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# THE DOMINANT RESONANCE RESPONSE OF PARKWAY BASIN

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## SUMMARY

An analysis of a suite of 85 earthquakes recorded on an array of 20 seismographs which had been installed on a small soft-soil basin, is described. The basin is a 400m wide, 600m long, resonant section of a valley filled with over 15m of soft soil. Summing normalised spectra of horizontal motion over all sites and all events showed three resonant frequencies. The dominant frequency of 1.57Hz was chosen for further study using a combination of narrow-band filtering, component rotation and forming wavenumber spectra. The response at this frequency was found often to be due to transverse waves travelling down valley at 1.3km/sec.

## INTRODUCTION

In 1995 a temporary array of 24 seismographs was installed on and around an alluvial basin at Parkway, New Zealand, in order to investigate local soil effects. A study by Taber and Smith [4] had previously identified a site resonance within the basin, and a programme of microtremor recording and analysis by Nakamura's method had established that the resonant soil occupied a region of roughly 400m diameter. Preliminary analysis by Stephenson and Chávez-García [3] showed that the horizontal response of the soil did not involve a single frequency, and that the vertical motion contained at least some laterally propagating waves. No propagating waves, and no normal modes, were seen in the horizontal components of motion, even though the horizontal motion is substantially amplified by the soft soils of the basin. As a result of further work, Chávez-García, Stephenson and Rodríguez [2] concluded that the "1D resonance peaks" for Parkway will be more or less contaminated by laterally propagating waves for each individual event, and that it is not possible to separate 1D from 2D site effects using frequency domain techniques. Nevertheless it is important for the understanding of this well-instrumented site, to separate local site response (1D) from whole-basin response (3D). This applies particularly to the resonant horizontal response.

## THE PARKWAY SITE

The Parkway test site, shown in Figure 1, is a drained swamp which lies in the mid to lower reaches of a valley which originally fed a now-infilled lake. Cone Penetrometer Tests and Seismic Cone Penetrometer Tests showed that the 400m wide and 600m long resonant region had materials with shear wave velocities of between 84m/s and 260m/s to depths of 14m, with one-way propagation times of around 100ms. It was considered that these tests did not reach the bottom of the flexible soil; Beetham [1] reports that the depth to basement is about 35m on the basis of extrapolating valley wall contours, or 45m – 50m on the basis of extrapolating stream gradients. It is planned that a shear wave profile to basement will be obtained during 1999.

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Beetham [1] described the Parkway site as a north-south aligned valley with rounded greywacke spurs at the east and west sides. He described the resonant area (as defined by analysis of microtremors) as not being confined by greywacke to the north and south where the margin is indistinct. He also considered that alluvial/colluvial fans have spread onto the valley floor from small gullies in the greywacke spurs.

The Parkway soil materials are best described as variably bedded, poorly consolidated muds, sands and gravels, extending to 35m

## THE PARKWAY EARTHQUAKE DATA SET

Earthquakes were recorded over a period of 3 months at the Parkway site, by four seismographs on the weathered rock surrounding the site, and a further 19 seismographs on the soft soils of the basin. The average recorder spacing was less than 40m, and the details of the instrumental layout are given by Chávez-García, Stephenson and Rodríguez [2]. Each three-component velocity sensor had a natural frequency of 1Hz, and was connected to an autonomous digital data logger that recorded data that was above the long term average background vibration at each site. This system led to a variable number of stations recording each of the 85 earthquakes that triggered 9 or more stations.

The events recorded had a wide range of magnitudes, source-array distances, source azimuths and depths. Two events were felt by people in Parkway, one originated in the New Hebrides Islands, and several originated in the Kermadec Island region. The largest earthquake had a magnitude of 5.9, and the smallest a magnitude of 2.1, although a recorded quarry explosion 7.6km away had a magnitude of 1.8 and one small close earthquake (s-p time of 1.4 sec) had no formal magnitude assigned.

## THE DOMINANT RESONANT FREQUENCY AT PARKWAY

Unlike at other resonant sites, no single resonant frequency was immediately obvious in the Parkway spectra. Instead, at any soil site, for any earthquake, a series of spectral peaks in the 1Hz to 3Hz range was seen. It was thought likely that this was a result of strong individual site responses overwhelming any whole basin response, so the following technique was devised to identify frequencies which persist over all the soil sites, and from earthquake to earthquake. First, the Fourier amplitude spectrum of each horizontal component was calculated, for each soil site, and for each earthquake. Then all these spectra were normalised so that the greatest spectral

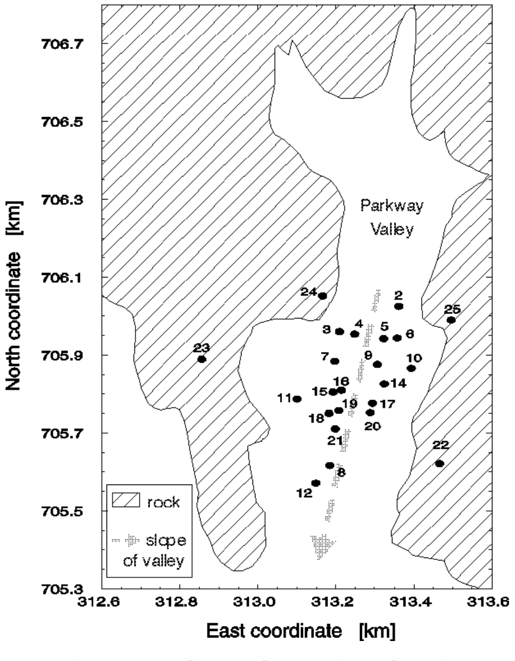

**Figure 1: The Parkway site, showing seismograph locations and valley orientation. Arrow gives drainage direction.**

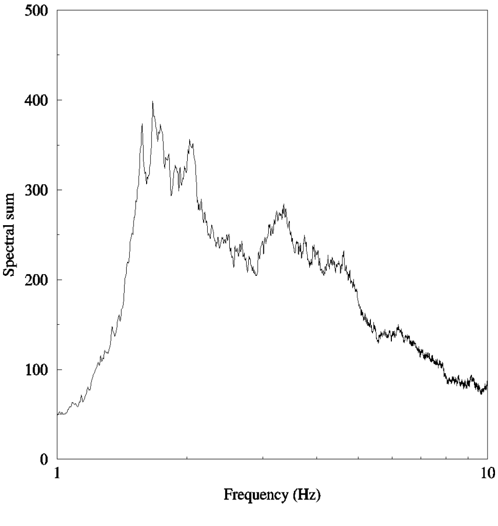

**Figure 2: Sum over all soil sites and all earthquakes, of normalised amplitude spectra of horizontal motion recorded at Parkway.**

ordinate for each record was made unity. Finally, these spectra were added. If a particular frequency is persistent over sites and events, a peak at that frequency should be evident in the summed spectrum. This is because each monochromatic waveform may be regarded as a modulated sine wave with a consequent carrier and sidebands. In the summation with respect to events, the spectral peak associated with the carrier should grow faster than those associated with the sidebands, as the sideband frequencies will vary from event to event dependent upon the envelope of the waveform. Accordingly the method should be able to distinguish between closely spaced frequencies. The method relies on good statistics – it will only function successfully when many sites and many earthquakes are processed. In the Parkway case, 1544 horizontal components were used, and the spectral sum, plotted in Figure 2, had peaks at 1.57Hz, 1.67Hz and 2.05Hz.

An examination of the individual spectra of all 85 events showed that frequencies of 1.57Hz, 1.67Hz and 2.05Hz were commonly present in the records, confirming that these frequencies are important in the basin response and that the peaks at these frequencies in Figure 2 are not merely random noise. Furthermore, an equivalent analysis of a similar but non-resonant site at Alfredton showed no such peaks.

## THE RESPONSE AT 1.57 HZ TO ONE EARTHQUAKE

As the most obvious resonant peak in Figure 2 is at 1.57Hz it was decided that the properties of this resonance should be investigated by choosing an earthquake for which 1.57Hz horizontal motion was dominant at all soil stations. Such an event was 950816.112715, a recording of teleseismic p-waves generated by a magnitude 5.9 earthquake, originating 135km below the earth's surface, 2737km north of Parkway. The summed spectra of horizontal components for all soil sites for this earthquake is shown in Figure 3, which shows that a large proportion of the energy in this earthquake is at 1.57Hz and 1.67Hz. To eliminate the spectral peak at 1.67Hz it was necessary to apply a narrow bandpass filter to the recorded data. A ten-pole, two pass filter with corner frequencies of 1.53 Hz and 1.63Hz was therefore applied to the north-south velocity record. Such a procedure is acceptable for the earthquake in question because the envelope of resonant motion varies slowly, with major components of the envelope having periods of greater than 10 seconds. The filtered record was processed (using SAC – Seismic Analysis Code) to form the wavenumber spectrum shown in Figure 4. This spectrum, with a peak at a wavenumber of 0.82/km, shows that a wave travels in the direction 210° at 1.9km/sec.

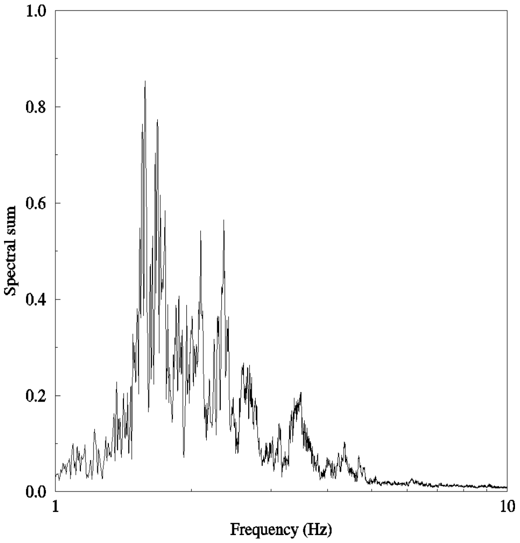

**Figure 3: Summed normalised horizontal spectra for event 950816.112715. This earthquake is rich in energy at 1.57Hz, and therefore can yield a reliable estimate of wave propagation parameters for this frequency.**

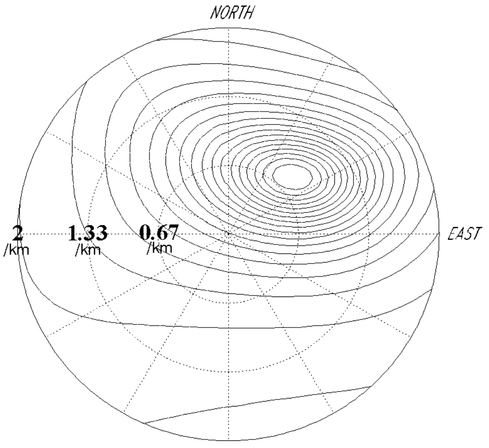

**Figure 4: Wavenumber spectrum for north components of event 950816.112715. This shows a wave from the direction 30° (i.e. in the direction 210°), of wavenumber 0.83 (1.57Hz propagating at 1.9km/s). The records were bandpass filtered between 1.53Hz and 1.63Hz.**

It is expected that particle motion for such a wave would be either in, or orthogonal to, the plane of propagation, so the procedure of bandpass filtering the waveform and then forming a wavenumber spectrum, was repeated for the 30° and 120° components of motion, these being along, or orthogonal to, the indicated direction of propagation . The outcome of this processing is shown in Figure 5 and Figure 7, which show two waves, both travelling in the direction 210°, but at different velocities.

It was noticed in passing that each soil station also had a spectral peak at 1.57Hz for the vertical motion, but that its amplitude was only about a tenth of the corresponding peak for each horizontal component.

## A TRANSVERSE WAVE

Figure 5 shows that, in the frequency interval 1.53Hz to 1.63Hz, a transverse wave propagates in the direction 210° at a velocity of 1.33km/sec. This does not prove that all the energy in this frequency band is associated with such a wave, but such a proof is possible if a process of beam-forming is employed. In this process the records from individual stations are added with time offsets applied. These time offsets are calculated for a wave travelling in the direction and at the velocity determined from the wavenumber analysis.

As a sine wave propagates across a seismograph array, the phase recorded at each station will vary, and if the array has a regular spacing and is an integral number of wavelengths long in the propagation direction, the vector sum of the Fourier coefficients from all the stations will be zero. A vector summation means that the phase as well as the amplitude of each coefficient is taken into account. If, however, a beam is formed with an appropriate speed and direction, the phases of the contributory records will be constant, and the amplitude of the Fourier coefficient of the sum will be the same as the sum of the amplitudes of the Fourier coefficients of the contributory records.

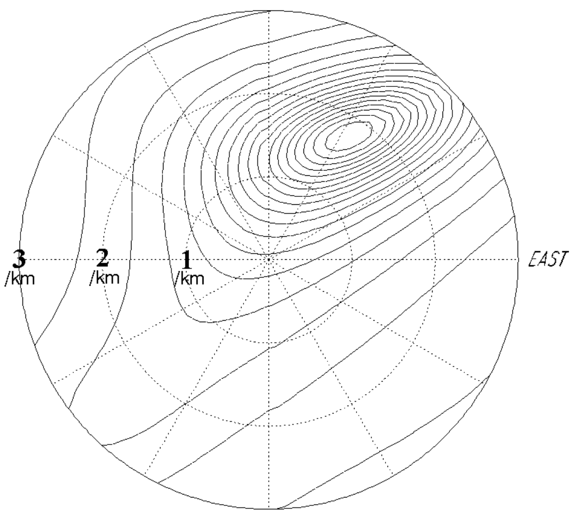

**Figure 5: Wavenumber spectrum for 120° components of event 950816.112715. This shows a wave propagating at 1.33km/s in the direction 210°. The records were bandpass filtered between 1.53Hz and 1.63Hz.**

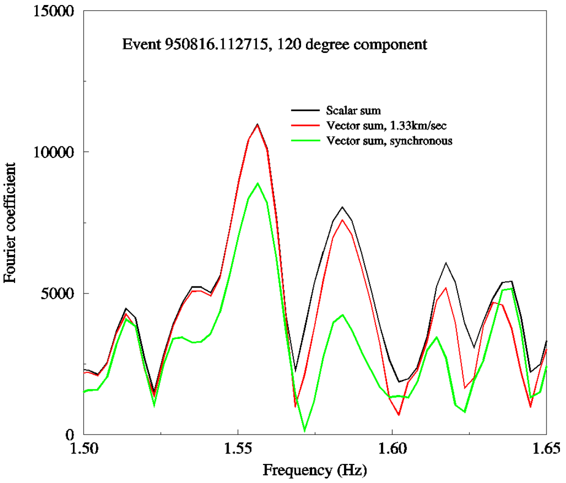

**Figure 6: Spectra for 120° components of event 950816.112715. The equality of the scalar sum, and the vector spectral sum for 1.33km/s, shows that all the energy at 1.556Hz is carried by a transverse wave propagating at 1.33km/s in the direction 210°. The difference between the scalar sum and the vector sum for synchronous motion confirms that this result is not fortuitous.**

This then provides a method to determine the contribution that a propagating wave makes to a resonant peak – a comparison is made between the amplitude spectrum of a beam-formed record, the sum of the amplitude spectra of the contributory records, and the amplitude of the vector sum of the complex spectra of the contributory records. It is necessary to include the last term in order to ensure that the first comparison is valid – for a sufficiently small array the phase changes across the array will be small and all three spectra will be similar, irrespective of the fraction of propagating energy. However, if the vector sum of coefficients for the beam-formed wave is the same as the scalar sum of the raw waveforms, and at the same time the vector sum of the coefficients of the raw waveforms is substantially less, it may be concluded that a majority of the energy for the resonant peak is propagating in the direction, and at the speed, employed in the beam-forming process.

Figure 6 shows that at 1.556Hz the scalar sum and vector sum differ by only 0.34%, while the scalar sum and vector sum for the raw waveforms differ by 19%. This constitutes good evidence that all the energy in this resonant motion is carried by a transverse wave that travels in the direction 210° at a velocity of 1.33km/sec.

## A LONGITUDINAL WAVE

Figure 7 shows that, in the frequency interval 1.53Hz to 1.63Hz, a longitudinal wave also propagates in the direction 210º but at a velocity of 2.72km/sec. Once again the contribution of such a wave to the total resonant motion may be determined by comparing a beam-formed spectrum with a scalar-summed spectrum and a vector-summed spectrum.

Figure 8 shows that at 1.576Hz the scalar sum and vector sum differ by 1.4%, while the scalar sum and vector sum for the raw waveforms differ by 7.8%. In this case the higher velocity of the wave assumed in beam-forming resulted in a smaller difference between the scalar sum and vector sum – the valley dimension is a smaller fraction of a wavelength at this velocity. In addition the scalar sum and beam-formed sum differ more than in the previous case and all that can be asserted is that over 80% of the amplitude of the resonant motion is borne by a longitudinal wave travelling in the direction 210º at a velocity of 2.72km/sec.

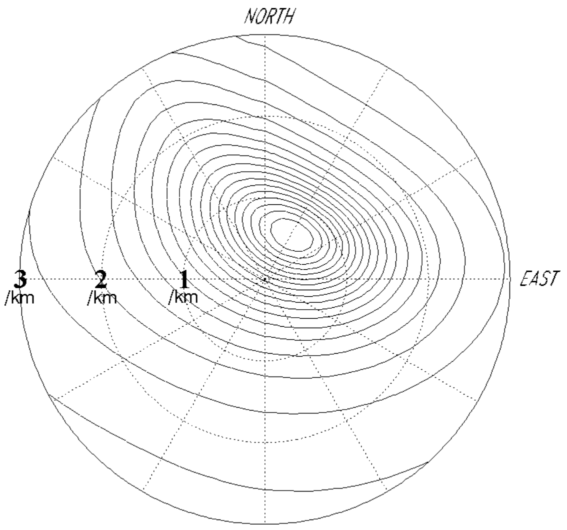

**Figure 7: Wavenumber spectrum for 30º components of event 950816.112715. This shows a wave propagating at 2.72km/s in the direction 210º. The records were bandpass filtered between 1.53Hz and 1.63Hz.**

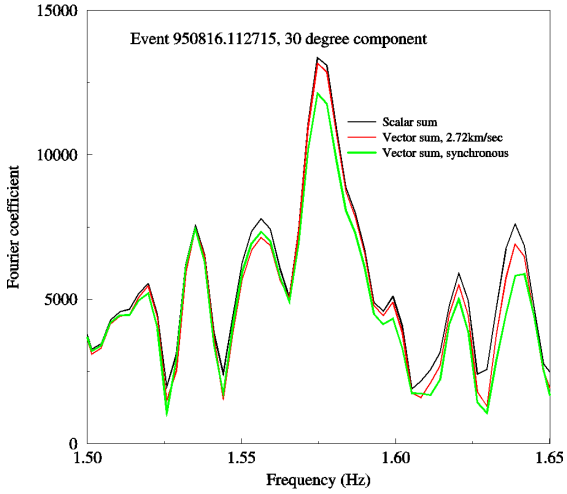

**Figure 8: Spectra for 30º components of event 950816.112715. This shows that most of the energy at 1.575Hz is carried by a longitudinal wave propagating at 2.72km/s in the direction 210º.**

The existence of a longitudinal component suggests the possibility of a Rayleigh wave, so a wavenumber spectrum for vertical motion between 1.53Hz and 1.63Hz was calculated. This showed a wave travelling in the direction 165˚ at 3.16km/sec. The peak at 1.57Hz in the vertical spectrum is only a factor of two above the background noise, so the direction and velocity could be significantly in error, and the vertical motion at 1.57Hz could be related to the longitudinal component propagating at 2.72km/sec at 210º. That is, the possibility that the longitudinal wave is in fact a Rayleigh wave, cannot be dismissed.

## INTERIM DISCUSSION

At this stage it is clear that a basin resonance at 1.57Hz (amongst other frequencies) is a commonly observed feature of the response of the Parkway site to earthquake shaking. Furthermore for one earthquake it has been established that the 1.57Hz resonance arises as a result of two monochromatic waves (one transverse and one longitudinal) travelling down the axis of the valley. When the two wave motions are separated it is evident that the transverse wave has a frequency of 1.556Hz while the longitudinal wave has a frequency of 1.575Hz.

Two questions arise – does the occurrence of the 1.57Hz resonance reflect a tendency of monochromatic waves to propagate down valley for many earthquakes, and what is the nature of these waves? The first question will be addressed in the next section by analysing a suite of earthquakes, and the second question addressed now.

The transverse (at 1330m/s) and longitudinal (at 2720m/s) waves noted for event 950816.112715 travel at speeds far in excess of the s-wave (84 – 260m/s) and p-wave (1600m/s) velocities measured for the soft soils at Parkway. Clearly the waves observed are not bulk s-waves and p-waves travelling in the soft material. However an analysis of the horizontal motions of event 950811.142508, provides additional useful information. This event also had a resonance at 1.73Hz associated with a transverse wave, travelling at 600m/s in the direction 160˚ and therefore apparently unrelated to the valley axis. Chávez-García, Stephenson and Rodríguez [2] found that the vertical motion for this event included a wave travelling at 635m/s in the direction 142˚. Evidently the basin can support waves of widely varying velocities for similar frequencies, suggesting the propagation of highly dispersive waves. Such dispersive waves can arise from waves which travel partly in the soft material, and partly in the stiffer surrounding material, with the wave amplitude decaying in the stiffer material, as distance from the soft/stiff boundary increases.

Given the likely scenario of dispersive waves being supported within the basin, a possible explanation of two transverse waves having similar frequencies but travelling in different directions at different speeds arises. It is that for the waves, propagation directions are determined in waveguide fashion by the boundary geometry; frequencies are determined in resonant layer fashion by the depth and shear wave velocity of the soft soil; and velocities are determined by the interaction of frequency and velocity in a dispersion relation.

## RESULTS FROM 20 EARTHQUAKES

The fact that a resonance at 1.57Hz is persistent over many earthquakes, and that in one case the resonance is associated with wave propagation in a direction related to the valley axis, offers the possibility that all instances of resonance at 1.57Hz may embody similar monochromatic wave propagation. As a first step in investigating this possibility, event 950811.142508 was analysed by the wavenumber spectrum and frequency spectrum methods described above. This event was a shallow magnitude 4.9 earthquake centred 81km from the Parkway site, had been studied by Chávez-García, Stephenson and Rodríguez [2], and was known to be rich in 1.57Hz motion. Analysis of this event showed transverse wave propagation at 1.57Hz in the direction 210˚ at 1.34km/sec, but it lacked the faster longitudinal wave seen for event 950816.112715. The importance of the transverse wave was again confirmed by beam-forming.

A total of 20 earthquakes (out of the set of 85 recorded), including the two already studied intensively, were identified as having a potentially useable spectral peak at 1.57Hz, although in many cases the peak was a minor feature of the spectrum. A full analysis of these including the identification of propagation directions and comparison of beam-formed spectra, while desirable, would be a major task, so a preliminary assessment of these 20 events was carried out in a modified fashion. The east component of each event was bandpass filtered between 1.53 and 1.63Hz, and its wavenumber spectrum formed, in order to establish the direction and velocity of waves travelling in a generally north-to-south direction.

The propagation vectors are shown in Figure 9, and they show a generally down-valley propagation at around 1.4km/sec, despite the fact that a selection of source azimuths and depths was involved. The mean velocity of these vectors is 1.38km/sec along 194˚. It appears likely that for spectra where the 1.57Hz peak is a minor feature, this peak will be contaminated with energy that is not related to transverse wave propagation, and that the contamination will act randomly on the speed and direction indicated by the wavenumber analysis. An example of the potential for contamination is given by event 950822.140822, where the area under the peak at 1.57Hz was only 1.7% of the area under the spectrum, and the envelope of the waveform was 7sec in length, offering opportunities for sidebands of other peaks to contribute to the filtered records. This earthquake gave rise to the extreme result of 2.25km/s along 166˚, evident as the largest vector in Figure 9. The idea of contamination randomly altering the calculated velocity vector is borne out by the fact that the mean velocity vector is close in magnitude and direction to the vectors obtained for the two events where the spectral peak was demonstrated to be entirely due to a transverse propagating wave.

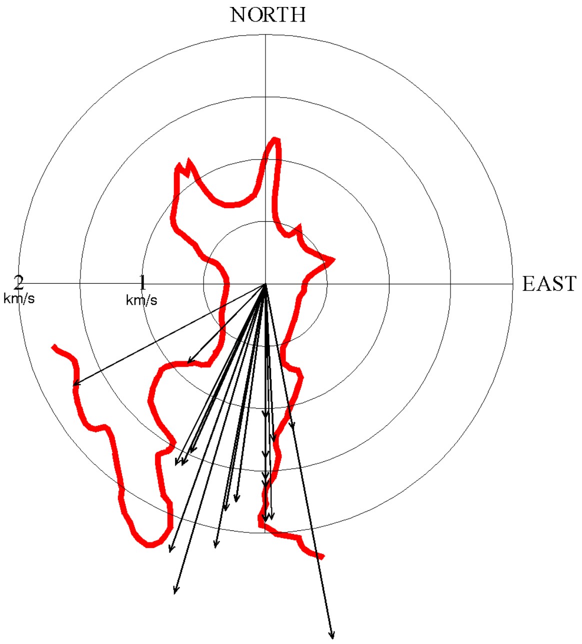

**Figure 9: Propagation vectors for transverse waves at 1.57Hz, derived from wavenumber analyses of 20 earthquakes. The mean velocity is 1.38km/s along 194º. Heavy (red) line is soil/rock contact, and defines the valley direction. These waves have a tendency to travel down valley irrespective of the source azimuth.**

The high velocities of the 1.57Hz waves are presumably associated with the velocities of the materials underlying the basin, and it follows that much of the energy in the observed waves is actually travelling in these stiffer materials. The waves may be thought of as being local to the basin area, but extending a fraction of a wavelength into the adjacent rock in both a vertical and horizontal sense. Energy will be most efficiently coupled from an incident earthquake wave to a basin wave when both waves have similar velocities. Candidates for exciting 1.57Hz transverse waves will therefore be waves that travel at about 1.33km/s, that have a transverse component, and that travel approximately in the direction 210˚. Such waves could be borne in crustal waveguides, and would most likely be generated by shallow, especially surface-rupturing, earthquakes. Such waves would also be late-arriving on account of their velocity, and by coupling to the basin waves, would give rise to monochromatic codas.

## CONCLUSIONS

The Parkway basin commonly resonates at 1.57Hz, 1.67Hz and 2.05Hz.

The 1.57Hz resonance is a manifestation of monochromatic transverse waves propagating down valley, with possible contributions from longitudinal waves travelling in the same direction.

The wave directions are probably determined by boundary geometry, the frequencies by the depth and shear wave velocity of the soft soil, and the wave velocities by a dispersion relation.

## REFERENCES

1. Beetham, R.D. (1999), “Microzoning project Parkway Basin subsurface investigations, Wainuiomata”, *Science Report 99/14, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.*
2. Chávez-García, F.J., Stephenson, W.R. and Rodríguez, M. (1999), “Lateral Propagation Effects Observed at Parkway, New Zealand. A Case History to Compare 1D versus 2D Site Effects”, *Bulletin of the Seismological Society of America, Vol. 89 No. 3, June 1999*, pp718-732.
3. Stephenson, W.R. and Chávez-García, F.J. (1998), “Preliminary assessment of resonant phenomena recorded by the Parkway Network”, *Science Report 98/18, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.*

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 for Earthquake Engineering, Vol. 25 No. 4, December 1992*, pp303-331.