THE ORIGIN OF RESONANCE IN THE VERTICAL COMPONENT OF EARTHQUAKES RECORDED ON SOFT SOIL AT WAINUIOMATA, NEW ZEALAND

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SUMMARY

Occasionally-observed resonances in the vertical components of earthquakes recorded at the Wainuiomata, New Zealand, soft site, are likely to be manifestations of the Airy phase of fundamental-mode Rayleigh waves which traverse the site. These packets of waves exist only when a soft, water-saturated layer of soil overlies a substrate with a much higher velocity. Other soft sites in Wellington also show the phenomenon, which may have implications for hazard estimates.

1. INTRODUCTION

Studies of strong ground motion during earthquakes usually emphasise the horizontal components. This is both because horizontal shaking is usually greater than vertical shaking (especially on soft soils) and because structures are necessarily designed with a substantial degree of vertical strength in order to withstand gravitational loading. This is well expressed in [1] which states that "The primary reason for geotechnical engineers to neglect the effect of vertical ground motion lies in the fact that earth structures are thought to have adequate resistance to dynamic forces induced by vertical ground motion that is generally much smaller than the horizontal ground motion. In engineering practice, the commonly used ratio of vertical to horizontal (V/H) response spectra is about two-thirds". However there have been occasional observations of amplified vertical motion. In [2] it is asserted that the amplification of vertical shaking during the 1995 Kobe earthquake was associated with incomplete saturation of near-surface soils, which causes substantial amplification of P waves but does not affect the propagation of S waves. In [3] asymmetric amplification of vertical motion was attributed to the nonlinear stress-strain response of cohesionless surface alluvium. Both these mechanisms involve relatively broadband motion whereas it is common for horizontal motion on soft soil to be monochromatic.

Given that the vertical component of motion can sometimes be amplified and knowing also that certain structural elements such as beams or cantilevers may resonate in a vertical sense, there is reason to investigate the origin and characteristics of amplified vertical motion. It would be undesirable for such structural resonators to encounter vertical ground motion at their natural frequency.

A closer look at the circumstances surrounding amplified vertical motion should be fruitful and accordingly a well-characterised, well-instrumented location sited on soft soil was sought. A vertical array of strong motion sensors installed at various depths in soft soil at Wainuiomata, New Zealand has sometimes shown amplified vertical motion in a narrow frequency range and this array therefore provides an opportunity to investigate such amplification, at least for the specific circumstances of that particular site.

2. SITE CONDITIONS AT WAINUIOMATA

The Wainuiomata site (Figure 1) attracted interest from 1990, when the Wellington Regional Council let a series of contracts intended to evaluate seismic hazard in the greater Wellington area. Close to the Wainuiomata Bush Fire Force building a seismic CPT probe [4] showed a considerable depth (22 m) of material with a shear wave velocity of 90 m/s, overlying another 9 m of material with a shear wave velocity of 150 m/s. Recordings of small earthquakes [5] at the Wainuiomata Bush Fire Force building and on a nearby rock site showed that for horizontal components rock motion at 0.8 Hz was amplified by a factor of 30 due to the action of the soil.

A hole nearby drilled to rock basement [6] allowed studies of the age, origin and composition of the various deposits down to bedrock at 61.6 m. The log of this hole indicated that the soft soils were formed by the filling of a shallow lake about 20,000 years ago. An ash layer from the Kaharoa volcanic eruption of 22,600 years ago was encountered 4.1 m below the surface, and a piece of wood 24,000 years old was recovered from 25.6 m. Evidently the process of infilling the lake was sudden.

The property that is most strongly related to amplification of ground motion is the shear wave velocity profile. A Seismic Cone Penetration Test (SCPT) was made 95m north of the Wainuiomata Bush Fire Force building [4] and the resultant geophone traces and their interpretation in terms of shear wave velocity are given in Figure 2.

The basic form of the Wainuiomata valley was initially cut into basement rock (greywacke) by alluvial action. The resultant channels were then partially filled with gravel deposits. Depressions in these gravels have subsequently been filled with lake and swamp sediments. It is these lake and swamp sediments which are of interest in terms of site response, and which underlie the sites described in this paper. The SCPT-derived shear-wave velocity profile for the WDAS site, which is at the centre of the valley, differs in detail from two nearby sites in terms of a soil layer of intermediate stiffness that lies just above the gravels. One of the surrounding sites lacks this lower layer and at the other the intermediate layer is thicker than at WDAS. Clearly it would be insufficient to model the WDAS site by assuming infinitely-extended uniform soil layers.

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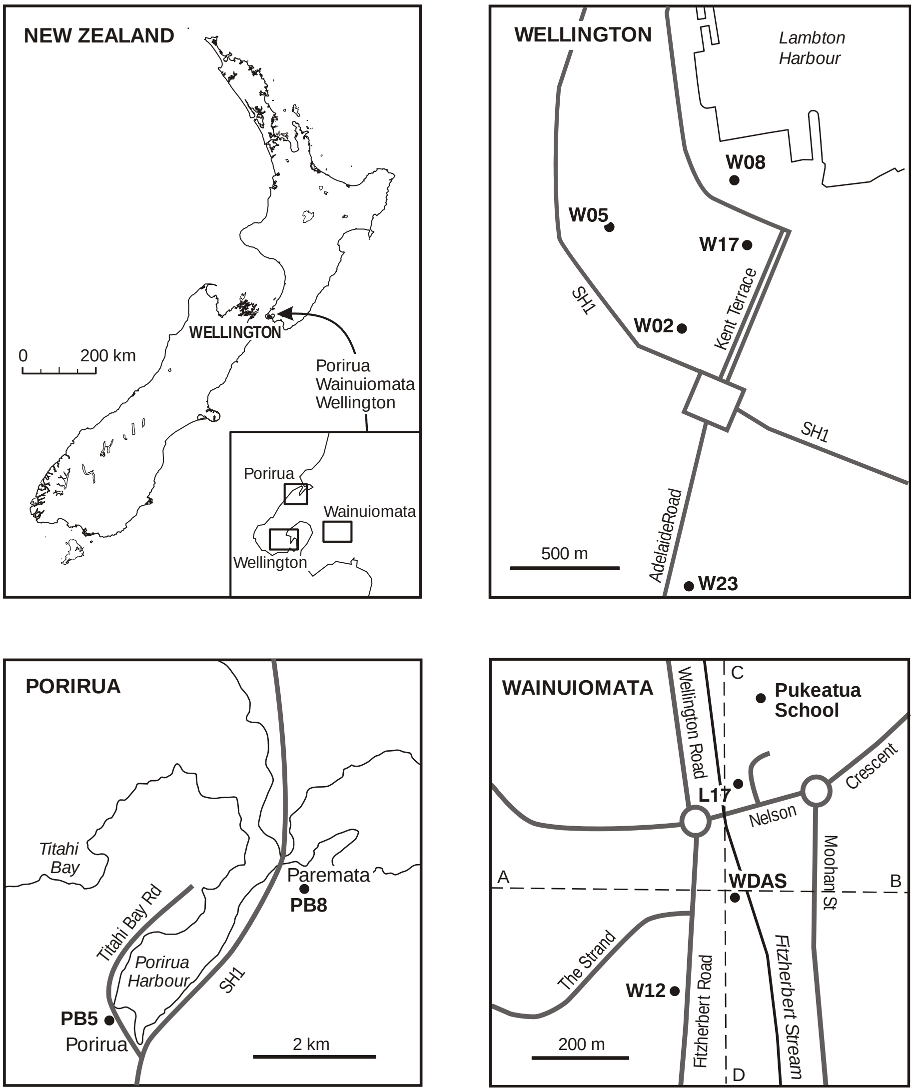

Figure 1: ***Location diagram. Within Wainuiomata, at the WDAS location there are strong motion accelerometers at depths of 0 m, 12 m and 22 m.; L17 was the site of a temporary velocity seismograph; SCPT probes were carried out at Pukeatua School, WDAS and W12. Within Porirua, PB5 and PB8 were sites of temporary velocity seismographs, PB8 being on rock and PB5 on soft materials. Within Wellington, sites W02, W05, W08, W17 and W23 are all soft soil sites, and all showed monochromatic signals on the vertical component.***

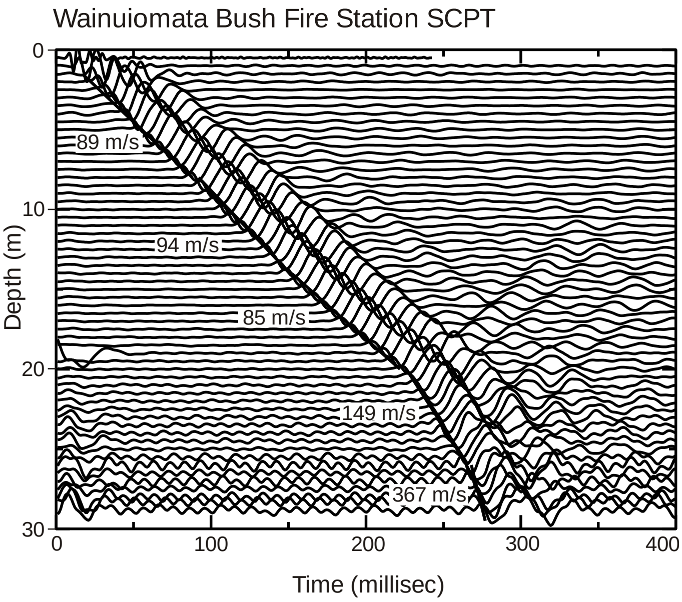

Figure 2: ***Seismic CPT traces for the WDAS site. A 22 m layer of soil with shear wave velocity 90 m/s overlies a 9 m layer with shear wave velocity 150 m/s. The 9 m thick lower layer is also present at W12 but is absent at Pukeatua School.***

The nearby sites are at the Pukeatua school, which is situated 450 metres up-valley from the WDAS site, and at site W12 (the Salvation Army building), which is situated 236 metres southwest of the WDAS site, both as shown in Figure 1. They will be discussed in detail later.

3. EARTHQUAKE INSTRUMENTATION AT WAINUIOMATA

In July 1991 a strong motion accelerograph was installed on the ground surface at Wainuiomata, in a building situated within the grounds of the Wainuiomata Fire Station but belonging to the Wainuiomata Bush Fire force. The station is currently named WDAS. The initial earthquake accelerograms obtained from this station were sufficiently interesting that the site was chosen to test a new technology for sensing subsurface earthquake motion, based on installing micro-machined silicon accelerometers in a detachable penetrometer cone that was placed at depth by a hydraulically-driven pushing mechanism (a standard CPT test rig). Such an approach reduces the cost of installation because the usual steps of drilling and casing are skipped.

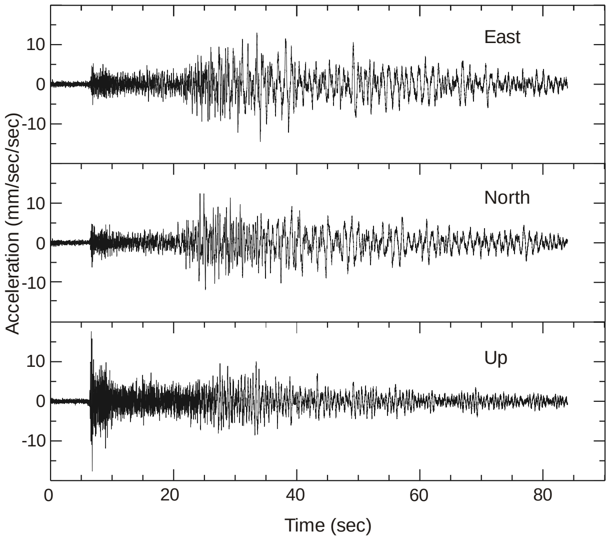

Figure 3: ***The three components of ground acceleration at WDAS for a magnitude 5.1 earthquake situated 125 km to the northeast. There is a monochromatic horizontal response at 0.8 Hz. Earthquake was at 2005 December 12, 13:56.***

A common drawback of designs based on micro-machined silicon accelerometers is a dependence of both span and offset on temperature; however a subsurface installation is not subject to large or rapid temperature variations and so can provide accurate data into the low frequency range as well as at high frequencies.

The prototype probe-based sensors were installed at depths of 12 m and 22 m at the WDAS site with the complete installation taking less than one day. These depths correspond to halfway down, and at the bottom, of the top layer of soft alluvial material. The signals were initially recorded by TerraTech DCA recorders, which were upgraded to TerraTech GSR recorders in February 1998, and then to a Kinemetrics K2 recorder in June 2004. Only at this last stage did digitizing noise become less than accelerometer noise, whereupon the system reached its full potential. Since the upgrade to the K2 recorder, 58 earthquakes have been recorded on both the subsurface recorders and the surface recorder, and all the records have been of extremely high quality. It is planned that a further sensor package will be installed at 31 m, where the shear wave velocity increases from 150 m/s to 367 m/s.

4. OBSERVATIONS OF HIGHER-FREQUENCY RESONANT GROUND MOTION AT WAINUIOMATA

The WDAS strong motion vertical array at Wainuiomata, New Zealand, typically responds to earthquake shaking in the fashion expected of a deep (31 m) soft (90 to 150 m/s) site. That is, the horizontal components of acceleration are dominated by monochromatic waveforms which are of greater amplitude than the vertical component and the dominant frequency of the horizontal components (0.8 Hz) is well approximated by considering vertically-propagating, multiply-reflected shear waves travelling within the soft material, when a layer with a free surface and rigid base is considered. An example record from a shallow earthquake is given in Figures 3 and 4, where monochromatic horizontal motion at 0.8 Hz is seen. In this example spectral peaks which would be expected on a multiple-reflection basis, at 2.4 Hz (3 times 0.8) and 4.0 Hz (5 times 0.8), are not seen. Note that in Figure 4 the vertical spectrum has a significant peak at 2.2 Hz, but that this frequency is not associated with any discrete packet of motion.

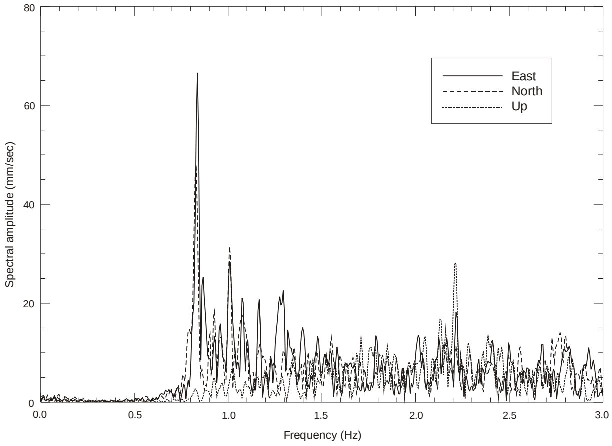

Figure 4: ***The three components of ground acceleration at WDAS for the earthquake of Fig 3, viewed in the spectral domain. This behaviour, with the main feature being amplification of both horizontal components at 0.8 Hz, is typical of the site.***

However when all the available records are examined in greater detail, this conventional picture changes slightly. On the horizontal components frequencies in accordance with the multiple-reflection model are always seen, but new slightly higher frequencies also become evident; the monochromatic responses are significantly delayed with respect to the incoming excitation; occurrences of vertical monochromatic response are sometimes evident. An example record showing all these features is given in Figures 5 and 6 (which treat a different earthquake than that of Figures 3 and 4).

Figure 5 shows a burst of monochromatic energy on the vertical component which has a frequency of 2.3 Hz as shown on Figure 6. Figure 6 also shows that the east (cross-valley) component has a peak at 1.0 Hz as well as the expected peak at 0.8 Hz. Note that in Figure 5 the p-wave arrives at 6.3 sec, the s-wave arrives at 11.3 sec, the 2.3 Hz vertical motion appears between 16 and 19 sec, and the 0.8 Hz motion on the north component appears after 23 sec. These new features require an explanation.

The vertical resonant motion of Figure 6 is a relatively rare occurrence – for the WDAS site it has only been seen for 5 of the 58 recorded events. On the face of it this makes the phenomenon somewhat unimportant, but it is possible that some features of highly damaging earthquakes might result in the vertical amplification being more important than suggested by the low magnitude earthquakes used here.

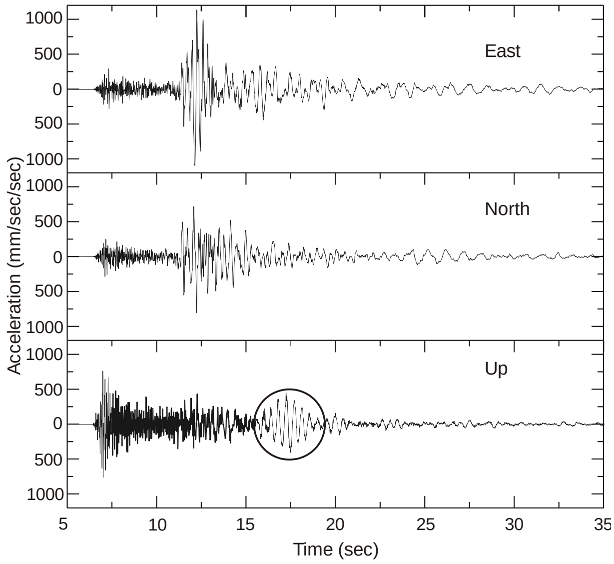

Figure 5: ***The three components of ground acceleration at WDAS for a magnitude 5.6 earthquake situated 21 km to the northeast. A delayed packet of vertical motion at 2.3 Hz is seen. Earthquake was at 2005 January 20, 18:56.***

In order to explain the unexpected vertical motion it is pertinent to consider the accepted approaches that account correctly for the horizontal motion, and to proceed in an analogous manner. It has been accepted for many years that for horizontal motion, site response at horizontally-layered locations may be treated in terms of the vertical propagation, including reflections, of horizontally-polarised shear waves. The justification for this is that as waves encounter lower near-surface propagation velocities, they will be refracted to travel nearly vertically. Such approaches predict a fundamental frequency at f and higher modes at 3f, 5f etc. [7].

At first sight it is tempting to adopt a similar approach in order to explain the observed vertical motion at WDAS. Multiple reflections of vertically-propagating p-waves within a layer that has a free surface and a rigid base may easily be evaluated. Because sites such as the WDAS one, which consist of extremely fine-grained water-saturated soils, are characterised by low values of s-wave velocity but much higher values of p-wave velocity, which approach that of water, site frequencies based on vertical multiple reflections of plane waves would be strikingly different for horizontal and vertical ground motion. In the case of WDAS the expected values for horizontal and vertical resonance would be 0.82 Hz and 12.1 Hz respectively. These values are based on four-way travel times as follows. For resonance of horizontal motion (due to vertically-propagating s-waves) a 22 m thick layer with a velocity of 90 m/s over a 9 m thick layer with a velocity of 150 m/s is assumed. For resonance of vertical motion (due to vertically-propagating p-waves) the two (22 m and 9 m) layers are lumped together as a single 31 m thick layer with a velocity of 1500 m/s (a value which assumes 100% water saturation in both layers).

Given that the observed values are instead 0.8 Hz or 1.0 Hz for horizontal motion and 2.3 Hz for vertical motion there is a need for some alternative explanation. Detailed computer modelling, both 2-D and 3-D, would allow the circumstances surrounding the occurrence of the delayed, monochromatic, vertical motion to be investigated, with a range of input wavefronts being specified. To carry out such an exercise it would be necessary to undertake an extensive programme of geophysical investigations in order to provide an adequate 3-D picture of the valley, with full modulus and density values.

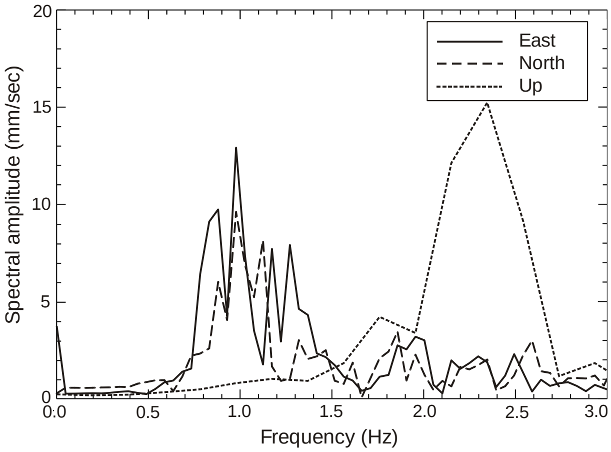

Figure 6: ***The three components of ground acceleration at WDAS for the earthquake of Fig 5, viewed in the spectral domain. In addition to the usual amplification of horizontal motion, a packet of monochromatic vertical motion at 2.3 Hz is seen. For horizontal motion a 20 second window was used. For vertical motion a 5 second window was used.***

There is available a more directly physical explanation of the delayed, monochromatic, vertical motion, based on well-known elastic wave phenomena as follows. In their Figure 11, Mooney and Bolt [8] show that for a particular set of soil and substrate properties, particle orbits of fundamental mode Rayleigh waves in a single soil layer over a half-space switch between prograde and retrograde motion as a function of frequency, involving purely horizontal motion at one frequency, and purely vertical motion at a higher frequency. This observation was refined [9], [10], [11] to discover the circumstances for which purely horizontal monochromatic motion occurs. It transpires that the switching between prograde and retrograde motion happens only when there is a large shear wave velocity contrast between the layer and the substrate, and when the layer also has a value of Poisson's ratio approaching 0.5, which implies that the p-wave velocity is much greater than the s-wave velocity. This in turn is most commonly seen in soft water-saturated sediments where the p-wave velocity becomes close to that of water while the s-wave velocity may be considerably lower as a consequence of high values of void ratio.

The fact that Rayleigh waves travelling in a well-defined layer of soft, water-saturated soil can have purely horizontal motion at one frequency, and purely vertical motion at a higher frequency, is interesting in itself, but does not suggest that such motions would have high amplitudes. There need to be additional factors that lead to a concentration of energy at the frequencies of purely horizontal motion and of purely vertical motion. One possibility for such amplification lies in the behaviour of Airy phases. Airy phases occur at frequencies for which the group velocity dispersion curve has stationary values. In these circumstances waves at a range of frequencies travel at much the same velocity, leading to large amplitudes at such frequencies. At other frequencies the action of dispersion causes waves with differing frequencies to travel at differing velocities, ensuring that the arrivals of the differing frequencies are spread in time and consequently have lesser amplitudes. This is known as the principle of stationary phase.

The cited studies of transitions between prograde and retrograde particle motion [8], [9], [10], [11] concentrate on the transitions and make no mention of Airy phases, yet calculations based on known soil properties at several sites show that for soft water-saturated sediments overlying stiffer materials, the frequencies associated with purely vertical motion and purely horizontal motion lie very close to the frequencies of Airy phases. This is shown in Figure 7 for the case of the WDAS site where it is seen that purely horizontal motion is expected at 0.76 Hz, close to an Airy phase at 0.81 Hz. In detail it is seen that this Airy phase is associated with an ellipticity of -10. For the higher frequency Airy phase at 1.81 Hz it is seen that nearly vertical motion (ellipticity 1/20) is expected.

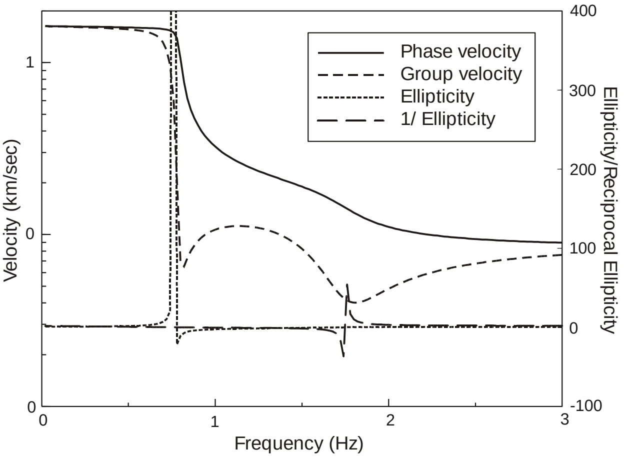

Figure 7: ***Theoretical dispersion curves and ellipticity of particle motion for a fundamental mode Rayleigh wave travelling in an extended, horizontally-stratified geology corresponding to the properties measured at WDAS using SCPT. The group velocity (dashed line; left hand axis) shows local minima at 0.8 Hz and 1.8 Hz ; these are therefore Airy phases. The elliptical particle motion is in a vertical plane along the line of propagation. The ellipticity and its inverse (dotted line and long dashed line; right hand axis) show that for the 0.8 Hz Airy phase the motion is nearly horizontal (dotted line) and for the 1.8 Hz Airy phase, nearly vertical (long dashed line).***

The forgoing analysis certainly suggests that fundamental-mode Rayleigh waves travelling in a soft, water-saturated soil layer which lies over a stiffer substrate, will exhibit monochromatic amplification of horizontal motion at a certain frequency, and monochromatic amplification of vertical motion at approximately twice that frequency, as seen at the WDAS site.

Thus far it is seen that Airy phases of fundamental mode Rayleigh waves could account for some commonly-accepted features of earthquake-induced motion at soft sites and add some new features that are not predicted by multiple-reflection models. The issue of higher-order responses (at 3f, 5f etc) seen at soft sites, for example at station CDAO in the Valley of Mexico [7], and predicted by multiple reflection models, remains to be addressed.

In this regard it is instructive to study the frequencies for which Airy phases of Rayleigh waves occur, allowing for higher modes, when they involve nearly horizontal particle orbits. As seen in Figure 8 these frequencies are in ratios close to 1:3:5:7…, just as expected for vertically-propagating plane waves. Thus most commonly observed characteristics of the seismic motion of soft soils are just as well explained by invoking Rayleigh waves of various modes as they are by invoking multiple reflections of vertically-propagating plane waves.

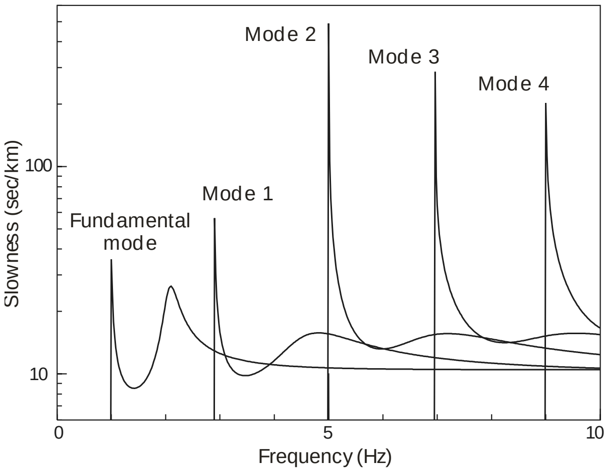

Figure 8: ***Slowness characteristics of Rayleigh waves, plotted on a logarithmic scale, for a model consisting only of the top soft layer, for the fundamental and higher modes. The horizontal motion has Airy phases at 1, 3, 5, 7 and 9 Hz., showing that the expected frequencies of resonant response are in the same ratios for both horizontally-propagating Rayleigh waves and for the multiple reflection of vertically-propagating shear waves.***

However in the case of WDAS records there is one detail not in accordance with modelling based on the known ground conditions. This detail is that the observed frequency of the vertical component of ground motion is not consistent with predictions based on fundamental mode Rayleigh waves travelling in infinitely-extended horizontal layers corresponding to the known shear wave velocity profile at WDAS.

5. ACCOUNTING FOR THE UNEXPECTEDLY HIGH FREQUENCY OF RESONANT GROUND MOTION.

The frequency of 1.81 Hz expected for an Airy phase involving vertical motion at WDAS (Figure 7) is not a satisfactory match to the 2.3 Hz observed for event 20050120.185631, and this discrepancy needs to be explained. The essential point to realise is that the WDAS site is not a series of infinitely extended horizontal layers as required by the theoretical modelling, but a deep point in a basin structure. To the north (at Pukeatua School, Figure 1) a slightly thinner (18 m) and slightly faster (94 m/s) layer is present, overlying the stiff gravels. To the southwest (W12, Figure 1) a layer of similar thickness (20.4 m) and similar speed (100 m/s) to the WDAS site is present above an intermediate 15 m layer of material with a velocity of 184 m/s, which in turn overlies the stiff gravels. These layerings are illustrated in Figure 9. A better picture of WDAS is therefore as shown in Figure 10, which suggests that along an East-West section an adequate model would consist of a 31 m thick layer embedded in stiff surroundings, whereas along a North-South section it would be more accurate to model in terms of an extended soft layer 22 m thick, merging into two local soft layers totalling 31 m thick. For the case of West-East travelling waves it is therefore sufficient to consider an Airy phase Rayleigh wave travelling in a plane layer whereas for the North-South case it is relevant to consider the behaviour of an Airy phase Rayleigh wave which travels initially in a layer of one thickness, then propagates into a thicker layer. The former case is standard and does not need to be discussed further, but the latter case deserves careful thought.

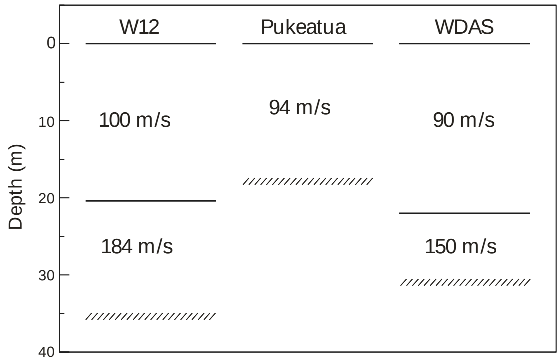

Figure 9: ***The different layerings for the profiles at Pukeatua School, WDAS and W12.***

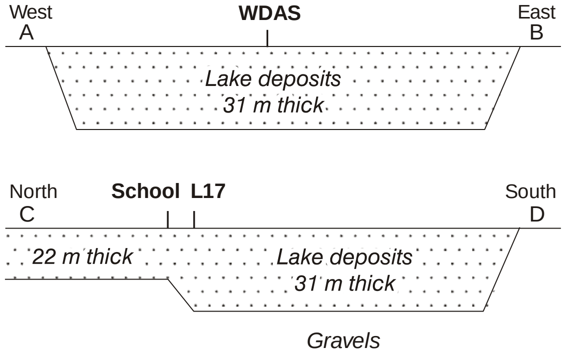

Figure 10: ***Indicative basin model based on the profiles of Fig 9, suggesting that Rayleigh waves travelling down valley would have Airy phases determined by the profile at Pukeatua School, and that these would be preserved at WDAS. By contrast waves travelling up valley or across valley would have Airy phases determined by the profiles at WDAS or W12.***

In a linear stress-strain situation it is fundamental that frequency will be conserved as a wave propagates through differing media. However it is equally fundamental that the mode shape of such a wave should be physically reasonable. A scenario that simultaneously meets these two requirements involves the launching in the extended thinner layer, of an Airy phase Rayleigh wave with a frequency, group velocity, phase velocity and mode shape appropriate to the thinner layer together with its substrate. This wave is envisioned to then propagate into the thicker layer, retaining its frequency, but with its group velocity, phase velocity and mode shape being appropriate to the thicker layer. On this basis it is to be expected that an arriving monochromatic packet of vertical motion will have a frequency that depends upon the direction from which the wave arrives. At WDAS the vertical motion associated with a north-to-south travelling Airy phase will have a frequency associated with the thinner layer, while the vertical motion associated with a west-to-east travelling Airy phase will have a frequency associated with the thicker layering. This is difficult to test experimentally (unless a small-scale array is installed) because the wave has only a small horizontal component and therefore the particle orbit in the horizontal plane, and hence the direction of travel, is hard to determine.

Similar arguments apply when the lower frequency Airy phase (involving horizontal monochromatic motion) is considered. For that phase there is no clear single direction of particle motion at 0.8 Hz, presumably because various waves arrive from various azimuths at different times.

As Figure 11 shows, the expected Airy phase associated with vertical motion at the Pukeatua School site has a frequency of 2.67 Hz whereas at W12 the expected Airy phase associated with vertical motion has a frequency of 2.20 Hz. At WDAS it is 1.82 Hz.

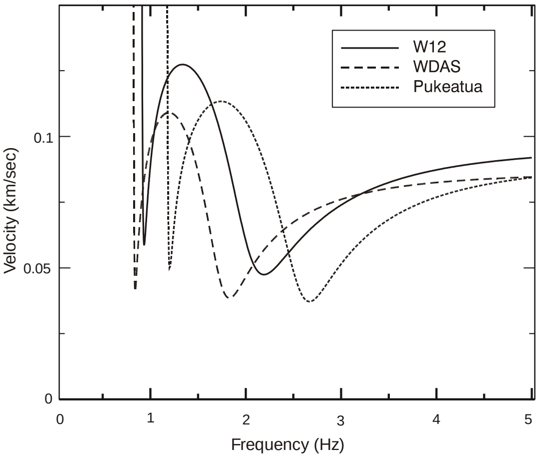

Figure 11: ***Dispersion curves for fundamental mode Rayleigh waves for each of the profiles of Fig 9. A fundamental mode Rayleigh wave travelling down valley would have an Airy phase of vertical motion at 2.67 Hz; travelling up valley would have an Airy phase of vertical motion at 2.20 Hz; and travelling across valley would have an Airy phase of vertical motion at 1.82 Hz.***

For the Pukeatua School site the frequency expected for the Airy phase associated with horizontal motion is 1.10 Hz and at W12 it is 0.96 Hz. At WDAS it is 0.82 Hz.

These frequencies for the Airy phases were obtained by using the known layer properties at Pukeatua School and at W12 as inputs to a suite of matrix propagator computer programs [12].

A scenario that satisfactorily explains the presence of higher than expected frequencies at WDAS involves waves being generated and initially propagated in the thinner layer, and somewhere near WDAS travelling in the thicker material with frequency conserved but the mode shape changed to accommodate new boundary conditions.

This idea may be tested by inspecting the frequency of vertical response at WDAS, together with the way the amplitude of that vertical response varies with depth. This will be done for one selected earthquake.

6. VERTICAL RESPONSE: ITS FREQUENCY, AND ITS VARIATION WITH DEPTH

In the earthquakes recorded at WDAS for which a high frequency resonance was observed on the vertical component, the resonant frequency varied between 2.2 Hz and 2.8 Hz. This would be a not unexpected consequence of Rayleigh waves initially travelling in layers of various thicknesses, eventually arriving at WDAS but preserving the frequency appropriate to the layering in which the wave initially travelled.

To investigate the variation of resonant motion with depth, an earthquake (20070207.004504) with a resonant frequency of vertical ground motion near the top end of the range (2.7 Hz) was selected.

The variation of resonant motion with depth is shown in Figures 12 and 13. It is clear that the motion is largely confined to the top 22 m of soil. From Figure 13 the frequency of motion is seen to be 2.7 Hz.

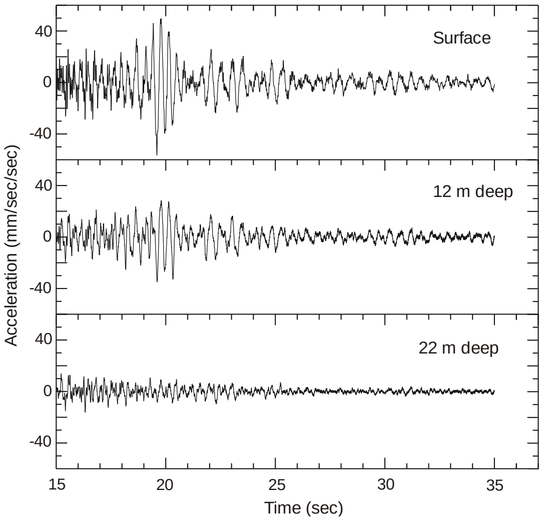

Figure 12: ***Vertical component of acceleration as a function of time and depth for a magnitude 4.7 earthquake situated 39 km to the northwest of WDAS, 52 km deep. The vertical motion is confined to the top soft layer of soil.***

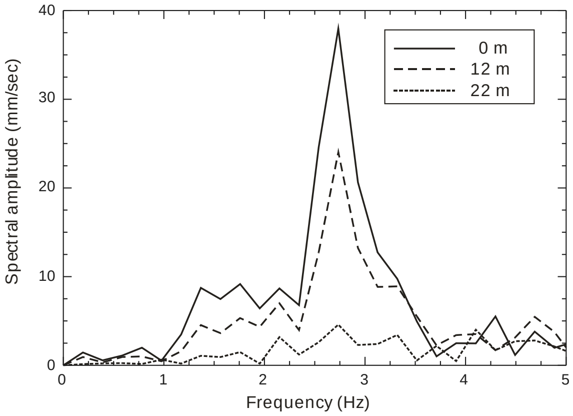

Figure 13: ***Spectrum of ground acceleration as a function of depth for the earthquake of Fig 12, showing that the monochromatic motion is confined to the top soft layer of soil.***

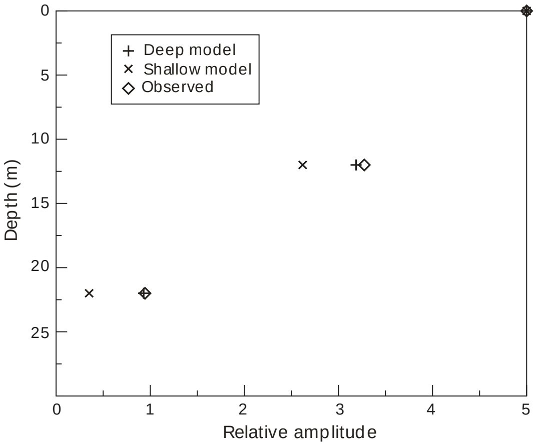

Figure 14: ***Measured and theoretical amplitudes of the spectral peak associated with Airy phase involving vertical motion, as a function of depth. Two models are assumed, one associated with the full profile at WDAS and the other associated with the top layer alone. The amplitudes are in accordance with the full profile even though the frequency is appropriate to the shallow profile.***

The change of relative amplitude with depth may be compared with that expected on the basis of modelling. The observed frequency is consistent with an Airy phase Rayleigh wave travelling in a relatively thin layer (at Pukeatua school a frequency of 2.61 Hz is expected), whereas the field measurements have been made at a point (WDAS) where the alluvium is substantially thicker. Hence in Figure 14 the amplitudes for the two theoretical cases have been plotted as a function of depth. The lesson is clear. For this earthquake the frequency is consistent with a wave that has travelled some distance in a thinner layer, whereas the amplitudes are consistent with the same wave after it has propagated into the thicker basin. Thus the variation in frequency is logically seen as a result of waves arriving after having travelled in layers of varying thickness depending on their travel azimuth.

7. EXCITATION LAGS

It is conceivable that the monochromatic vertical motion which is the focus of this paper could be explained by the action of 3-D geometry or of anisotropy in the soil material. However the observed instances of resonance in the vertical motion recorded at WDAS all occur substantially after the arrival of the corresponding p-waves or s-waves. Such behaviour is consistent with this vertical motion being due to slowly-travelling Rayleigh waves generated at some local impedance discontinuity, and it would require special pleading for 3-D effects or anisotropy to be considered as candidates. In the case of the earthquake 20050120 of Figures 5 and 6, the distance to the discontinuity at which the postulated Rayleigh waves are launched can be estimated by noting that the peak of the envelope of 2.5 Hz vertical motion occurs 10.8 seconds after the p-wave arrival, and 6.1 seconds after the s-wave arrival. Assuming the wave travels at its theoretical group velocity of 37 m/s its origin would be 401 m distant if excited by p-waves, or 226 m distant if excited by s-waves. Because the motion has no horizontal component its polarisation cannot be used to determine the arrival azimuth of the waves, and hence no physical feature at either 401 m or 226 m can be identified as the source of the waves. A small-scale array with an aperture of a few tens of metres could be used to resolve this uncertainty in the travel direction of the waves, and if such an array were implemented using sensitive recorders the verdict could be obtained in a short time.

8. OTHER SOFT SITES

During 1990/1991 the Wellington Regional Council funded investigations into the role of local soil conditions in modifying damage due to earthquake shaking. One part of these investigations was the operation of local networks of velocity seismographs at various sites within the greater Wellington area. The seismograms were usually interpreted by forming soil-to-rock spectral ratios, and three networks were operated within the Porirua basin, the Hutt valley, and parts of Wellington City. Some of the original data from these investigations have been retained, allowing a search for the effects already seen at Wainuiomata. In the reporting that follows the ground motion is usually plotted as velocity (the entity being recorded) because for the low magnitude earthquakes recorded there is a preponderance of high frequency motion, and a transformation into acceleration serves mainly to emphasise these frequencies at the expense of masking sought-after features.

The analysis for the WDAS site suggested that the presumed Airy phase would be characterised by delayed, monochromatic, vertical motion for a soft water-saturated site near a rock-soil boundary, and that the frequency of this vertical motion would be about twice the frequency of the usual horizontal response seen at such sites. Accordingly, the approach was, for each earthquake, to plot the vertical component of all recorders on a single page, whereupon sites with a delayed monochromatic response were immediately obvious. Eight examples, each from a different site, have been chosen to exemplify the non-rareness of the phenomenon. Other possible examples were noted, but have not been shown here because there was no clear indication of a single dominant frequency of horizontal motion, at around half the frequency of vertical motion. In some cases this was thought to be because of the limited spectral content of the small earthquakes used.

Despite their age, these recordings were made with relatively sophisticated equipment. The seismometer outputs were fed to low-noise amplifiers, and then to gain-ranging, 12-bit digitisers. The ground motion in every case was small, hence there is no possibility of clipping of the data. At the time of the project, data storage was expensive, so a triggering system was employed to reject non-earthquake data. This was done by comparing short-term and long-term signal averages, and employing a 5-second ring buffer to capture pre-trigger data. In the soft-soil, urban environments chosen it was usual for the triggering to be initiated by the s-wave. Consequently full recordings of earthquakes including the arrival of the p-wave, were rare.

The local geology at these additional sites is less well-known than it is at Wainuiomata. In particular it is not easy to ascribe a distance to the boundary where Rayleigh waves could originate. Such boundaries usually had no surface manifestation.

The case for WDAS responding as an Airy phase of a Rayleigh wave seems clear cut. Judgement of whether the additional sites are responding as Airy phases of Rayleigh waves is left to the reader. The delayed vertical waveform at around twice the frequency of the horizontal waveform is certainly in accordance with an Airy phase, and difficult to explain otherwise (e.g. as an Sv phase).

Figures 15 to 26 show the waveforms and spectra from the additional Lower Hutt and Wellington sites. At all sites except W23 (shown in Figure 21) the monochromatic vertical waveform occurs several seconds after the arrival of s-wave energy, suggesting the slow travel of a wave over a significant distance, or excitation by a later phase than s, or perhaps a combination of these two possibilities. However at site W23 the high frequency vertical motion starts at the same time as the arrival of s-waves, suggesting a very small basin. Site W23 has not been reported on in detail, but it is clear from the local topography that the width of the infilled stream channel is at most 150 metres. Penetrometry [13] established that the local shear wave velocity profile at site W23 accounts for the frequency (3 Hz) at which horizontal motion is amplified, and the frequency at which vertical motion is amplified is three times this (9 Hz).

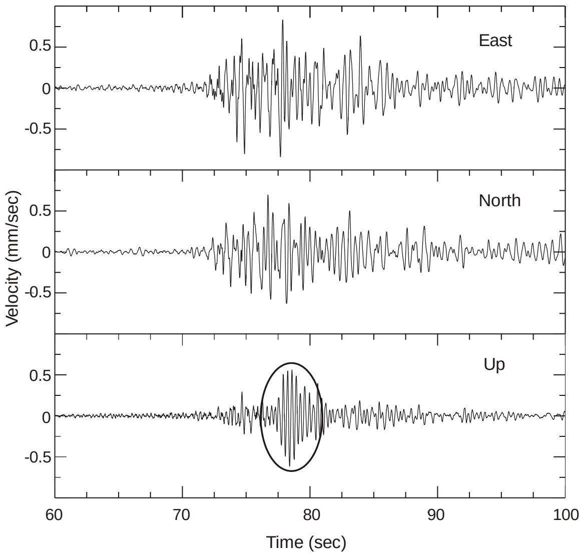

Figure 15: ***The three components of ground velocity at W02 for a magnitude 5.1 earthquake situated 125 km to the northeast. The packet of delayed monochromatic waveform on the vertical component is highlighted.***

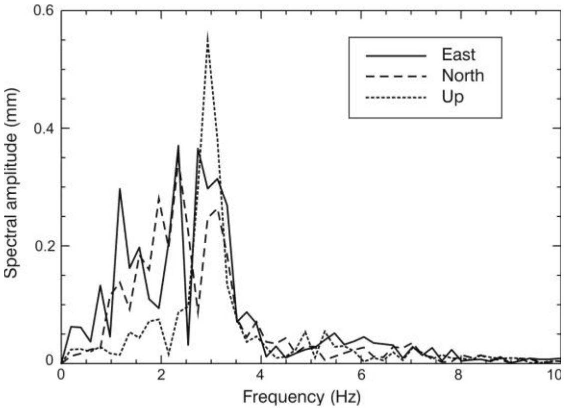

Figure 16: ***The three components of ground velocity at W02 for the earthquake of Fig 15, viewed in the spectral domain.***

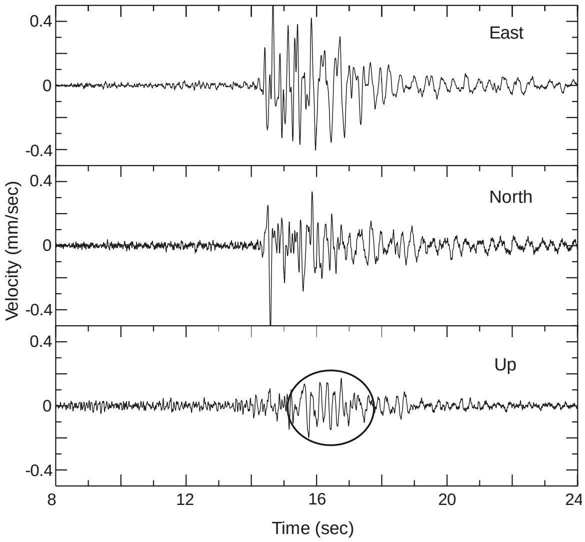

Figure 17: ***The three components of ground velocity at W05 for a magnitude 3.9 earthquake situated 47 km to the east. The packet of delayed monochromatic waveform on the vertical component is highlighted.***

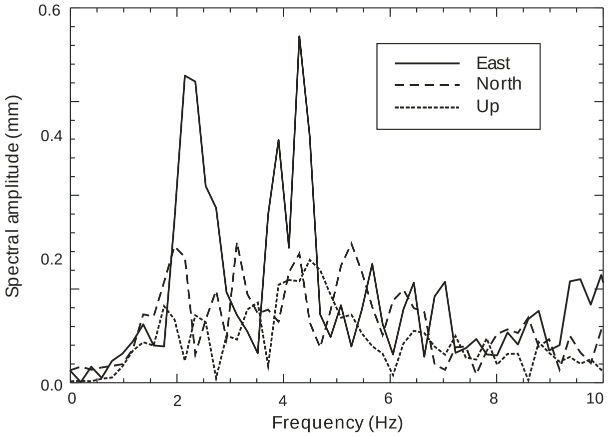

Figure 18: ***The three components of ground velocity at W05 for the earthquake of Fig 17, viewed in the spectral domain.***

The Porirua stream estuary at Porirua Harbour, Wellington, New Zealand has been of interest for a number of years from a seismic hazard point of view because initial SCPT testing showed a low-velocity layer of soil with a high velocity contrast to the substrate [14]. The SCPT results show that a four metre thick layer of reclaim material overlies an eight metre layer of silts and sands, these two layers having a mean velocity of 110 m/s. The water content of the natural material is around 50%. Between the silt and sand layer and bedrock is layer of gravels which is assumed to be 12m thick on the basis of data given in [15]. The rock is assumed to have the velocity profile used in [16].

Modelling the propagation of fundamental-mode Rayleigh waves on the basis of the layering described above shows that two Airy phases are expected at PB5, the lower frequency one characterised by horizontal motion and the higher frequency one characterised by vertical motion. The higher frequency one appears at 4.69 Hz, has a group velocity of 43m/s, a phase velocity of 162m/s and an ellipticity of 0.108. The lower frequency one appears at 2.20 Hz, has a group velocity of 58m/s, a phase velocity of 1315m/s and an ellipticity of -11.6.

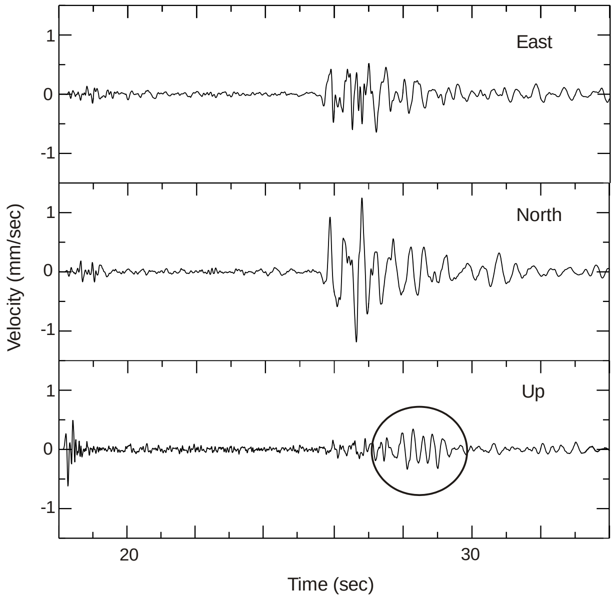

Figure 19: ***The three components of ground velocity at W08 for a magnitude 3.9 earthquake situated 35 km to the northwest. The packet of delayed monochromatic waveform on the vertical component is highlighted.***

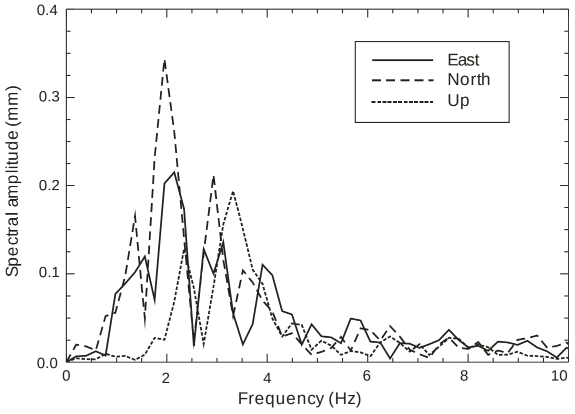

Figure 20: ***The three components of ground velocity at W08 for the earthquake of Fig 19, viewed in the spectral domain.***

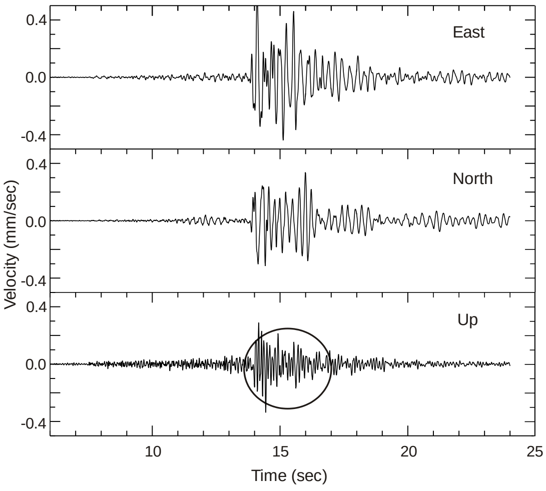

Figure 21: ***The three components of ground velocity at W23 for a magnitude 3.9 earthquake situated 47 km to the east. The packet of monochromatic waveform on the vertical component is highlighted. In this case the packet is not delayed, apparently because the patch of soft soil is very small.***

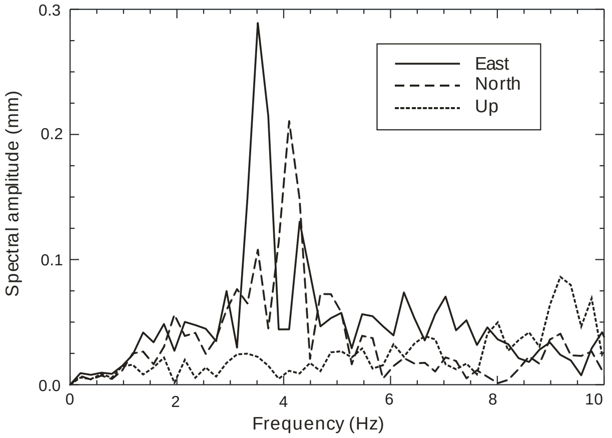

Figure 22: ***The three components of ground velocity at W23 for the earthquake of Fig 21, viewed in the spectral domain.***

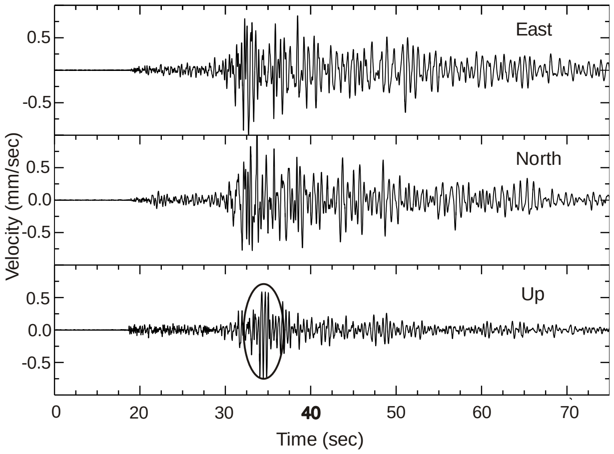

Figure 23: ***The three components of ground velocity at W17 for a magnitude 5.1 earthquake situated 90 km to the southwest. The packet of delayed monochromatic waveform on the vertical component is highlighted.***

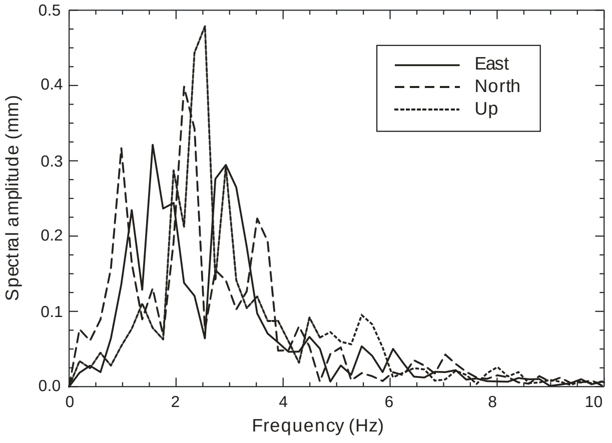

Figure 24: ***The three components of ground velocity at W17 for the earthquake of Fig 23, viewed in the spectral domain.***

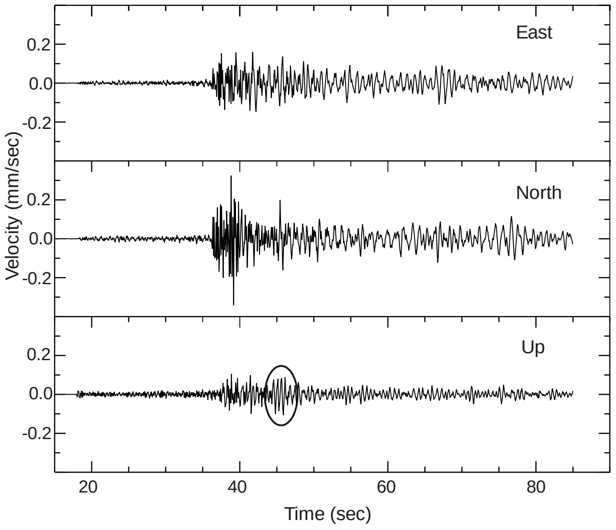

Figure 25: ***The three components of ground velocity at L17 for a magnitude 4.5 earthquake situated 167 km to the north. The packet of delayed monochromatic waveform on the vertical component is highlighted.***

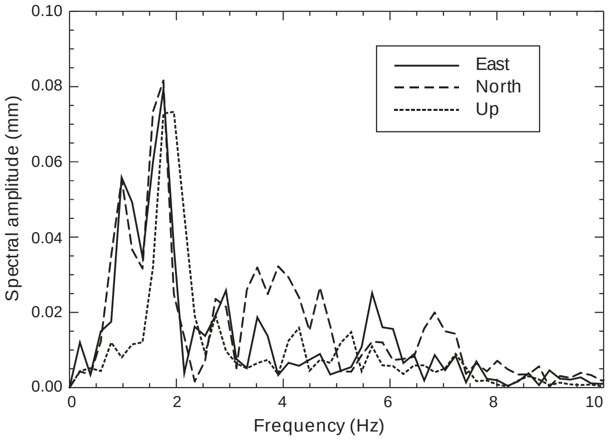

Figure 26: ***The three components of ground velocity at L17 for the earthquake of Fig 25, viewed in the spectral domain.***

Only one site at Porirua, PB5, showed delayed monochromatic vertical motion, and there was little variation in the frequency of this motion from earthquake to earthquake. A suite of 32 earthquakes recorded in a month at PB5 [5] included five that showed delayed monochromatic vertical motion. The frequency of this vertical motion is consistent with the preceding calculations, the observed frequency of vertical motion being 4.3 Hz in each case as shown in Figure 27. One record, that of event 900604.124407, is of particular interest because of the dominance of the monochromatic vertical motion as shown in Figure 28 where the ground motion is plotted as acceleration. The dominance of monochromatic vertical motion is presumably linked to a major peak in the spectrum of the north-south motion on rock as shown in Figure 29. The rock site (PB8) is 4km to the northeast of PB5. The p-wave arrives at PB5 at 19 sec and the s-wave at 24 sec, whereas the monochromatic motion commences at 27 sec. Assuming that it is the s-wave that initiates the Airy phase it follows that the point of initiation is only 180 m from PB5, this being the distance that a 58 m/s wave travels in 3 sec.

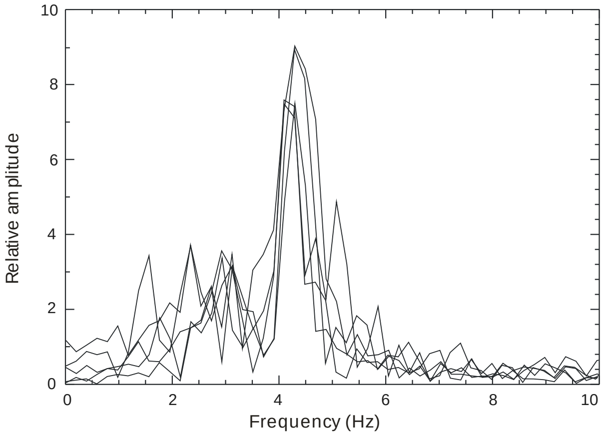

Figure 27: ***Scaled spectrum of the vertical component for each of five earthquakes recorded at PB5. Note the consistent frequency of 4.2 Hz. In each case a 3 second window containing the monochromatic packet has been chosen.***

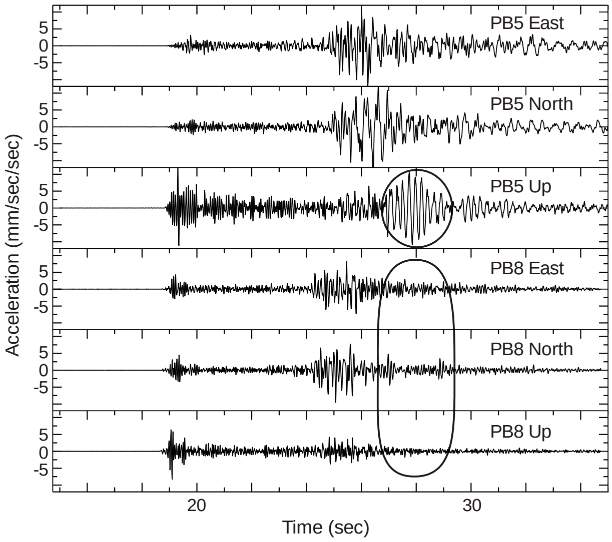

Figure 28: ***The three components of ground acceleration on soil (PB5) and rock (PB8) for a magnitude 3.9 earthquake situated 31 km to the north. just below the plate interface. The monochromatic vertical motion on the soil is not present on the rock.***

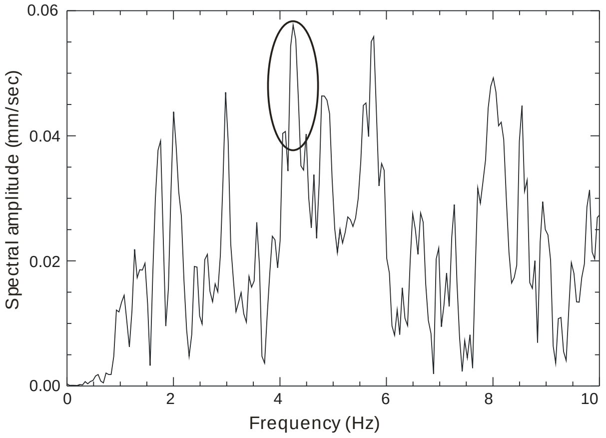

Figure 29: ***The north component of ground velocity on rock for the earthquake of Fig 28, viewed in the spectral domain. There is a peak at the frequency of the Airy phase on soil, potentially explaining why the Airy phase is so dominant for this earthquake.***

The WDAS (Wainuiomata) and PB5 (Porirua) sites are similar in that they display a variety of delay times for the onset of monochromatic vertical motion and they have a similar proportion of earthquakes for which the motion is excited. However they differ in that PB5 records have a constant frequency (4.3 Hz) while WDAS records have a range of frequencies.

These properties make PB5 a suitable candidate, additional to WDAS, for further seismometer array studies of the velocity and point of origin of the waves.

9. LAUNCHING THE WAVE

The mechanism by which the postulated Airy phase Rayleigh wave might be generated is not known. It is likely that that the process takes place as some arriving phase interacts with a lateral boundary of the soft soil. More than one Rayleigh wave could be launched from various parts of the boundary and subsequently superposed.

A suitable approach to future investigations of the process of launching the wave might well involve a combination of experimental investigations, and numerical modelling. The intent of the experimental investigations would be to discover when and where the secondary waves are generated, and thus to give an immediate focus to modelling studies so that only realistic situations are modelled.

By implementing a small, sensitive array of velocity seismographs to record microearthquakes, and analysing the seismograms in the frequency-wavenumber domain, it should be possible to establish the speed and direction of the secondary waves, and thus to establish their time of origin and point of origin, much as was done in [17].

This information would allow physically realistic situations to be modelled.

A suitable array would have at least four stations with a variety of inter-station separations on a scale of tens of metres (to avoid spatial aliasing). It is likely that at WDAS the waves under consideration will have a frequency of 2.5 Hz and a velocity of 130 metres per second, and that they will consequently have a wavelength of around 50 m. Accordingly an array aperture of around 20 m would be appropriate.

Three of the earthquakes studied involved large amplitudes of the Airy phase. These earthquakes were 900604.124407, 20050120.185631 and 20070207.004459. It was noticed that all of these probably had epicentres close to the subduction interface, and it was thought likely that this may have been a factor in the launching of the wave.

Accordingly a study of the proximity of all the WDAS events of 2004 and 2005 to the subduction interface was undertaken. Following [18], the interface was taken to be defined by a horizontal cylinder of radius 260 km, with its axis 275 km beneath the earth’s surface, bearing 40 degrees east of north, and passing beneath Riversdale Beach township (on the east coast of the Wairarapa). The distance of each epicentre above or below this surface was calculated.

No special relationship between the distance to the interface and the excitation of the Airy phase was noticed, and in fact for the sequence of 20050120.185631 and its aftershocks, only the main shock excited the Airy phase. The aftershocks were vertically within 600 m of the mainshock. Evidently some factor other than proximity to the subduction interface is responsible for the excitation. In fact because the 20050120.185631 mainshock was associated with a large monochromatic vertical signal, but its aftershocks were not, path effects in general may be ruled out.

10. CONCLUSIONS

Delayed packets of monochromatic vertical motion are sometimes seen in recordings of earthquake ground motion made on soft soil. On occasions these packets may have greater amplitude than the horizontal motions. Their delays suggest a slow-travelling wave, and their frequencies and variations of amplitude with depth suggest that they could be Airy phase fundamental-mode Rayleigh waves. Variations in their observed frequencies could be due to their initial propagation in layers of differing thickness.

Details of how the waves are generated, and especially the circumstances which lead to them being dominant, are uncertain. Further studies of the topic would be worthwhile, with small seismograph arrays at WDAS and PB5 being of crucial importance. They would make an ideal student project.

ACKNOWLEDGMENTS

The data from WDAS owe their existence to the implementation of the vertical array at the site. In turn the design of that array and its installation would not have been possible without the sterling efforts over the years, of Peter Barker. GNS workshop staff built the sensor units, and David Baguley of GNS has kept the array running for many years. The archival microearthquake data were gathered by John Taber (then of Victoria University of Wellington) and Euan Smith (then of DSIR). Martha Savage of VUW liberated many of these data, and John Taber kindly forwarded copies of the rest from his location in Washington. All these contributors are thanked for their efforts. This paper benefited from reviews by Rafael Benites and Bill Fry of GNS Science and they are thanked for their efforts.

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