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MICROZONE EFFECTS IN WELLINGTON, NEW ZEALAND DEMONSTRATED BY RECORDS FROM A STRONG-MOTION ARRAY

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ABSTRACT

Wellington, the capital of New Zealand, lies in a high-seismicity region adjacent to the boundary of the Pacific and Australian tectonic plates. Significant depths of marine or alluvial deposits in parts of the region are likely to produce considerable amplifications of bedrock motions in at least some earthquakes, and in places are also susceptible to liquefaction. These factors and the importance of the city prompted a major seismic microzoning study. The microzone maps covering surface fault rupture, ground shaking amplification, liquefaction and landslide potential have been used for planning emergency responses, and in a coordinated review of engineering lifeline networks that resulted in the implementation of mitigation measures.

This paper describes one aspect of the microzoning study, the use of records obtained from a long-established strong-motion array to confirm earthquake ground-shaking zonings and site amplifications in part of the region, the lower Hutt Valley and Wainuiomata. Strong-motion array records generally supported amplification characteristics deduced from surface and sub-surface geological mapping, penetrometer tests, shear-wave velocity measurements and short-term microzone surveys performed with denser instrumental coverage. Strong long-period amplification in records from sites on the deeper part of the Hutt Valley suggested that the highest amplification zone should be extended beyond the area indicated by the short-term microzone survey.

KEYWORDS

Seismic microzoning; earthquake lifelines; strong-motion array.

INTRODUCTION

The Wellington region is subject to major earthquakes because of its location adjacent to the boundary of the Pacific and Australian Plates. It is traversed by several major active faults with average recurrence intervals of rupture ranging from several hundred to a few thousand years. The Wellington fault runs through the urban areas of Wellington City and the Hutt Valley, with geological evidence suggesting surface-rupturing earthquakes of about magnitude M_W 7.6. The Wairarapa fault, at a shortest distance of 22km from central Wellington, last ruptured in 1855 along a length of 100km, with a maximum surface horizontal displacement of 12m in an earthquake with an estimated magnitude of 8.0-8.3. The earthquake lifted and tilted most of the Wellington region to the west of the fault, with a maximum uplift of 6.4m. As well as the major active surface faults of the region generating large earthquakes, the interface between the subducting Pacific Plate and the overlying Australian Plate beneath Wellington at a depth of about 30 km may also be the source of large magnitude earthquakes.

Significant depths of recent marine and alluvial deposits occur in parts of the Wellington region, such as the reclaimed areas of the central business district of Wellington, alongside Porirua Harbour, the Petone foreshore area of the Hutt Valley and Wainuiomata. Shear-wave velocities of less than 100m/s have been measured to depths of 20m at some sites, with extensive zones having average shear-wave velocities of less than 200m/s in the top 20m (Stephenson and Barker, 1992). Recorded motions show that there are considerable amplifications of bedrock motions in at least some earthquakes. Some of these deposits have exhibited liquefaction in previous earthquakes.

In recognition of the threat to the Wellington region from earthquakes, the Wellington Regional Council instituted a multi-year programme to better identify the earthquake hazard, to assess the Region's susceptibility to the hazard, and to develop risk reduction measures. The earthquake hazard assessment phase considered a variety of components: surface fault rupture, strong ground shaking, liquefaction and ground damage, landslides and tsunami. The results of these assessments have been published as series of maps accompanied by brief explanatory booklets. The maps and accompanying information have been used by various public and private sector organisations in the Wellington region for assessing the hazard in defining their own mitigation and earthquake response measures, often backed up by further detailed assessments of site specific hazards relevant to their operations.

Much of the progress in implementing mitigation measures can be attributed to the efforts of the Wellington Earthquake Lifelines Group, a voluntary organisation of professionals involved in the seismic hazard and mitigation fields and/or engineering lifelines operations. This group has promoted public and political awareness of the earthquake risk in the area, identified critical areas that are particularly vulnerable in terms of the level of hazard and concentration of multiple lifelines, encouraged local authorities and other lifeline operators to undertake appropriate remedial measures, and provided a forum for lifeline operators to coordinate their efforts in developing mitigation measures and response plans for highly interdependent systems (e.g. Wellington Earthquake Lifelines Group, 1993).

This paper describes a small facet of these overall studies, the contribution of information from earthquake acceleration records from a long-established strong-motion array in the region to defining ground shaking hazard zones. A more detailed discussion is given by Sritharan and McVerry (1992). The paper is restricted to consideration of the Hutt City area, but analyses of strong-motion records have contributed in a similar way to zoning of the central Wellington and Porirua areas. The strong-motion information has been combined with information from a variety of techniques in developing the ground shaking hazard maps. The other approaches included surface and subsurface mapping of geological materials (Dellow et al., 1992), performing cone and seismic cone penetrometer probing tests (Stephenson and Barker, 1992) and the operation of a short-term microearthquake array (Taber and Smith, 1992).

THE HUTT VALLEY MICROZONE ARRAY

As part of the New Zealand strong-motion network, the Institute of Geological and Nuclear Sciences maintains an array of accelerographs in the Hutt Valley and the neighbouring Wainuiomata basin for studying microzone effects. Since the first strong-motion accelerograph was installed in 1966 through to the end of 1992, there were more than 20 earthquakes of magnitude greater than 4 which triggered strong-motion instruments in the Hutt Valley. This paper summarises the results of analyses of records from three rock sites and four soil sites in the Hutt Valley and the quantification of their site characteristics, together with records from three other soil sites instrumented since the completion of the report for the Wellington Regional Council. Two of the newly-instrumented sites (WAI and NAES) were selected because they produced large amplifications in a microzone survey (Taber and Smith, 1992), while the third new site (CFT) was selected to provide records to better define the nature of the ground response in an area of reclamation.

The study used records from nine earthquakes, ranging in magnitude from M_L 4.9 to 7.0, at epicentral distances from the INS reference site of between 40km and 240km, and focal depths of 23km to 173km. These events produced contrasting types of ground motions in the Hutt Valley. THe motions from moderate to large magnitude (M_L > 5.5-6.0) distant earthquakes were generally rich in low frequencies, which brought out the longer-period response of deep alluvial and soft sediment sites, like many of those in the Hutt Valley.

SITE CONDITIONS

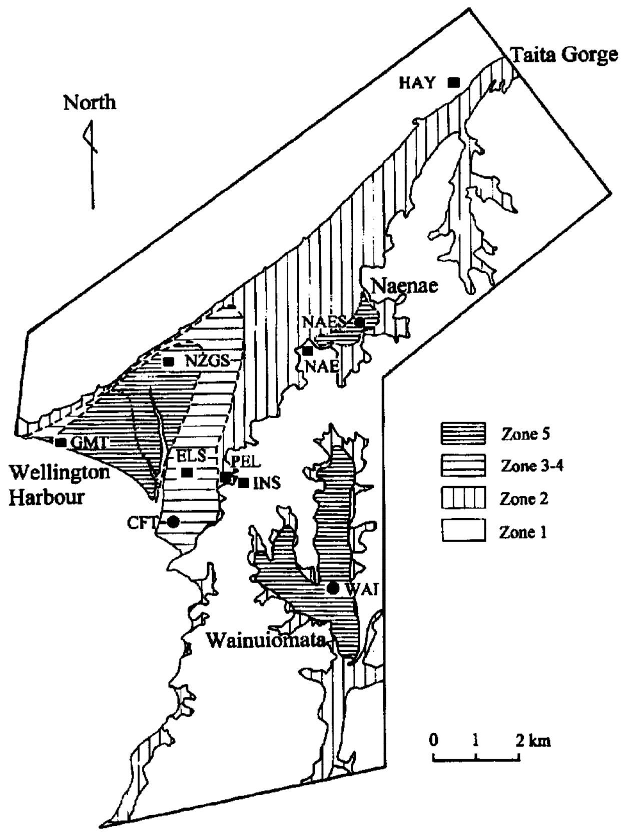

Fig. 1. Microzone map of the Hutt Valley for earthquake ground shaking hazard, showing zones 1, 2, 3-4 and 5 in order of increasing amplification, and the 10 strong-motion sites.

The Hutt Valley (Fig. 1) is an elongated sedimentary basin overlying greywacke basement rock. The valley is bounded by moderately steep hills along its length. From the mouth of Taita Gorge, it forms a V-shape flat which runs in a south-west direction for about 14 km, with the lower part of the valley open to Wellington harbour. The Wellington fault lies near the western boundary of the valley. According to the geological map in Dellow et al. (1992), the depth of sediment is about 10-20m in the Taita area and increases gradually in the south-west direction towards the harbour, reaching over 300m in the Petone foreshore area. Wainuiomata lies in a neighbouring basin, filled in places by very soft recent swamp and stream deposits.

The Hutt Valley (including Wainuiomata) has been divided into four site amplification zones, denoted 1, 2, 3-4 and 5 in order of increasing amplification (Van Dissen et al., 1992). Zone 1 consists of rock at the surface, or with up to 10m of deeply weathered gravel on rock. Zone 2 contains alluvial gravel and fan alluvium; compact fine to coarse gravel, up to 200m thick, interfingered with beds and lenses of finer grained sediment (sand, silt, clay, and peat), usually less than 5m thick; the coarser sediment typically has moderate to high Standard Penetration Test (SPT) values of N = 20- >60. Zone 3-4 has up to 15m of fine-grained sediment (fine sand, silt, clay, and peat) within the top 20m or so of alluvial gravel, underlain by up to 250m of alluvial gravel and finer grained sediment. The near-surface fine-grained sediment typically has low SPT values ($N \leq 20$), whereas the coarser cosolidated sediment generally has moderate to high SPT values (N = 20- >60). Zone 5 contains soft sediment (fine sand, silt, clay, and peat), greater than 10m thick, at or very near the surface, underlain by bedrock or a variable thickness of gravel and other finer grained sediment. Near-surface sediment in Zone 5 is characterised by low shear-wave velocities for the upper 10-30m, approximately 175m/s in the Hutt Valley and 90-150m/s in Wainuiomata. These soft sediments may be underlain by up to about 300m of gravels.

The three strong-motion sites in Zone 1, including the reference site INS adjacent to the eastern edge of the valley, are located on rock part way up the surrounding hills. Two of the Zone 1 rock sites, INS and HAY, are on flat excavated terraces about 30m and 60m above the valley floor respectively. The third rock site, NAE, is on a ridge about 90m above the valley floor. The sole Zone 2 site, PEL, is located just within the valley, about 400m from the reference site, on 20m of sediments composed of 12m of loose-medium dense gravel and soft-firm silt over 8m of medium dense sand, silt, and gravel. Zone 3-4 contains two accelerograph sites, ELS and CFT, underlain by about 200m and 150m of alluvium respectively, with 20m of soft deposits at each site overlying the very dense gravels. The shallower of these sites (CFT) is on reclaimed land. There are four sites in Zone 5, two (NZGS and GMT) with deep sediments (over 250m of stiff alluvium and dense gravels) underlying 10m and 30m of soft materials respectively (typical shear wave velocity 175m/s), and the other two (NAES and WAI) on shallower, very soft sediments (measured shear-wave velocity of 90m/s for the top 20m at WAI).

EXAMPLES OF MICROZONE EFFECTS

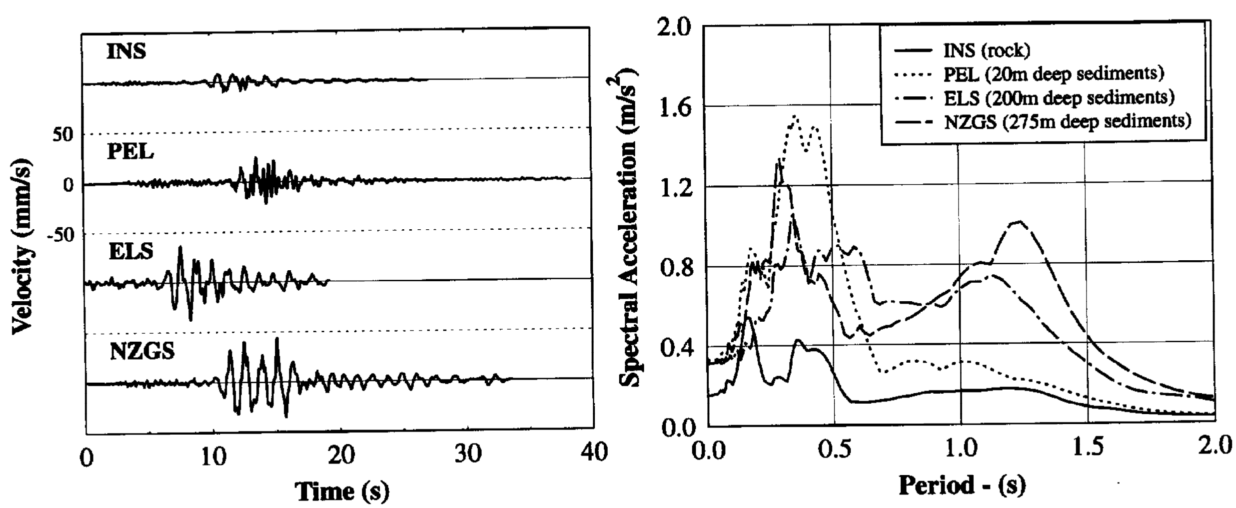

Fig. 2. Comparison of the cross-valley velocity histories and 5% damped acceleration response spectra in Palliser Event 1 in 1990, showing the effect of sediment depth.

The microzone effects observed in the Hutt Valley are demonstrated by sets of records obtained from the 1973 Central North Island, the 1990 Palliser (Event 1) and 1991 offshore Bulls earthquakes.

The different character of the motions at various sites is illustrated by plots of the ground velocities and 5% damped acceleration response spectra for the cross-valley component in the Palliser earthquake of 5 October 1990 (Fig. 2). Although of only moderate magnitude of around 5, this event centred 70 km from the Hutt Valley contained a significant portion of its energy at longer periods. The peak velocity at the PEL alluvium site was amplified by a factor of 2.3 with respect to the INS rock site 400m away. The PEL site exhibits an along-valley resonance in its response to many earthquakes, and even the cross-valley component shown here is dominated by motion at the site period of about 0.4s. The maximum ground velocity at the deep sediment NZGS site was 4.5 times stronger than at INS, the significant motion continued considerably longer than the 6s duration strong phase apparent at INS and PEL, and the velocity record showed a predominant period corresponding to the acceleration response spectrum peak at 1.2s period. The NZGS spectrum also has a prominent short period peak, at shorter period than the strongest peak at PEL.

The deep M_L 7.0 Central North Island earthquake in 1973 showed similar variations of site characteristics in the Hutt Valley. Ratios of the 5% damped acceleration response spectra in the along valley N54E direction were calculated for PEL, ELS and GMT with respect to INS (Fig. 3). The PEL ratio has its strongest peak at 0.45 seconds period, with an amplification exceeding 5. ELS shows very similar amplification to PEL at short periods up to 0.6s. At intermediate periods, ELS has stronger amplification than PEL, similar to that of the deep GMT site, growing to a second amplification peak exceeding 5 at 0.85s, before falling to amplifications intermediate between those at PEL and GMT at long periods. At GMT, the site with deepest sediment, the high frequencies are attenuated considerably and the ground motion is dominated by low-frequency cycles. GMT shows little amplification for periods less than 0.4s, before growing to a series of peaks with broad-band character in the 0.5-2.0 seconds period range. Its strongest amplification peak in this record occurs at 1.7 seconds period.

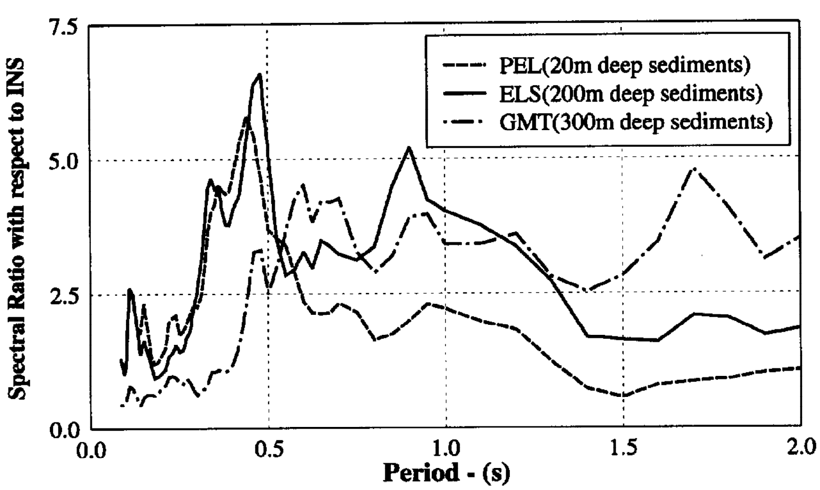

Fig. 3. The amplification of the cross-valley component of the 5% damped acceleration response spectra at 3 soil sites with respect to the INS rock site in the 1973 earthquake.

Records from a number of recent earthquakes since 1992 are available to compare the site characteristics with those determined in the study performed for the Wellington Regional Council. Also, the recent records allow the site response characteristics to be determined for the three recently instrumented sites, NAES, WAI and CFT. The CFT site which is on reclamation land in the south-east corner of the Hutt Valley has been placed in the same microzone as the nearby ELS site, and the new records offer the possibility of evaluating this zonation. Also, the records provide the opportunity to determine whether the NAES and WAI sites show the extreme amplification that was apparent in the microearthquake survey (Taber and Smith, 1992).

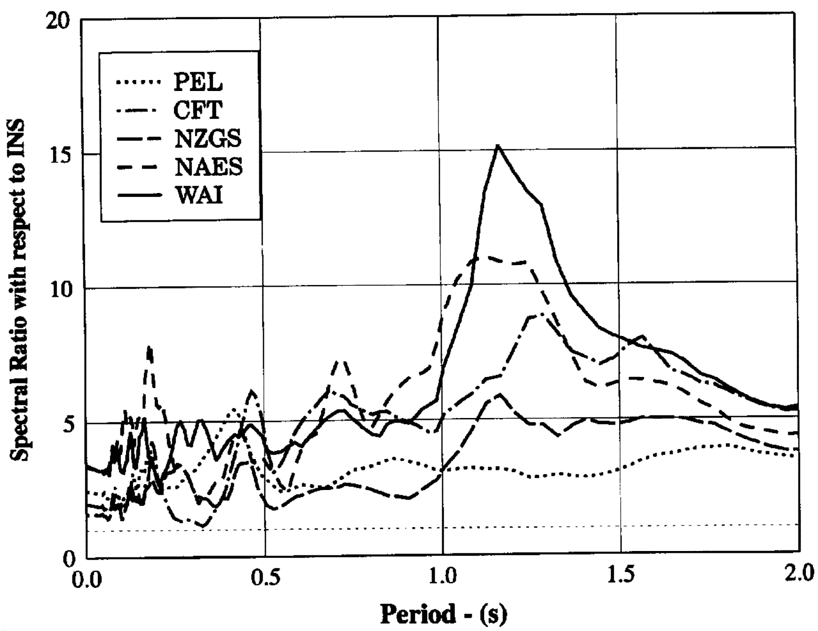

Fig.4. The 5% damped acceleration response spectrum ratios with respect to INS of the cross-valley components in the 1991 offshore Bulls earthquake, showing the strong amplification at long-period of the recently-instrumented soft soil sites at NAES and WAI.

One set of records from a recent earthquake was in an event of magnitude M_L 6.3 centred 87 km deep offshore from Bulls at an epicentral distance of about 110 km from the Hutt Valley. The ground motions in the Hutt Valley (PGAs 0.015g at INS to 0.055g at NAES) from this earthquake were generally dominated by strong high-frequency components, despite its moderate magnitude and large distance from the valley. The long-period character of many Hutt Valley sites is obvious in the response spectrum ratios of Fig. 4, for the cross-valley components, although not readily apparent without close inspection from the acceleration response spectra. The spectral ratios for NAES, WAI, CFT and NZGS are all dominated by peaks in the long-period range (greater than 1s), with the maximum amplifications exceeding 5 for all these sites, exceeding 10 for NAES, and reaching around 15 for WAI. Only PEL shows its strongest amplification peak at a period less than 0.5s, with a maximum amplification of 5.5 at 0.42s. NAES, WAI and CFT also have short-period (less than 0.5s) amplification peaks exceeding 5, as well as their dominant long-period peaks. The long-period amplification at WAI and NAES considerably exceeded that at the older Zone 5 site, NZGS, confirming the extreme amplification that was apparent at these sites in the micro-earthquake survey.

SITE RESPONSE CHARACTERISTICS

Records from many different earthquakes showed that there are marked variations in the characteristics of earthquake ground motions within the Hutt Valley study area. This is to be expected from the range of site conditions, including bedrock, thick alluvium and soft Holocene sediments. Analysis of the records from the strong-motion array together with those from a microearthquake study (Taber and Smith, 1992) enable the individual responses to be generalised for various microzones.

It must be emphasized that all the accelerograms used in this study are from weak to moderate ground shaking which produced peak horizontal accelerations of up to about 0.1g in the Hutt Valley. The periods corresponding to the peak amplifications may increase in stronger motions because of greater flexibility of the soil at large strains, with the amplification decreasing because of increased damping provided by hysteretic action of the soil in nonlinear, large-amplitude motions.

In general, the ground motions at the three rock sites INS, NAE and HAY are characterised by short-period peaks, with the strongest peaks of the acceleration response spectra occurring between 0.1 and 0.25s. Short-period amplifications of up to 3 with respect to the reference site INS as measured for HAY may be obtained in Zone 1 of the ground shaking microzonation as a result of topographic effects on the steep slopes and because of the presence of shallow remnants of old weathered terraces. This spectral amplification factor of up to 3 within Zone 1 is in line with the microearthquake observations (Taber & Smith, 1992). The amplitudes of the longer-period motions are relatively small for these rock sites.

The three soil sites located across the lower part of the valley (PEL, ELS and GMT) have systematic variations in their site responses. The thickness of the soil overlying the bedrock and the position of the site in relation to the edge of the valley plays a major role in determining the site response characteristics. For shallow sites located adjacent to the edge of the valley (e.g. PEL), the predominant periods and peak amplifications fall in the short-period range, while for deep sediment sites (e.g. GMT and NZGS) the dominant amplification peak tends to be at longer period.

There was no permanent strong-motion instrument located on the valley floor between Taita gorge and central Lower Hutt city, so it was not possible to determine how the strong-motion response varies as the depth of sediment decreases in northern Lower Hutt. However the microearthquake results of Taber and Smith (1992) suggest that the influence of the thickness of soil layer is a significant factor moving not only across the valley direction but also moving along it. (The total thickness of sediment was a much less critical factor in determining the local amplification characteristics in the study of central Wellington city, where the material of the deposit was the prime factor).

Zone 2 sites are expected to produce short-period amplification with respect to rock sites. The PEL site adjacent to the edge of the valley on 20m of sediment strongly amplifies the INS rock motion at short periods, as shown repeatedly in many earthquakes. This particular site generally shows motion strongly aligned in the along valley direction, although strong directionality is not necessarily a characteristic of the response of Zone 2 sites. The average ratio for the 5% damped acceleration response spectrum of PEL with respect to INS for ten earthquakes had a well-defined peak of 4.1 at 0.35s for the along-valley N54E component, while the N36W component had a less well-defined peak reaching a maximum of 3.3 at the same period. The mean log ratio at zero period over the 20 components gave a factor of 2.2 between the horizontal peak ground accelerations of PEL and INS, while at long period there was a nearly constant factor of about 2 in the average ratio for periods in excess of 1.0s. Individual records gave maximum amplifications in the period band of 0.25s to 0.5s reaching up to 10. A shortcoming of the microzoning map is that it mainly reflects relative amplification of sites at periods exceeding about 0.5s. Zone 2 sites have their strongest amplification at short periods. The short-period amplification of some of these sites, such as PEL, is sufficiently strong that their motions may be stronger and more damaging in occasional earthquakes than those at sites in Zones 3-5.

Sites in the intermediate 3-4 zone (e.g. ELS and CFT) show frequency response characteristics reflecting both the short-period amplification of the Zone 2 sites and the intermediate-period (approximately 0.5-1.0s) amplification of the deep Zone 5 sites, before falling to amplifications between the Zone 5 and Zone 2 sites at periods greater than about 1.0s.

The deep Zone 5 sites with up to 300m of stiff sediments under soft near-surface material (e.g. GMT and NZGS) give broad-band amplifications with peaks up to 2s period, with typical maximum amplifications of the 5% damped spectrum of 5-10. The significant motion at these sites also often lasts much longer than the strong-motion phase apparent at the rock and Zone 2 sites. There may be deamplification of short-period (less than approximately 0.25s) motions at some Zone 5 sites with respect to Zone 1 and 2 sites. The Zone 5 region was was expanded north to include the central business district of Lower Hutt city (near NZGS) on the basis of long-period amplification apparent in some of the strong-motion records but not in the microzone survey. The area around NZGS north of the dotted line in Fig. 1 was included in Zone 5 on this basis.

The greatest amplifications, exceeding 10 for the 5% damped acceleration response spectra, were obtained at the two sites (NAES and WAI) which are located on the relatively shallow very soft deposits. The peak amplifications at these sites were obtained in the period band of 0.7s to 1.2s at NAES, and at a peak at 1.2s at WAI.

CONCLUSIONS

Wellington, the capital city of New Zealand, is located in a highly seismic region containing a wide variety of site conditions, including some that are susceptible to high amplification or liquefaction in earthquakes. Records from a strong-motion array generally confirmed amplification characteristics deduced from a variety of other techniques, and allowed the amplification values to be quantified. The strong-motion array produced information on long-period amplification on the deeper parts of the Hutt Valley that suggested that the highest amplification zone (Zone 5) should be extended beyond the area indicated by the short-term microzone survey. The microzone maps have been used for a number of mitigation studies and for earthquake response planning.

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