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EXPERIENCES FROM THE SEISMIC INSTRUMENTATION OF THREE SMALL SOFT BASINS IN NEW ZEALAND.

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ABSTRACT

In recent years three alluvial basins in the North Island of New Zealand, with dimensions of around 400 m and depths of a few tens of metres, have been densely instrumented with three-component velocity seismographs in order to investigate extreme site response to earthquake shaking. At each site a month of recording resulted in several tens of useful earthquake records. These recordings were supplemented with geophysical and geotechnical investigations.

Although all three basins were roughly equivalent in their size, depth and flexibility, their responses to earthquakes were strikingly different. Alfredton basin only amplified earthquake motion slightly, and no valley-wide resonances were evident. The Horizontal-to-Vertical Spectral Ratios of microtremors showed a low, broad peak. Parkway basin shows several valley-wide frequencies, which correlate with peaks in the Horizontal-to-Vertical Spectral Ratios of microtremors. These valley-wide frequencies are associated with large amplifications. Wainuiomata basin is composed of several distinct sub-basins each with its own resonant character. On the most evident sub-basin, Horizontal-to-Vertical Spectral Ratios of microtremors showed a single narrow, very high peak, as well as a trough at twice the frequency of the peak.

Keywords: Basin Array, HVSR, Resonance

INTRODUCTION

Although it has long been recognised that local soil conditions have a profound effect upon the amplitude and duration of earthquake shaking, it is only recently that the availability and pricing of instrumentation have allowed useful dense seismograph arrays to be implemented. Furthermore on a global basis the financial support offered to array projects has varied over the years as earthquakes have or have not shown strong site effects.

From a global perspective this has meant that prior to 1960 array instrumentation was prohibitively expensive; that the 1967 Caracas and the 1968 Manila earthquakes alerted politicians to the need for investigations into site effects; that the 1971 San Fernando earthquake with its lack of strong site effects dampened this imperative; and that the 1985 Michoacán earthquake reawakened the subject.

From a local perspective this has meant that an early attempt to construct an array in New Zealand (Stephenson, 1974) was curtailed after preliminary recordings; that a second attempt (Stephenson & Barker, 1991) was of limited value on account of inappropriate instrumentation; but that three subsequent arrays on other basins yielded useful data. In each of these three cases a basin with a strong valley-wide resonance was sought, but the Alfredton array (Stephenson, 1996) proved non-

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resonant and as a consequence the Parkway array was implemented. A casual inspection of initial seismograms and their spectra from Parkway suggested that valley-wide resonance was absent, and planning therefore started for the Wainuiomata array (Stephenson et al., 2002).The Wainuiomata array proved to consist of several sub-basins, each showing valley-wide resonance.

The locations of these three arrays are shown in Fig. 1, and this paper will describe each basin in turn, and summarise the essentials of the response of each.

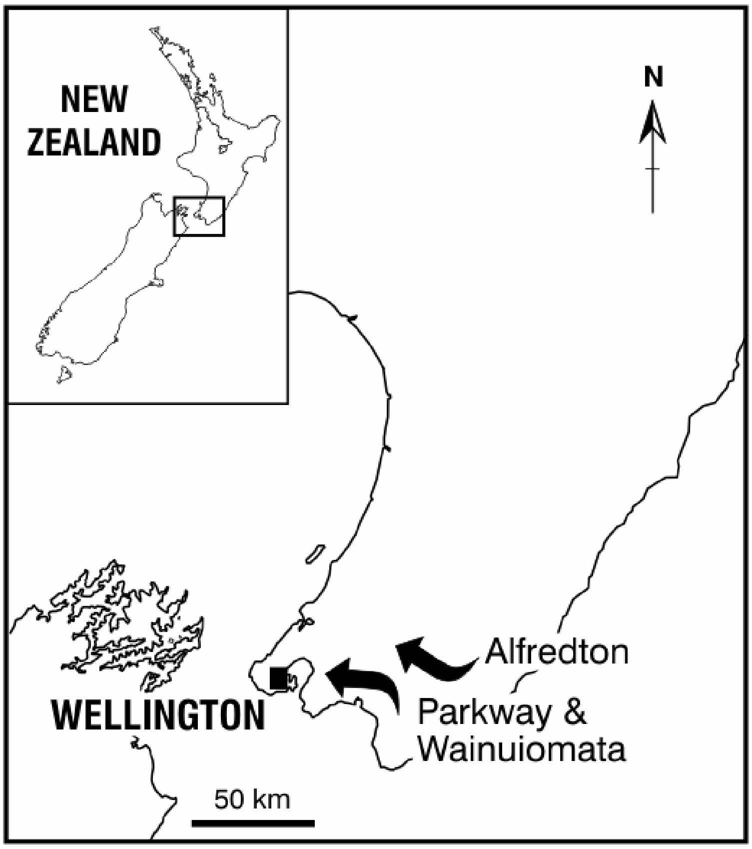

Figure 1. Locations of the Alfredton, Parkway and Wainuiomata temporary seismograph arrays. All three are on soft-soil basins. The centres of the Parkway and Wainuiomata arrays are separated by 1.6 km.

ALFREDTON

The Alfredton basin in the North Island of New Zealand was formed by periodic vertical offsets of the Alfredton fault which dammed the Ihuaura river, followed by subsequent sedimentation as described by Stephenson (1996). The centre of the soft material may be taken as the site A02, which is located at 40.6875° S, 175.8582° E. Seismographs were installed at sixteen soil sites and four rock sites. The soil stations were on a roughly rectangular grid. The material surrounding the basin is relatively soft mudstone, and ancient river paths have left a complex topography in the basement. Fig. 2 illustrates this by showing the different shear wave velocity profiles at two sites separated by 210 m.

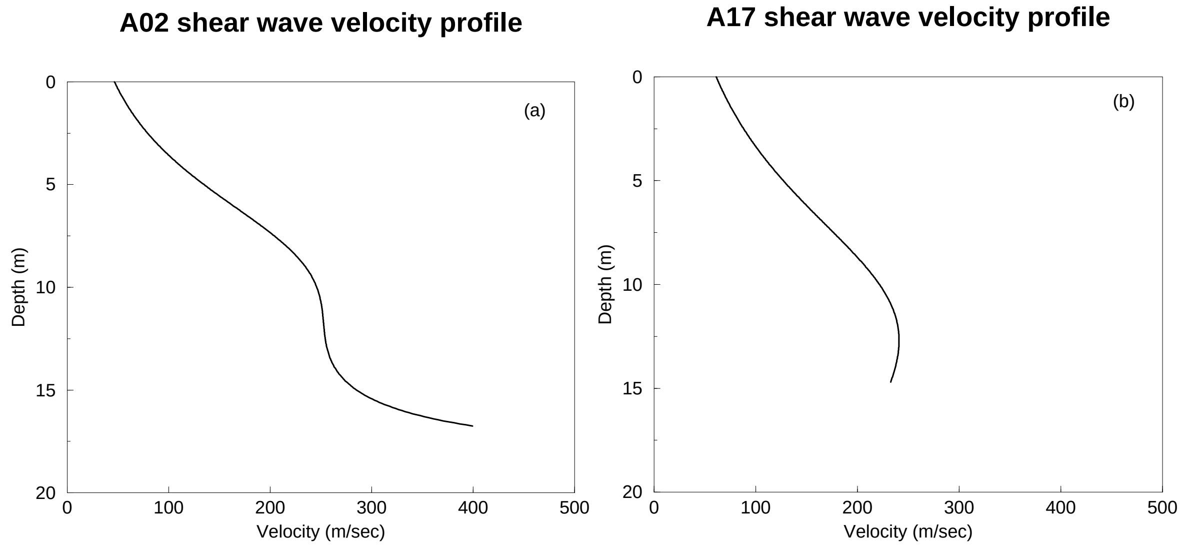

Figure 2. SCPT-derived shear wave velocity profiles at two soil sites of the Alfredton array.

The complex basement topography and the variable nature of the sediment combine to make infinite horizontal layering an inappropriate way of regarding the site, and this lack of horizontal layers ensures that the Horizontal-to-Vertical Spectral Ratios (HVSR) of microtremors do not indicate any site resonances as shown in Fig. 3a. In addition, the low impedance contrast between the sedimentary infill and the Tertiary mudstone basement ensures that energy cannot be trapped in the near-surface material. The seismic section of Fig. 3b shows no reflected energy travelling upward, which confirms this lack of trapping.

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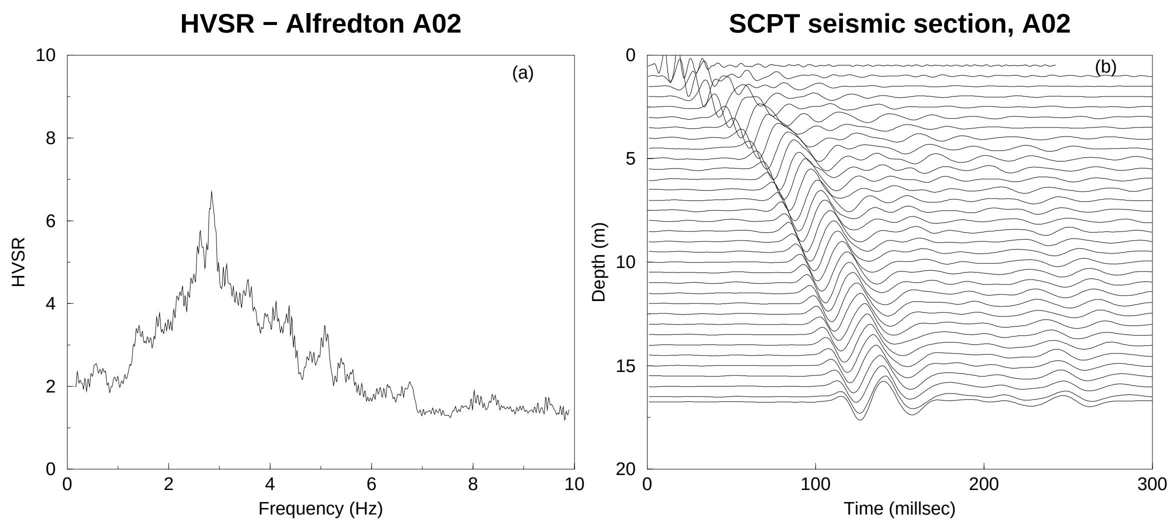

Figure 3. Alfredton basin. (a) microtremor HVSR (Nakamura ratio) showing no resonant peak; (b) SCPT seismic section showing no vertically-propagating reflected energy.

The Alfredton basin was chosen on the basis of its obvious flat alluvial nature coupled with an SCPT (Seismic Cone Penetration Test) probe that established the presence of 10 m of soil having a shear wave velocity of less than 200 m/s.

The Alfredton basin recorded earthquakes, geotechnical investigations, a simple model and sample seismograms and their spectra were given by Stephenson (1996). This report shows that the majority of the seismometers were placed on a regular rectangular grid, which was possible because of the rural nature of the area. The remote rural location also raised the spectre of vandalism which in the event did not occur, presumably because the landowner raised bulls on the property. Close liaison with the landowner allowed the earthquake-recording phase to be carried out just after grazing stock had been moved from the basin area to allow regrowth of the grass

Alfredton basin response

Despite its soft alluvial nature, the response of the Alfredton basin to earthquake shaking was significant but not large, and not resonant. Because the objective of setting up the array was to investigate a small resonant basin this lack of resonant response was seen as an experimental failure, but in fact the anomaly in response is worthy of investigation in its own right. The lack of a dramatic response has led to a paucity of analyses (Haines & Yu, 1997; Yu and Haines 1995).

Because Alfredton basin was investigated as being a candidate for valley-wide resonant response, but did not exhibit such behaviour, its potential importance regarding other soft-site effects was forgotten. Haines et al. (1994) point out that the Alfredton basin experiences amplifications only slightly greater than average New Zealand soil sites, suggesting that more extensive studies of amplification could be of limited value. However it is nevertheless a basin where other important effects could be studied.

Apart from amplification, soil sites exhibit relative displacements, which can be important contributors to the damage incurred by extended structures. Studying relative displacements at Alfredton, perhaps by examining coherencies between stations separated by varying distances, could be useful in this regard. Stephenson (1996) shows spectra that vary dramatically between adjacent soil stations at frequencies down to 1 Hz, suggesting that even at close spacings and low frequencies, coherencies will prove to be low. This in turn suggests the importance of relative displacements at Alfredton.

PARKWAY

The Parkway basin in the North Island of New Zealand was formed by the sedimentation of one arm of an ancient lake, with layers of alluvium and swamp subsequently being deposited over the lake deposits. The centre of the soft material is located at 41.2486° S, 174.9342° E. The layering of alluvium over soft clay has led to a velocity inversion in the infill material because the alluvium is significantly stiffer than the lake deposits. The basement material is relatively stiff greywacke, allowing the potential trapping of energy within the basin.

The Parkway basin was chosen because of its strong resonant response to earthquakes (Taber & Smith, 1992), coupled with microtremor HVSR values indicating that a substantial area of the valley responded in a resonant fashion as shown in the examples shown in Fig. 4a. Seismographs were installed at twenty soil sites on the basin and at four surrounding rock sites.

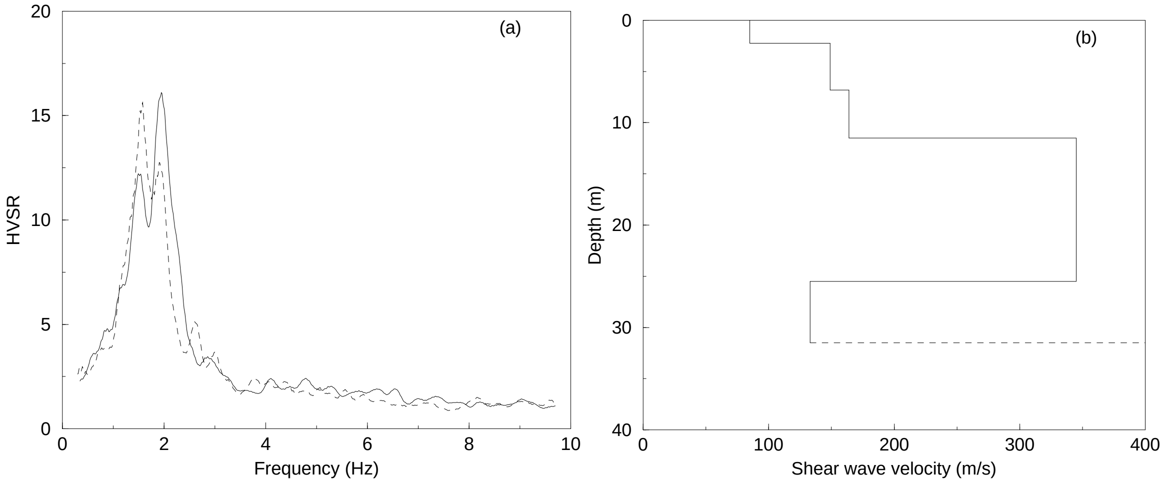

Figure 4. Parkway basin. (a)Horizontal-to-Vertical Spectral Ratios obtained at two sites within the experimental area eventually chosen. (b) Shear wave velocity profile for the basin. The profile of part (b) explains the lower-frequency peak of part (a), and the low velocity layer from 25.6 m to 31.5 m has its origin in soft organic clays laid down by an ancient lake.

Initial SCPT probes met refusal at around 14 m, and they implied a one-way shear wave propagation time of 79 ms, which is inadequate to explain the observed site resonant response at 1.6 Hz. It was deduced that a hard layer “floating” above true basement had caused penetrometer refusal, and that by drilling through that layer and filling the drill hole with bentonite, a better profile might result. The shear wave velocity profile shown in Fig. 3b was obtained in this manner, and is consistent with the observed site frequency. The procedure was expensive, and was complicated by a hydrostatic head of 4 m, which led to problems of sealing and of water-flow noise. As a result no further deep probes were made, and it is assumed on the grounds of the sedimentation process, and the strong site resonance, that the profile of Fig. 4b is representative of the resonant region.

The installation of the Parkway seismograph array was influenced by preliminary microtremor recordings which established a likely region where valley-wide response was likely to occur, by a limit on the number of available seismographs, and by constraints related to the urban nature of the area. Some property owners were unable to be contacted, a very few refused access, and those that agreed to an installation invariably nominated some outbuilding as the location. The result deviated considerably from the regular evenly-spaced rectangular array that was envisaged. However the eventual layout with its wide variation of inter-station distances was serendipitous in that it reduced spatial aliasing.

The installation of each seismograph in a secure private building conferred a great degree of security on the network, and vandalism was not a problem.

Parkway basin response

Of the three basins discussed in this paper, Parkway has attracted most attention because of its strong response and close station spacing.

In terms of spectral response the Parkway seismograph array recordings were consistent with the findings of Taber & Smith (1992). That is, all the soil stations displayed a resonant response at around 2 Hz. The first significant refinement of this finding was accomplished by summing normalised spectra from all the soil stations over several earthquakes (Stephenson & Chávez-García, 1998), and it established that valley-wide response occurred. Subsequent work (Stephenson, 2000) showed that the valley-wide motion was a manifestation of monochromatic waves, with transverse and longitudinal waves being present and traveling down-valley at different speeds. This was accomplished by narrow-band filtering, coupled with iterations of component rotation and wavenumber spectra evaluation, and was only possible because of the density of recorders and range of recorder spacings.

A later refinement (Stephenson, 2002) involved partitioning the vertical motion of these waves so that part was associated with the transverse wave and part was associated with the longitudinal wave. This analysis revealed that the longitudinal wave was in fact a Rayleigh wave, whereas the transverse wave resembled a Love wave except that the lateral boundaries enforced some vertical motion resulting in a "sloshing" motion propagating down valley.

The density of seismographs in Parkway together with the identification of valley-wide resonant phenomena has thus allowed the identification of guided waves traveling along the axis of the valley. In addition to the waves which were identified, valley-wide motion at another discrete frequency was noted, but was unable to be associated with waves in the same direct manner. This additional motion was investigated by using a visualisation technique (Stephenson, 2007). The movies associated with the visualisation, which show "cellular resonant modes" (Stephenson, 1975) may be viewed at http://data.gns.cri.nz/paperdata/paper.jsp?id=117653. These movies offer unique and valuable perspectives on the nature of basin response and the reader is strongly recommended to view at least Movie1. From the movies it is evident that (with the exception of the rotational response) the motion at 1.7 Hz has much in common with propagating waves, but further work is clearly needed in order for the basin response at 1.7 Hz to be fully understood.

Recent, as yet unpublished work (Liao et al., 2007) has drawn attention to the value of the Parkway data for evaluating relative displacement effects (which are important for extended structures). This was achieved by studies of coherency, and once again the range of station separations proved important.

The incorporation into the array of four rock sites surrounding the soft soil basin has allowed a study of reference sites to be undertaken (Yu & Haines, 2003). It found that the use of mean spectra from several stations reduces the variability of Standard Spectral Ratios.

WAINUIOMATA

The Wainuiomata basin was formed by the sedimentation of an ancient lake (Begg et al., 1993). It consists of several sub-basins which are not obvious at the surface, but which were revealed by geotechnical investigations (Barker & Stephenson, 2003). The centre of the main basin of soft material, site W03, is located at 41.2576° S, 174.9482° E. The long-established WBFS site also lies within this main basin. The Wainuiomata basin differs from the Parkway basin by virtue of its greater extent. This extent has prevented alluvial deposits, and the stratigraphy is infilled lake with upper layers of swamp. The Wainuiomata array consisted of sixteen soil-based seismographs and three on the surrounding rock

The Wainuiomata basin was chosen because for several years a strong motion accelerograph at the WBFS site usually recorded long duration monochromatic motion, with a particularly clear example being available from -
ftp://ftp.geonet.org.nz/strong/processed/Proc/1992/1992-05-27_223036/Vol1/plots/D92646A5.pdf.
Other recordings made at WBFS prior to the installation of the Wainuiomata array in the year 2000 are listed in Appendix A. Subsequent to the operation of the array a permanent rock-based accelerograph (ARKS) was established 1.6 km from WBFS and it has shown that the long durations are not present on rock.

In addition, an SCPT probe to 31 m, shown in Fig. 5b, established that two low velocity layers lay above the basement, quantitatively accounting for the monochromatic response, and microtremor recordings had HVSR values peaking at the same frequency as shown in Fig 5a.

Significant features of Fig. 5a are the large value of the peak at 0.77 Hz and the small value of the trough at 1.93 Hz. These imply that on the one hand large monochromatic amplification is expected at the site, and on the other hand that the microtremors, at least at 1.93 Hz and by association at other frequencies, consist mainly of Rayleigh waves. Love waves would be expected to always have large HVSR values as they consist of purely horizontal motion.

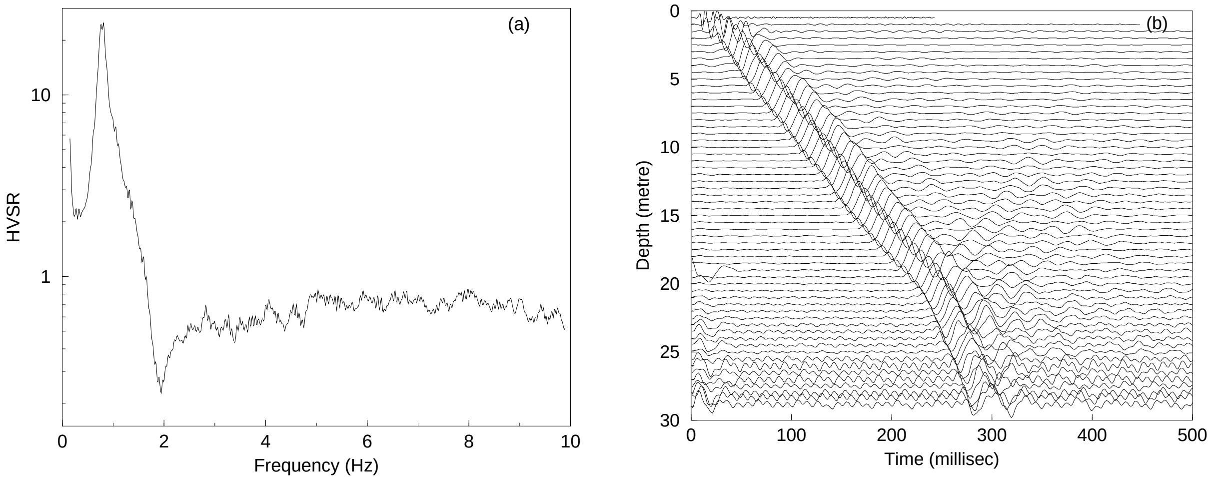

Figure 5. (a) Horizontal-to-Vertical Spectral Ratio values for microtremors recorded at the WBFS site. (b) SCPT-derived seismic section at the WBFS site. A 22 m thick layer of soil with a shear wave velocity of 90 m/s lies over a 9 m layer of soil with a shear wave velocity of 150 m/s. Energy is reflected from interfaces at 22 m and 31 m.

Prior to the operation of the Wainuiomata array it was realised that a knowledge of the details of subsurface motion is essential to understanding basin response. In particular the variation of particle orbit with depth is diagnostic of Rayleigh waves. The WBFS site in Wainuiomata was therefore augmented with sensors at 12 m and 22 m below the ground surface in order to clarify the nature of the monochromatic motion observed at the site. This was achieved by using penetrometry to install accelerometers based on Microelectromechanical Systems (MEMS) technology, a method which has now been patented. The value of such recordings may be seen in Fig 6 which shows an earthquake recorded during the array operation.

In these records the monochromatic signal after 28 seconds becomes smaller with depth, being virtually absent at 22 m (the bottom of the 90 m/s surface layer). Had the earthquake been larger and more distant, this phase would have been more dominant.

Installation of the seismographs of the Wainuiomata array proceeded in an incremental fashion in order that a developing understanding of the basin response could modify the layout in order to improve the usefulness of the data. In retrospect however, the information on sub-basins was present in the microtremor recordings, and it would have been better to have taken notice of subtle variations in microtremor-derived site frequencies when planning the array.

As was the case for Parkway, the installation of each seismograph in a secure private building conferred a great degree of security on the network, and vandalism was not a problem.

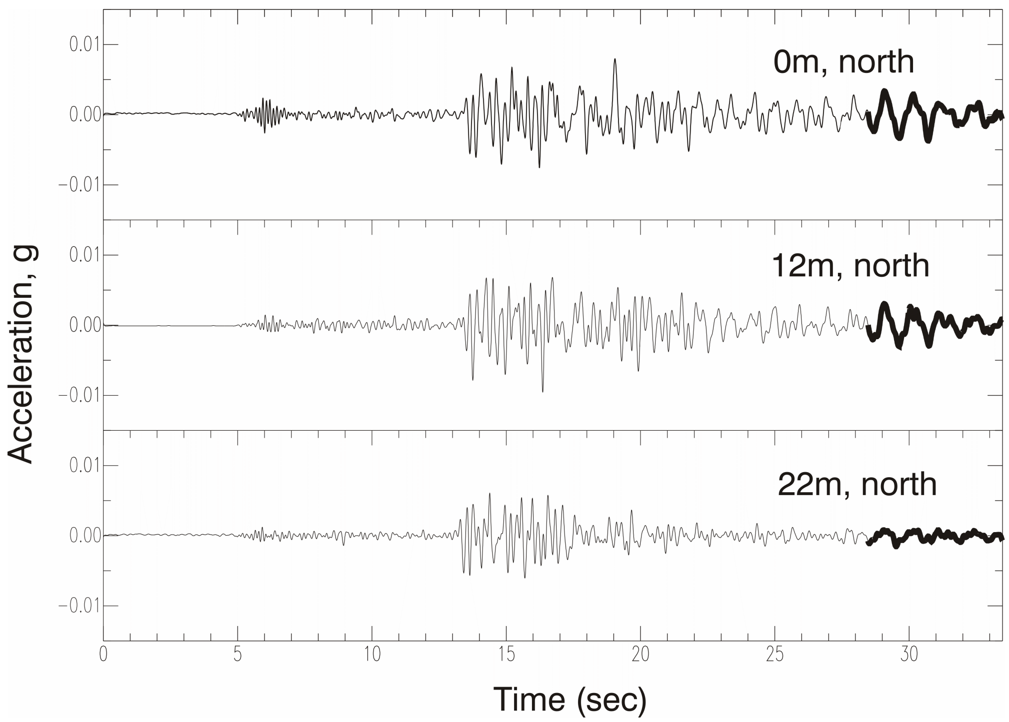

Figure 6. North components of accelerograms recorded at various depths below station WBFS near the centre of the Wainuiomata basin. The earthquake was of magnitude 5.2 and it occurred 50 km distant from WBFS at a depth of 50 km. Note the decrease with depth, of the monochromatic waveform (rendered bold) after 28 sec.

Wainuiomata basin response

An initial evaluation of the response of the main Wainuiomata basin, based on the array recordings, was presented by Stephenson et al. (2002). As was the case with Alfredton the seismograms have attracted little attention, but for different reasons. Unlike the Alfredton basin, the Wainuiomata basin responds in a dramatic fashion, with the soil motion being prolonged and monochromatic. However the extent of the Wainuiomata Valley and the supposition that it functioned as one resonant entity led to large spacings between the seismometers, and consequently each sub-basin had only a few recorders. This apparently ruled out the type of study that was possible for Parkway array recordings.

However it is possible that behaviour of the type seen at Parkway is present in the Wainuiomata data, but is masked by the sub-basin responses. A hint of this is seen in SSR values averaged over several earthquakes, because a small peak at 1.1 Hz is seen on many soil sites. It is possible that a valley-wide 1.1 Hz response due to the 22 m thick top layer of soft soil, may occur.

COMPARATIVE BASIN RESPONSES

Mean Standard Spectral Ratios (SSR) for all well recorded earthquakes at a site near the centre of each basin array are shown in Fig. 7. Averaging of spectra over all rock sites, and many earthquakes, ensured that the SSR curves were robust.

This evaluation of SSR gives a clear idea of the different responses of the three basins upon which the seismograph arrays were laid out. Standard Spectral Ratios are the ratios of spectra of earthquake motions recorded on soil and on rock. In the case of the basins it was considered best to choose representative stations near the basin centres so as to avoid basin edge effects.

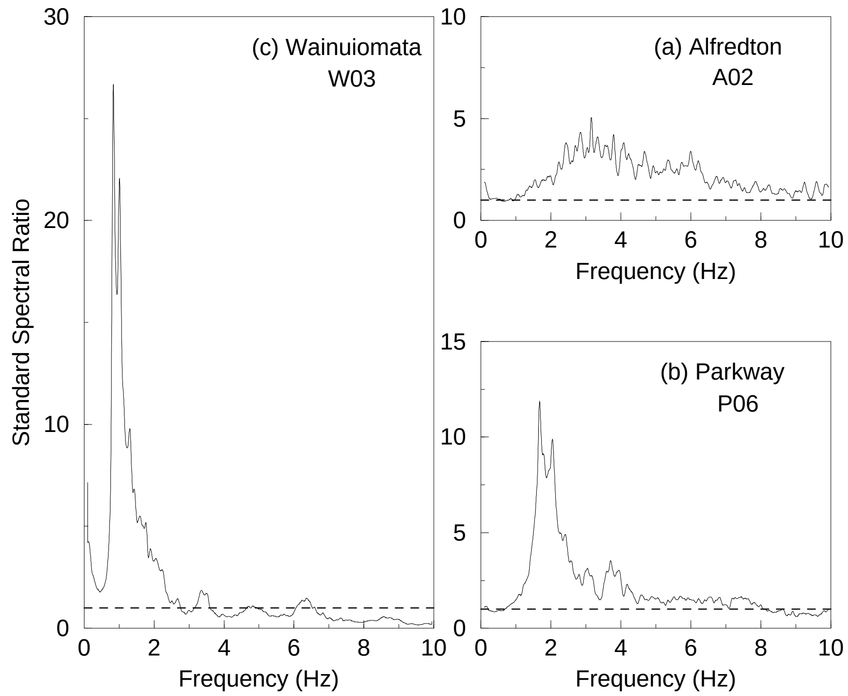

Figure 7. Mean values of Standard Spectral Ratio for a site near the centre of each basin array. The dashed lines specify an SSR of 1 and the vertical scales are the same for each plot.

Alfredton basin amplifies earthquake shaking to a small extent, over a broad range of frequencies. This is consistent with the shear wave velocities of the soil being low, but becoming progressively higher with depth until an eventual low contrast with bedrock velocity occurs.

Parkway basin amplifies earthquake shaking in a complex resonant fashion, with shaking at several frequencies being amplified to various extents. The frequencies being amplified are broadly consistent with what is known about the shear wave velocity profile.

Each Wainuiomata sub-basin amplifies earthquake shaking in a resonant fashion, with extreme amplifications at around 1 Hz. At these frequencies the shaking is greatly prolonged. At frequencies above 7 Hz, shaking is attenuated, with the layer of soft soil functioning as a low pass filter. The surface layer of soft soil, having an abrupt impedance contrast with deeper material is responsible for this behaviour.

LESSONS LEARNED

Dense temporary arrays of velocity seismographs can provide valuable insights into the responses of small basins filled with soft soil. In the short deployment times of a few weeks the earthquakes recorded were seldom felt – none for the Alfredton array, one for the Parkway array and one for the Wainuiomata array. Therefore the recordings only apply to low amplitude shaking, where the soil is expected to behave in a linear manner. However an understanding of linear response is a prerequisite to a full understanding.

As technology has improved it has become more feasible to record ground motion continuously. At the times that the three arrays of this paper were set up however, data storage was at a premium, and it became necessary to allow each recorder to operate autonomously, using preset criteria to determine whether a given data stream was worth recording. We used the STA/LTA method (ratio of short term average to long term average), with an overarching amplitude criterion in case of strong shaking of an emergent nature. This was because during the earlier phases of recording at Alfredton it was found that the signal on soft soil caused by a distant earthquake often rises slowly, and the STA/LTA approach can fail. Our approach today would be to record everything, to examine the recordings on a daily basis, and to reject non-earthquake data quite early on.

The establishment and operation of the Alfredton array, together with later recordings of microtremors, confirmed that microtremor recordings can be used to distinguish between resonant and non-resonant basins. Had microtremors been recorded and analysed prior to the Alfredton project, that array would not have been installed because a valley-wide response was being sought. In the case of the Parkway and Wainuiomata arrays, microtremor recording provided insights that both these areas would undergo valley-wide response. Microtremors played an important role in choosing these areas in preference to other areas simultaneously under consideration.

In terms of the analytical techniques employed, the varied inter-station spacings employed for the Parkway array were preferable to the regular grid of the Alfredton array or the large inter-station spacings of the Wainuiomata array. When a selection of inter-station spacings is used, spatial aliasing is avoided while at the same time both high and low wave speeds can be accommodated. In the case of studying the behaviour of coherency with distance a spread of inter-station distances enables a better spread of data points, better enabling relevant curves to be plotted. In respect of array layout, Parkway was superior to both Alfredton and Wainuiomata.

At Parkway four stations on the rock surrounding the basin were used. The same was not possible in Wainuiomata because one site owner withdrew consent at short notice a few days after recording had started. Four stations allowed better averaging of the rock signal, and potentially can be used to reconstruct the fronts of incident plane waves.

Seismic CPT proved an invaluable tool for characterising the basins, especially when the velocity inversion that is present at Parkway is considered. It was our intent for each basin to carry out a very few SCPT probes, and then to correlate any layers identified by CPT with known velocities. At Alfredton this failed because of the inhomogeneity of the sediments; at Parkway it failed because CPT probes were unable to penetrate a hard layer; and at Wainuiomata severe problems were encountered with groundwater because a deep aquifer carried water at high pressure and penetrometry to this depth resulted in flooding in urban parks, with attendant problems of sealing a high pressure leak.

The computation of spectra in the wavenumber domain, combined with frequency filtering and component rotation allowed complex propagation phenomena to be untangled, and simplex optimisation allowed vertical motion at Parkway to be partitioned between two waves. When this approach failed at one frequency, displaying the motion as a real-time movie was very instructive, showing the reality (but insignificance) of torsional types of response.

Much has been learned from studies of the three basins from the perspectives of both understanding basin response, and instrumenting basins. Nevertheless much still remains to be gained from further studies. At Alfredton the behaviour of coherency as a function of frequency and station separation remains unstudied, and a simple technique to predict the lack of valley-wide response needs to be devised. At Parkway a valley-wide resonant response at 2.05 Hz remains unexplained. For Wainuiomata there still exists a possibility of valley-wide response for the whole valley system including sub-basins. Summing normalised spectra over all soil sites and all earthquakes as accomplished for Parkway (Stephenson & Chávez-García, 1998) could be a useful way of investigating this.

ACKNOWLEDGEMENTS

The establishment and operation of arrays such as the three described, and the subsequent characterisation of the basin properties, are onerous tasks, and many of the staff at GNS Science have contributed to them. Those people are thanked for their work, but special thanks are due to Peter Barker who has been closely involved with all the basin projects, and Jiashun Yu, Fred Langford and Ray Maunder who did sterling work setting up and running the Alfredton and Parkway arrays. F. J. Chávez-García brought his understanding of wavenumber-based techniques, and of R. B. Hermann's wave analysis software, to the Parkway project, and contributed his extensive knowledge of wave propagation in general. His support and guidance leveraged a commonplace dataset into useful results. The use of SAC (Seismic Analysis Code) from Lawrence Livermore National Laboratory is gratefully acknowledged.

APPENDIX A

The following seismograms from site WBFS recorded prior to 2000 show the resonant nature and long duration of ground motion commonly observed.

ftp://ftp.geonet.org.nz/strong/processed/Proc/1991/1991-07-12_044224/Vol1/plots/D91646A1.pdf
ftp://ftp.geonet.org.nz/strong/processed/Proc/1991/1991-09-08_135032/Vol1/plots/D91646A2.pdf
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