

GUIDED LOVE- AND RAYLEIGH-WAVES IN PARKWAY VALLEY, WAINUIOMATA, N.Z.

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ABSTRACT

A detailed analysis of one earthquake recorded by a dense array of seismographs on the surface of an alluvial valley shows two locally-generated waves which propagate down-valley. The faster travelling one is a Rayleigh wave, and the slower one is similar to a Love wave, but has a vertical component thought to arise from the need to meet lateral boundary conditions. These waves can mimic normal modes, and their interaction provides a basis for explaining directional resonances.

1. INTRODUCTION

In 1995 a dense array of velocity seismographs was operated on the soft soils of Parkway Valley, Wainuiomata, Wellington, New Zealand, in order to provide experimental verification of the many modelling studies of basin response which have been carried out in the recent past, e.g. [1-6]. The array also opened the possibility of discovering new phenomena which modelling studies could fail to highlight, perhaps due to inadequacies in assigning elastic moduli and boundaries, or in using non-representative input wavefields.

The Parkway array and its records have previously been described [7-10] but a short summary follows:

A temporary network of 24 digital seismographs was installed from 1st August until 12th October, 1995, in Parkway Valley, Wainuiomata, New Zealand. During this time 85 earthquakes were well recorded by the network. Each recording station consisted of a triaxial, 1 Hz, velocity seismometer coupled to a EARSS seismograph [11]. Time was received by each station from the New Zealand official time radio broadcast. Station 1 was installed about 2 km to the NW of the basin, on firm rock. Four of the remaining stations were installed on the soft rock (weathered greywacke) surrounding and underlying Parkway basin, while the other 19 were installed on the surface of the soft sediments filling the valley. A detailed description of the subsoil structure of the valley is not yet available, but this is not necessary in terms of the objective of this paper. A description of the local geology around Parkway is given in [7], and some Cone Penetration Test (CPT) and seismic CPT (SCPT) profiles have been obtained [12]. A deeper SCPT profile was later obtained by drilling a hole through a hard gravel layer, filling the hole with bentonite, and proceeding as usual [13] for SCPT. Figure 1 shows the distribution of the stations. The average distance between stations on the soil was 40 m.

2. IDENTIFYING PERSISTENT RESONANCES

Early inspections of the Parkway seismograms and their spectra led to an immediate belief that no whole-basin modes were present. No discernible patterns appeared to be present in either the time or frequency domain, possibly because

many of the earthquakes recorded were of low magnitude, and may not have had source spectra capable of exciting the low-frequency phenomena later seen.

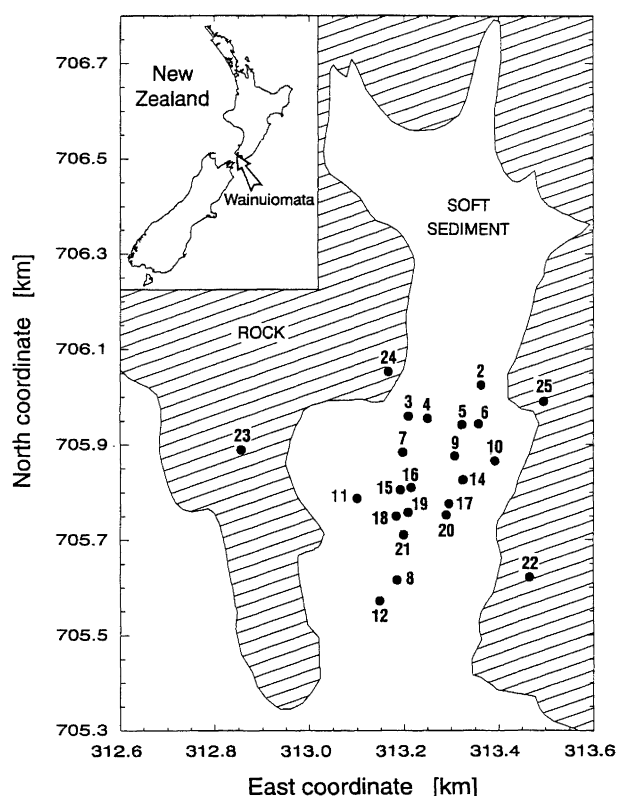


Figure 1. The Parkway valley and its seismograph stations.

At a later date an alternative approach was taken [9] in which normalised spectra of the recorded velocities were summed over all sites and over all events in order to identify behaviour, which was valley-wide and persistent across events. This analysis revealed that four frequencies were persistent in the horizontal motion, with 1.58 Hz particularly so. The summed, normalised velocity spectra are shown in

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Figure 2. Standard deviations of the sums were not computed. It was noted [9] that high correlation existed between horizontal and vertical motion at 1.58 Hz, and between horizontal and vertical motion at 4.47 Hz, suggesting elliptical particle orbits at these frequencies.

Because of the dominance of energy at 1.58 Hz, a selection of 20 earthquakes particularly rich in this frequency was chosen for more detailed analysis [10]. Each record was

bandpass filtered between 1.53 Hz and 1.63 Hz, and the filtered records subjected to wavenumber analysis. There was a pronounced tendency for these monochromatic waves to travel downvalley, regardless of the azimuth of each individual epicentre, even when an incoming event propagated upvalley in the base rock. This constitutes evidence that the waves at 1.58 Hz are locally generated and that their propagation direction is controlled by the geometry of the valley walls.

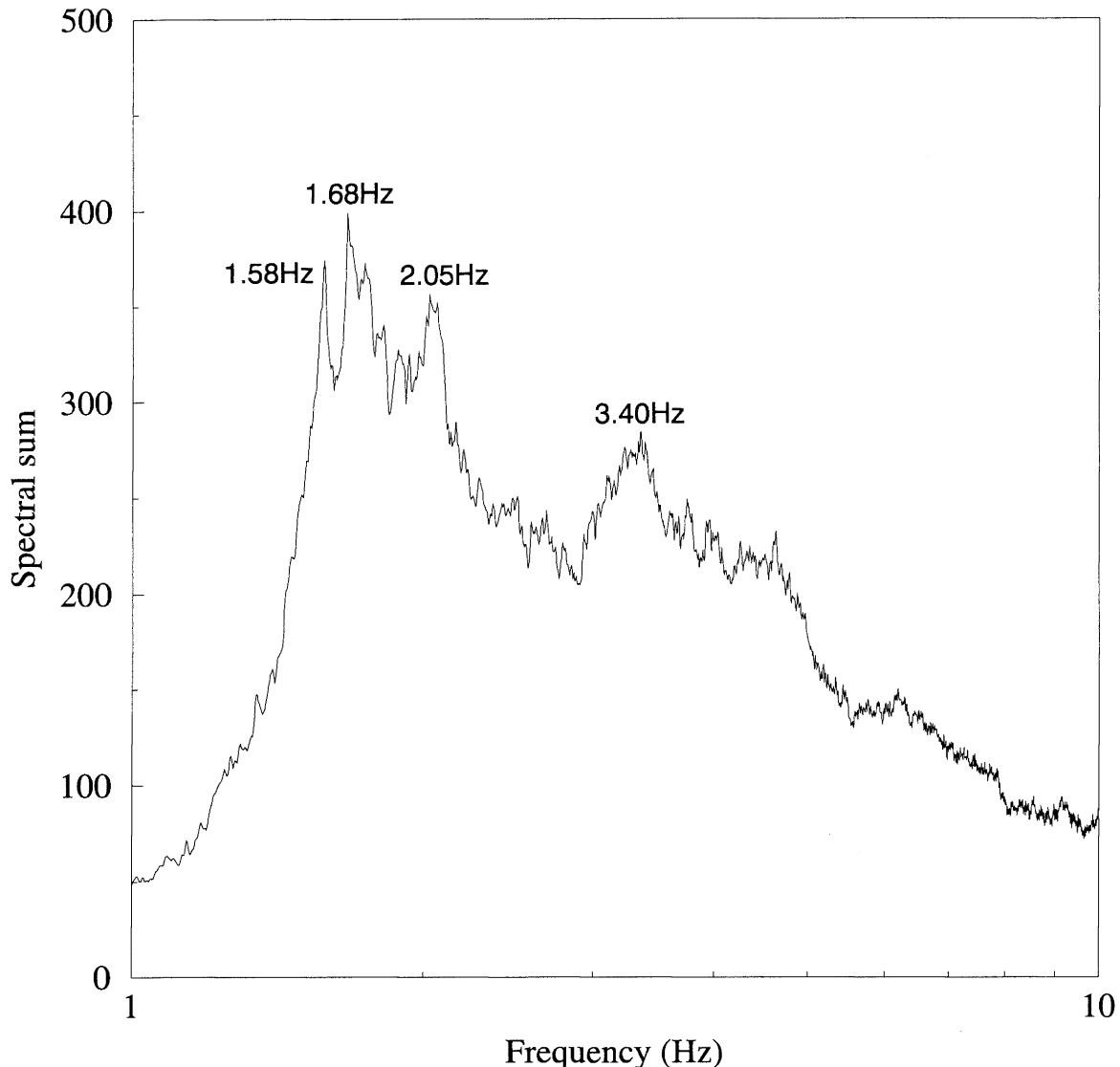


Figure 2. Summed normalised spectra of all horizontal components, for all earthquakes, at all stations. Whole-valley resonant response is seen at 1.58 Hz, 1.68 Hz, 2.05 Hz and 3.40 Hz. Because the records are normalised the ordinates have no units.

3. IDENTIFYING THE WAVES RESPONSIBLE FOR RESONANT RESPONSE

Following the identification of the 1.58 Hz frequency as being dominant in determining the response of Parkway Valley, one earthquake which was particularly rich in energy at that frequency was selected for intensive investigation by wavenumber analysis [10]. Because the earthquake selected also had abundant energy at 1.68 Hz it was necessary to employ sharp bandpass filtering prior to the wavenumber

analysis. This earthquake was of magnitude 5.9, and originated 135 km below the earth's surface, 2737 km north of Parkway, on August 16, 1995 at 11:27 UT. Only the p-phase was recorded and analysed. Arrivals of p-waves on Wellington net seismographs showed that these waves arrived travelling along an azimuth of 178 degrees.

Initial investigations in the wavenumber domain [10] showed that the direction of 30 degrees East from North (roughly along the axis of the valley) was important, so the horizontal

records for each station were rotated parallel and perpendicular to this direction.

Wavenumber spectra [14] for these filtered records, taken for the 13 sites at which the event was recorded, are shown in Figures 3 and 4. Wavenumber is a vector quantity, the inverse of wavelength, and as such provides a good tool for examining wave propagation. Because the filtered records are monochromatic, the peaks of the wavenumber spectra may

be converted directly to phase velocities of the waves analysed – 1.33 km/s along 210 degrees for a transverse wave, and 2.72 km/s along 210 degrees for a longitudinal wave. The propagation direction of these waves is unrelated to the propagation direction of the incoming rock-borne waves (178 degrees), showing that they are locally-generated. Their velocities are characteristic of near-surface materials.

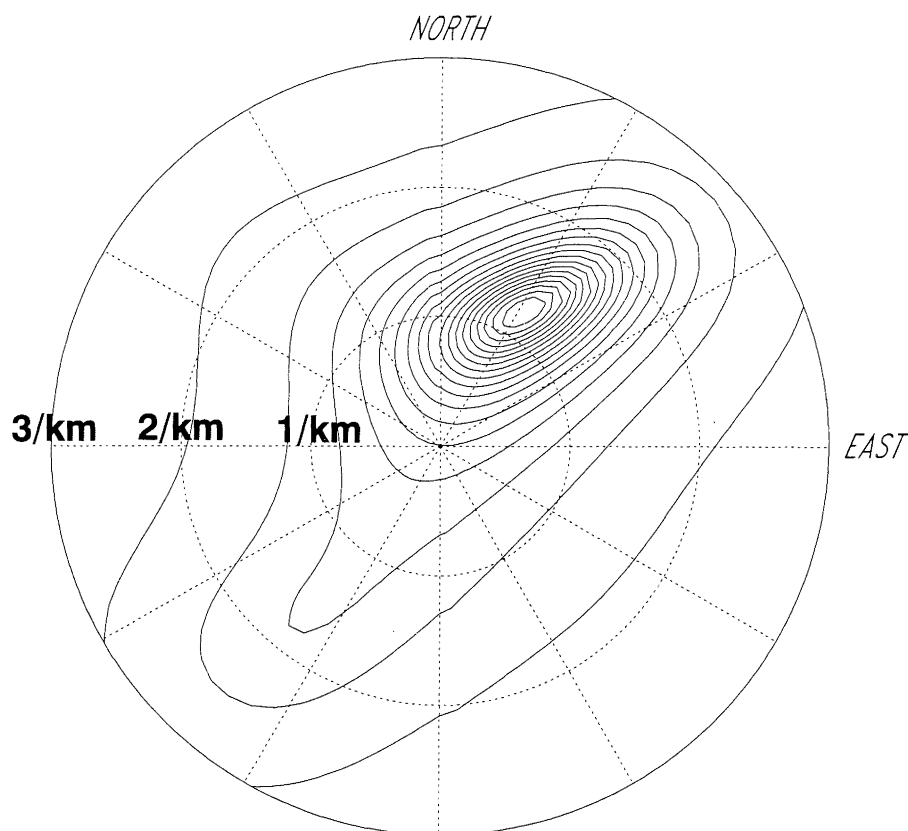


Figure 3. Wavenumber spectrum at 1.58 Hz, for the 120 degree component of motion, for a distant earthquake. Transverse waves travel down-valley (at 210 degrees) at 1.3 km/s.

Taking the best model of Parkway modulus distribution [13] and evaluating surface wave dispersion curves, Airy phases are predicted for a fundamental mode Rayleigh wave with a phase velocity of 1150 m/s and for a fundamental mode Love wave with a phase velocity of 790 m/s. It is tempting to identify the observed transverse wave with a Love wave, and the observed longitudinal wave with a Rayleigh wave. If such an identification were valid, a wavenumber analysis of the vertical records would show a velocity of 2.72 km/s for the vertical component. This is because a classical Love wave has no vertical component, so all the vertical motion must be associated with the Rayleigh wave which travels at 2.72 km/s. The wavenumber analysis of the vertical records is shown in Figure 5, and it is sufficiently different from Figure 4 in magnitude and direction that it is clearly not associated with the longitudinal motion. It could be interpreted as being due to a wave travelling in the direction 165 degrees at 3.16 km/s, but this 3.16 km/s wave interpretation should certainly not be taken at face value.

What then is the significance of a velocity of 2.72 km/s along 210 degrees not appearing at 1.58 Hz for the vertical component? An obvious possibility is that the vertical motion is associated with the passage of both the longitudinal and transverse waves – in short that the transverse wave is not a pure Love wave, and that its associated particle motions have vertical components. Under this scenario the total vertical motion would be a superposition of two waves travelling down-valley at different speeds. In this case the expected waveforms at a single station would be as idealised in Figure 6, which treats the hypothetical situation of a transverse wave followed by a longitudinal wave. The longitudinal wave has its vertical and horizontal components 90 degrees out of phase, as befits a Rayleigh wave, while the transverse wave has its vertical and horizontal components in phase. Figure 6 shows the nature of the decomposition problem – that the horizontal contributions are separable by rotation, but that the vertical contributions remain combined. The decomposition problem is that with a knowledge of traces a, c and e, we must recover traces b and d.

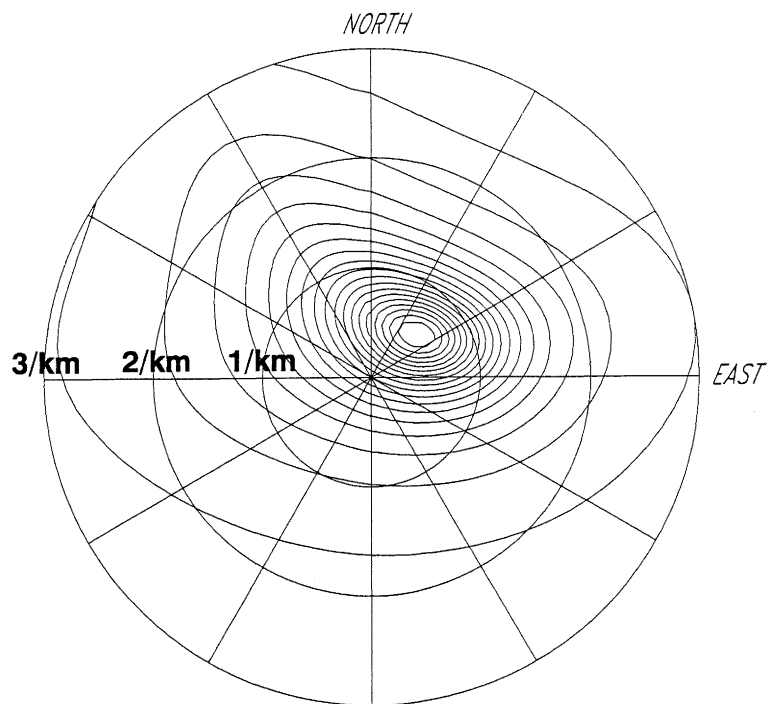


Figure 4. Wavenumber spectrum at 1.58 Hz, for the 30 degree component of motion, for a distant earthquake. Longitudinal waves travel down-valley (at 210 degrees) at 2.7 km/s.

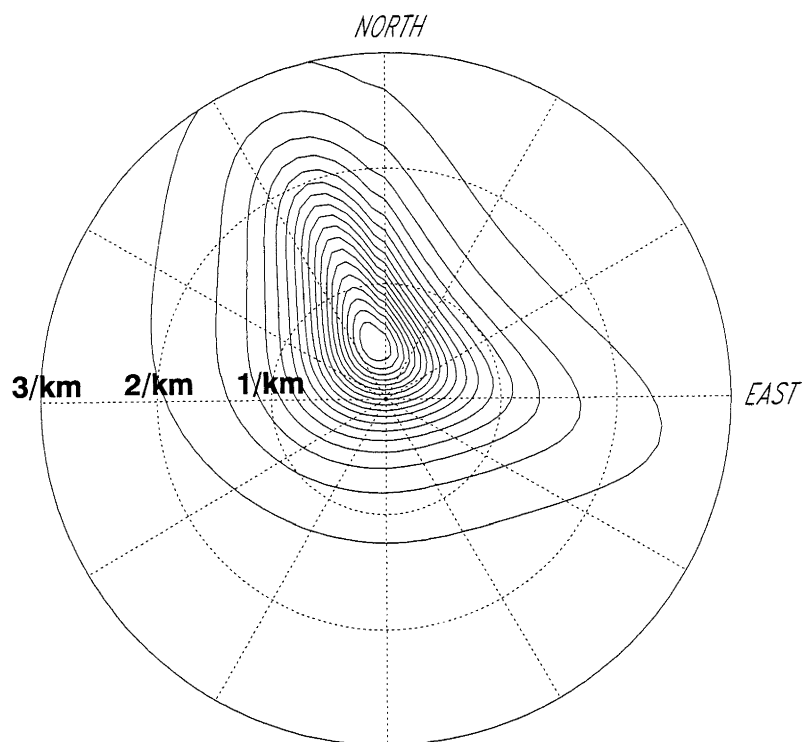


Figure 5. Wavenumber spectrum at 1.58 Hz, for the vertical component of motion, for a distant earthquake. Any waves are unrelated in speed or direction to those of Figures 3 and 4.

This is an optimisation problem, and many computer programs have been written to solve such problems. However the purpose of this paper is not to review nor to explain optimisation, but to present the results of a particular

optimisation. In terms of Figure 6, if the longitudinal wave had its horizontal and vertical particle motions (a and b) out of phase and the transverse wave had its horizontal and vertical particle motions (c and d) in phase, the optimisation

would consist of obtaining a coefficient by which to scale trace (a) (when phase shifted 90 degrees), and a coefficient by which to scale trace (c) such that the sum of the scaled traces gave trace (e). One way of finding these coefficients is to employ the simplex algorithm [15], which has the attractive feature of being very robust.

For the real task of decomposing vertical motion for a record from some station of the Parkway network, there is no *a*

priori knowledge that either the transverse or longitudinal wave will have its vertical and horizontal motion totally in phase or out of phase. The optimisation must therefore seek four coefficients; one for in-phase longitudinal motion, one for out-of-phase longitudinal motion, one for in-phase transverse motion, and one for out-of-phase transverse motion.

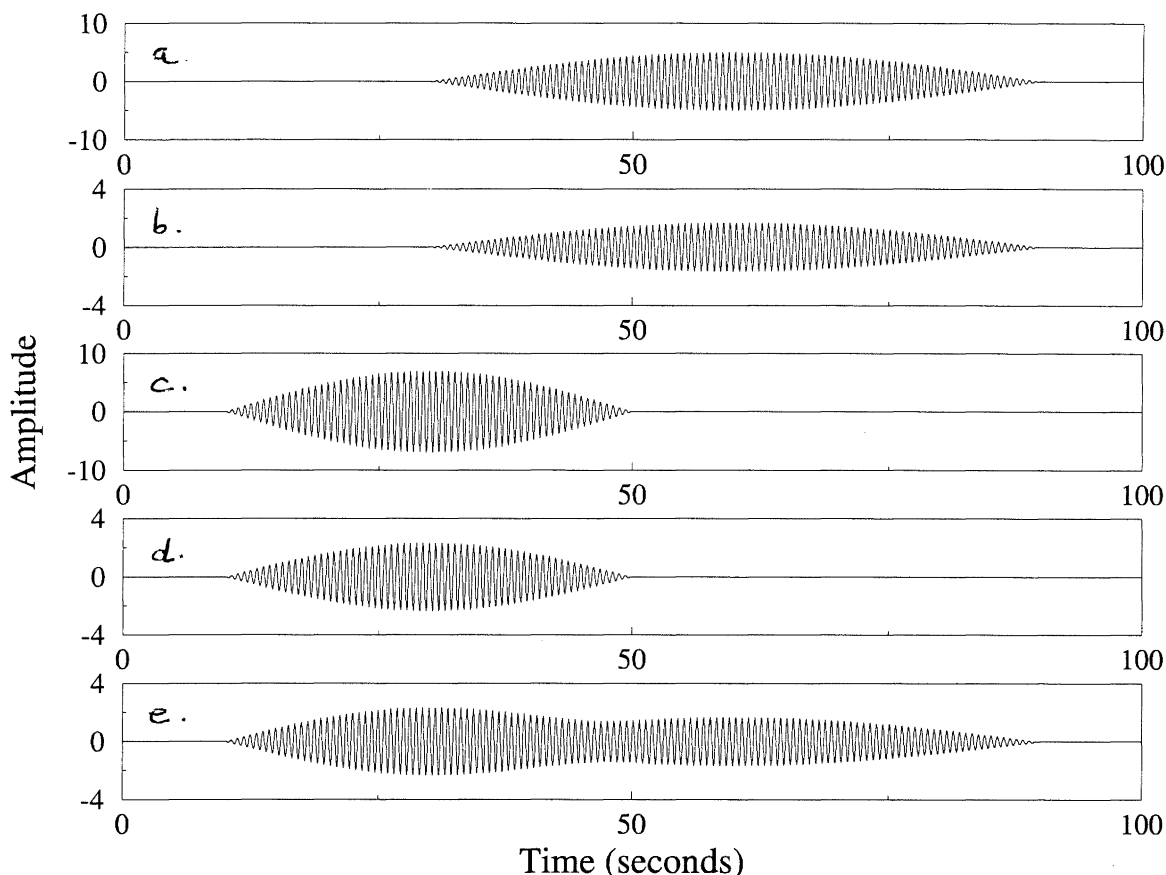


Figure 6. Components of motion for a hypothetical transverse wave and a hypothetical longitudinal wave travelling down a valley. (a) longitudinal wave, horizontal component, (b) longitudinal wave, vertical component, (c) transverse wave, horizontal component, (d) transverse wave, vertical component and (e) total vertical motion, which cannot easily be decomposed, unlike the horizontal motions which can be decomposed by rotation. (a) and (b) are in phase quadrature, while (c) and (d) are in phase.

Because there is significant motion at 1.68 Hz which would otherwise interfere with the optimisation, all records must be filtered prior to the optimisation to remove signals at this frequency. The records were therefore bandpass filtered using a two pole, two pass filter with corner frequencies of 1.53 Hz and 1.63 Hz.

The complete procedure for decomposing the vertical motion for one earthquake at a single station is :

1. Bandpass filter all three components between 1.53 Hz and 1.63 Hz.
2. Rotate the horizontal components to 30 degrees and 120 degrees.
3. Produce a phase-shifted version of each of the two horizontal components by introducing a quarter-cycle delay.
(Let the four filtered horizontal waveforms be named in30, in120, out30, out120).
4. Use the simplex algorithm to find the optimum coefficients c_1 , c_2 , c_3 and c_4 so that $c_1 \cdot \text{in30} +$

$c_2 \cdot \text{in120} + c_3 \cdot \text{out30} + c_4 \cdot \text{out120}$, best matches the filtered vertical waveform. The simplex algorithm must minimise the area under the curve described by the difference between the raw and the synthesised vertical waveforms.

On a trial basis this procedure was implemented, for the same earthquake, which gave rise to Figures 3 and 4. The records used are from the p phase of an earthquake, which occurred in the New Hebrides Islands of the South Pacific. This was GNS event 835477, also known as 950816.112715 by its arrival time in Parkway. It should be noted that this earthquake is not representative of destructive events on account of its extreme distance (2,700 km) and its depth (135 km). Its magnitude of 5.9 however ensures an abundance of low frequency energy, and its distance ensures a long wavetrain, which in turn allows the use of rapid filter transitions in the frequency domain.

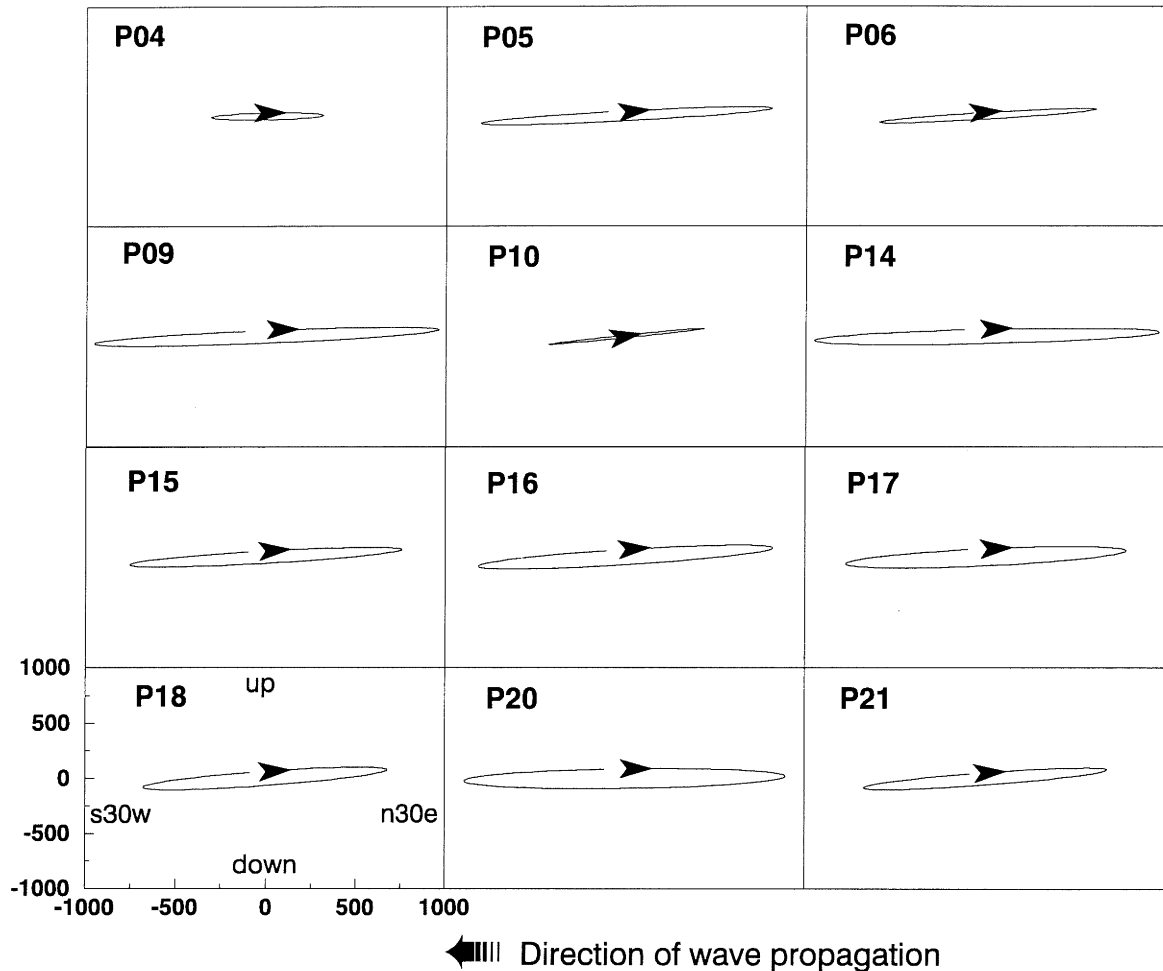


Figure 7. Representative particle orbits in a vertical plane at each station, for the longitudinal wave generated by the distant earthquake. The orbits are retrograde elliptical and are tilted down in the direction of propagation, consistent with a Rayleigh wave propagating down-valley. Because the orbits are representative, the scales have no units, but represent ground velocity. (See text for the meaning of “representative”).

After decomposition, the derived vertical waveforms ($c1 \cdot \text{in}30 + c3 \cdot \text{out}30$, and $c2 \cdot \text{in}120 + c4 \cdot \text{out}120$) were combined with the transverse and longitudinal waveforms to give particle orbits for the two waves. Because each individual vertical component is a scaled version of a waveform of either the longitudinal or transverse wave, it must travel at the velocity of that wave. The conundrum of the vertical motion has been banished, by finding two waves each of which has a vertical component.

4. PARTICLE ORBITS FOR THE LONGITUDINAL WAVE

Figure 7 summarises representative particle orbits for the longitudinal wave, for each station. The particle orbits shown are representative in the sense that they are constructed from

the real and imaginary parts of the Fourier transform of each signal, thus recovering the phase difference between the vertical and horizontal components as well as preserving relative amplitudes. Such a procedure gives a clearer idea of particle orbits because it avoids the confusing superposition of many cycles of varying amplitude. When the total (filtered) particle motion is plotted, it takes the form of many ellipses of different sizes, but all having the same major axis and sense of motion, as the representative plot.

In every case the representative orbits are retrograde and tilted down in the direction 210 degrees, in accordance with a Rayleigh wave travelling down valley. Because the fitting was done with waveforms of the 2.72 km/s wave, that value must be the velocity of the fitted vertical component. It follows that the longitudinal wave is a Rayleigh wave travelling down valley at 2.72 km/s.

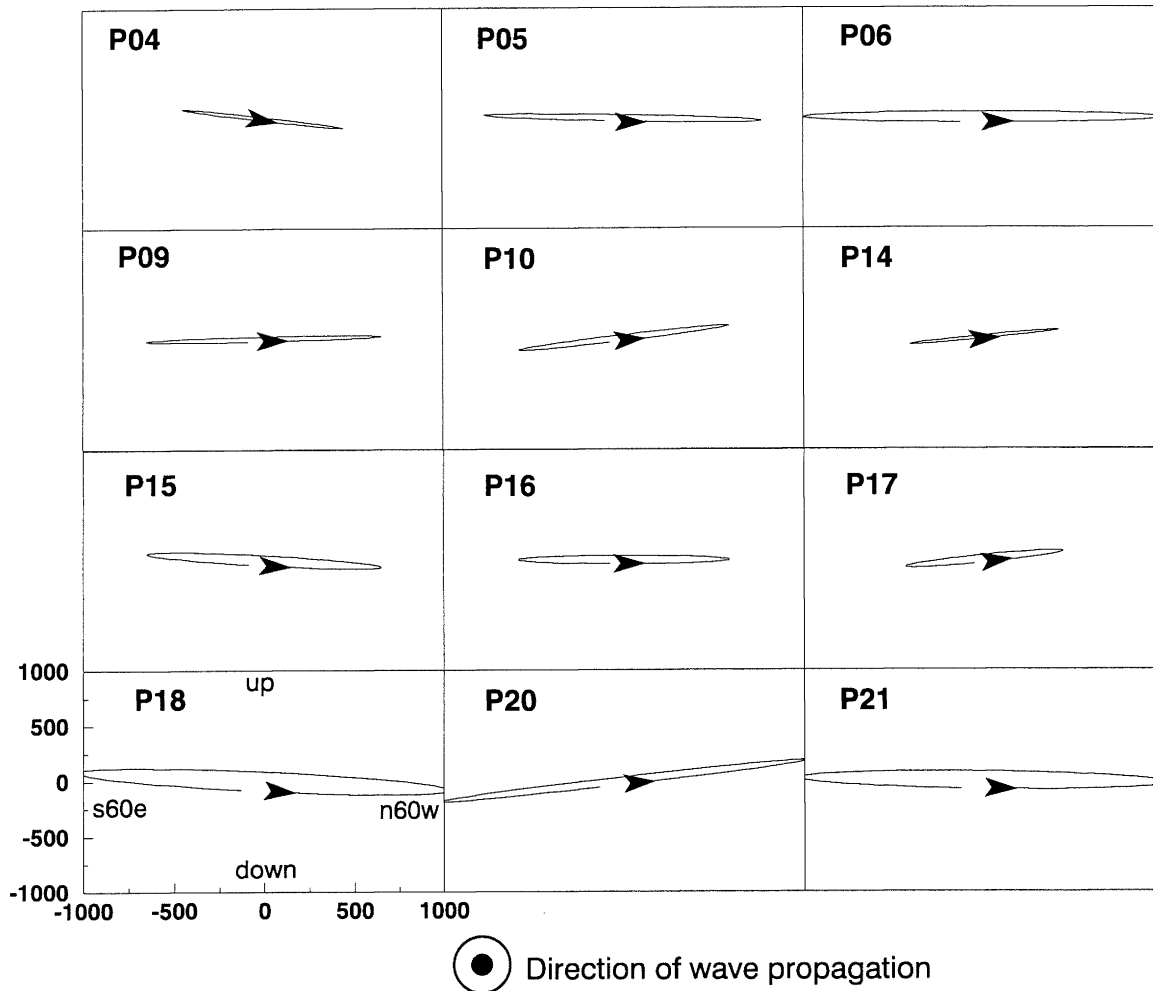


Figure 8. Representative particle orbits in a vertical plane at each station, for the transverse wave generated by the distant earthquake. The senses of the elliptical orbits and the inclinations of the ellipse axes, apparently have no consistent pattern. Because the orbits are representative, the scales have no limits, but represent ground velocity.

5. PARTICLE ORBITS FOR THE TRANSVERSE WAVE

Figure 8 summarises representative particle orbits for the transverse wave, for each station. The same comments on, and explanation of, “representative particle orbits” apply as for the longitudinal wave. At first inspection there appears to be no pattern discernible – the orbits are sometimes clockwise, and sometimes anticlockwise, and the inclinations vary in an apparently random way. However, if there are waves travelling down valley along the azimuth 210 degrees, it is sensible to examine the particle orbits using a frame of reference related to the valley geometry as shown in Figure 9, which adopts station 9 as the origin of a convenient coordinate system. Now if the angle of the axis of each ellipse to the horizontal is plotted against the distance of the station from the centre line Y1-Y2 of the valley with X1 being positive, as shown in Figure 10, it is clear that the variations are systematic, and consistent with motion of a “sloshing” nature shown in cartoon form in Figure 11. A classical Love wave would not be able to propagate along a closed valley because of difficulties meeting the condition of a rigid lateral boundary. In a material such as the soil filling the Parkway valley, the fact that the material is much more easily sheared than it is compressed, means that the energetically favourable way of meeting the condition of a

rigid boundary is by “mounding up” along the boundary rather than by being laterally compressed.

6. GOODNESS OF FIT

The emergence of patterns in particle orbits, that are consistent with known waves, is of itself an indicator that the fitting procedure is valid. However it is of value to examine the degree to which the fitted waveforms match the original vertical waveforms. As the fits are similar for all the sites, only one site, p09, is examined here. In assessing the goodness of fit it is important to realise that it is not only a match of envelopes which is required, but also the detailed matching, cycle to cycle, as the transverse and longitudinal waves are likely to have different phases at any given time.

Figure 12 shows at the top, the synthesised vertical waveform, and below it, the recorded vertical waveform, for p09. The most obvious features are that the match is excellent after 40 seconds, and that the recorded vertical signal exceeds the synthesised one at 11 seconds. These features suggest that some other phenomenon, perhaps another wave, occurs early on. The two lower traces of Figure 12 show the filtered longitudinal and transverse waveforms from which the fitted waveforms were derived. They reinforce the idea that the vertical motion in the first 20 seconds has little to do with the horizontal motion.

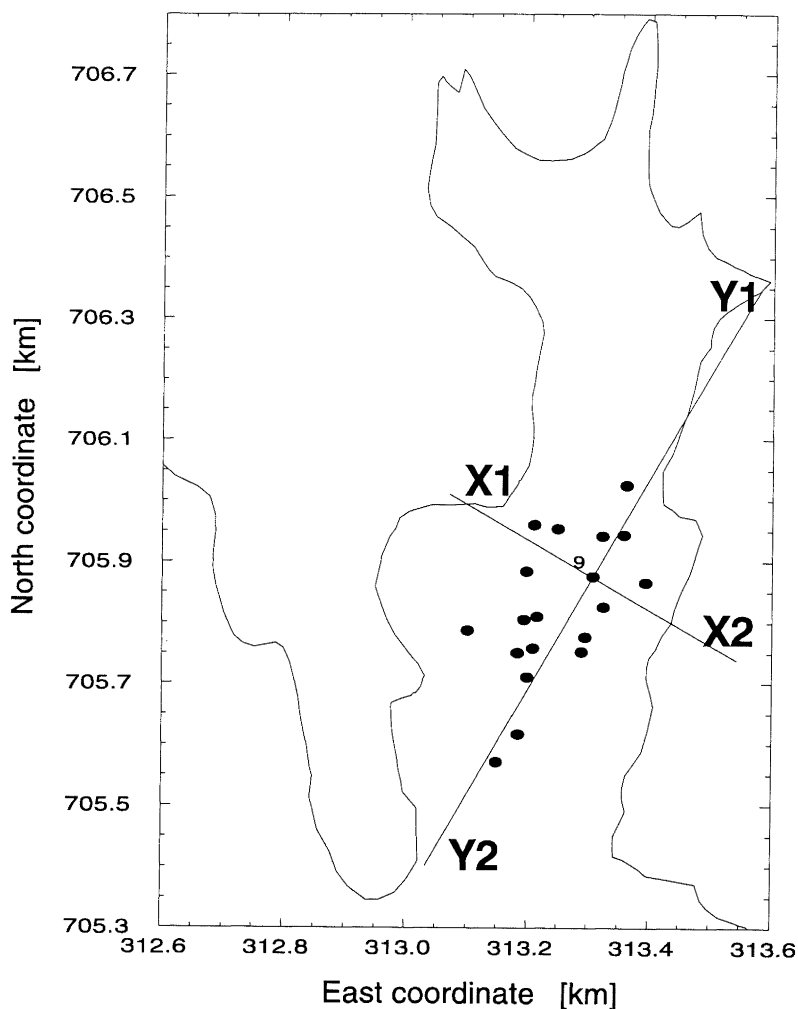


Figure 9. Coordinate system adopted to evaluate the particle orbits for the transverse wave. Distances given in Figure 10 are from the Y1-Y2 axis, with X1 distances being positive. Site p09 is at the intersection of the X and Y axes.

When fitting is carried out with the first 40 seconds of record ignored, the error term falls by a factor of 4, confirming that much of the error term arises from the anomalous early vertical response. For station p18, where the vertical contributions from the longitudinal and transverse waves are approximately equal, ignoring the first 40 seconds allows us to see the improvement in fit resulting from using both the longitudinal and transverse waveforms. On the one hand, a fit using only the transverse waveform has a residual of 10.0×10^3 , and a fit using only the longitudinal waveform has a residual of 9.6×10^3 , whereas on the other hand a fit using both waveforms has a residual of 6.1×10^3 . This improvement in fitting gives an indication of the validity of the partitioning of vertical motion.

7. INTERPRETATION

Because the vertical motion for each station has been partitioned into one part associated with the longitudinal wave, and another part associated with the transverse wave, each part must travel with the velocity of the associated wave. The problem of a vertical component travelling at 3.16 km/sec has been removed. The motion at 1.58 Hz has been decomposed into two waves, one Rayleigh-like, and one Love-like. Because the incident azimuth is a few degrees east of south (178 degrees), and the propagation direction is west

of south (210 degrees), these must be locally-generated waves.

8. DISCUSSION

The decomposition of vertical motion has only been carried out for one event. However previous analysis [10] showed that at 1.58 Hz it is common for a transverse wave to be launched down-valley, travelling roughly along the valley axis. It is possible that all such waves are of the "sloshing Love" type which have been reported here. No investigation of persistent down-valley longitudinal waves has been undertaken, but it is again possible that they exist, and are locally-generated Rayleigh waves, guided down valley.

Stable, locally-generated waves of the type described, can mimic motions which have previously been described for soft soil sites. The Love-like wave in particular closely resembles normal modes of a type previously described [16], the key difference being that the transverse wave identified in this paper appears as if it were a normal mode travelling down-valley. It is noteworthy that for Parkway, the valley length and transverse-wave phase velocity mean that the valley is only a half-wavelength long, and the resemblance to a normal mode is strong. This could be why a normal mode was identified in one record of the Parkway data [17].

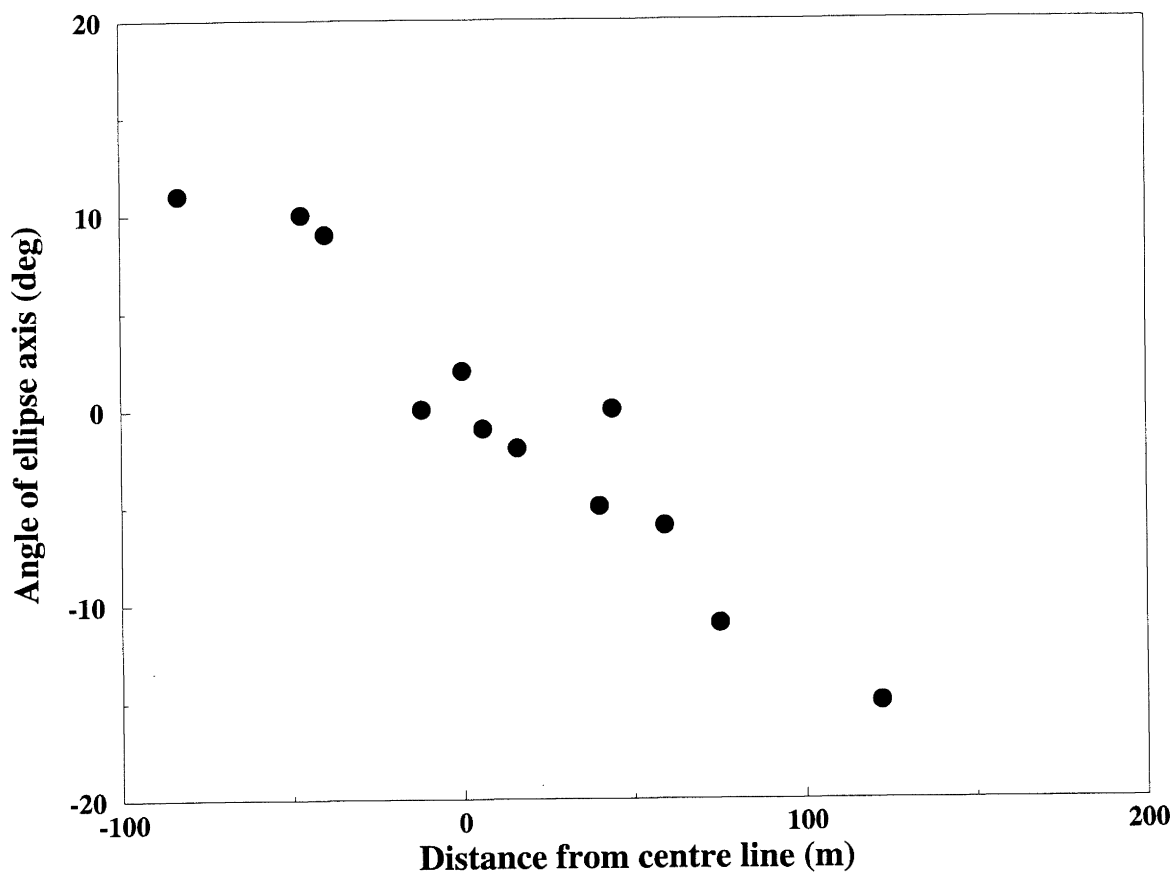


Figure 10. Angles (to the horizontal) of the ellipse axes for the transverse wave versus distance the from the centre line (Y1-Y2) of the valley. The pattern is consistent with Love Waves, which adopt some vertical component in order for the horizontal motion to meet the rigid boundary conditions at the valley sides. See Figure 9 for the geometry of the valley and distance from the centre line. Distances in the direction X1 are positive.

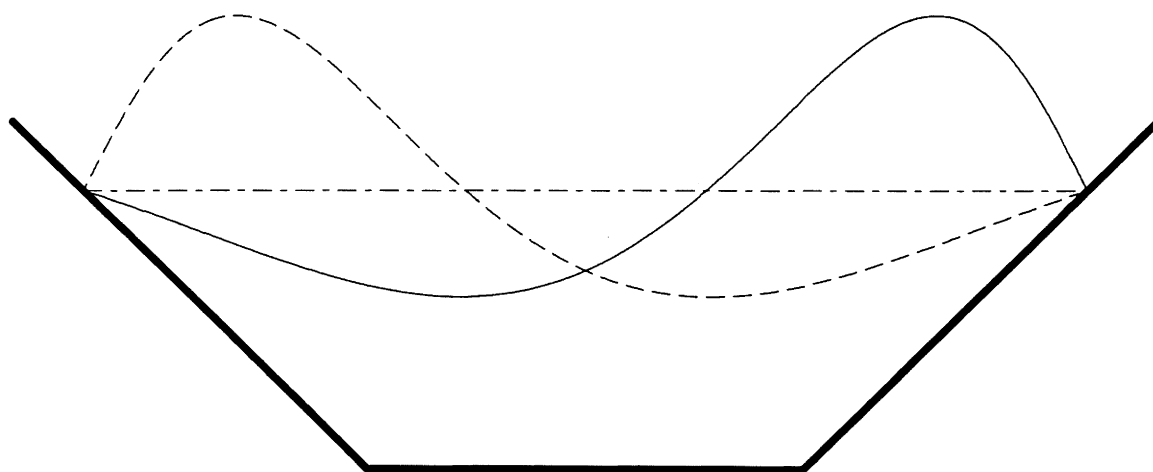


Figure 11. Cartoon showing the way in which Love waves can adopt a vertical component in order for soil motion to meet the rigid boundary conditions at the valley sides. The solid and dashed lines represent the surface for two extremes of motion. The dot-dashed line represents the unperturbed surface. Note that the surface moves laterally as well as vertically.

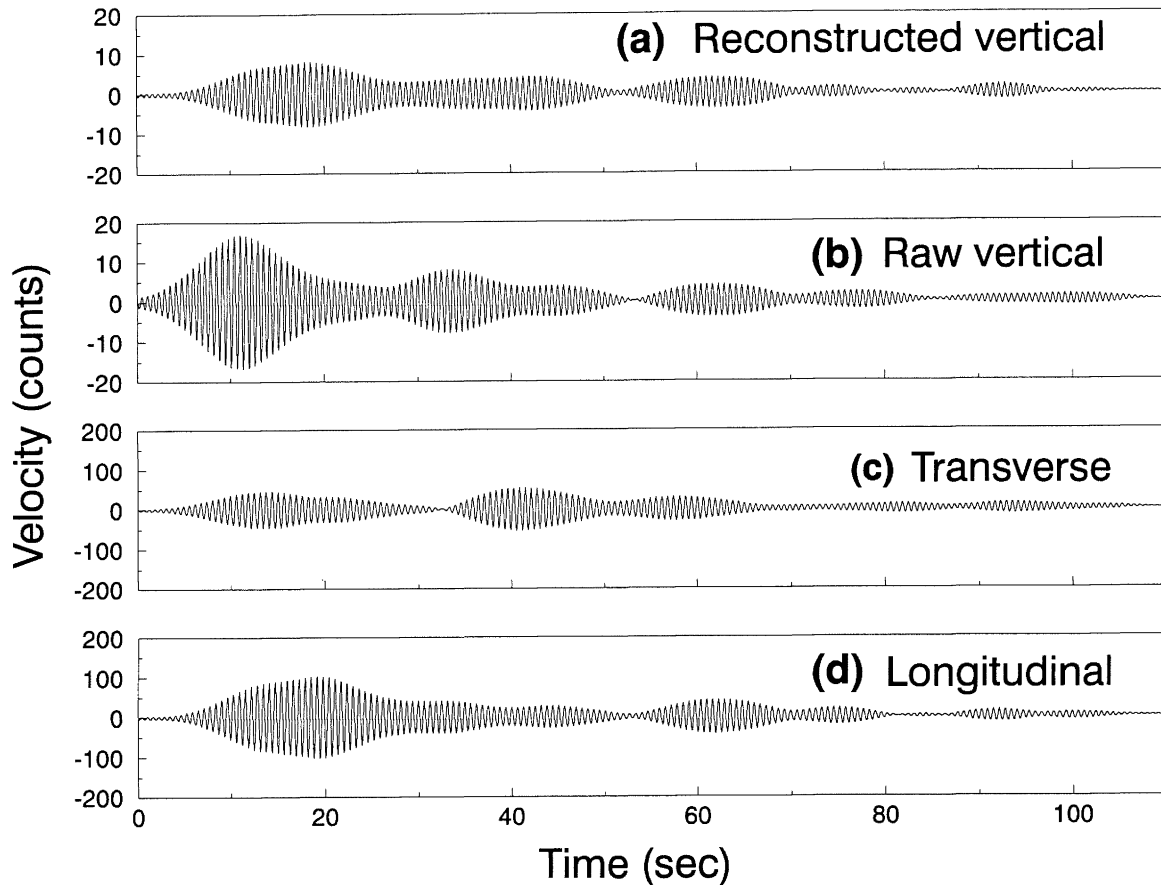


Figure 12. *Filtered velocities associated with site p09. (a) Vertical signal obtained by summing the fitted contributions of the longitudinal and transverse waves. (b) Original vertical signal. (c) Transverse signal. (d) Longitudinal signal. After 40 seconds the reconstruction is good. However the vertical signal in the first 20 seconds appears not to be associated with either the transverse or longitudinal wave. One “count” is a velocity of 6×10^{-8} metres/second.*

As the monochromatic Rayleigh and Love-like waves travel down valley at different speeds their relative phase will vary with distance. In general this will mean that particle orbits in the horizontal plane will be elliptical. However there will be positions where the longitudinal and transverse components will be in phase, so that the motion will be rectilinear, just as for directional resonances [18-20]. Such positions have not been sought to date, but undertaking a search would be an obvious thing to do.

As shown by [10], the majority of the energy at 1.58 Hz is borne by locally-generated Love-like waves and by Rayleigh waves for the p phase of a teleseismic event. If this is true of most other events the mechanisms by which local surface waves are generated is clearly of overwhelming importance in understanding and predicting the response of small alluvial valleys to earthquake shaking.

The forgoing analysis treated only one earthquake at one frequency, and unless the same phenomena can be identified for other earthquakes, and perhaps at other frequencies, the types of wave identified could be regarded as interesting but unimportant. It seems likely that locally-generated waves will have stable properties, and that a study of other earthquakes at 1.58 Hz is the approach most likely to duplicate the results of this paper. Candidate earthquakes would need to be of long duration in order for meaningful filtering to be applied,

and should be recorded at many stations in order that wavenumber analysis can be undertaken properly.

Figure 2 identified three frequencies other than 1.58 Hz, which are important to the response of Parkway valley. It is not known whether these frequencies correspond to the wave types found in this study, and therefore there is no guarantee that such wave types would be found at these frequencies. A preliminary study of event 950816.112715 at 1.68 Hz was not able to isolate longitudinal and transverse waves and therefore could not be pursued further.

9. CONCLUSION

One record of the Parkway small earthquake dataset has been analysed so as to show the existence of a locally-generated transverse wave and a locally-generated longitudinal wave travelling down the Parkway valley. Further analysis of the vertical motion confirms that the longitudinal wave is a Rayleigh wave, and that the transverse wave is similar to a Love wave, except that it adopts a vertical component near the valley margins in order to accommodate the rigid lateral boundary.

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