THE WAINUIOMATA "LOCAL EFFECTS" SEISMOGRAPH NETWORK

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ABSTRACT

The Wainuiomata "local effects" network of 16 seismographs was established and operated during three months of the year 2000. The effectiveness of earlier such networks is discussed, together with the way that the results from the earlier networks influenced the establishment and operation of the Wainuiomata network. An overview is given of the results obtained, together with a sample analysis of one set of seismograms.

1. INTRODUCTION.

Local geology is well recognised as being an important controller of ground shaking and hence of damage, during earthquakes. The effects of local geology on shaking have in some cases been codified e.g. by using the Vs30 criterion [1].

Certain special cases appear to be of great importance, as for instance when in 1985 shaking exceeded building design parameters in Mexico City [2]. Understanding the mechanisms involved in such cases is a worthwhile pursuit, and although numerical modelling techniques have advanced rapidly, there is a need for "ground truth" to be established experimentally. The special cases typically involve a basin of very soft material which has a large impedance contrast to the basement material.

To provide an experimental basis for investigating basin-related amplification, four networks of closely spaced seismographs have been operated for short periods in New Zealand. The Wainuiomata network which operated late in the year 2000 was the fourth of these, and was a network of sixteen velocity seismographs temporarily installed at spacings of a few hundred metres on the surface of a basin of soft soil.

This paper describes the installation and operation of the network, summarises the data, and demonstrates the type of result obtained, by analysing the seismograms from one earthquake.

2. PREVIOUS NETWORKS

To understand the philosophy of the Wainuiomata network it is useful to examine similar networks which were operated in New Zealand, because experiences with those networks led to the Wainuiomata configuration.

The initial site (at Pukehou, on the east coast of the North Island) was selected on the basis of it being a peat swamp of known depth, lying in a limestone depression of relatively small dimensions, and situated in an area with frequent earthquakes. Thus the desirable qualities of high impedance contrast with the basement, small dimension (so that spatial aliasing could be avoided using relatively few recorders) and frequent useable earthquakes, were all present. However the available instruments (strong-motion accelerographs) coupled with a tendency of the site to become flooded, meant that most stations of the network had to be withdrawn, before the only sizeable earthquake occurred in the area [3]. However the one useable event, recorded at one rock station and one soil station, did show that the site was ideal. Unfortunately the landowner has discouraged the establishment of better recorder networks on his property. Should the landowner's policy change however, Pukehou would be an ideal site in which to deploy a network of modern, sensitive recorders.

Following the unsatisfactory performance of the Pukehou network, a search was made for a similar situation by studying geological maps, topographical maps and aerial photos, starting at Wellington (for operational reasons), and working north. A candidate site was found at Alfredton, in the northern Wairarapa [4], and preliminary investigations were carried out to ensure that the site was adequate. These investigations were hand augering, cone penetrometry (CPT) and seismic cone penetrometry (SCPT), and a trial deployment of a velocity seismograph for 8 days in the centre of the soft area. The Alfredton site [4], was formed by episodic vertical movement on the Alfredton fault, progressively damming the Ihuraura river, and leading to the deposition of soft fine-grained materials.

The test augering showed soft material, with the presence of vivianite (typical of swamps). CPT and SCPT probe results showed 12 m of Holocene silty materials overlying Tertiary mudstone. The Holocene soft surface material had shear wave velocities increasing from 80 m/s at the surface, to 300 m/s just above the mudstone basement. The preliminary seismograph installation returned 6 seismograms with signals well above the noise. These seismograms were characterised by horizontal motion dominating vertical motion (as expected for a soft site), and by high spectral peaks. On this basis 15 velocity seismographs were installed in a grid with 100 m spacing on

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the soft material, and a further 4 velocity seismographs were installed on the soft rock (Tertiary mudstone) surrounding the site. This installation comprised the Alfredton seismograph network.

The geotechnical properties of the basin were evaluated by an additional series of CPT and SCPT probes, by two seismic refraction lines, and by ultrasonic wave propagation tests on core samples recovered from the basement material in a standard penetration test (SPT) barrel. A complete account of the basin properties and seismogram data is available [4].

Analysis of the seismograms recorded by the network over a period of 38 days revealed only moderate amplification [5, 6], with no whole-basin resonances. Clearly this was not a site which would have relevance to such matters as the excessive damage in Mexico City in 1985. However the data raised a problem, in that Alfredton, on first appearances, and according to evaluation schemes still in place, would be classified as an amplification hazard, which it clearly is not. The lack of amplification is thought to arise from the steady increase of shear wave velocity with depth in the soil, and the low impedance contrast with the basement – the shear wave velocity only increases from 310 m/s to 850 m/s with the change from Holocene sediment to Tertiary mudstone.

The lessons from Pukehou and Alfredton were well learned, and a different strategy was adopted to select a third network site. Areas in Miramar (Wellington City), Timberlea (Upper Hutt City), and Parkway (Hutt City) were evaluated using the method for analysing microtremors described by Nakamura [7]. All three areas yielded quasi-spectral ratio curves that implied resonant amplification, and thus all three seemed promising. However the Miramar soft patch spread over too large an area, and the Timberlea area included a sporting field, which would have led to problems for the installation and maintenance of seismographs. On the other hand very high soil/rock spectral ratios had been measured in Parkway for earthquakes [8], so the Parkway valley was chosen for the third basin area, and a seismograph network was established there in 1995. Descriptions of the geotechnical properties of the valley [9] and the processing of the observed seismic data [10] have been compiled. Subsequent to the work described by Beetham, a Spectral Analysis of Surface Waves (SASW) test was carried out [11], and a deep SCPT test was carried out [12], giving additional pertinent subsurface information.

Early Parkway results did not appear to show the whole-basin resonances which had been expected, and in view of the long lead time involved in obtaining research funding and locating a further basin, an immediate start was made in the planning of what eventually transpired to be the Wainuiomata network.

However, in the long run the Parkway site proved to be a rich source of diverse information – dominant frequencies were found [13]; propagating waves were found [14]; excitation of a normal mode was reported [15]; a correlation was found between amplification and spatial coherence [16], and recommendations made regarding the choice of rock reference sites [17].

3. LOCATING A SUITABLE FOURTH BASIN

One key feature of the 1985 Mexico City records was the long-duration monochromatic motion that occurred on soft soil [18], and that was presumably associated in some way with the great damage [19], so we endeavoured to locate a basin with this characteristic.

Neither Alfredton basin nor Parkway basin showed evidence of long duration, monochromatic wavetrains, so in locating a fourth basin we adopted a philosophy of inspecting strong motion accelerograms recorded in New Zealand over the years, seeking such records. In this respect, two sites stood out – Wainuiomata and South Dunedin. Both showed long duration monochromatic wavetrains, particularly during the 1994 Arthur's Pass earthquake [20]. Both areas were known to have significant depths of soft material [21, 22]. Furthermore the South Dunedin area was known to have amplified the 1974 Dunedin earthquake [23]. Because neither Alfredton nor Parkway had behaved as expected we adopted a strategy of incremental investigations in Dunedin, which would allow us to withdraw from the area if it proved unsatisfactory. First a series of microtremor recordings was made at 30 locations, and analysed by Nakamura's method [7] in order to find the extent of the resonant area. Then earthquakes were recorded at one rock site and three representative soil sites for 78 days, during which six useable earthquakes were recorded. Finally, penetrometry (CPT and SCPT) was used to explain the microtremor and earthquake results.

Our verdict on South Dunedin was [22] - "South Dunedin is not a suitable area in which to establish a temporary dense seismograph network for the purpose of investigating whole-basin seismic response, despite encouraging early indicators of resonant behaviour and observed earthquake amplification. The area is unsuitable on account of the relative paucity of earthquake shaking greater than ambient background vibration, and the small size of the resonant region. This small size of the resonant region is due to the local nature of a deep soft region, which is probably an infilled channel."

Attention was then focussed on Wainuiomata, shown on a map of New Zealand in Figure 1. It was considered important that the basin chosen should show the long monochromatic beating codas which are characteristic of sites in the Valley of Mexico. To evaluate this, a temporary seismograph was operated at the Wainuiomata Bush Fire Station (WBFS; see Figure 2) for a period of six weeks. The records obtained did not show long monochromatic beating codas, but because such codas had previously been seen at Wainuiomata for large magnitude earthquakes [20], we elected to proceed. The subsequent clear annunciation [24] that a large source magnitude, a large epicentral distance, and a soft soil, are required simultaneously in order for long monochromatic beating codas to exist in the Valley of Mexico, justifies our decision to proceed with a network at Wainuiomata.

An additional reason for preferring the Wainuiomata area was the existence of a vertical array of strong motion accelerometers at the centre of the valley. There was a good prospect that during the planned three month deployment of the network of surface recorders, there would be at least one earthquake that had sufficiently large ground motion to obtain useful records from the vertical array, while not overloading the more sensitive velocity transducers of the surface network. The vertical array has sensors at depths of 12 m and 22 m, as well as one at the surface, and the internet address http://www.gns.cri.nz/earthact/probe describes the new technology involved in their installation.

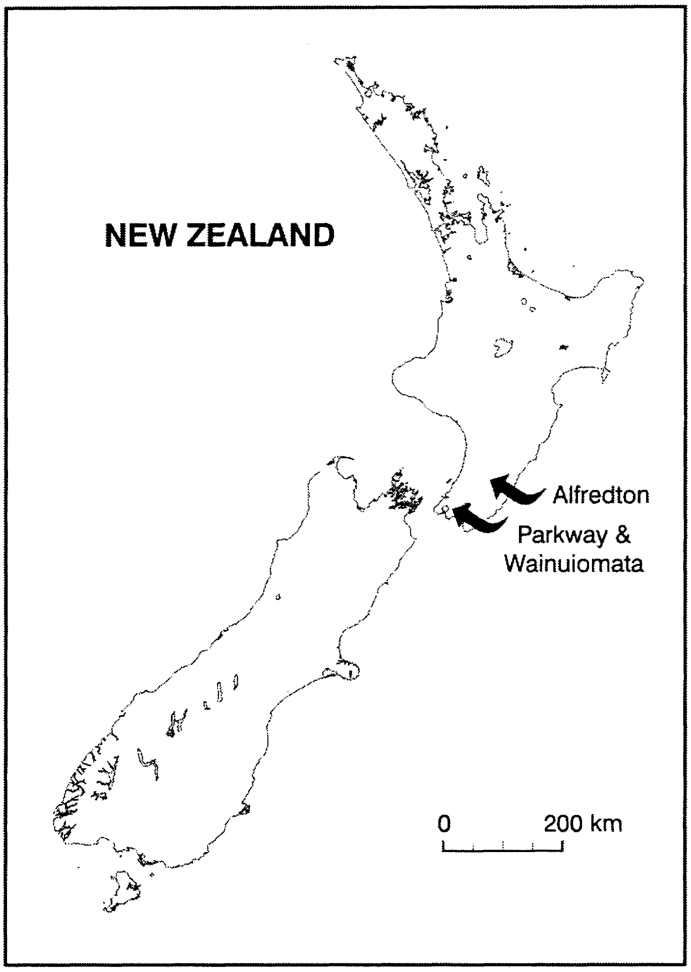

Figure 1. Locations of networks mentioned in the text. A more precise description of the relationship of the Parkway and Wainuiomata network locations is given in Figure 2.

Later in the preliminary investigation of Wainuiomata, a series of microtremor measurements was made at 20 sites in the area. These measurements were analysed by the method described by Nakamura [7] in order to discover the way that dominant ground frequency varies from site to site in Wainuiomata. It was found that the Horizontal-to-Vertical-Spectral-Ratio (HVSR) was consistent with the propagation of Rayleigh waves in a layer (a large peak with a trough falling to less than unity at about twice the peak frequency) at all sites investigated. A Y-shaped area extending downstream from the central commercial area and up both the Parkway and Wellington Road valleys was found to be resonant. A large variation of peak HVSR amplitude among the sites was taken to mean that the relative proportions of Rayleigh wave to other forms of vibration was also variable. Variations of the natural frequency between 0.8 Hz and 1.1 Hz were thought to reflect local conditions, and to be so small that they could be ignored.

4. ESTABLISHMENT AND OPERATION OF THE NETWORK

Installation of the seismograph network proceeded in an incremental way so that the network could be adjusted on the basis of the observed character of ground response as the recording programme proceeded. On the basis of early analyses of the Parkway results it was anticipated that the total resonant response of the Wainuiomata system would be due to monochromatic waves traversing the axes of the two main Wainuiomata valley branches, at velocities of around 1 km/sec and wavelengths of around a kilometre, as well as the local vertical resonance. On this basis there would be no need for close (~ 100 m) instrument spacing to avoid spatial aliasing. However a note of caution was sounded by a theoretical analysis of Rayleigh waves propagating in the known geotechnical profile at the subsurface recording site. This analysis showed waves at 1.1 Hz, which would be the natural frequency for just the 22 m thick surface layer, travelling at a phase velocity of 300 m/s. This would demand a site spacing of 100 m to avoid spatial aliasing.

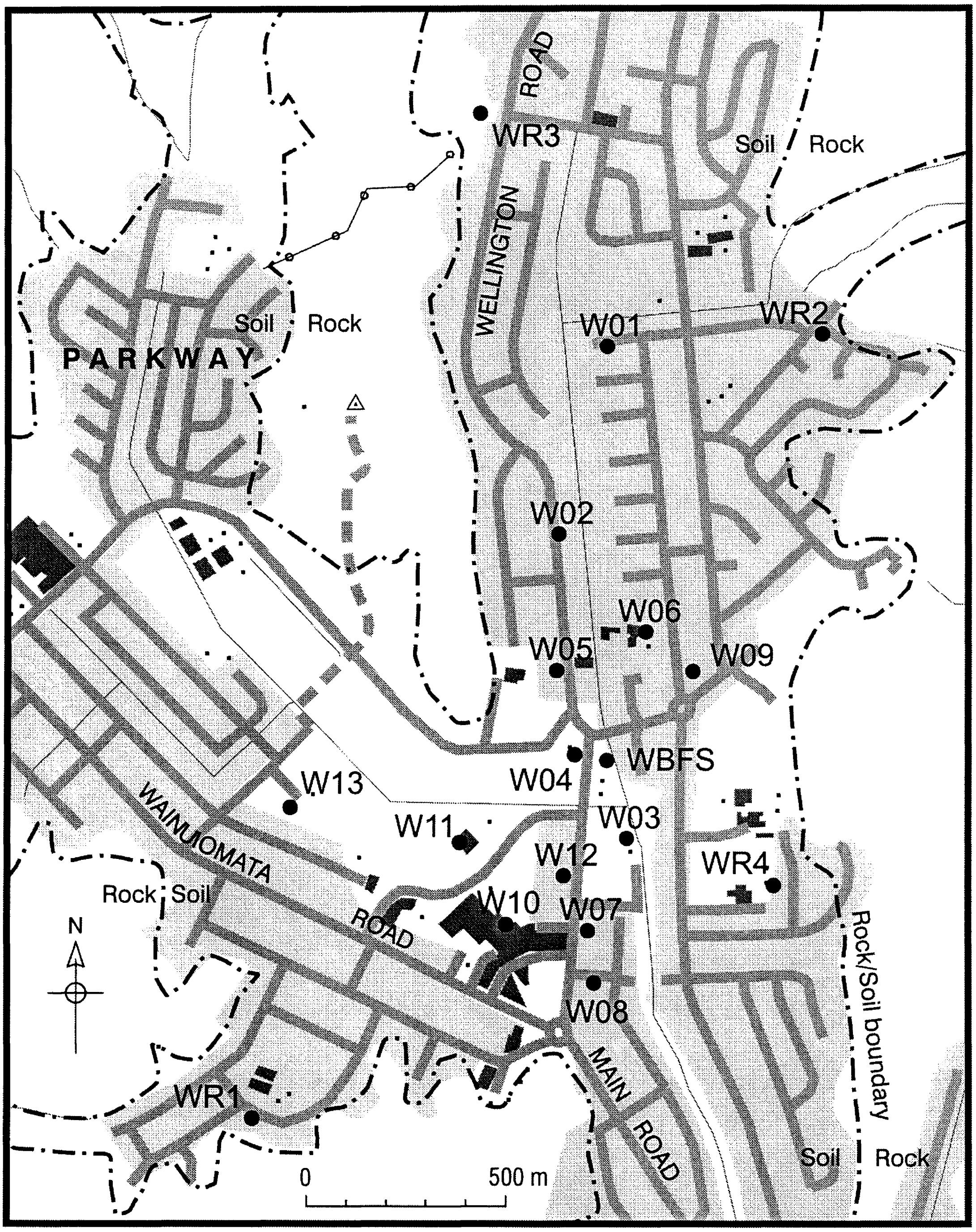

Figure 2. Layout of the Wainuiomata seismograph network. WBFS (Wainuiomata Bush Fire Station) is the vertical array of strong motion sensors, WR1, WR2, WR3 and WR4 are rock stations and the remaining stations are situated on soil. WR2 was withdrawn early due to operational requirements. Dot-dashed line marks the soil-rock boundary and the residential areas are shaded grey. An earlier seismograph network was operated in Parkway (top left).

Another uncertainty was that there were subtle differences in the natural frequencies indicated by Nakamura analysis of microtremors. Our initial approach was to install a single recorder (W01, see Figure 2) early, and to monitor it for an extended time. The earthquakes it recorded excited strong resonances at 1.1 Hz. After 5 weeks, a second recorder (W02) was installed 500 m to the south. In the course of a week it also recorded earthquakes that excited strong resonances at 1.1 Hz. Then in the course of three days we installed sites W03, W05, W06, W07 and W08 to complete a line down the valley in order to capture presumed up/down valley waves. Shortly after, W09 was also installed. It then became clear that a relatively small area around site W03 was associated with the original 0.8 Hz resonance, so sites W04 ,W10 and W11 were established in order to locate and characterise this small resonant area. At the same time rock sites WR1, WR2, WR3 and WR4 were established in order to characterise incoming wavefields. The WR2 installation was relatively short-lived due to a change of attitude by the person responsible for allowing us access to the site. Finally instrument W12 was installed to explore the centre of the resonant patch, and W13 was installed to confirm that the patch did not extend into the Parkway arm of the Wainuiomata system.

The locations of the recorders within the basin are shown in Figure 2.

This full system was left operational for a month. In that time 69 earthquakes were recorded at a high percentage of sites, including events ranging in magnitude from 1.4 to 7.6. Source depths ranged from 10 km to 685 km, and source distances ranged from 8.6 km to 2,280 km. On five occasions the strong motion recorders of the vertical array at the centre of the network (surface, 12 m, 22 m) all recorded the event. For one of these, event 1632935, the strong motion records were well above digitisation noise, and all 16 surface network instruments recorded the event as well.

5. GEOTECHNICAL INVESTIGATIONS.

We considered that an important part of any investigation in Wainuiomata would be a thorough characterisation of the linear elastic characteristics of the basin. Penetration tests which give the shear wave velocity profile already existed for a few sites, [21] and we plan to augment these in future. These existing measurements are in excellent agreement with the preliminary resonant frequencies seen at the soft soil sites.

6. INSTRUMENT TIMING, LOCATIONS AND ORIENTATIONS.

When carrying out studies of simultaneous recordings of earthquakes [13, 14] it is vital that the timings, locations and orientations of the recorders be known accurately. The EARSS recorders [25] used in the project were in the process of being changed from a dependence on the national radio time signals, to a GPS-based system, so that at any station the timing could be derived from either source. The accuracy of both systems was enough that absolute times of all records were known to within 10 milliseconds.

At the time of installation of the recorders most units were installed with their north sensing axes aligned along some obvious feature such as a building wall, so that later use could be made of surveying techniques in order to obtain accurate orientations. However sites W05, W07 and W08 were mistakenly oriented to magnetic north using a magnetic compass. While this is a valid technique to use in a rural area, suburban New Zealand tends to have many iron objects, which may not be obvious. Consequently the orientations of these stations may not be completely reliable. Subsequent to the operation of the network each site was visited with a hand held GPS station, and the orientation determined by walking along the line of the recorded feature and noting the direction of travel.

A hand-held gps receiver used in a stand-alone mode is not of sufficient accuracy for locating the instruments of an urban seismic network, so differential gps was used with respect to a known survey point. Repeat measurements using this technique gave readings to well within a metre of the original one. One gps unit was situated at a trig station, and radio linked to the other, which was taken in turn to a fixed point near each seismograph. The final distance and bearing from each fixed point to each seismograph was established by tape and compass, this step being needed because many of the seismograph locations were not in view of gps satellites.

7. RESULTS

It is our intention that the seismograms and supporting data will eventually be made widely available, but it is our preference that any initial data releases be in the context of collaborative work. This would allow the incorporation of local knowledge about a complex geological situation. There is a pressing need to understand the distribution and properties of the subsurface materials, and input to this area of investigation would constitute a sound basis for collaboration.

To date there has been little opportunity to analyse in any detail, the data which has been acquired. However it has been possible to carry out preliminary work on one earthquake in order to indicate the sort of result that we expect to obtain. The earthquake is GNS catalogue number 1632935 (also known as event 001030.163219 by its origin time and date), and is described as follows:-

Date	2000 OCT 30
Time	1632 19.10
Location	40.78S 175.00E
Depth	51.3 km
Local magnitude	5.2

Traces from each velocity seismograph are given in Figure 3, and traces from each strong-motion accelerometer of the vertical array are given in Figure 4.

Some key points of the basin response to this earthquake are evident on inspection of the records from a few of the stations. These are

- one soil station (W08) responds more like rock than soil (Figure 3)

- one rock station (WR4) has significantly less motion than the other rock stations (Figure 3)
- typical rock and soil recordings are quite dissimilar (Figure 5)
- at the resonant frequency of the valley, the soil still responds at a time when the rock motion has become small (Figure 6)
- about 20 seconds after s-wave arrival, a monochromatic, 0.85 Hz wave train starts to dominate the record from station W12 (Figure 7)
- assuming a southward-travelling wave, this monochromatic wave train has particle orbits which are prograde elliptical, with the major axis tilted down to the south (Figure 8)
- a theoretical dispersion curve for the site for a fundamental mode Rayleigh wave shows an Airy phase at 0.925 Hz, which has a group velocity of 66 m/s, phase velocity of 871 m/s, and a prograde particle orbit (Figure 9). An Airy phase is characterised by stationary values of group velocity with respect to frequency, and accordingly will often dominate a seismogram.
- the rock/soil interface is roughly 800 m to the north of site W12 (Figure 2) so that the Airy phase would take 12 seconds to travel from this interface to station W12
- the mode shape of an Airy-phase fundamental-mode Rayleigh wave is in agreement with the depth variation of resonant motion (Figure 10)

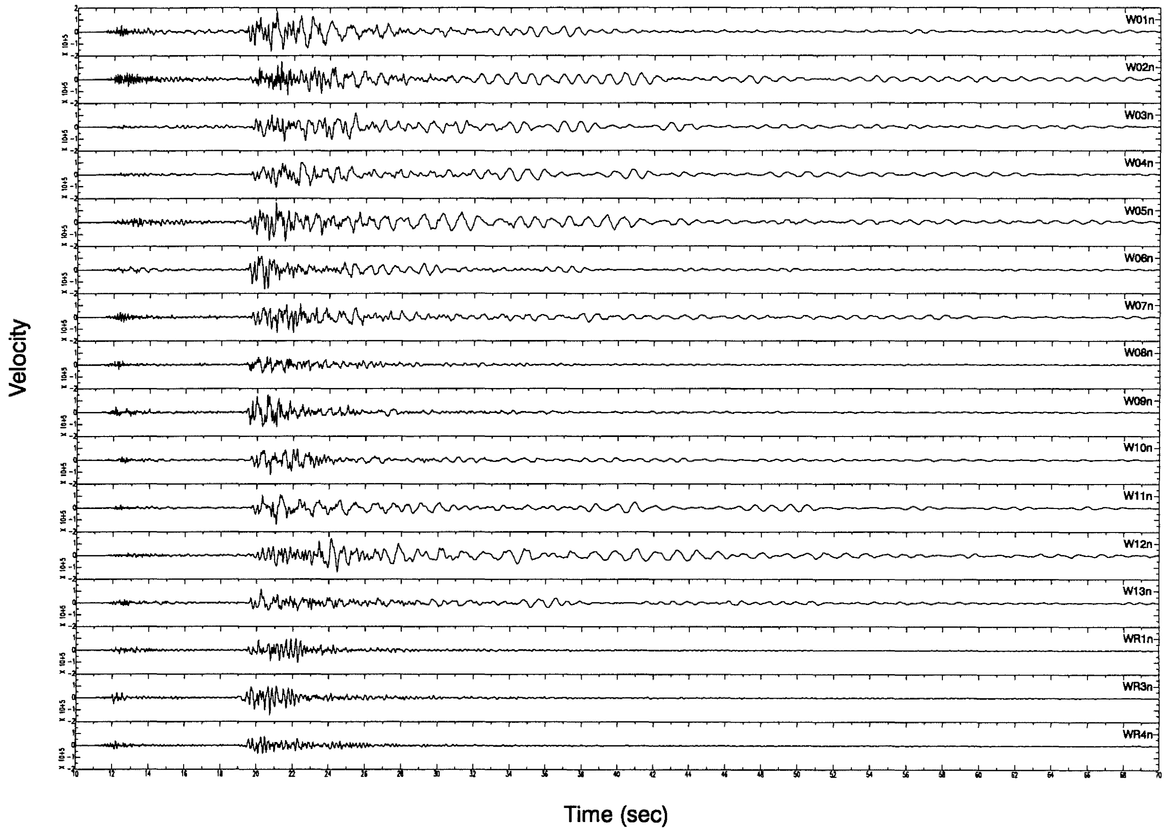

Figure 3. North velocity recordings on the surface recorders for a magnitude 5.2 earthquake, 50 km deep and 50 km distant. Note that the W08 record strongly resembles the rock records.

In the last three points mentioned above, an Airy phase Rayleigh wave is cited as a presumptive mechanism leading to the late resonance. In fact other possibilities exist, such as layer resonance or wave coupling between layers. Much more work is required before a definite mechanism can be assigned. The crucial point is that the frequency of 0.85Hz lies on a part of the dispersion curve characterised by low group velocities, and this is the underlying reason why the resonant response is delayed.

The waves described above are quite unlike those recorded by the Parkway network [14, 26] in that they are much slower, and have prograde rather than retrograde motion. The particle orbits involved may be quite unfamiliar to people who have not studied Rayleigh wave propagation in layers of soft soil, with the nearly horizontal particle orbits seeming at first sight more consistent with Love waves, but such Rayleigh wave orbits are what theory predicts and they have been used [27] to explain the peaks of Horizontal-to-Vertical Spectral Ratios of microtremors.

It should be borne in mind that even though the network recorded a magnitude 7.6 earthquake, that particular event was deep. In the time that the network was operational there was no instance of a shallow large magnitude earthquake close enough to be recorded at a significant number of stations. Thus the experiment could be deficient in data that shows, for example,

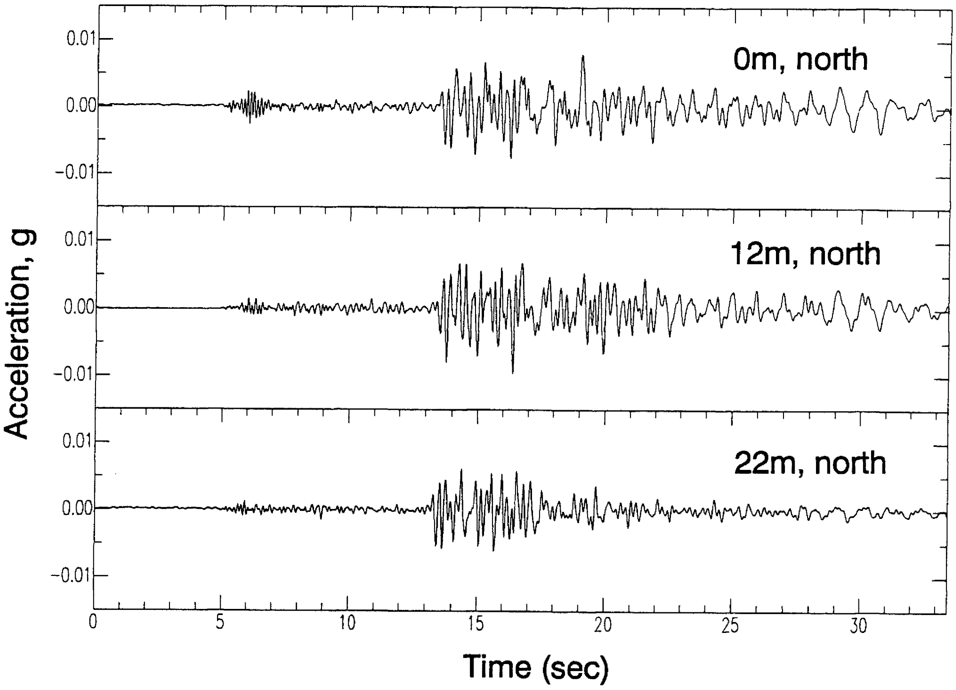

Figure 4. North acceleration records at the surface, at 12 m depth and at 22 m depth, for the earthquake shown in Figure 3. Note the fall off of long period (0.8 Hz) motion with depth.

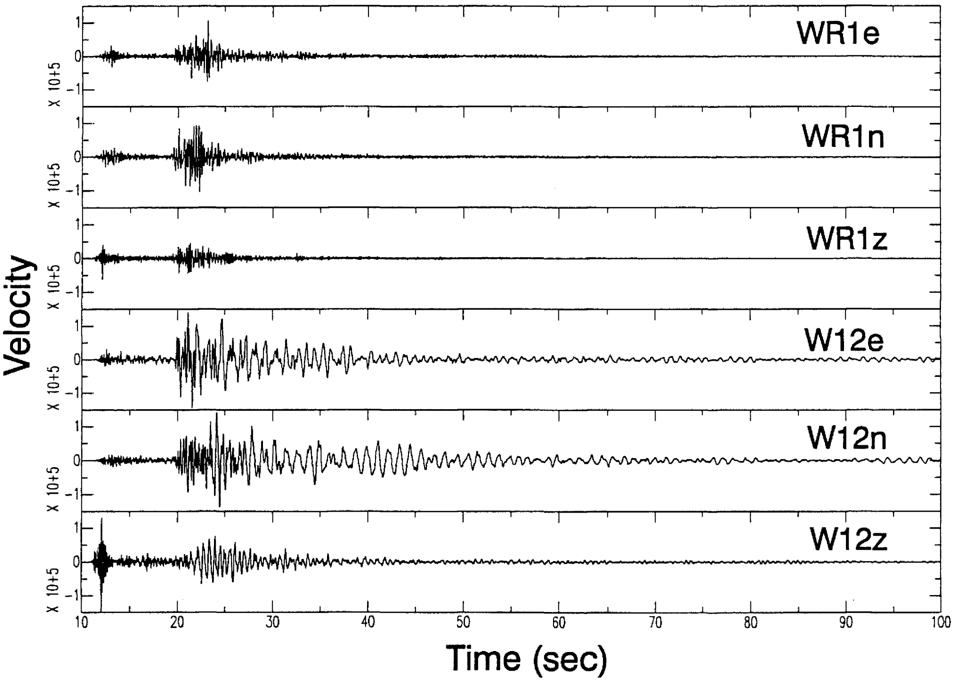

Figure 5. Rock and soil records for the earthquake shown in Figure 3. Note the magnification of 0.8 Hz horizontal motion on the soil, and its prolongation on the north component.

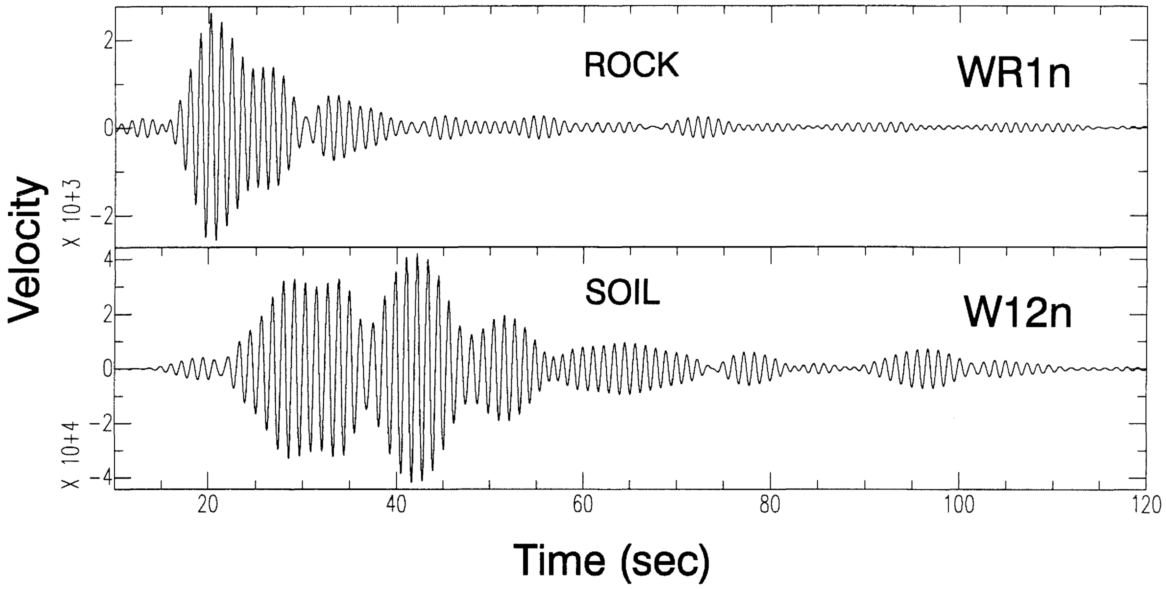

Figure 6. Rock and soil motions at site W12 for the earthquake shown in Figure 3, filtered around 0.8 Hz. The northerly rock motion is not the cause of the (northerly) resonant motion at site W12, because it is not present at 40 seconds.

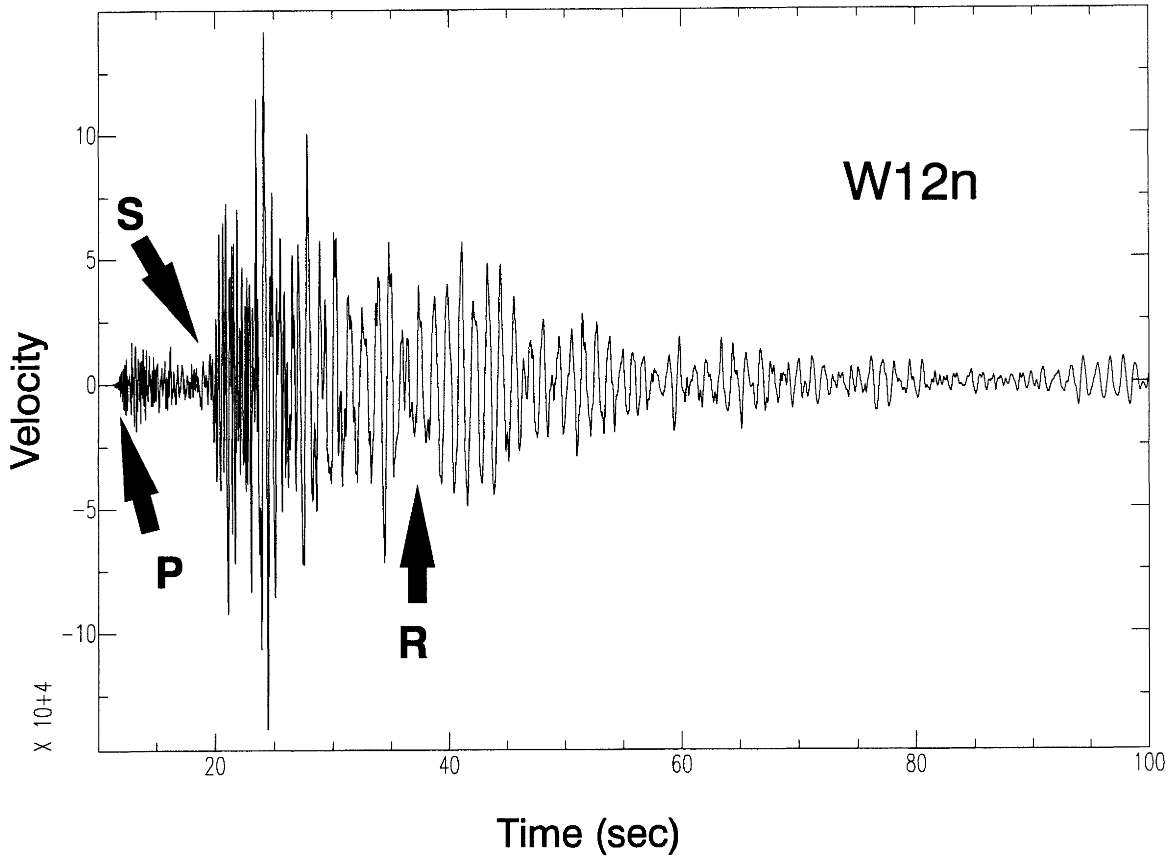

Figure 7. North soil motion for the earthquake shown in Figure 3. P-wave arrival is denoted by P, S-wave arrival is denoted by S, and R marks where a strong 0.85 Hz signal starts to dominate the recording after the s-wave arrival.

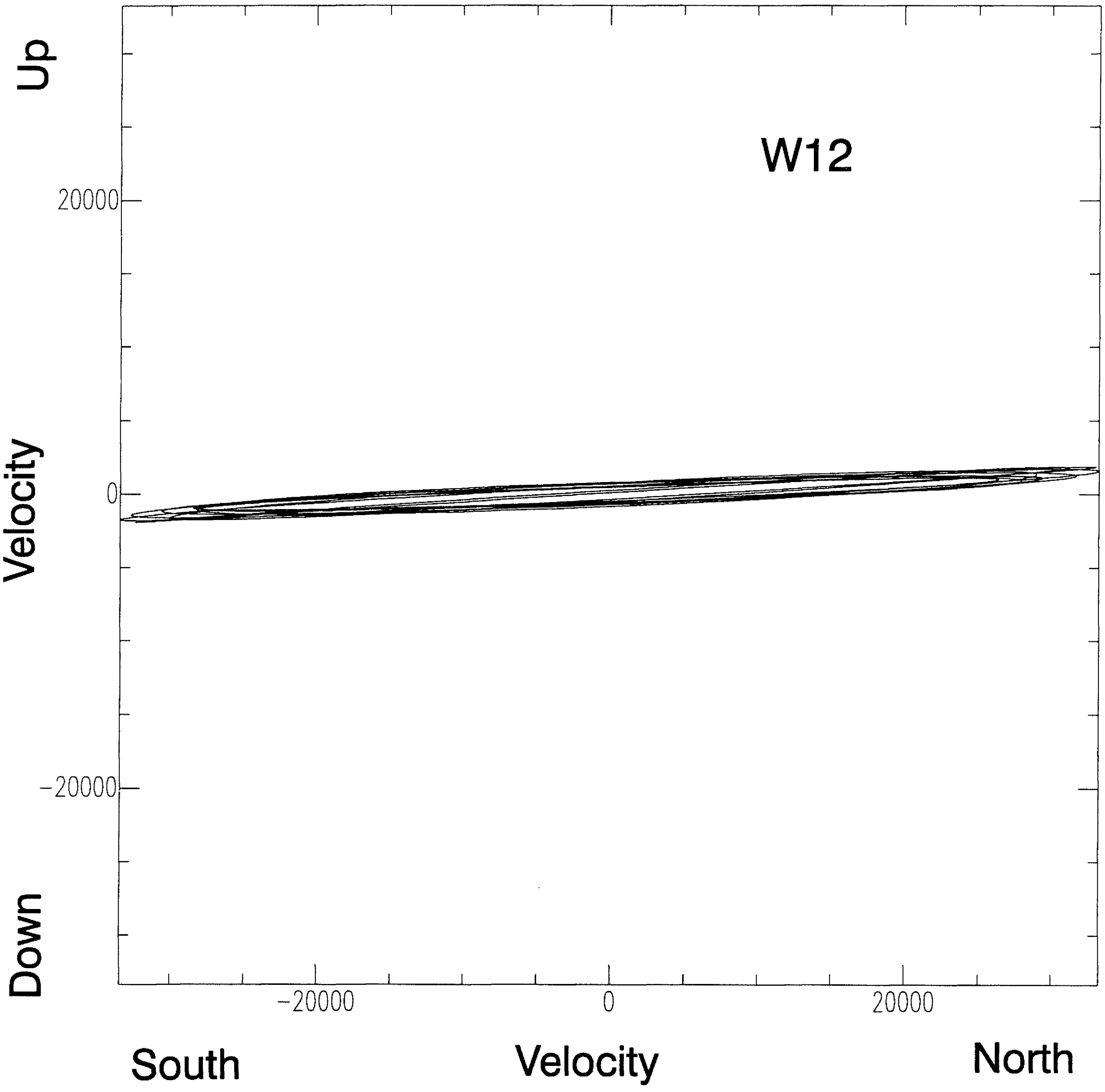

Figure 8. ***Particle motion at station W12 for the earthquake shown in Figure 3, from 40 to 60 seconds, filtered around 0.85 Hz, in the north/vertical plane. The motion is anticlockwise, corresponding to prograde motion for a south-travelling Rayleigh wave.***

the late excitation of the basin by crustal guided modes of the incoming wave. Such hypothetical excitation could be an alternative or additional explanation of late-occurring, monochromatic site response.

Our nearest approach to a large, shallow, distant earthquake was event 001101.103555, catalogue 1635267, magnitude 6.2, depth 9 km, distance 840 km, which was recorded at site W03 for 163 seconds, as well as at the rock site WR1. The soil record of this event has spectral peaks at both 0.9 Hz and 1.1 Hz.

8. CONCLUSIONS

The Wainuiomata "local effects" seismograph network gathered a wealth of data, which when combined with future geotechnical observations should significantly advance our empirical understanding of basin amplification, in particular the important issue of long duration monochromatic response. The Wainuiomata network complements the Parkway network rather than supersedes it because the types of waves recorded by the two networks are very different.

ACKNOWLEDGEMENTS

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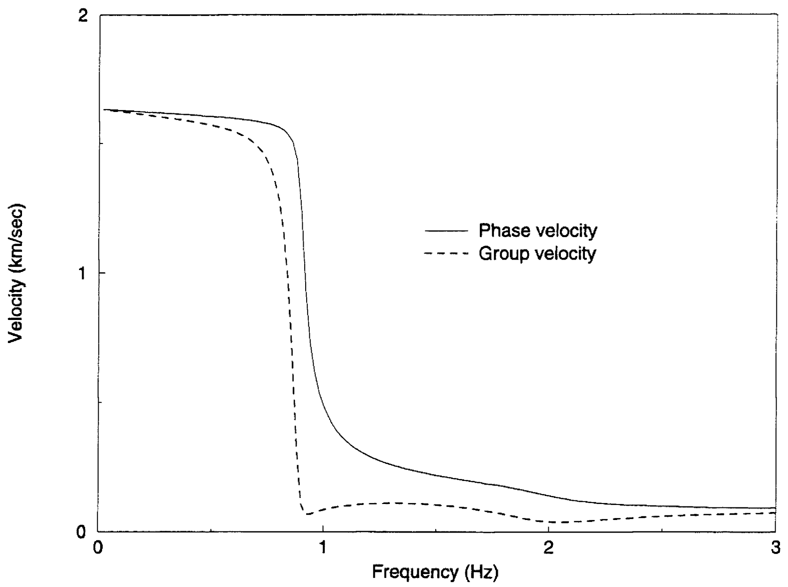

Figure 9. ***Theoretical dispersion curve for a fundamental-mode Rayleigh wave for a model based on measured and inferred site properties of the central part of Wainuiomata valley. Note that the group velocity has a low minimum of 66 m/s for the Airy phase. This velocity and the distance of the northern rock/soil boundary account for the delay before 0.85 Hz motion is seen at station W12 after 40 seconds.***

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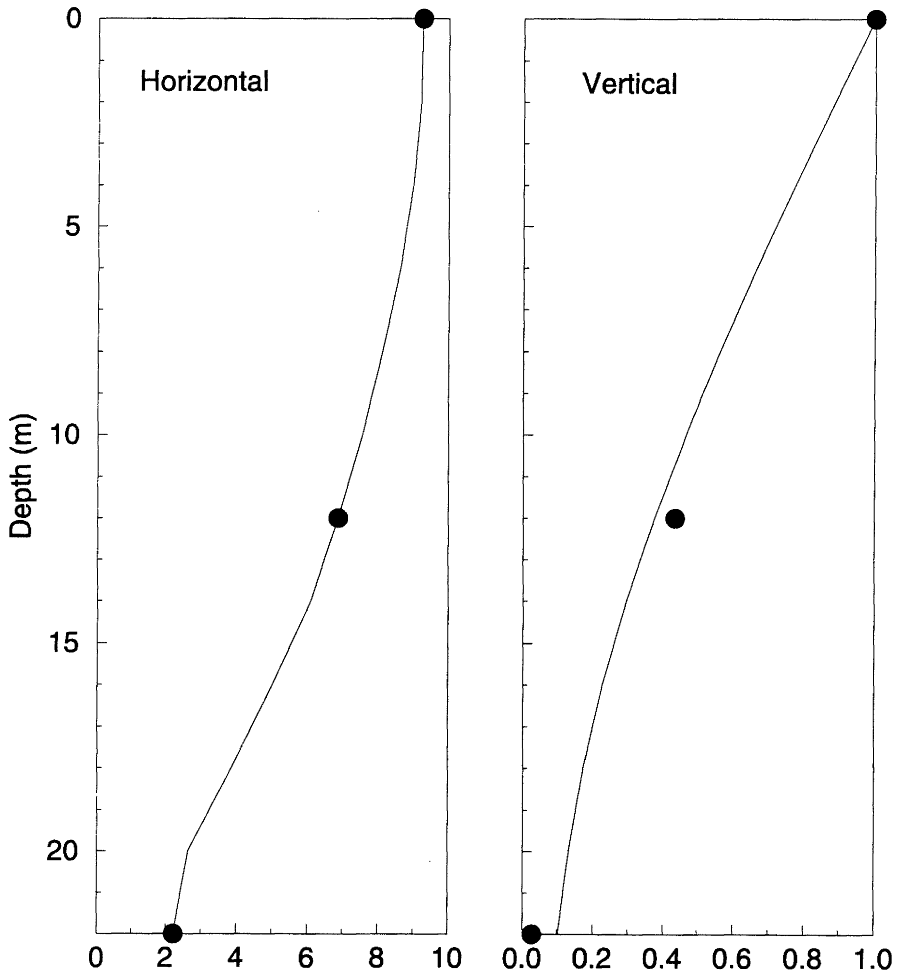

Figure 10. Theoretical mode shape curves for the 0.9 Hz Airy phase expected at site WBFS, together with the normalised spectral amplitudes measured at 0.85 Hz on the vertical array.

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