 is 2.24m thick,	s 85m/s,	p 1650m/s,	rho 1.8 T/m^3,	depth 2.24m
Layer 2 is 4.56m thick,	s 149m/s,	p 1650m/s,	rho 1.8 T/m^3,	depth 6.8m
Layer 3 is 4.7m thick,	s 164m/s,	p 1650m/s,	rho 1.8 T/m^3,	depth 11.5m
Layer 4 is 14.0m thick,	s 345m/s,	p 1650m/s,	rho 1.8 T/m^3,	depth 25.5m
Layer 5 is 6.0m thick,	s 133m/s,	p 1650m/s,	rho 1.8 T/m^3,	depth 31.5m
Half space is	s 1750m/s,	p 3500m/s,	rho 2.6 T/m^3	

The ellipticity maximum for this model occurred at 1.42Hz (the data from Rodríguez et al (2000) indicated 1.5Hz) , and the better match with the measured Rayleigh wave dispersion curve is shown in Figure 4.

This model (Model 3) represents our best attempt to represent reality. Neither it nor the Sutherland and Logan (1998) profile can give a value for the s-wave velocity in the deeper materials. It is worth noting that in the situation of a resonant layer, the Rayleigh wave dispersion curve does not indicate the velocity in the substrate until frequencies below the resonant frequency of the layer have been examined. This did not happen for the Sutherland and Logan (1998) study, possibly because vertical sensing seismographs were used, whereas Rayleigh wave particle orbits for frequencies near resonance are nearly horizontal.

An attractive feature of Model 3 is that its shear wave profile accounts for the fundamental resonant frequency of the site (1.5Hz) on an infinite plane layer basis. That is, it supplies the missing 62 milliseconds vertical propagation time that was a key factor in selecting Parkway for this study.

As can be seen in Figure 5, the SASW-derived and SCPT-derived models correspond well for the top 10m of the site, but below that they are increasingly at odds. As can be seen in Figure 4 however, these two models do not give dramatically different Rayleigh wave dispersion curves. The lessons applying to the inversion of Rayleigh wave dispersion curves are clear – inversion results should be regarded with caution, measured p-wave velocities should be used, and the raw dispersion values are best used to supply valuable constraints when other results such as SCPT or shear-wave reflection/refraction, are being interpreted.

Finally, Figure 6 shows the s-wave arrival times as a function of depth, based on the Sutherland and Logan (1998) s-wave velocity profile. The lack of such a set of arrivals in Figure 1 suggests that the SASW profile was not accurate at depth.

7.0 SUMMARY

Objectives 2 and 3 of the original proposal have been met completely. In respect of objective 1, the presence of flowing artesian water made the field procedures more difficult than envisaged, but we still believe that the concept would constitute a useful method in non-artesian systems, which in our experience are more common than the situation encountered.

The use of previously-obtained Rayleigh wave dispersion values provided a constraint which allowed true first s-wave arrivals to be picked with confidence.

Modifications of the technique should enable it to give better results in future investigations.

8.0 RECOMMENDATIONS

Our original intent was to avoid the usual drilling and casing costs associated with conventional vertical seismic profiling. In the event, the drilling contractor found it necessary to case the hole in order to fill it with bentonite, and the only saving was of $2400 in retrieved casing. An additional benefit should have been the removal of the effects of the casing, but this was countered to some extent by the presumed dilution of the bentonite slurry. These factors would make us approach the project differently in the event of a similar test.

In a future exercise of this type we would specify wire-line drilling with continuous coring, with the bentonite/barites/cement backfill being placed dry in muslin bags to be pushed down to the bottom of the casing as the casing is withdrawn. This material would hydrate naturally as ground water entered the bags.

In such a future exercise we would also employ a double-ended shear-wave source, using some sort of mechanism to deliver a standardised blow to each end of the source in turn, allowing us to cancel converted-p phases. We would work down from the surface when deploying the geophone and using it to measure seismic arrivals.

Countering the problems due to artesian water proved a time-consuming distraction. In future we would require the near-surface casing to be threaded at its top, so that simple threaded fittings could be used to curb the water flow, while still enabling the bentonite-filled hole to be re-used.

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FIGURES

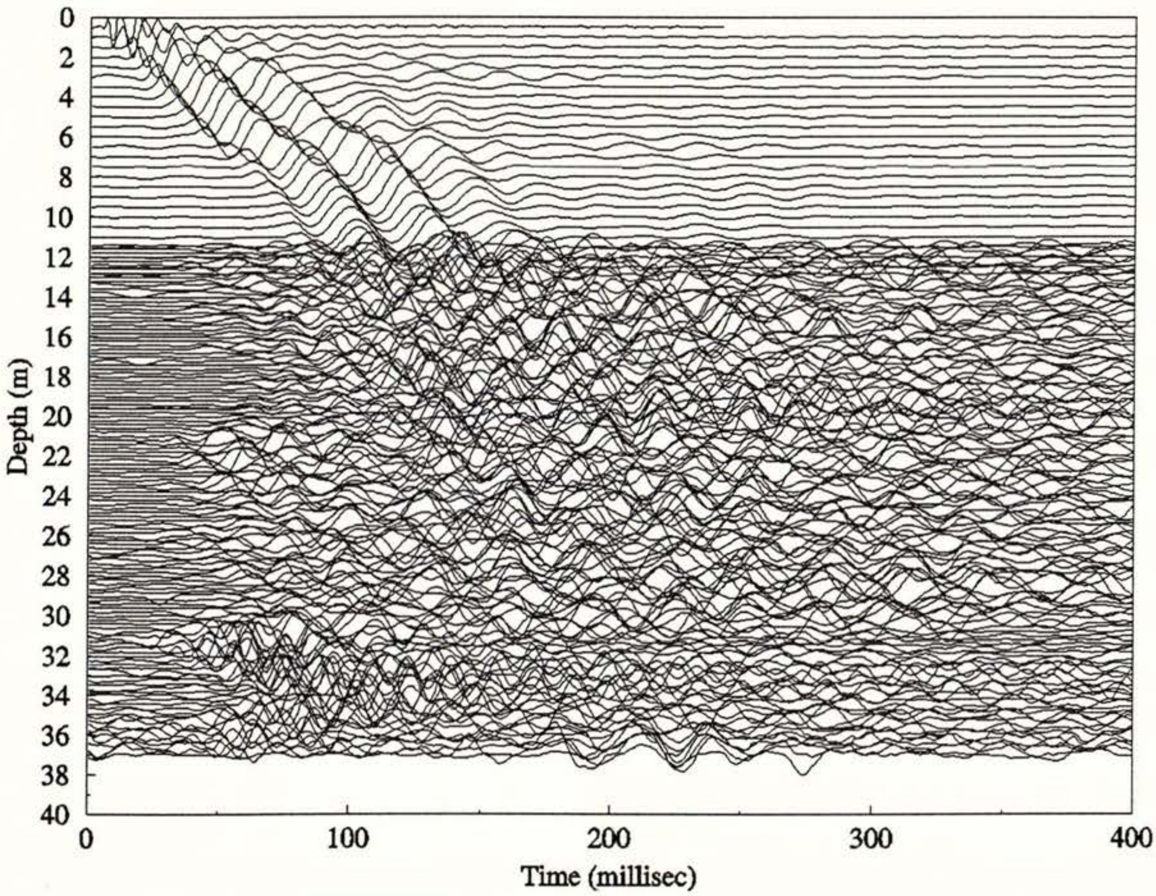

Figure 1: Seismograms of horizontal motion plotted as a function of depth, for the Parkway SCPT probe.

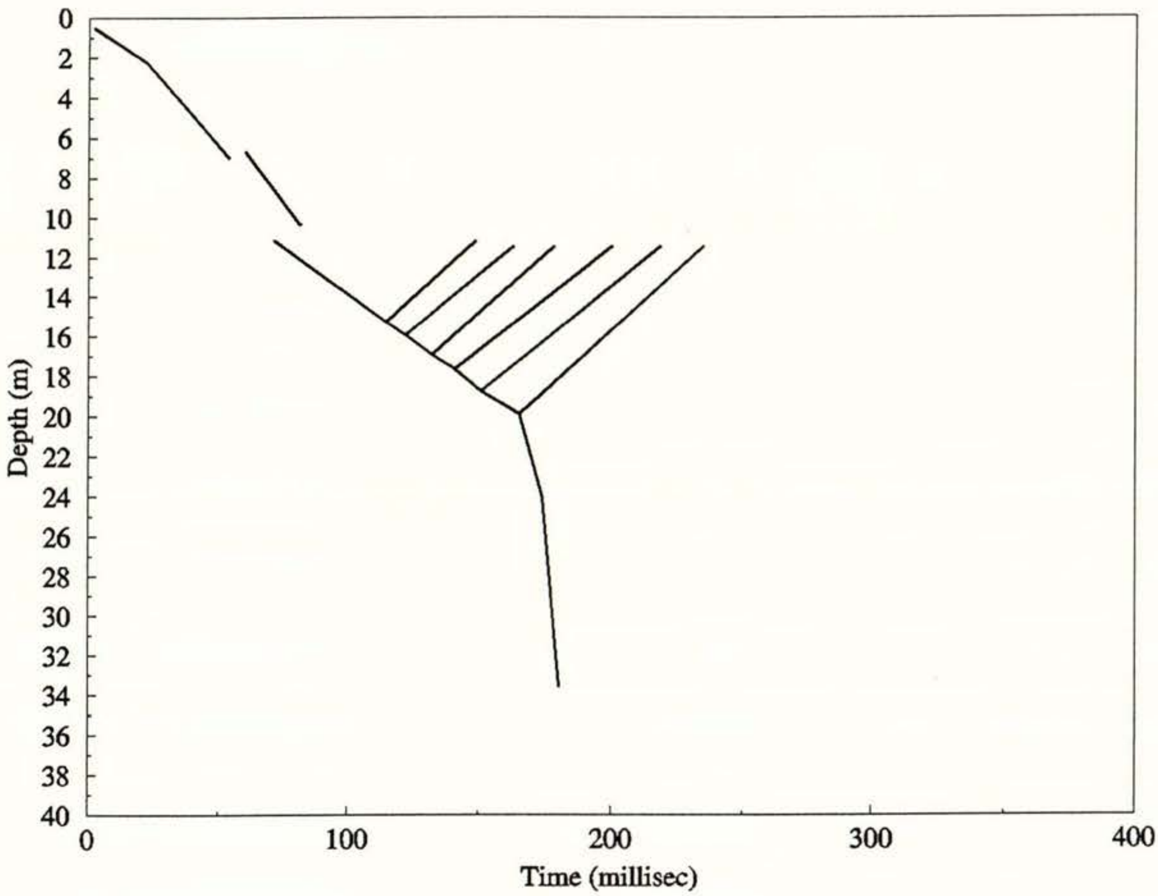

Figure 2: Initial picked s-wave arrivals, corresponding to model 1.

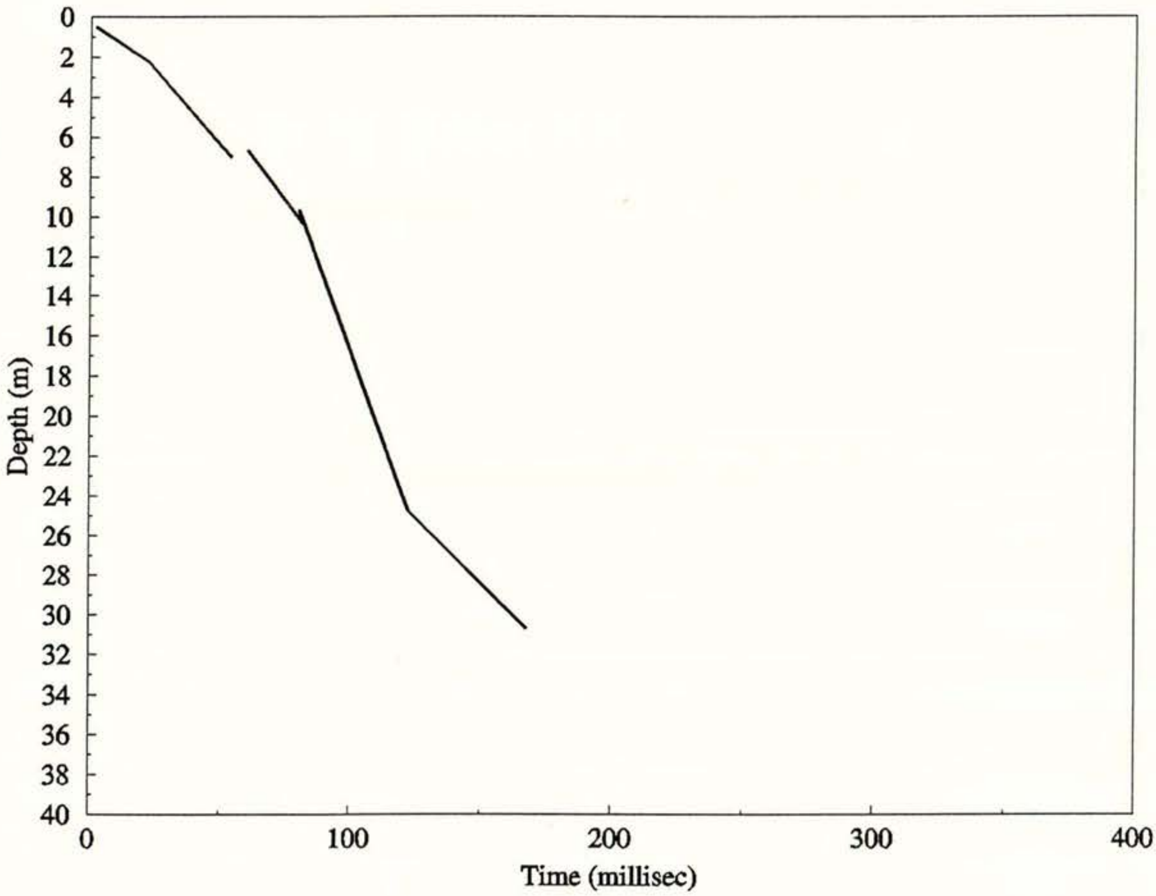

Figure 3: Picked s-wave arrivals corresponding to model 3.

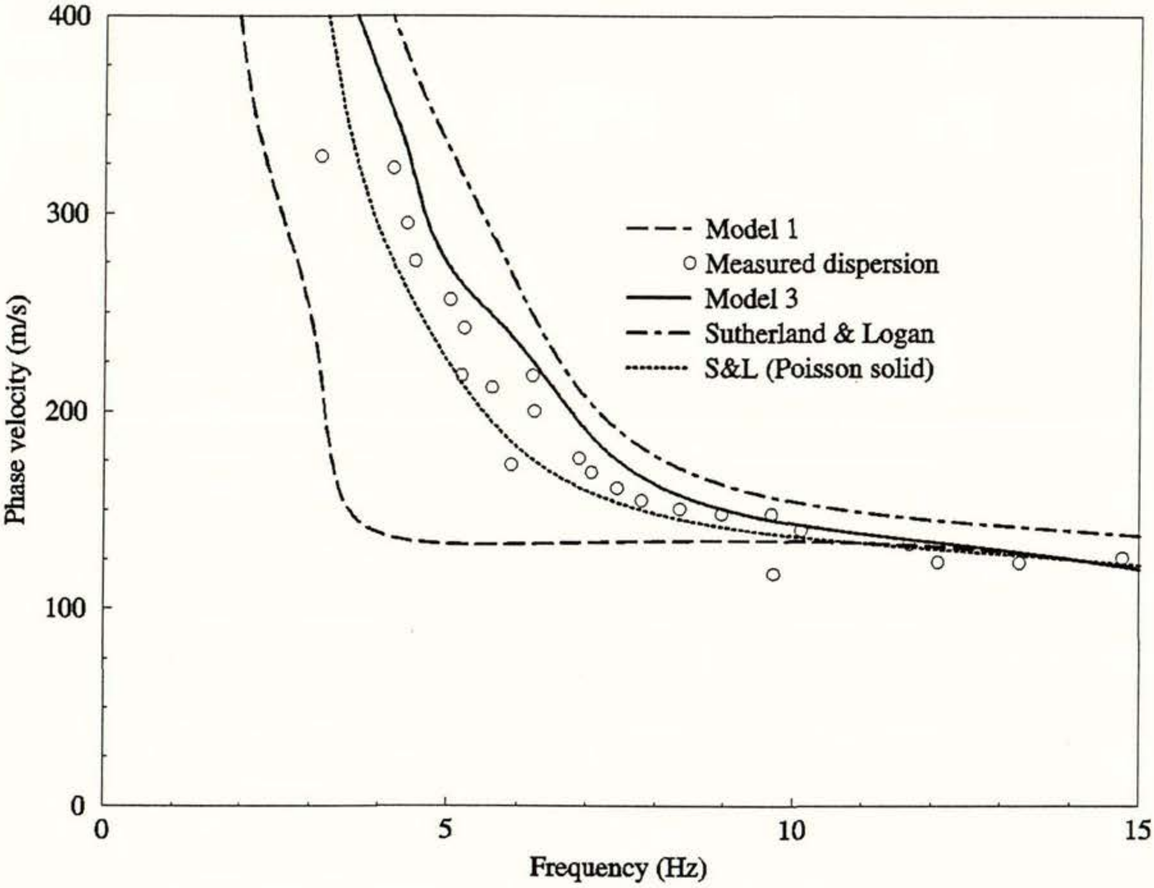

Figure 4: Calculated and observed dispersion values for the Parkway site. Model 1 is clearly inadequate to explain the measured dispersion, while model 3 is acceptable, being comparable to the Sutherland and Logan (1998) result if a Poisson solid is assumed. The Sutherland and Logan (1998) s-wave profile, when combined with measured p-wave velocities, gives less credible dispersions.

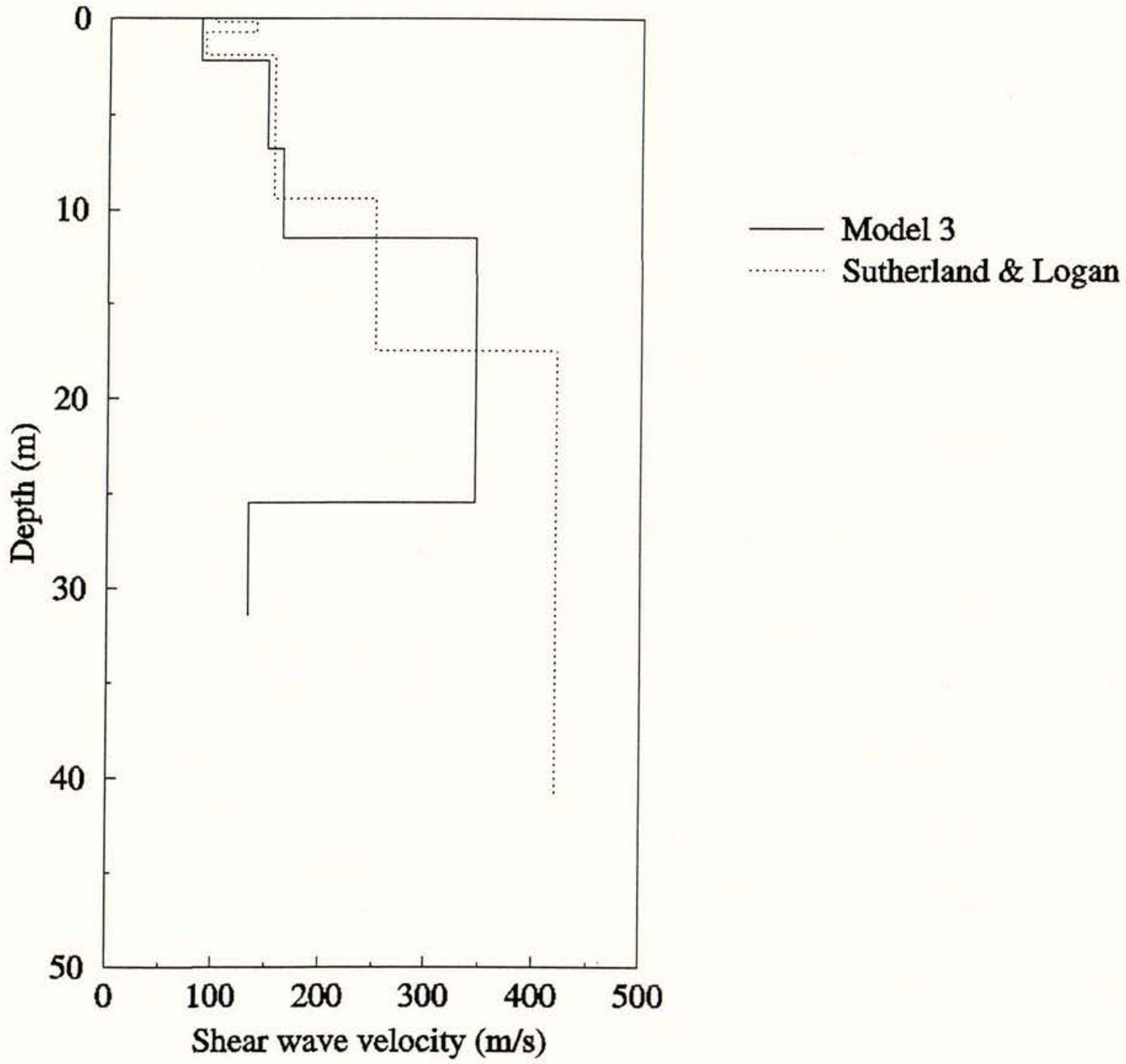

Figure 5: Our deduced s-wave profile compared with that of Sutherland and Logan (1998). Discrepancies increase with depth.

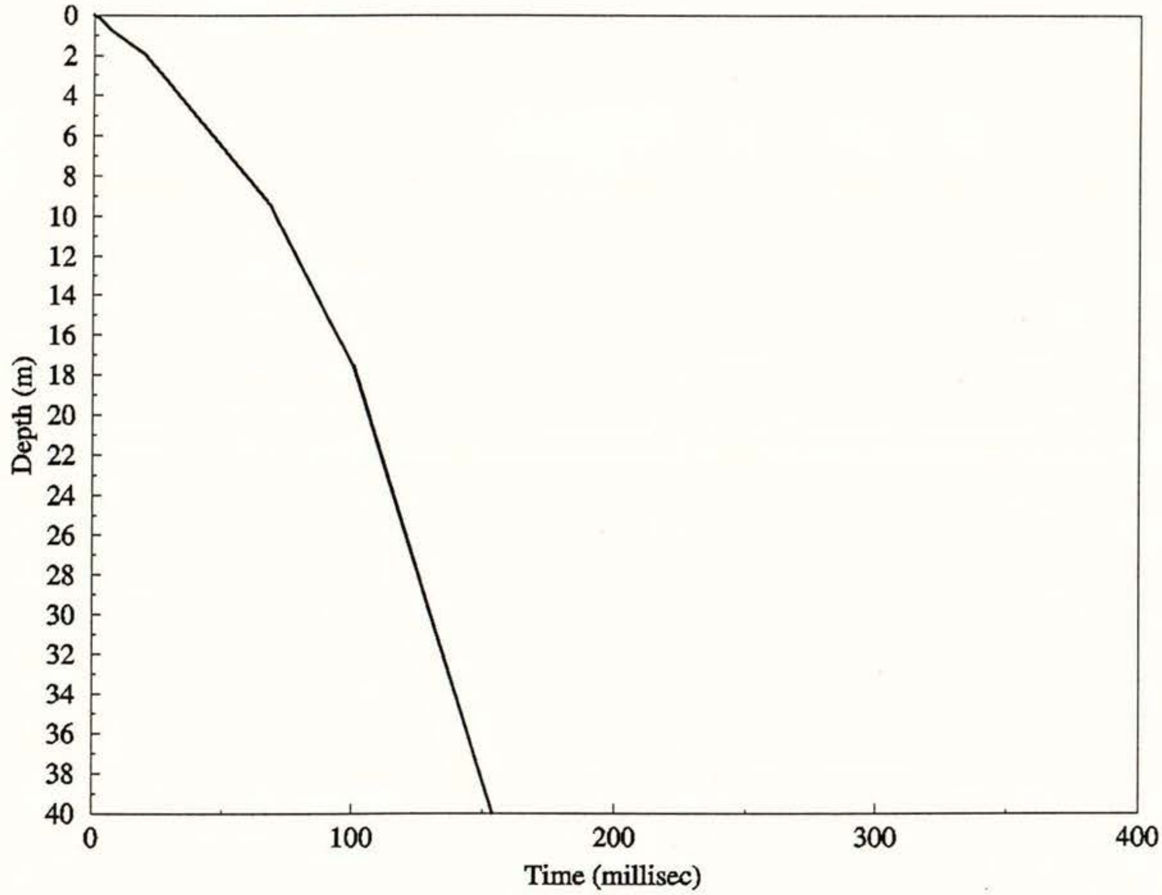

Figure 6: Expected s-wave arrivals as a function of depth for the Sutherland and Logan (1998) model. No such line is readily obvious in figure 1.

APPENDIX 1

CONTRACTOR'S DRILLING LOG

CONTRACTOR'S DRILLING LOG

Depth (m) From	To	Material Type
0.00	2.00	Auger drilled - brown dry firm sandy silt & silty sand
2.00	6.40	Grey silty sand & sandy silt layers. Occasional gravel silt sand layers with gravel sizes to 50mm.
6.40	6.80	Dark brown organic silty sands, sandy silt layers
6.80	7.30	Grey silt, sandy silt, silty sand layers
7.30	9.20	Light brown sand silt & gravel mixed Possible overlying colluvium
9.20	10.0	Brown & grey silty sandy gravels. Possible overlying colluvium
10.00	10.50	Brown & grey silty sand, sandy silt, some organic traces with greywacke gravels evident. Possible colluvium
10.50	12.50 continued to 20.8	Light brown silt sand clay and greywacke gravel, intermittent layers, possibly overlying colluvium. Old landslip deposits.
20.80	32.50	Grey layers of silty sands, sandy silts, silts fine gravels in silty sand, organic layers and traces of vegetation (core samples show up bands of the above)
32.50	37.20	Brown silt sand clay and gravels, some blue of same. Mixed & layers. Possible colluvium mixed with sediments.
32.70	39.00 EOB	Blue/grey silty sandy gravels.

After hole completion, took grout mixer and pump to job. Mixing 3 bentonite to 1 cement from bottom up. Added 4 bags barytes to weigh down. 2 stage grout

Welded 150mm casing to 11.50 metres depth
100mm socketed wellsinker to 20.7m depth.

Artesian flow 30 litres/minute. Between 20.70m and 39.00m.

All permeable layers appear to yield artesian flow due to increases in flow with depth of hole.

Type of bit: Drag   Fluid loss: gain

Artesian flow encountered from approx 8.00 metres. Very slow but increasing with depth via permeable layers.

APPENDIX 2

CORE DESCRIPTIONS

Parkway Borehole

Core Descriptions

Core No	Depth (m)	Description
1	12.25- 12.50	Orange brown gravelly silty sand
2	16.0 – 16.8	Orange brown silty sand with some small stones
	16.8 – 16.9	Olive brown sandy silt with some small stones
	16.9 – 17.0	Orange brown silty sandy gravel
3	20.0 – 20.6	Orange brown gravelly silty sand
4	24.0 – 24.08	Dark grey brown silty sandy gravel
	24.08 – 24.82	Dark blue grey banded silty fine sand. Thin (3mm) layer of white (?) clay at 24.48m and 24.53m. Thin (3mm) layer of dark chocolate brown organic silt at 24.70m
	24.82 – 25.0	Blue grey gravelly silty sand
	25.00 – 25.38	Banded dark grey/ chocolate brown fine sandy silt
	25.38 – 25.5	Medium grey silty sandy gravel
5	29.5 – 30.15	Angular/ sub-angular greywacke stones (40mm) at top of core. Blue/ green grey very gravelly silty sand
	30.15 – 30.35	Blue grey and chocolate brown silty sand
	30.35 – 30.67	Chocolate brown organic sandy silt
	30.67 – 30.8	Dark grey gravelly silty sand
6	37.0 – 37.12	Orange brown gravelly sandy silt
	37.12 – 37.75	Light blue grey gravelly silty sand/ sandy silt
	37.75 – 38.35	Blue grey gravelly silty sand/ sandy silt
	38.35 – 38.46	Olive brown gravelly sandy silt
	38.46 – 38.60	Dark grey gravelly silty sand. Piece of wood at 38.58m

Described by: P R Barker
March 2000

APPENDIX 3

EQC PROPOSAL

Seismic Cone Penetration Test in Strong Soils (Application 99/380)

Objectives:

1. To demonstrate that the Seismic Cone Penetration Test (SCPT) can be simply adapted to allow the economical determination of shear-wave velocity profiles in difficult materials.
2. To directly determine a shear-wave velocity profile for the Parkway basin, Wainuiomata, using a modification of SCPT. This particularly applies to depths below 14m where impenetrable materials are encountered.
3. To compare this shear-wave velocity profile with the shear-wave velocity profile determined by Sutherland and Logan in an EQC contract using Spectral Analysis of Surface Waves (SASW).

Method:

A 150mm diameter hole will be drilled to a depth of 30m to 40m in the sediments underlying Parkway basin. Representative soil samples will be taken from the hole in order to characterise the material drilled. The hole will then be filled with a stiff bentonite-cement mixture, which will be within the capacity of a 3 tonne penetrometer rig.

Then a standard SCPT test will be carried out down the hole, the bentonite-cement providing coupling between the in-situ soil and the geophone of the SCPT probe.

Relevance:

It is well established that the near-surface shear-wave velocity profile of a soil is the parameter that dominates the amplification of earthquake shaking by soft soils. Prior to 1987, determining accurate shear-wave velocity profiles for New Zealand sites relied upon a relatively expensive procedure of drilling and casing a hole, down which geophones were lowered. Other, indirect, techniques (Spectral Analysis of Surface Waves, shear-wave refraction) relied on inversion procedures which have ambiguities. The determination of shear-wave velocity profiles was either expensive or imprecise.

The introduction of the Seismic Cone Penetration Test (SCPT) to New Zealand in 1987 by Stephenson and Barker, ushered in an era where accurate shear-wave velocity profiles could be obtained, and the resonant frequencies at sites such as Porirua, Pukehou, Wainuiomata and South Dunedin could readily be predicted. These predictions were subsequently verified. The low cost of the method was a result of SCPT eliminating the step of drilling and lining a hole.

A major limitation of SCPT is that it is only applicable to soft sites, where cone penetrometry is viable. Occasionally this limitation can be due to the presence of a relatively thin layer of compact gravel sandwiched between layers of finer-grained softer material. The gravel layer stops the penetration process. Such a problem can be overcome by carrying out testing down to the gravel, withdrawing the SCPT probe, drilling through the gravel, and then continuing the test, with a small section of the profile left undetermined.

The proposed technique will allow those parts of a profile which formerly needed to be drilled, and thus bypassed, to have their shear-wave velocities determined. This can include cases where most of the profile is impenetrable.

In addition, a shear-wave velocity value from the stiffer sediments underlying Parkway basin will add to our knowledge of the properties of stiffer soils of this general type.

Research Programme:

Note: This proposed project will be carried out in a public park, and will therefore need to be carried out with due sensitivity. It may not be possible to gain access to the site without leaving deep wheel ruts, until settled spring weather. For this reason the timetable has been set out with considerable flexibility.

1999 (after early April, access-dependent)	Contractor drills and backfills hole
1999 (after mid-April, weather-dependent)	SCPT probing carried out
1999 (end of December)	Reporting complete

Review of past research:

The two main non-invasive contenders for obtaining shear-wave velocity profiles are shear-wave reflection/refraction and SASW. Both these techniques have been applied at Parkway; shear-wave reflection/refraction by Duggan (1997); SASW by Sutherland and Logan, (1998). Each technique has its disadvantages in a situation such as Parkway.

In the case of shear-wave reflection/refraction, changes in shear-wave impedance are usually much larger than changes in p-wave impedance, and signal losses accordingly greater. In addition the shorter wavelength of shear-waves means that they are attenuated more with distance. Thus the first shear-wave arrivals are likely to be masked by the earlier and stronger p-wave arrivals, and an inferred s-wave velocity profile impossible to determine

In the case of SASW, recent work by Wills (1998) and by Boore and Brown (1998) casts doubt on the accuracy of methods based on inversion of surface-wave phase velocities. It has been found that such methods tend to under-estimate near-surface velocities, and to over-estimate velocities at greater depths.

Given these shortcomings, it is important to make a direct determination of the shear-wave velocity profile at Parkway both to corroborate the SASW data and to provide accurate values for input to computer models.

References:

- Boore, D.M. and Brown L.T. (1998) Comparing Shear-Wave Velocity Profiles From Inversion of Surface-Wave Phase Velocities with Downhole Measurements: Systematic Differences Between the CXW Method and Downhole Measurements at Six USC Strong-Motion Sites. *Seismological Research Letters, 69(3), May-June 1998, 222-229.*

- Duggan, E.B. (1997) Shallow seismic structure of Parkway Basin, Wainuiomata, New Zealand. *B.Sc.(Hons) Thesis, Victoria University of Wellington, New Zealand.*

- Sutherland, A.J. and Logan T.C. (1998) SASW Measurement for the Calculation of Site Amplification. *EQC Research Project 97/276. Central Laboratories Report 98-522422, Opus International Consultants, Lower Hutt, New Zealand.*

- Wills, C.J. (1998) Differences in Shear-Wave Velocity due to Measurement Methods: A Cautionary Note. *Seismological Research Letters, 69(3), May-June 1998, 216-221.*

Availability of existing data:

Existing data on the shear-wave velocity profile at Parkway falls into two categories – the SCPT profiles already determined for the Institute of Geological and Nuclear Sciences by Barker Consulting under a Public Good Science Fund contract, and an SASW profile determined by Opus International under an EQC contract. We already have copies of the Barker data (as owners) and of the Opus data (by courtesy).

Co-operative role of other organisations:

Opus International have undertaken to cooperate with us in this project, insofar as their knowledge of geotechnical properties at Parkway goes. Peter Barker has a good working relationship with Griffiths drilling.

Correctly modelling the seismic response of Parkway basin is important because of the high-quality site response data that has already emerged from the seismometer network. John Haines (currently at Cambridge) has expressed an interest in obtaining better geotechnical data in order to better model the basin, and Paco Chávez-García of UNAM has obtained both supercomputer time and advanced code (from P. Moczo) in order to model the basin.

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