

GROUND SHAKING HAZARD PORIRUA

NOTES TO ACCOMPANY

SEISMIC HAZARD MAP SERIES: GROUND SHAKING HAZARD
MAP SHEET 2 PORIRUA (FIRST EDITION) 1:25000

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Compiled by

P A Kingsbury and W J Hastie

POLICY AND PLANNING DEPARTMENT



1. INTRODUCTION

1.1 BACKGROUND

The occurrence of earthquakes in the Wellington Region is inevitable due to its location at the boundary of two crustal plates. Earthquakes have the potential to cause significant adverse effects within the Region, including loss of life, injury, and social and economic disruption. In recognition of these potential effects the Wellington Regional Council initiated a project in 1988 to:

- * Assess the risks posed by earthquakes.
- * Identify mitigation options.
- * Implement measures to ensure that the level of risk is acceptable.

The first step in the project is to define the characteristics of the hazard. Information on the type and magnitude of possible effects, the probability of these occurring and the location of the effects within the Region is required. For the purposes of the project *earthquake hazard* has been divided into a number of separate but interrelated components, including:

- * Ground shaking.
- * Surface fault rupture.
- * Liquefaction and ground damage.
- * Landsliding.
- * Tsunami.

Although not all the effects will occur during every earthquake, and many will be localised, all components must be considered to obtain a complete picture of earthquake hazard.

1.2 PURPOSE OF MAP AND BOOKLET

A series of six map sheets, with accompanying booklets, have been compiled to describe the *ground shaking hazard* for the main metropolitan areas in the Region (refer to Index Map on accompanying map sheet):

- * Sheet 1 - Wellington.
- * Sheet 2 - Porirua and Tawa.
- * Sheet 3 - Lower Hutt.
- * Sheet 4 - Upper Hutt.
- * Sheet 5 - Paekakariki, Paraparaumu, Waikanae and Otaki.
- * Sheet 6 - Featherston, Greytown, Carterton and Masterton.

The purpose of the maps is to show the geographic variation in ground shaking hazard that could be expected during certain earthquake events. The map sheets and booklets have been compiled from Wellington Regional Council reports and detailed reports prepared for the Wellington Regional Council by DSIR Geology and Geophysics, Land Resources and Physical Sciences, and Victoria University of Wellington. A list of the reports is given in Appendix 1.

The intention of the map and booklet series is to raise public awareness of ground shaking hazard in the Wellington Region. The information should be useful to a range of potential users, including land use planners, civil defence organisations, land developers, engineers, utility operators, scientists and the general public.

Information on active faults in the western part of the Region has been published in a map series by the Wellington Regional Council - *Major Active*

Faults of the Wellington Region (Map sheets 1, 2 and 3: 1991). Tsunami hazard information for Wellington Harbour is also available.

1.3 BOOKLET STRUCTURE

This booklet is divided into four main parts. Part 1 provides background information on the study. Part 2 outlines the hazard assessment approach and details the mapping methodology. Parameters used to quantify the hazard zones are also discussed. Part 3 states the assumptions and limitations that determine the certainty with which the hazard zones can either be mapped or quantified. A brief summary is given in Part 4.

Technical terms are defined in Appendix 2.

2. HAZARD ASSESSMENT

2.1 DATA SOURCES

The geographic variation in earthquake ground shaking was defined using geological and geotechnical information from drillhole records, seismic refraction surveys, microearthquake records and penetrometer logs. Numerical techniques to model the seismic response of soft *flexible* sediments in Porirua were also used. An array of 12 digital seismographs were used to measure the response of various geological materials during microearthquakes.

2.2. EARTHQUAKE SCENARIOS

The Wellington Region is located across the boundary of the Pacific and Australian plates (Figure 1). As a consequence, the Region is cut by four major active faults, and is frequently shaken by moderate to large earthquakes (Figures 2 and 3).

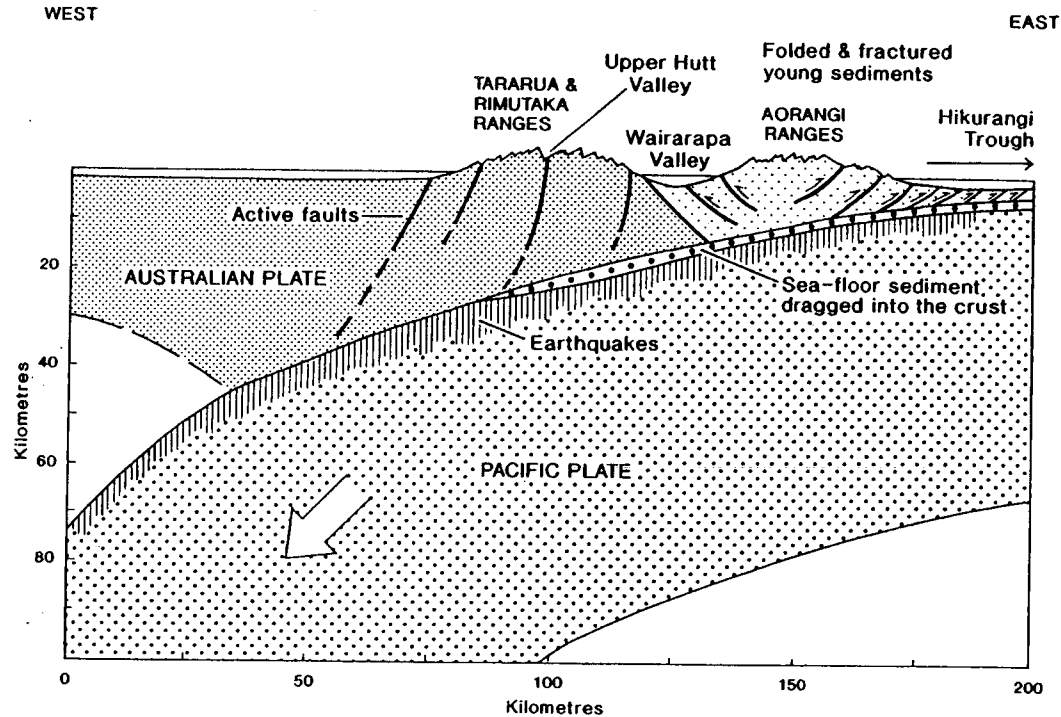


Figure 1: Source of earthquakes at plate boundary and along active faults (After Stevens, 1991)

Because no single earthquake event adequately describes the potential ground shaking hazard in the Region, two earthquake scenarios were used to define the hazard.

Scenario 1 is for a large, distant, shallow earthquake that produces Modified Mercalli intensity (MM) V-VI on bedrock (Appendix 3). It is expected that this type of earthquake will produce the largest variation in ground response. Scenario 1 implies minor damage to structures founded on the *best* sites and significant damage to certain structures on the

worst sites. An example of such an event would be a Magnitude (M) 7 earthquake centred about 100 kilometres from the study area at a depth of less than 30 kilometres. Twenty years is a minimum estimate for the return time of a Scenario 1 event. This return time is derived from the historical occurrence of both large earthquakes and moderate

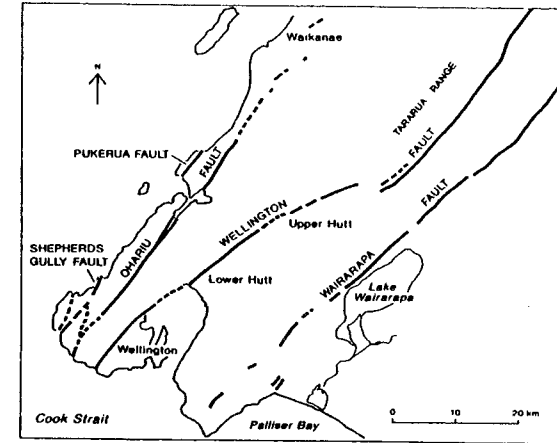


Figure 2: Active faults in the western part of the Wellington Region.

sized local events. A maximum estimate is 80 years, which is the return time of MM VII or greater shaking at bedrock sites in the Wellington Region.

Scenario 2 is for a large earthquake centred on the Wellington-Hutt Valley segment of the Wellington Fault. Rupture of this segment is expected to be associated with a Magnitude 7.5 earthquake at a depth less than 30 kilometres, and up to 5 metres of horizontal and 1 metre vertical displacement at the ground surface. The return time for such an event is about 600 years and the probability of this event occurring in the next 30 years is estimated to be 10 percent. The values for near-source shaking resulting from a Scenario 2 earthquake are given with less certainty. This is because there are so few near-source ground motion data from large earthquakes, and factors such as proximity to local asperities along the rupture plane and random cancellation and reinforcement of seismic waves can locally suppress the effects caused by near-surface geological deposits. Furthermore, amplification of some local geological deposits will

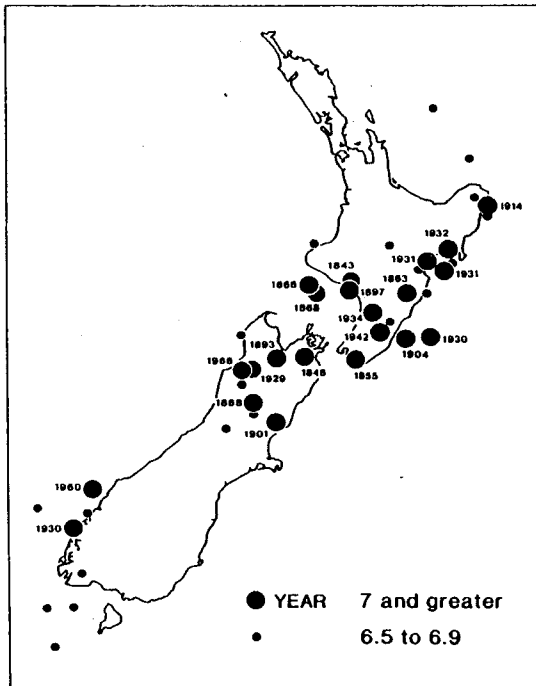


Figure 3: Epicentres of shallow earthquakes of magnitude 6.5 and greater since 1840 (After Van Dissen, 1991).

not occur at particular ground shaking frequencies and strengths.

2.3 MAPPING METHODOLOGY

2.3.1 Surface geology

The surface geology of the Porirua area was mapped using nine units:

- * Fill.
- * Swamp.
- * Alluvial gravels and small alluvial fans.
- * Marine silt, sand and estuarine peat.
- * Windblown sand.

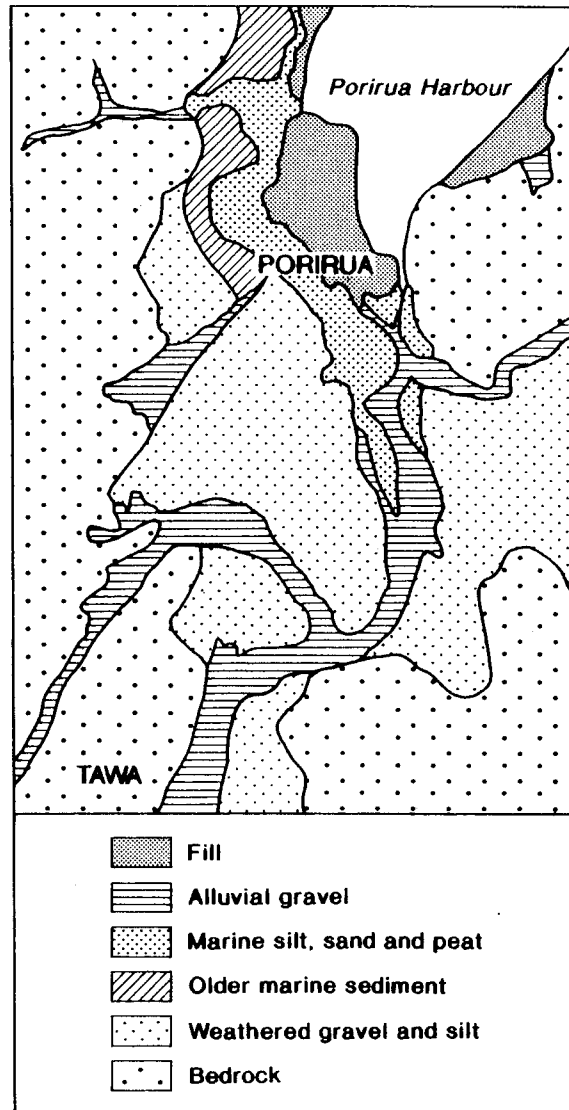


Figure 4: Surface geology deposits in the Porirua-Tawa area.

- * Older marine silt, sand and fine gravel.
- * Older alluvial silt, sand and gravel.
- * Deeply weathered sandy gravel and silt.
- * Bedrock (Torlesse Supergroup Greywacke).

The distribution of surface geology deposits between Porirua and Tawa is shown in Figure 4. Subsurface geology was interpreted from drillholes, standard penetration tests (SPT), cone penetrometer tests (CPT) and seismic refraction surveys.

The geology information provided the base for the ground shaking hazard zones.

2.3.2 Weak ground motions

The microearthquake recording sites sampled a variety of geological ground conditions, ranging from bedrock to significantly thick soft *flexible* sediments.

The relative shaking response of each site was expressed as an averaged ratio of the Fourier spectra of the seismograms compared to a reference bedrock site. The recorded ground shaking at the *flexible* sediment sites was 10 to 20 times stronger than that of the reference bedrock site, and occurs over a narrow frequency band (1 to 3Hz). The ground response at firm sites, including bedrock sites and sites where bedrock is overlain by more than 10 metres of deeply weathered gravel and loess, was also measured. With the exception of one site, the spectral ratios for firm sites varied from no amplification to factors of about 3 relative to the hard rock reference site. The exception was a firm site on a small ridge in Whitby which showed a spectral ratio of nearly 10 at 5.5Hz. The amplification at this site could in part be due to topographic effects since spectral ratios of up to 8 have been recorded at hard ridge-crest sites. Cone penetrometer results discount the possibility of a significant thickness of soft sediment near this site.

2.3.3 Penetrometer probings

The nature of the near-surface material at several sites was further defined using cone penetrometer and seismic-cone penetrometer probing. The results of CPT investigations at Kura Park (Titahi Bay) are shown in Figure 5.

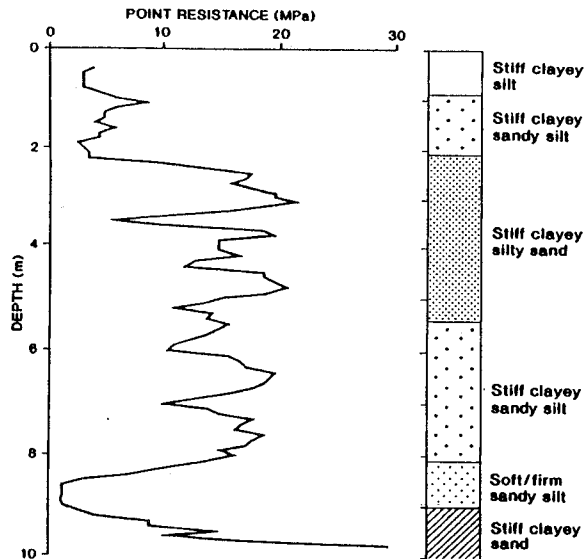


Figure 5: Cone penetrometer test results at Kura Park, Titahi Bay.

2.3.4 Ground shaking hazard zones

Based on the distribution of geological materials and the measured response of these materials to seismic waves the Porirua study area was mapped into three ground shaking hazard zones; Zone 1, Zone 2, and Zone 5 (refer to accompanying map sheet).

Zone 1, the least hazardous zone, is characteristically underlain by bedrock and typically shows very low to low amplification of seismic waves. Zone 2 is characterised by areas underlain

by 10 metres or more of gravel and *compact* sand and only slight amplification of seismic waves. Areas underlain by a significant thickness (about 10 to 30 metres) of soft *flexible* sediment show greatly amplified shaking, and are mapped as Zone 5.

2.4 GEOLOGICAL DESCRIPTION OF HAZARD ZONES

Descriptions of the geological materials that typify each hazard zone are given in Appendix 4. A summary of some of the engineering properties of the geological materials is given in Table 1.

2.5 QUANTIFICATION OF HAZARD ZONES

The shaking response of the ground shaking hazard zones was assessed for the two earthquake scenarios (as described in Part 2.2). The response of each zone was expressed as a set of ground motion parameters, comprising:

- * Expected Modified Mercalli intensity.
- * Peak horizontal ground acceleration.
- * Duration of strong shaking.
- * Amplification of ground motion with respect to bedrock - expressed as a Fourier spectral ratio.

MATERIAL DESCRIPTION	ENGINEERING PROPERTIES			
	DRILLING/PROBING		LABORATORY TESTING	
	SPT (blows/300 mm)	CPT (cone res MPa)	Water Content (%)	Void Ratio (e)
PORIRUA ARM				
Soft Sediments (to 15 m depth)				
Silts and Sandy Silts	1-10	1-5	20-40	1.0-1.5
Sands (and gravelly sands)	10-20	5-10	40-60	0.6-1.0
Coarse Grained Alluvial Sediments				
Clayey Gravels	30-100	>30	Not tested	Not tested
Silty Sandy Gravels	15-30	>30	Not tested	Not tested
PAUAHATANUI ARM				
Soft Sediments	-	1-5	Not tested	Not tested
Gravels	-	>30	Not tested	Not tested
HARBOUR ENTRANCE				
Soft Sediments	-	-	Not tested	Not tested
Coarse Grained Alluvial Sediments	-	>30	Not tested	Not tested

Table 1: Summary of typical engineering properties for Quarternary age sediments in the Porirua area.

Some of these parameters were measured directly, others were estimated using comparisons found in the published scientific and engineering literature.

The Loma Prieta earthquake (1989, San Francisco) is significant to this study because of the recorded variations in ground motion related to local geological conditions and because the magnitude is similar to that expected for the Scenario 1 earthquake. Therefore, the values calculated for the ground motion parameters used in this study were compared with those measured for the Loma Prieta event.

2.5.1 Modified Mercalli intensity

Scenario 1: The Scenario 1 earthquake (a large, distant, shallow earthquake, resulting in MM V-VI shaking on bedrock) will be of sufficient duration and contain sufficient long period energy to allow strong long-period response to develop at deeper sediment sites. The shallow focal depth will allow strong surface wave effects. The result will be a marked difference between the shaking of the *worst* sediment site and the *best* firm site. It is not uncommon during an earthquake to have a spread of three to four units of MM intensity separating the response of the *best* site from the response of a nearby *worst* site. A difference of three to four MM units is therefore expected between the response of Zone 1 and Zone 5. The response of Zone 2 is expected to be slightly stronger than Zone 1.

In terms of MM intensity the response of Zone 1 is expected to be MM V with some VI, Zone 2 is MM VI, and Zone 5 is MM VIII-IX (Table 2).

Scenario 2: The effects of a Scenario 2 event (a large, local Wellington Fault earthquake) will be a marked increase in the shaking throughout the study area, relative to Scenario 1, a decrease in the

SCENARIO 1				
Zones	MM Intensity	Peak ground acceleration (g)	Duration	Amplification of ground motion (FSR)
1	V-VI	0.02-0.06	<5 sec	1-3x
2	VI	0.02-0.1	2-3x	2-5x
5	VIII-IX	<0.3 generally between 0.1-0.2	>3x	10-20x
SCENARIO 2				
Zone	MM Intensity	Peak ground acceleration (g)	Duration	
1	VIII	0.3-0.6	15-40 sec	
2	VIII-IX	0.3-0.6	1-2x	
5	X-XI	0.5-0.8	>2x	

Table 2: Ground motion parameters for the ground shaking hazard zones in the Porirua area.

average difference in shaking between Zone 1 and Zone 5, and an increase in the variability of shaking within each zone.

An important factor influencing ground shaking for a Scenario 2 event is distance from the earthquake source. In general, shaking decreases with increased distance from the source. The Porirua study area is about 4 kilometres from the Wellington Fault. Therefore sites in Porirua are expected to shake less than similar sites in the Lower Hutt valley.

Epicentral intensities for the 1989 Loma Prieta earthquake were MM VIII. However, the Loma Prieta earthquake was smaller than the Scenario 2 event (M 7.1 compared to M 7.5). Epicentral intensities for similarly sized New Zealand earthquakes have been MM IX (1848 Marlborough), MM IX-X (1931 Hawkes Bay) and MM VIII-IX (1968 Inangahua).

On the basis of these relationships, MM VIII is expected in Zone 1. In Zone 2 the response is expected to be MM VIII-IX. Violent shaking, MM X-XI, is expected in Zone 5 (Table 2).

Some of the possible ground damage effects that are likely in the various hazard zones for the two earthquake scenarios are given in Table 3. These are based largely on the expected MM intensities, as well as knowledge of earlier damaging earthquakes in the Wellington Region and elsewhere.

2.5.2 Peak horizontal ground acceleration

Scenario 1: Peak ground acceleration for Zone 1 is expected to be in the order of 0.02 to 0.06g. This compares to the 0.06g recorded during the Loma Prieta earthquake at a hard rock site 95 kilometres from the epicentre. Accelerations of 0.02 to 0.1g are expected in Zone 2. For Zone 5, average accelerations of 0.1 to 0.2g are expected. Accelerations could be as high as 0.3g, based on the 0.29g acceleration recorded 97 kilometres from the Loma Prieta epicentre on a *soil site* (Table 2).

Scenario 2: The average peak ground accelerations expected for Scenario 2, based on a variety of attenuation relations and geological site considerations are as follows: Zone 1, 0.3 to 0.6g; Zone 2, 0.3 to 0.6g; and Zone 5, 0.5 to 0.8g (Table 2).

2.5.3 Duration of strong shaking

Duration provides a qualitative estimate of the effects that local geological deposits can have in increasing the length of time a site will experience strong shaking. In general, amplitudes and durations

SCENARIO 1 EARTHQUAKE	
Hazard Zones	Ground conditions and likely effects
1	"Greywacke"/Argillite Bedrock : Little ground damage. Small (<100 m ³) local failures on steep slopes and unsupported cut batters. Small local failures on cuts in weathered gravels.
2	Alluvial Deposits : Little or no significant damage likely. Small local failures on river banks possible.
5	Soft Sediments : Widespread minor slumping of steep banks (>2 m high). Localised lateral spreading of ground adjacent to river and stream banks with sand ejection (liquefaction effects). Differential settlement and collapse possible in some areas - especially in areas where the water table is close to the ground surface and adjacent to river banks.
SCENARIO 2 EARTHQUAKE	
Hazard Zones	Ground conditions and likely effects
1	"Greywacke" Bedrock : Small failures of bedrock and surficial deposits. Widespread on steep slopes and on steep unsupported cuts (>2 m high).
2	Alluvial Deposits : Only little significant ground damage expected. Small localised failures of river banks and cuts. Cracking and lateral spreading likely adjacent to river and stream channels with sand ejection due to liquefaction. Minor settlement and collapse of saturated materials in most places.
5	Soft Sediments : Effects as for Zones 2 and 3-4 - except that damage will be widespread, and at a greater scale. Liquefaction effects (sand ejection, cracking, lateral spreading and settlement) would be widespread, and seriously damaging in some places, especially areas adjacent to river and stream courses.

Table 3: Ground damage effects likely in each ground shaking hazard zone for the two earthquake scenarios.

of shaking increase with decreasing firmness of the underlying sediment. This has been observed in the Wellington area for non-damaging earthquakes and elsewhere for larger damaging earthquakes. In this study *duration* refers to the time between the first and last accelerations that exceed 0.05g.

Scenario 1: The expected duration of strong shaking in Zone 1 during a Scenario 1 event is less than 5 seconds (Table 2). The expected increase in duration, relative to bedrock, is 2 to 3 times in Zone 2 and more than 3 times in Zone 5.

Scenario 2: Length of fault rupture is a controlling factor regarding the duration of near-source ground shaking. The Loma Prieta earthquake produced about 10 seconds of strong shaking, resulting from a 40 kilometres bilateral rupture (rupture propagation from the centre of the fault to the ends). Had the rupture been unilateral (rupture propagation from one end of the fault) the shaking would have lasted much longer, perhaps up to 20 seconds. Rupture of the Wellington Fault in Scenario 2 is expected to be about twice as long as the rupture that produced the Loma Prieta earthquake. The duration of shaking for Zone 1 during Scenario 2 is expected to be 15 to 40 seconds, by comparison with the Loma Prieta event and depending on whether the rupture propagates bilaterally or unilaterally. The increase in duration, relative to Zone 1, is 1 to 2 times for Zone 2 and greater than 2 times for Zone 5 (Table 2).

2.5.4 Amplification of ground motion spectrum

Characteristic peak Fourier spectral ratios are summarised in Table 2. The results are useful for determining relative shaking and for identifying the frequencies over which this shaking will be most strongly amplified during certain earthquakes, specifically Scenario 1 type events.

Spectral ratios vary from 1 to 3 for most firm sites and up to about 20 for flexible sediment sites. Ground motion amplification at most of the sites in the Porirua study area occur over a broad frequency band from 0.5 to 5Hz. However, some sites, particularly those in Zone 5, exhibit a narrow (resonant) frequency response. Results from other studies suggest that the frequency of amplified shaking during small earthquakes remains the same for larger damaging earthquakes. Site resonance is of most concern where built structures have

natural periods that coincide with the resonant period band(s) of strong ground shaking.

Even though the ground motion amplifications measured in Porirua were recorded during non-damaging earthquakes it is significant to note that intensity maps, prepared in the 1970s for the San Francisco Bay area, anticipated all of the areas that experienced high intensity shaking during the 1989 Loma Prieta earthquake. The level of amplification during even larger ground motions at near-source sites is unresolved. An amplification of FSR greater than 5 is unlikely to persist to extreme motions. This is because at high strain levels weak sediments begin to behave in a non-linear fashion - they begin to lose strength and increase wave attenuation or damping. Nevertheless, variations in the nature of seismic response can still be expected from one zone to another. High amplification of small bedrock ground motions, such as the Scenario 1 bedrock motions, means that significant local damage in Zone 5 could result from an earthquake that would cause little or no damage in Zone 1. Amplification of small bedrock ground motions are best characterised by measured spectral ratios and are therefore given only for Scenario 1.

3. ASSUMPTIONS AND LIMITATIONS

Important assumptions that limit the certainty with which the ground shaking hazard zones can either be mapped or quantified are discussed below.

(1) Within each hazard zone there are isolated occurrences of materials that may cause ground motions that are not typical of the zone as a whole. The mapped fills in Porirua East are on bedrock and are included with Zone 1. However,

these fills are over 20 metres thick in places and may respond more like Zone 2. Conversely, some areas mapped in Porirua as Zone 5 may not be underlain by enough sediment to cause high amplifications of ground motion. At these sites a more favourable response may result.

Significant variations in amplified resonant response over relatively short distances in some areas, emphasise the importance of site specific studies to determine the nature and response of the materials at a site.

- (2) High amplifications were recorded at Titahi Bay but the distribution of the materials causing these amplifications is not well defined. The poorly resolved boundary around the Zone 5 area is denoted as a *dashed* line on the ground shaking hazard map.
- (3) Amplification of ground motion due to topographic effects has not been addressed for this study. Though probably localised, these effects can be pronounced.
- (4) There is a marked directionality in the response at some strong motion sites at select frequencies. It is unclear whether this directionality is consistent in different earthquakes.
- (5) The ground damage effects given in Table 3 are estimated from a general knowledge of past earthquakes in the Wellington Region and elsewhere, and have not been the subject of detailed study.

(6) Scenario 2 ground motion parameters are defined with less certainty. There is a worldwide lack of near-source ground motion data recorded during large earthquakes. During a large local earthquake near-source seismic wave propagation will be complex and non-uniform, and ground strains will be large enough to cause some sediments to exhibit non-linear response. These effects will tend to increase the variability of shaking within a zone, decrease the average difference in shaking between zones and decrease the certainty with which expected ground motions can be characterised. Also, near-source ground motions for an earthquake associated with a long fault rupture, such as Scenario 2, may be correlated with proximity to local asperities along the fault rupture, rather than proximity to the fault itself.

(7) The information given in this booklet and on the accompanying map is the result of a regional scale multi-disciplinary study of ground shaking hazard. The booklet and map provide useful information for the mitigation of ground shaking hazard in the Porirua study area but should not be used to replace site specific studies.

Detailed geological mapping, additional penetrometer probing, seismograph instrumentation, and topographic and mathematical modelling would resolve some of these issues.

4. SUMMARY

The geographic variation in ground shaking was defined using information from drillhole logs, microearthquake records, penetrometer logs and from numerical modelling. Three ground shaking

hazard zones were established. These are Zone 1, Zone 2 and Zone 5. The geographic distribution of the zones is shown on the accompanying map.

Zone 1 areas are the least hazardous and are underlain by bedrock. Zone 2 areas show low to moderate amplification of earthquake shaking and are underlain by firm material. Zone 5 areas show high to very high amplification of earthquake motion and are underlain by more than 10 metres of soft and/or loose material.

The expected response of each ground shaking hazard zone to two earthquake scenarios is given by Modified Mercalli intensity, peak ground acceleration, duration and amplification of ground motion parameters. The two parameters most easily understood are MM intensity and duration. For a large distant earthquake (Scenario 1) MM values range from V-VI in Zone 1 to VIII-IX in Zone 5. The response will range from *some alarm and damage* in Zone 1 areas to *general panic and substantial damage* in Zone 5 areas. Strong shaking will last for less than 5 seconds in Zone 1 areas but continue for more than 15 seconds in Zone 5 areas. For a large earthquake centred on the Wellington Fault (Scenario 2), there is less difference between the zones, with strong shaking experienced everywhere. However, Zone 5 areas are expected to shake strongly for twice the duration of Zone 1 sites and to experience MM intensity 1 to 2 units higher on the scale.

Important assumptions that limit the certainty with which the ground shaking hazard zones can either be mapped or quantified must be considered when interpreting the hazard information.

APPENDICES

APPENDIX 1: CONTRIBUTING REPORTS AND REFERENCES

Dellow G D *et al* (1991). Geological setting of the Porirua Basin, including distribution of materials and geotechnical properties. DSIR Geology and Geophysics Contract Report 1991/46 (prepared for Wellington Regional Council).

Hastie W J and Grindell D S (1991). Natural disaster reduction plan - seismic hazard: Summary report on work carried out in 1990/91. Technical Report LR1991/1, Policy and Planning Department, Wellington Regional Council.

Stephenson W R and Barker P R (1991). Wellington Regional Council regional natural disaster reduction plan - seismic hazard: Report on cone penetrometer and seismic cone penetrometer probing in Wainuiomata, Eastern Harbour Bays, Stokes Valley, Kura Park (Titahi Bay) and Whitby. DSIR Land Resources Contract Report 91/21 (prepared for Wellington Regional Council).

Stevens G (1991). On shaky ground: A geological guide to the Wellington metropolitan region. DSIR Geology and Geophysics and the Geological Society of New Zealand, Lower Hutt.

Van Dissen R J (1991). Ground shaking hazard map for the Lower Hutt and Porirua areas: A summary report. DSIR Geology and Geophysics Contract Report 1991/42 (prepared for Wellington Regional Council).

APPENDIX 2: GLOSSARY OF TECHNICAL TERMS

Active fault A fault with evidence of surface movement in the last 50000 years or repeated surface movement in the last 500000 years.

Hazard A potentially damaging physical event.

Liquefaction Process by which water-saturated sediment temporarily loses strength, usually because of strong shaking and behaves as a fluid.

Risk The combination of a natural hazard event and our vulnerability to it. Risk can be specified in terms of expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular natural hazard.

Seiche Oscillation of the surface of an enclosed body of water owing to earthquake shaking.

Seismic To do with earthquake or earthquake-like motions in the earth.

Tsunami An impulsively generated sea wave of local or distant origin that results from seafloor fault movement, large scale seafloor slides or volcanic eruption on the seafloor.

APPENDIX 3: MODIFIED MERCALLI INTENSITY SCALE

MM 1 Not felt by humans, except in especially favourable circumstances but birds and animals may be disturbed. Reported mainly from the upper floor of buildings more than 10 storeys high. Dizziness or nausea may be experienced. Branches of trees, chandeliers, doors and other suspended

systems of long natural period may be seen to move slowly. Water in ponds, lakes and reservoirs may be set into seiche oscillation.

MM II Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed. The long period effects listed under MM I may be more noticeable.

MM III Felt indoors but not identified as an earthquake by everyone. Vibration may be likened to the passing of light traffic. It may be possible to estimate the duration but not the direction. Hanging objects may swing slightly. Standing motorcars may rock slightly.

MM IV Generally noticed indoors but not outside. Very light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building. Walls and frames of buildings are heard to creak. Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock and the shock can be felt by their occupants.

MM VI Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. Slight damage to Masonry D. Some plaster cracks or falls. Isolated cases of chimney damage. Windows, glassware and crockery broken. Objects fall from shelves and pictures from walls. Heavy furniture overturned. Small church and school bells ring. Trees and bushes shake or are heard to rustle. Loose material may be dislodged from existing slips, talus slopes, or shingle slides.

MM VII General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars. Trees and bushes strongly shaken. Large bells ring. Masonry D cracked and damaged. A few instances of damage to Masonry C. Loose brickwork and tiles dislodged. Unbraced parapets and architectural ornaments may fall. Stone walls cracked. Weak chimneys broken, usually at the roofline. Domestic water tanks burst. Concrete irrigation ditches damaged. Waves seen on ponds and lakes. Water made turbid by stirred-up mud. Small slips and caving in of sand and gravel banks.

MM VIII Alarm may approach panic. Steering of motorcars affected. Masonry C damaged, with partial collapse. Masonry B damaged in some cases. Masonry A undamaged. Chimneys, factory stacks, monuments, towers and elevated tanks twisted or brought down. Panel walls thrown out of frame structures. Some brick veneers damaged. Decayed wooden piles broken. Frame houses not secured to the foundations may move. Cracks appear on steep slopes and in wet ground. Landslips in roadside cuttings and unsupported excavations. Some tree branches may be broken off. Changes in the flow or temperature of springs and wells may occur. Small earthquake fountains may form.

MM IX General panic. Masonry D destroyed. Masonry C heavily damaged, sometimes collapsing completely. Masonry B seriously damaged. Frame structures racked and distorted. Damage to foundations general. Frame houses not secured to the foundations shifted off. Brick veneers fall and expose frames. Cracking of the ground conspicuous. Minor damage to paths and roadways. Sand and mud ejected in alleviated areas, with the formation of earthquake fountains and sand craters. Underground pipes broken. Serious damage to reservoirs.

MM X Most masonry structures destroyed, together with their foundations. Some well built wooden buildings and bridges seriously damaged. Dams, dykes and embankments seriously damaged. Railway lines slightly bent. Cement and asphalt roads and pavements badly cracked or thrown into waves. Large landslides on river banks and steep coasts. Sand and mud on beaches and flat land moved horizontally. Large and spectacular sand and mud fountains. Water from rivers, lakes and canals thrown up on banks.

MM XI Wooden frame structures destroyed. Great damage to railway lines and underground pipes.

MM XII Damage virtually total. Practically all works of construction destroyed or greatly damaged. Large rock masses displaced. Lines of sight and level distorted. Visible wave-motion of the ground surface reported. Objects thrown upwards into the air.

APPENDIX 4: GEOLOGICAL DESCRIPTIONS OF HAZARD ZONES

Zone 1: Greywacke bedrock, including areas overlain by less than 10 metres of deeply weathered gravel and loess, or well engineered fill.

Zone 2: Alluvial gravel and fan alluvium; fine to coarse gravel, up to 200 metres thick, with some beds and lenses of finer grained sediment (sand, silt, clay, and peat) usually less than 5 metres thick. The coarse sediments typically have moderate to high SPT values (20 to 60). At Titahi Bay, 10 to 20 metre thickness of extremely weak silty sandstone with lenses of gravel or about a 5 to 10 metre thickness of windblown sand.

Zone 5: Soft sediment (fine sand, silt, clay and peat) up to 10 to 30 metres thick, at or very near the surface, underlain by bedrock or a variable thickness of gravel and other finer grained sediment. Shear wave velocities for these *flexible* sediments at Porirua are in the order of 110 metres/second.