MODELING SITE EFFECTS IN THE LOWER HUTT VALLEY, NEW ZEALAND

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SUMMARY

Lower Hutt City lies atop a wedge of Quaternary sediments forming a long alluvial valley. On its western edge the sediments butt up against the near vertical wall of the potentially active Wellington Fault, capable of an earthquake of moment magnitude 7.6. A two-dimensional linear finite-element method has been used to model the propagation of antiplane SH waves within the soft sediments and surrounding bedrock. The technique has proved to be an efficient and accurate means of modeling fine geological detail. Two detailed geological cross-sections through the Lower Hutt were modeled to gain an overall impression of the valley's seismic behaviour. It was found that horizontally propagating surface waves, generated at the valley edges, are the cause of significant amplification. The aptly named basin-edge effect – speculated to be the cause of a belt of severe shaking during the 1995 Kobe earthquake – is observed in the simulation results, occuring some 70-200 metres out from the fault. Fourier spectral ratios across the valley indicate a behaviour dominated by two-dimensional resonance, and compare favourably in magnitude with previously collected weak motion data. Certain resonant frequencies within the range 0.3-2.5 hertz are amplified up to 14 times that for nearby outcropping bedrock. Results are likely to be conservative due to the linear modeling, yet exclude fault-rupture effects due to the teleseismic nature of the input scheme.

INTRODUCTION

In this paper we describe our use of a two-dimensional finite-element numerical scheme to simulate ground motions from earthquake shaking in the soft sediments in-filling the Lower Hutt Valley. Lower Hutt City is situated at the southern tip of the North Island, New Zealand, and is home to 96,000 of the 340,000 people living in the Wellington region. Around 57,000 of these reside on the ~35 km2 of flat land created by ~400,000 years of sedimentary deposition within the valley. The Lower Hutt Valley (Fig. 1) is approximately 12 km long with a maximum width of 4.5 km. It slopes and widens gently from Haywards south-west down to the foreshore of the Wellington Harbour, dropping only 30 metres in elevation. The alluvial and marine sediments extend to a maximum depth of 300 metres in the south-western corner, adjacent to the Wellington Fault which forms a clear lineation along the true-right of the valley.

The Wellington Fault is one of a number of active strike-slip faults in the highly tectonic region situated above the shallow subduction interface between the Pacific the Australian Plates. Paleoseismic studies indicate characteristic-style events on the faults in the area, with the Wellington Fault likely to produce a magnitude (Mw) 7.6±0.3 earthquake within the next few hundred years [Van Dissen and Berryman, 1996]. This threat has lead to significant interest in the seismic behaviour of the Lower Hutt basin.

Similar sedimentary basins have historically been sites of significant damage in earthquakes. The 1995 Hygoken-Nambu earthquake in Kobe was characteristed by a band of intense damage inside the Osaka basin and parallel to the fault. It was later identified as a result of both the basin-edge effect [Kawase, 1996] – caused by the constructive interference between horizontally propagating surface waves, and body waves travelling vertically through the sediment – and near source effects such as directivity [Pitarka et. al., 1998]. A similar band of damage occuring in Santa Monica, CA, during the 1994 Northridge earthquake has also been attributed to the basin-edge effect [Graves et. al., 1998], this time occuring independantly of forward directivity. Physical

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similarities between Lower Hutt and the Osaka Basin at Kobe, especially the presence of the Wellington Fault forming an almost vertical wall to the sediments, has lead us to investigate the possibility of the basin-edge effect occuring here.

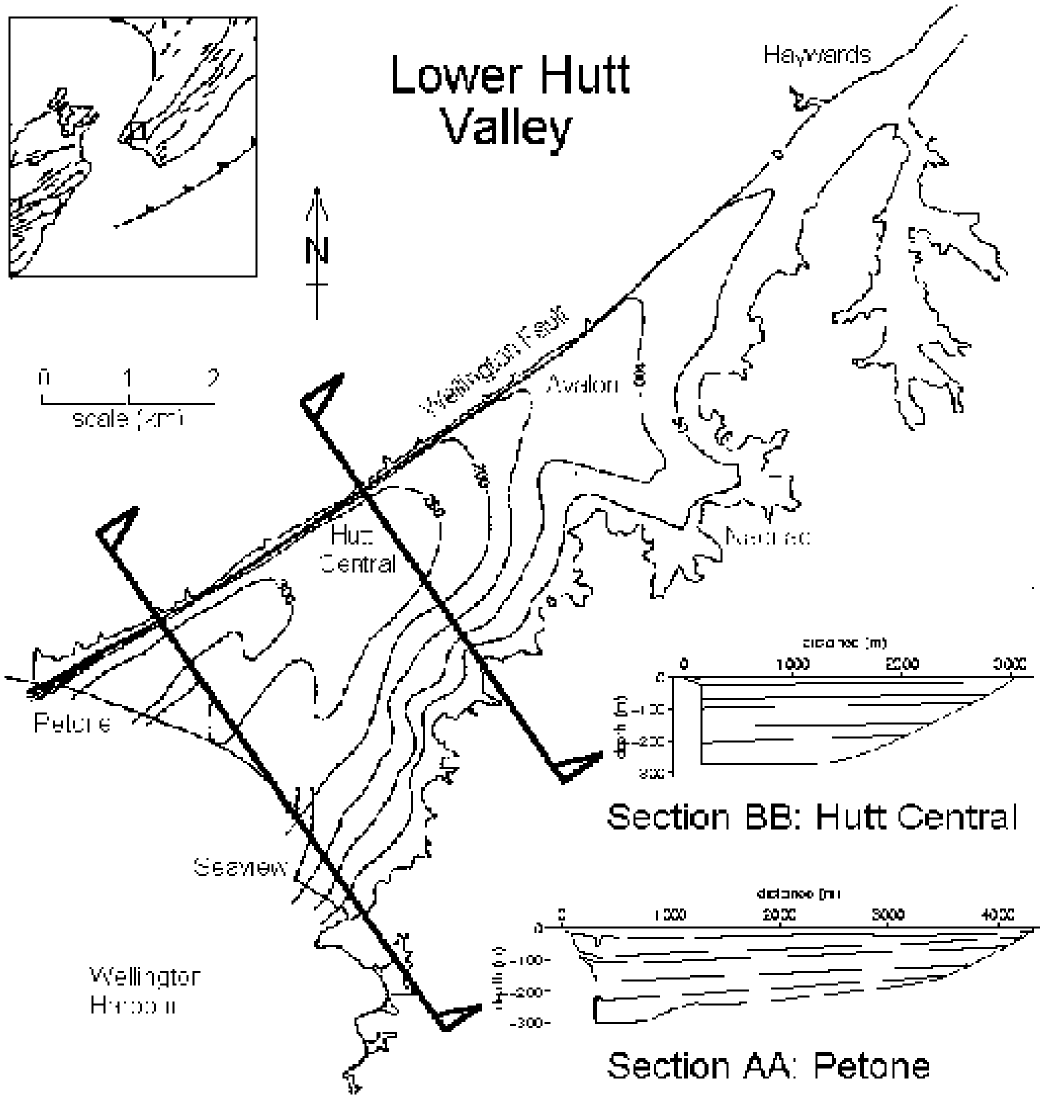

Figure 1: Map of the Lower Hutt Valley extending southwest into the Wellington Harbour. The valley is 12km long and 4.5km wide. The vertically dipping Wellington fault extends up the north-western edge of the valley. Depth-to-bedrock contours and geological cross-sections through the valley are also shown.

Several studies have been conducted looking at the frequency-dependant amplification found in recorded data from the Lower Hutt. To date, the only records available are for ground motions with PGA's between 0.0005g [Taber et. al., 1993] and 0.15g [Stritharan and McVerry, 1992], originating from a wide range of hypocentral locations. Amplification of shaking appears to increase gradually from Haywards to the Petone foreshore. Fourier spectral ratios in the deepest part of the valley reach peak values of 10-14 [Stritharan and McVerry, 1992; Taber and Smith, 1992]. Amplification at most sites occurred over a broad frequency band from 0.5 to 5.0 Hz, while for strong motions, the deep sites had a greater low frequency response, and the shallow edge sites had a greater high frequency response. In general, the highest spectral peaks occur in the 1 to 3 Hz range. Unusually located peaks from some earthquakes suggested the influence of two, or even three-dimensional site amplification. The exclusive availability of only relatively weak-motion records places questionable limitations on the applicability of these results to the estimation of strong shaking, although their usefulness for correlation with elastic modeling is nonetheless highly valuable.

GEOLOGICAL MODELS

Two-dimensional geological cross-sections through the Lower Hutt (Fig. 1) were constructed from existing borehole and gravity data. The deep bedrock-sediment interface is defined by contours from a gravity survey [Dellow et. al, 1992] and constrained by three boreholes extending down to the soil-bedrock interface. The sedimentary columns are described from borehole data [Dellow et. al., 1992; N.D. Perrin, pers. comm.] which is abundant across the width and length of the valley to a depth of 30 metres or more.

Table 1: Properties and descriptions of the basement rock and sedimentary units of the Hutt Formation.

Layer	Descriptor	S-wave velocity V_s (m/s)	P-wave velocity V_p (m/s)	Poisson's ratio ν	Density ρ (kg/m^3)	Shear modulus μ (10^6N/m^2)	Lame's constant λ (10^6N/m^2)	Elastic modulus E (10^6N/m^2)
A	Post-European loose rock and hydraulic fill	100	444	0.473	1750	18	309	52
B/Bb	Post glacial Holocene marine sands, silts and gravels	175	776	0.473	1750	54	947	154
C	Last Glacial gravels and sands with some clay	285	1264	0.473	1800	146	2584	431
D1	Last interglacial gravels, sands and silts	325	1441	0.473	1850	195	3453	573
D2/3	Glacial and interglacial poorly-consolidated sediments	460	2040	0.473	1900	402	7104	1186
D4/5	Glacial and interglacial stiff sediments	600	2661	0.473	1950	702	12405	2068
D6	Late Quaternary weathered and undifferentiated seds	675	2994	0.473	2000	911	16102	2685
E	Lithified, fractured basement greywacke (Torlesse Complex)	1500	3489	0.387	2700	6075	20711	16847

The Hutt Valley sediments have been idealised into six homogenous units, each denser and stiffer than the one above. The actual sediments are in fact highly anisotropic and inhomogeneous and are not so clearly defined into separate layers as the model assumes. Greywacke bedrock in the Wellington region is also far-from-ideal, being highly fractured, especially in the fault-parallel direction, and variably weathered. Material properties and descriptions of the rock and sedimentary units used in the modeling are shown in Table 1. Damping in the soil has been assigned a ratio of 2% of critical ($Q \approx 25$).

The cross-sections were taken at an angle perpendicular to the north-western edge of the valley to align the out-of-plane axis in the long-valley direction, along the trend of the Wellington and other strike-slip faults in the area. Two models were constructed; one along cross-section AA though Petone and Seaview at the widest point of the valley and one along cross-section BB through Lower Hutt Central (Fig. 1). The limiting condition on the geometric complexity of each model was the accuracy of the existing geological data. Boundaries between deeper sedimentary units have been in the main interpolated from only a few points.

NUMERICAL SIMULATIONS

We use the finite-element software package, Archimedes [Bao et. al., 1996], developed at Carnegie Mellon University as part of the National Science Foundation Grand Challenge Quake Project. Finite element methods allow the use of elements of differing sizes and proportions to give a high degree of geometric detail. Node spacing can be tailored in proportion to the local shear-wave velocity to give similar numerical accuracy and high computational efficiency throughout the geometry of the problem. Thus for problems such as ours, with shear-wave velocities differing by as much as a factor of 15 (100m/s and 1500m/s), large reductions in computation requirements can be made. Elements have been sized to allow for the simulation of seismic waves up to six Hertz. Our 2-D Archimedes simulations were run on a single 512MB machine operating Digital UNIX with a processing time between 12 and 18 hours.

The input motion was a single vertically propagating Ricker wavelet in the form of an anti-plane SH pulse. For the case of a Wellington Fault rupture, most of the energy is likely to be released from a depth of the order of 10km, well outside the computational domain. Thus the method of seismic input used is that developed by Bielak and Christiano [1984] and Cremonini et. al. [1988] whereby the excitation is applied along an arc of finite elements just inside the absorbing boundary. The time of excitation of each node on the arc is adjusted so to represent a horizontal wavefront starting simultaneously over the width of the mesh.

RESULTS

We first describe the transient response of the ground surface due to the incident plane Ricker pulse. Closely spaced nodes on the surface allow us to present results as a continuous function of both location and time. Using this approach we can visualise both the arrival of body-waves through the medium, and the paths of surface waves along the ground. Several significant peaks in maximum displacement are noted across the width of the valley. In the frequency domain, spectral amplification resulting from the geological structure of the cross-sections is presented as Fourier spectral ratio (FSR), also plotted as a continuous function of position and time, a technique proved useful for viewing resonant behaviour in the sediments and the associated patterns of surface amplification. Throughout this section we will look at the results of the two models side-by-side in order to gauge a general picture of the valley as a whole.

Time Domain Response

In Fig 2a, seismograms have been plotted close together on a position-time axis for each cross-section. The first motion on the seismogram occurs in the rock to either side of the valley (at t~1.3s). Free-surface doubling gives it an amplitude of twice the input, as it is reflected back down into the model to be removed by the absorbing boundary. In contrast, softer sediments in the valley delay the arrival of the Ricker pulse and amplify both the duration and intensity of shaking.The first arrival at the surface creates an inverted picture of the basin shape, and subsequent reflections between the free surface and the bottom of the basin lead to later arrivals that also mimic the basin shape with lower amplitude pulses. The first of these reflections returns to the surface approximately one second after the first arrival.

A most distinctive feature of the transient response is the generation of surface waves (commonly called edge-waves) from each side of the valley. In this case, the anti-plane nature of our modeling requires that they be Love waves. They appear to be highly dispersive, with group velocites (taken from the slope of a line joining the highest amplitudes in the wave train) of 175 and 240 m/s, and phase velocites (the slope of travelling wave peaks) between 240 and 520 m/s. In section BB, vertical resonance in a soft layer on the western side generated a number of edge waves at regular time intevals. Edge waves significantly add to the duration of the record, especially in the central regions of the valley. They are intially of quite high amplitude yet attenuate rapidly as they travel across the basin.

On both models in Fig. 2b we see three distinct locations where ground motions are highly amplified; the first two being close to each edge, and the third a few hundred metres in from the valley's western side. The peaks at the valley edges appear to be caused by vertical resonance in the shallow sediments. The third peak, however, is the site of the largest displacement. It occurs during the initial arrival of the Ricker pulse through the sedimentary basin, and appears to be a clear example of the basin-edge effect [Kawase, 1996]. It can be seen in Fig. 2a to occur at the point of contact between a horizontally propagating edge wave, and the first arrival of the Ricker pulse through the sediment.

Frequency Domain Response

Fourier spectral ratio has been plotted to form a continuum with across-valley position in Fig. 2c. The FSR is a measure of the Fourier amplitude normalised against that recorded on a nearby rock site. In this way we see exclusively the effect of the sedimentary basin. Thus we see that FSR in the rock to each side of the basin is approximately unity, as expected. Within the valley, however, FSR ranges between 1 and 14, being highly dependant on both frequency and position. Widespread amplification occurs across the valley roughly within the range 0.4 to 3.5 Hz, and in a pattern indicative of two-dimensional resonance [eg. Bard and Bouchon, 1985]. The first four vertical modes – each with a corresponding set of horizontal modes – can be recognised, occuring at approximately 0.5, 1.1, 1.7 and 2.3 Hertz. On the whole, eigenfrequencies in Lower Hutt Central are generally 5% to 20% higher than those in Petone.

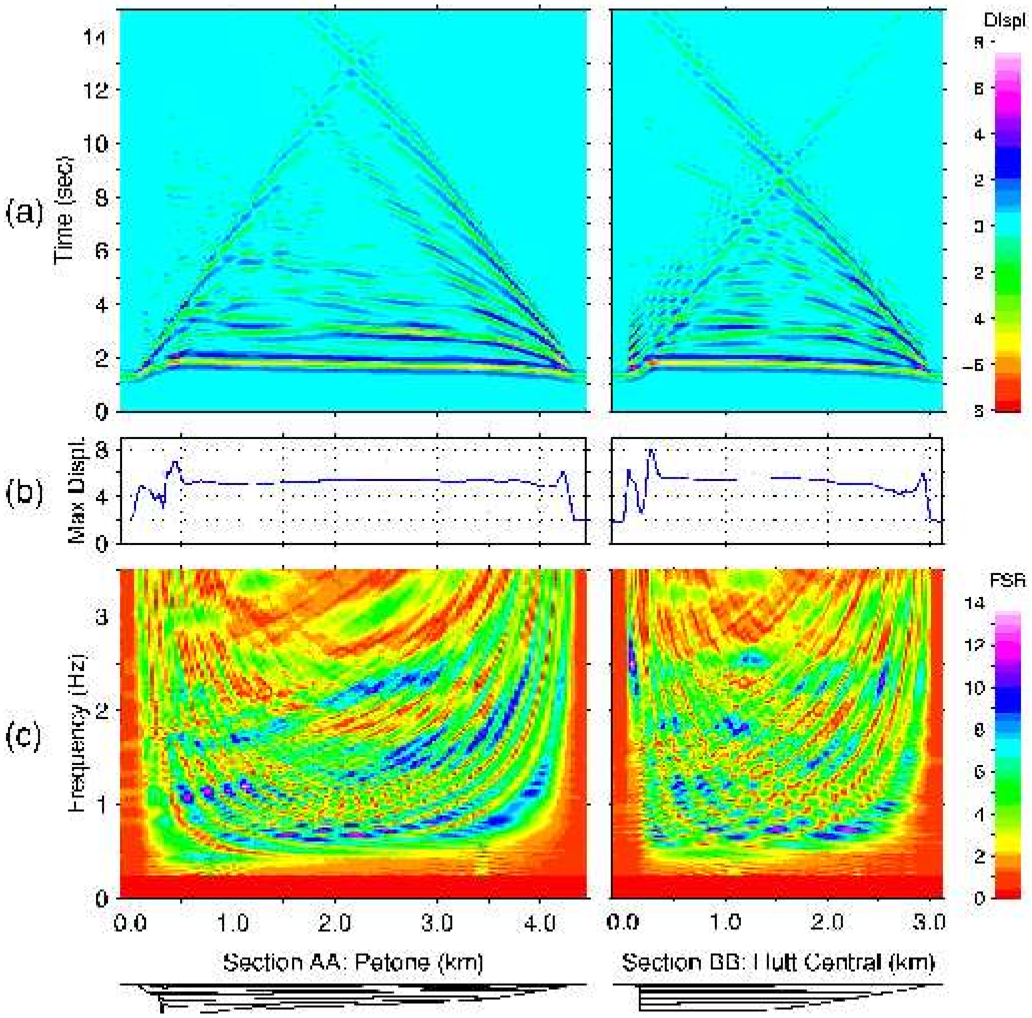

Figure 2. Simulation results across the surface of the valley for a single, vertically incident Ricker pulse. (a) The transient displacement response of each cross-section is plotted as a continuous function of cross-valley location and time. Displacement amplitude shown as a colour scale and has been normalised against the input amplitude. (b) Maximum displacement vs. across-valley position. (c) Fourier spectral ratios calculated from the displacement data shown in (a), here showing clearly a pattern of two-dimensional resonance.

DISCUSSION

Results from cross-sections through the Lower Hutt Valley both at Petone and Hutt Central have many similarities. The behaviour of various parts of the valley are dominated to various degrees by the single- or multi-dimensional resonance; and edge effects such as shallow vertical resonance or the basin-edge effect.

The Basin-Edge Effect

The fault-plane forming a vertical western edge to the valley appears to lie between 100 and 300 metres from the base of the western hills. Seismograms from both cross-sections in Fig. 1 and plots of maximum displacement in Fig. 2b indicate that the basin-edge effect will occur some 70-200m south-east this discontinuity. In both models we see strong pulses of energy in the seismograms at these locations. In the frequency-domain (Fig 2c), however, we see little amplification due solely to the basin-edge effect.

Indications are that the basin-edge effect should occur along the whole length of the Lower Hutt Valley's western edge. Its distance from the vertical fault-plane is likely to decrease further up the valley as the sediment thins. The narrow band of strong motion will, at the top end of the valley, be situated along the line of the Hutt River, which meanders down the western edge until reaching Hutt Central where its course takes it diagonally across the valley. Strong shaking here could increase the liklihood of liquefaction on the riverbanks, and result in damage to bridges and other nearby structures. At the southern end of the valley in Petone, the band of strong shaking will be located though an area of residential and industrial development.

Two-Dimensional Resonance

Fig. 2c shows a two-dimensional resonant amplification pattern with many similarities to the analytical solution for a simple homogeneous rectangular valley [Bard and Bouchon, 1985; Bielak et. al., 1998]. Curving extremum lines of amplified motions are prominent features. Because the deepest part of the valley is found adjacent to the fault along the western edge, the resonant modeshapes are all skewed westward. Higher resonant modes (both vertical and horizontal) have been attenuated in the soft soil, and have much lower amplitudes. In general, the soil exhibits spectral ratios up to 14 at certain locations across the entire width of the valley between 0.3 and 2.5 Hz, and ratios up to 4 over the whole frequency range shown (0-3.5Hz). This compares well with previously recorded data where FSR reaches values as high as 14 at deep sites in Petone [Taber and Smith, 1992].

Although the 2-D pattern is clear, interference effects [Wirgin, 1995] from higher vertical-mode sets has created a complex patchwork of amplification. The close spacing of eigenfrequencies in the Lower Hutt Valley are a distinguishing feature separating it from smaller basins such as the nearby Te Aro Basin in Wellington [Adams et. al., 1999] or the Kirovakan Valley, Armenia [Bielak et al., 1998]. In a general sense, we can characterise amplification by patches in space-frequency, yet in a local sense amplification is also highly variable in both dimensions. A 0.1 Hz change on frequency or a 300 m change in cross-valley position may alter the amplification by as much as a factor of 14. Whether or not it is possible to actually record such sharp changes in amplification is unknown.

The Validity of a Two-Dimensional Analysis

The use of 2-D rather than 1-D modeling has shown beyond doubt the significance of 2-D effects in magnifying and changing the form of the basin response. It is crucial then that we have some idea of how good our 2-D approximation is at modeling the real 3-D situation in the Hutt Valley. Although the valley does not extend as a perfect prismatic shape with constant cross-section to infinity in either direction, we do have a basin that is significantly longer than wide. In fact our cross-sections of width 3-4km and depth 0.3km are modeling a sediment wedge approximately 18km long, with deep sediments extending out into the Wellington Harbour. The north-western side of the valley is relatively straight, following the vertical edge of the Wellington Fault. In contrast the eastern side of the valley is much more ragged with many minor gullies and ridges, indicating that the base of the sediment wedge is also likely to have an irregular surface.

Horizontal resonance and interference edge-effects are both directly linked to the presence and amplitude of surface waves. Multi-dimensional behaviour will not occur at a site sufficiently distant from the basin edge, where the edge-generated surface waves have decayed to some insignificant amplitude. On the same note, horizontal resonance can only occur when the sediment is constrained by bedrock in both directions. The open-ended nature of the Lower Hutt valley makes the presence of horizontal resonance in the longitudinal direction unlikely, although local edge effects in this direction are a distinct possibility. The north-eastern end of the valley is likely to exhibit a 3-D response due to the highly enclosed and irregular nature of its geometry, while the lower part of the valley is quite open-ended in both directions, and likely to be dominated by 2-D cross-valley behaviour. Irregularities along the eastern margin, however, appear to have the potential to create localised out-of-plane edge waves that cannot be accounted for in the 2-D model. Directivity and energy radiation effects are also likely to be significant in the event of a Wellington Fault rupture, yet are unaccounted for by the 2-D model.

Non-Linear Behaviour

During a major rupture of the Wellington Fault, the near-surface flexible sediments are expected to lose stiffness and behave in a non-linear manner. Testing of soft cohesionless sands and gravels has shown that material damping increases dramatically above cyclic shear strains of 0.01 to 0.001 %, indicating the onset of inelastic behaviour [eg. Beresnev and Wen, 1996]. A corresponding decrease in shear modulus and shear-wave velocity works to reduce the peak ground motions and increase the duration of strong motion.

There is substantial evidence [eg. Borcherdt et. al., 1989] that linear results from elastic modeling or weak-motion recordings may be used successfully to predict both the amplified frequencies and to a lesser extent the amplitude of spectral ratio peaks for PGA up to at least 0.1 or 0.2g. Yet for higher PGA, indications are that weak motions may be used successfully to estimate only the fundamental frequency of a site [Lermo and

Chavez-Garcia, 1994]. Results from our elastic analyses are likely to be on the conservative side of reality in terms of peak response. Non-linear effects will probably lead to lower peak ground motions. The spectral ratios may be reasonably accurate, while the real duration of shaking is likely to be much longer than predicted. It would be sagacious to look at records from other bedrock-bounded valleys to get an idea of the duration to be expected.

Limitations aside, this two-dimensional analysis simulating the propagation of antiplane SH waves has proved to be a substantial step toward determination of the seismic response of the Lower Hutt Valley. It would be prudent for planners and developers to be aware of the risks associated with urban development within the Lower Hutt, and to ensure adequate protection is available to withstand the type of strong ground shaking outlined above. It is also notable that various other sedimentary basins in the Wellington region such as Upper Hutt, Wainuiomata, Porirua and Mirimar are also likely to amplify seismic motions by the mechanisms of multi-dimensional site effects, including resonance and constructive amplification.

CONCLUSIONS

The behaviour of various parts of the valley are dominated to various degrees by the effects of single- or multi-dimensional resonance; and edge effects such as shallow vertical resonance or the basin edge effect. A finite element technique has been used to simulate the propagation of antiplane SH waves through two-dimensional cross-sections of the Lower Hutt Valley. The seismic response of the southern Lower Hutt Valley is characterised by two-dimensional resonance across its width, the basin-edge effect along a band parallel to the Wellington Fault and one-dimensional vertical resonance close to all edges.

- Two-dimensional resonance describes the behaviour of the full width excluding a 100m wide band adjacent to each edge. Frequencies within the range 0.4 to 2.5 Hz are amplified up to a Fourier spectral ratio (FSR) exceeding 14. The distribution of amplification is highly variable with both location and frequency. Resonant interference effects are the cause of strong amplification at frequencies above 1.1 Hz. The strongest amplifications in the centre of the valley occur at a frequency around 0.75 Hz.

- The basin-edge effect creates strong pulses in the seismogram along a narrow band parallel to and some 70-200 m southeast of the Wellington Fault trace. The basin-edge effect is strongly dependant on the presence of the sub-surface vertical wall forming the western side of the valley.

- One-dimensional vertical resonance of shallow sediments within 100 metres of the valley edges amplifies frequencies within the range 2.0 to 3.5 Hz. In areas of soft fill, the FSR may exceed 14.

- Fourier spectral ratios from our elastic modeling compare well in magnitude and general frequency content with Fourier spectral ratios calculated from previously recorded weak motion data within the Lower Hutt.

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