GROUND SHAKING HAZARD WELLINGTON

NOTES TO ACCOMPANY

SEISMIC HAZARD MAP SERIES: GROUND SHAKING HAZARD MAP SHEET 1 WELLINGTON (FIRST EDITION) 1:20000

OCTOBER 1992

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Publication WRC/PP-T-92/45

Compiled by

P A Kingsbury and W J Hastie

POLICY AND PLANNING DEPARTMENT

WELLINGTON REGIONAL COUNCIL

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, has 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 logs, microearthquake records, strong motion earthquake records and penetrometer logs.

The distribution of geological materials in the Wellington City area was mapped primarily on an assessment of 804 drillhole logs. The shaking response of a representative suite of these materials was assessed at 27 sites using records from 30 microearthquakes, and at 12 sites using strong motion earthquake records from a Magnitude 6 and a Magnitude 7 earthquake. The properties of the *softer* geological materials were further quantified using four cone penetrometer and three seismic-cone penetrometer probings.

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).

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 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.

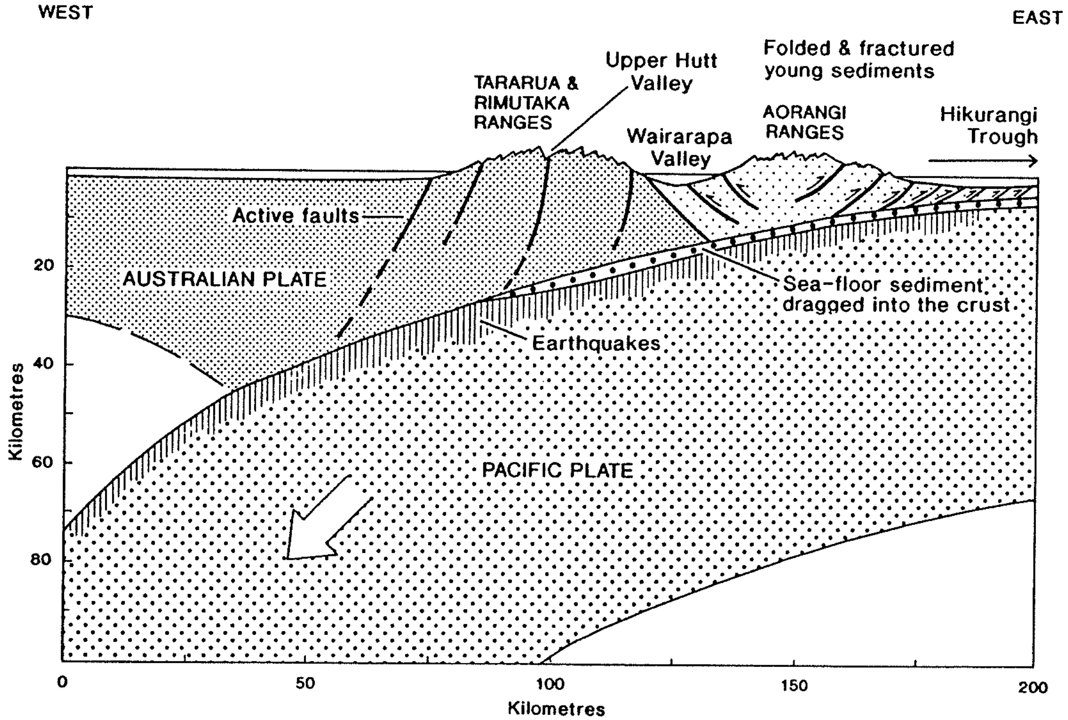

Figure 1: Source of earthquakes at plate boundary and along active faults. (After Stevens, 1991).

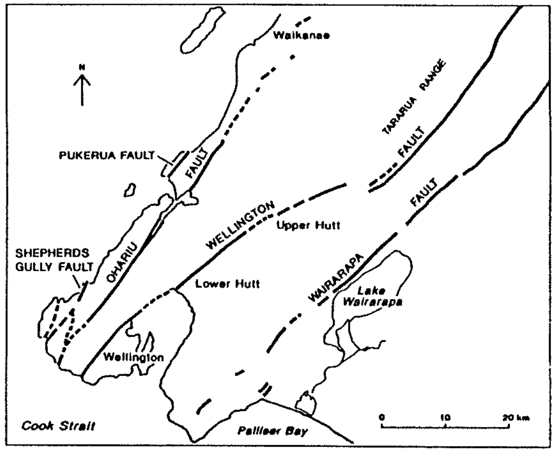

Figure 2: Active faults in the western part of the Wellington Region.

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

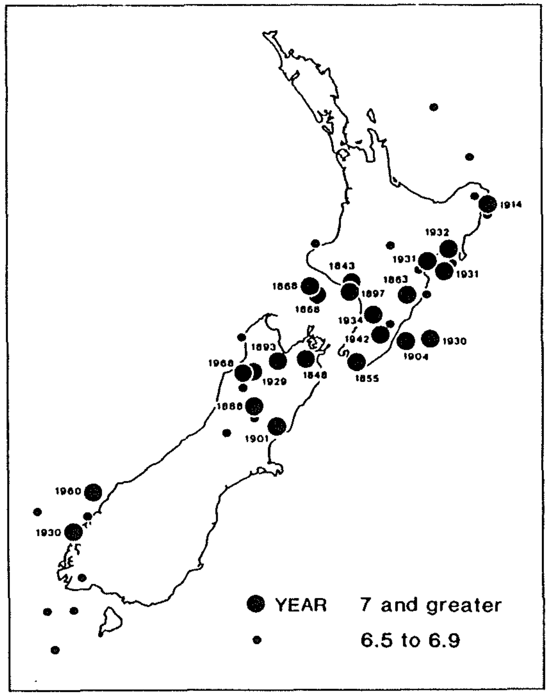

Figure 3: Epicentres of shallow earthquakes of magnitude 6.5 and greater since 1840 (Van Dissen et al, 1992).

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 not occur at particular ground shaking frequencies and strengths.

2.3 MAPPING METHODOLOGY

2.3.1 Surface geology

The distribution of Quaternary sediments was summarised in a series of maps at scales of 1:10000 and 1:20000. The maps, based on the drillhole logs, depict:

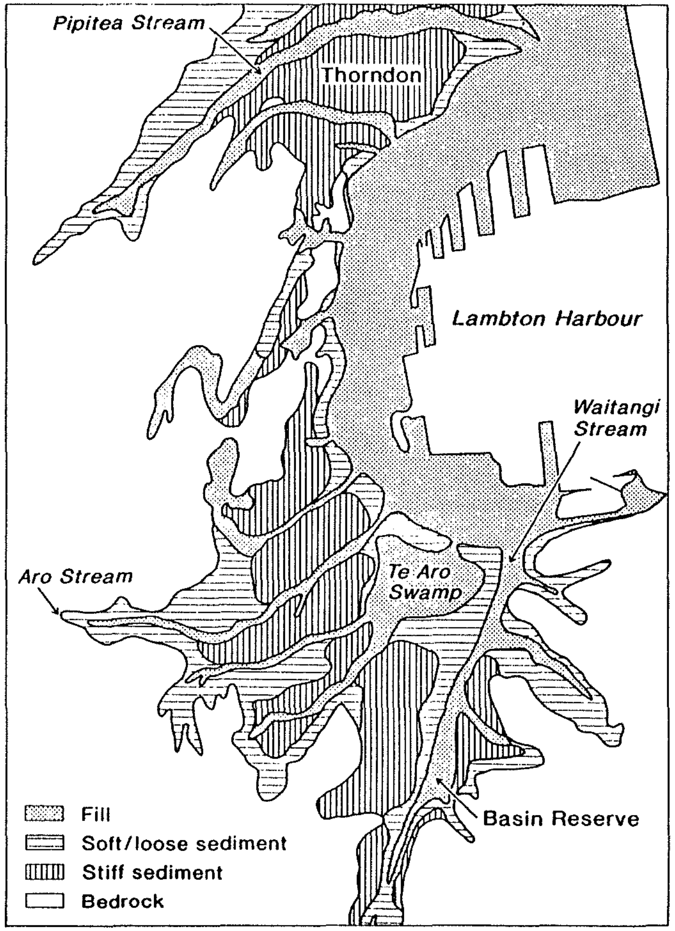

Figure 4: Sediment distribution in Wellington central city area. (After Perrin and Campbell, 1992).

* The distribution of surface sediment types (Figure 4).
* The thickness of near-surface soft and/or loose sediment (Figure 5).
* The total sediment thickness to bedrock.

The maps provide the geological base for the ground shaking hazard zones.

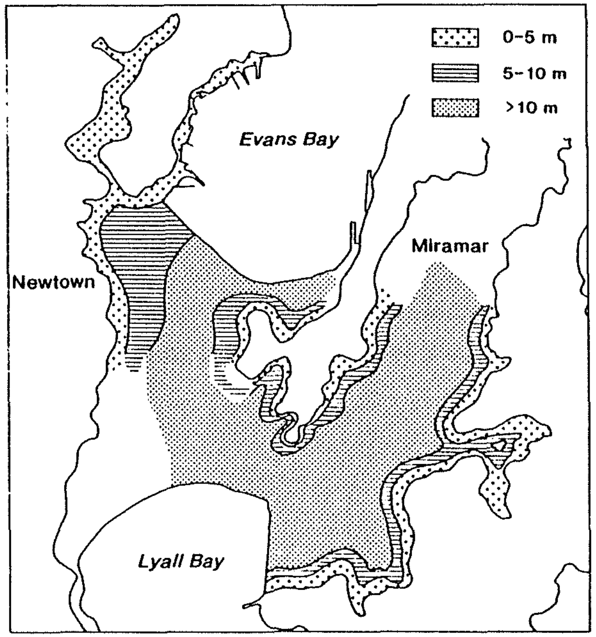

Figure 5: Soft sediment thicknesses in the Miramar-Kilbirnie area. (After Perrin and Campbell, 1992).

2.3.2 Weak ground motions

The microearthquake recording sites sampled a variety of geological ground conditions, ranging from bedrock to thick, soft, fine-grained marine sediment.

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 six bedrock sites had peak Fourier spectral ratios (FSR) of less than 1.7. Sites showing the highest amplifications of earthquake ground motions, relative to the reference bedrock site, were located adjacent to Lambton Harbour, in Miramar, Te Aro, Kent Terrace, Seatoun, the airport and part of Wellington Hospital. These sites had high to very high peak amplifications (FSR = 5.1 to 6.6), and with the exception of Seatoun, were underlain by more than 10 metres of soft and/or loose material. Nine of the weak motion sites were located on firm material (compact gravel and/or stiff to hard clay). These sites had low to moderate amplifications of earthquake ground motions (FSR = 1.6 to 3.3). The remaining four sites were underlain by 5 to 10 metres of soft and/or loose material, and showed moderate to high amplifications (FSR = 2.7 to 4.5).

2.3.3 **Penetrometer probings**

The nature of the near-surface material at several of the highest amplification sites was further defined using cone penetrometer and seismic-cone penetrometer probing (Figure 6). In Miramar the probe reached 7 metres before refusal, the result of accumulated side friction rather than high tip resistance. Using the seismic probe a shear wave velocity of 200 metres/second was measured for the upper 5 metres. The probe site in the grounds of Wellington Hospital reached 10 metres before refusal. Much of the material encountered was low strength with a shear wave velocity of 122 to 224 metres/second. In Te Aro (Jacobs Place) probing revealed at least 6 metres of material (fill, gravel and soft *flexible* sediment) with a shear wave velocity between 125 to 150 metres/second. The probes refusal at 6.2 metres may have been the result of a gravel layer, rather than the base of the deepest soft *flexible* layer.

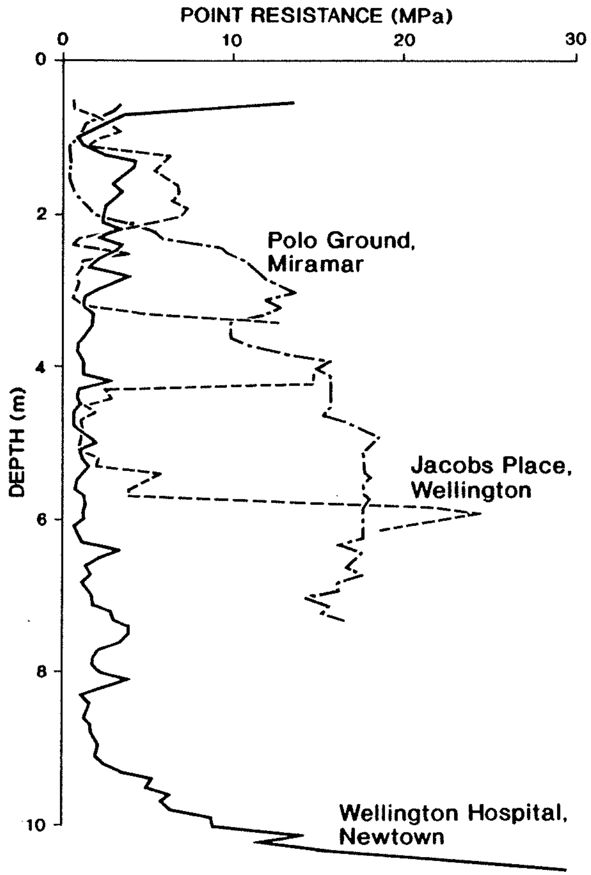

Figure 6: Cone penetrometer test results at three sites in Wellington City area. (After Stephenson and Barker, 1992).

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 Wellington study area was mapped into four ground shaking hazard zones; Zone 1, Zone 2, Zone 3-4, 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 areas are underlain by firm material, including compact gravel and stiff to hard clay or less than 5 metres of soft and/or loose material, and show low to moderate amplification of earthquake shaking, relative to bedrock.

Zone 3-4 represents a transition zone between the low to moderate amplification of ground shaking anticipated in Zone 2 and the high to very high amplification anticipated in Zone 5. Zone 3-4 areas are typically underlain by 5 to 10 metres of near surface soft and/or loose material, and are characterised by moderate to high amplification of earthquake ground motion relative to bedrock.

Zone 5 areas are underlain by more than 10 metres of soft and/or loose material. These materials generally have shear wave velocities in the order of 200 metres/second or less. Zone 5 areas are characterised by high to very high amplification of earthquake ground motion, relative to bedrock, and are therefore subject to the greatest ground shaking hazard.

Figure 7 illustrates some of the relationships between the ground shaking hazard zones and the geology.

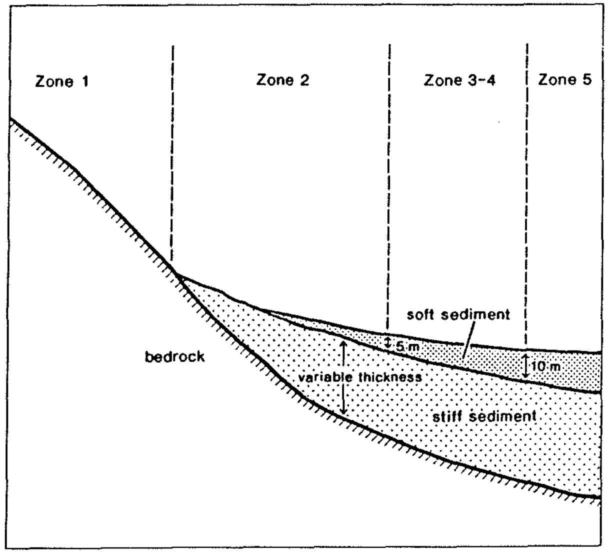

Figure 7: Diagrammatic cross section showing typical relationships between lithologies and ground shaking hazard zones. (After Van Dissen *et al*, 1992).

LITHOLOGY		DESCRIPTION	SPT N (Blows/300 mm)	SHEAR WAVE VELOCITY m/sec.
A	Fill	Loose rock fill, hydraulic fill	0 to 35 Typically 5	50 to 150
B	Loose	Sand/gravel/non-cohesive silt. Post-glacial.	5 to 60 Typically 20	150 to 200
Bb	Beach	Sand/silt/gravel with shells. Post-glacial.	Predominantly 5 May be up to 35 where gravelly	100 to 200
C	Soft	Clay/cohesive silt/peat. Post-glacial.	5 to 40 but typically 10	100 to 200
D	Stiff	Clay/silt with gravel. Organic layers present, also dense gravel. Pleistocene.	Main range 30 to 70, with soft layers <2 m thick to N=10	200 to 500
E	Bedrock	CW sandy silt/clay HW weak gravel MW mod. hard rock SW-UW hard rock	5 to 150 >150 >150 >150	Approximately 500 500 to 750 750 to 1000 1000 to 2000

Table 1: Summary physical properties of lithologies.

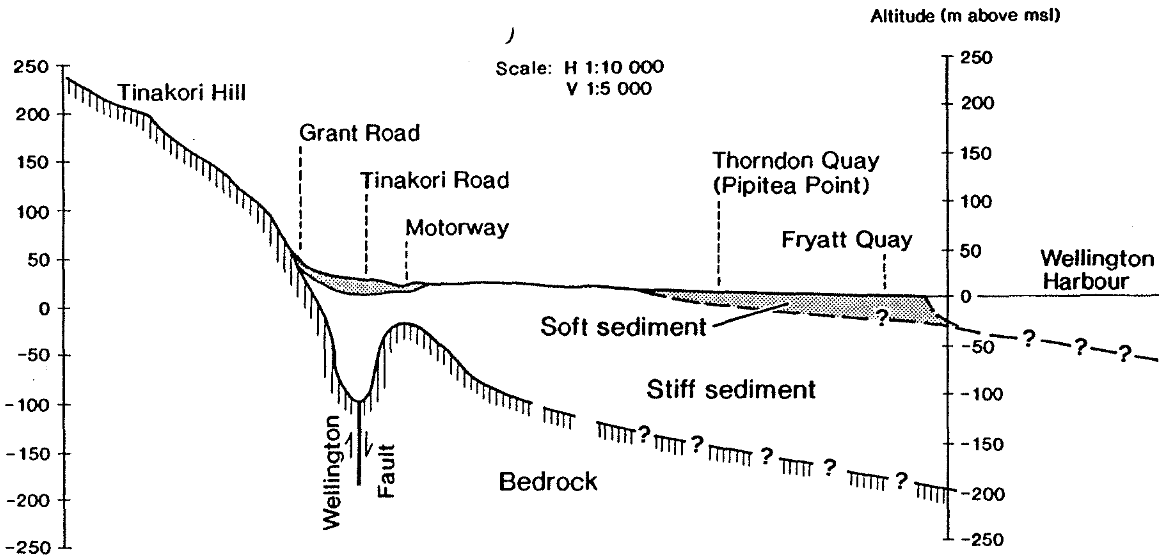

Figure 8: Geological cross section through Wellington City area. (After Perrin and Campbell, 1992).

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 physical properties of the geological materials is given in Table 1. Figure 8 shows the subsurface distribution of materials between Tinakori Hill and Fryatt Quay.

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.

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 Zones 2 and 3-4 is expected to be slightly stronger than Zone 1.

Scenario 1				
Zones	**MM Intensity**	**Peak Ground Acceleration (g)**	**Duration**	**Amplification of Ground Motion (FSR)**
1	V-VI	0.02-0.06	< 5 sec.	< 2x
2	VI	0.02-0.1	2-3x	1.5-3.5x
3-4	VI-VII	0.02-0.1	2-3x	2.5-5x
5	VIII-IX	< 0.3 generally between 0.1-0.2	> 3x	> 5x*
Scenario 2				
Zones	**MM Intensity**	**Peak Ground Acceleration (g)**	**Duration**	
1	IX	0.5-0.8	15-40 sec.	
2	IX-X	0.5-0.8	1-2x	
3-4	IX-X	0.5-0.8	1-2x	
5	X-XI	0.6-0.8	> 2x	

* Peak amplifications at most sites within Zone 5 occurred within a narrow frequency band between 1-2Hz.

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

In terms of MM intensity the response of Zone 1 is expected to be MM V with some VI, Zone 2 is MM VI, Zone 3-4 is MM VI-VII and Zone 5 is MM VII-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 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. However, the entire Wellington study area is within 8 kilometres

<table>
<tr><th colspan="2">SCENARIO 1 EARTHQUAKE</th></tr>
<tr><th>Hazard Zones</th><th>Ground conditions and likely effects</th></tr>
<tr><td>1</td><td>"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.</td></tr>
<tr><td>2</td><td>Alluvial Deposits : Little or no significant damage likely. Small local failures on river banks possible.</td></tr>
<tr><td>3-4</td><td>Thicker Alluvial Deposits : Little widespread damage expected. Small localised failures of banks adjacent to rivers, streams, or cuts. Some local cracking and sand ejection possible at MM VII.</td></tr>
<tr><td>5</td><td>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.</td></tr>
<tr><th colspan="2">SCENARIO 2 EARTHQUAKE</th></tr>
<tr><th>Hazard Zones</th><th>Ground conditions and likely effects</th></tr>
<tr><td>1</td><td>"Greywacke" Bedrock : Small failures of bedrock and surficial deposits. Widespread on steep slopes and on steep unsupported cuts (>2 m high).</td></tr>
<tr><td>2</td><td rowspan="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.</td></tr>
<tr><td>3-4</td></tr>
<tr><td>5</td><td>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.</td></tr>
</table>

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

of the surface trace of the Wellington Fault. Therefore, distance from the Fault is not expected to be a dominant factor in determining the relative levels of shaking within the study area.

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 IX is expected in Zone 1. In both Zones 2 and 3-4 the response is expected to be MM IX-X. 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 Zones 2 and 3-4. 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*. Strong long period response is also anticipated for the deepest sediment sites within the study area.

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, 0.5 to 0.8g; Zone 2, 0.5 to 0.8g; Zone 3-4, 0.5 to 0.8g and Zone 5, 0.6 to 0.8g.

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 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 Zone 3-4, 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 Zone 3-4, and greater than 2 times for Zone 5 (Table 2).

2.5.4 **Amplification of ground motion spectrum**

Characteristic peak Fourier spectral ratios, within the frequency band of 0.5 to 4 Hz, 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.

Ground motion amplification at most of the sites in Wellington occurs over a broad frequency band. However, some sites, particularly those in Zone 5, exhibit a narrow (resonant) frequency response. Site resonance is of most concern where built structures have natural periods that coincide with the resonant period band(s) of strong ground shaking. All Zone 5 sites had peak amplifications within a narrow (less than 2 Hz wide) frequency band. The maximum occurs in the range from 1 to 2 Hz, except for Kent Terrace and Wellington Hospital where maxima occur at 2.5 and 4 Hz respectively. Seatoun is also noted for its amplified (FSR greater than 4) high frequency response between 5 to 12 Hz.

Even though the ground motion amplifications measured in Wellington were recorded during non-damaging earthquakes it is significant to note that intensity maps, prepared in the 1970's 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. For example, it is unclear whether infilled channels in the Willis Street/Cuba Street area (mapped as Zone 3-4) are extensive enough to result in the moderate to high amplifications anticipated in Zone 3-4. A conservative approach was adopted.

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

(2) The distribution of materials causing high amplifications is not well defined in some areas. The poorly resolved boundary around the Zone 5 areas is denoted as a *dot-dash* line on the ground shaking hazard map.

(3) Near-surface shear wave velocities, including velocity profiles, for the geological materials in the Wellington study area are not well known. Shear wave velocity is the parameter that best correlates with site amplification.

(4) Amplification of ground motion due to topographic effects has not been addressed for this study. Though probably localised, these effects can be pronounced.

(5) 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.

(6) 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.

(7) 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.

(8) 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 Wellington 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, strong motion earthquake records and penetrometer logs. Four ground shaking hazard zone were established . These are Zone 1, Zone 2, Zone 3-4 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 3-4 areas show moderate to high amplification of earthquake motions and are typically underlain by 5 to 10 metres of near-surface soft and/or loose 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

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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.

g: Gravity. For an earthquake which produces a ground acceleration of 0.4g the actual acceleration is 40 percent of gravity.

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.

Quaternary: Geological time period spanning the last 2 million years.

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 few a 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 wakened. 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 V Generally felt outside and by almost everyone indoors. Most sleepers awakened. A few people frightened. Direction of motion can be estimated. Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Some windows cracked. A few earthenware toilet fixtures cracked. Hanging pictures move. Doors and shutters may swing. Pendulum clocks stop, start or change rate.

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: Bedrock. Moderately to very strong sandstone and siltstone (argillite), collectively referred to as *Greywacke*, also includes areas where bedrock is overlain by less than 10 metres of deeply weathered gravel and loess or well engineered fill.

Zone 2: Stiff Sediment. Compact to very compact granular material, and stiff to hard clay (completely weathered bedrock), up to a thickness of about 120 metres. Materials in this zone typically have Standard Penetration Test (SPT) values in the range of 30 to 70, and are primarily composed of Pleistocene gravel, including periglacial deposits, and stream and fan alluvium. The coarser deposits are often interfingered with beds and lenses of finer grained sediment (sand, silt, clay and peat) usually less than 5 metres thick. Areas where fine-grained sediment is present at the surface are also mapped as Zone 2 when the thickness of fine-grained sediment is less than 5 metres.

Zone 3-4: Transition Zone Between Zone 2 and Zone 5. Non-bedrock areas that are not mapped as Zone 2 and are underlain by less than 10 metres of near-surface soft and/or loose sediment. Zone 3-4 areas are typically underlain by 5 to 10 metres of near surface soft and/or loose sediment and a variable thickness, up to about 150 metres, of stiff sediment.

Zone 5: Soft and Loose Sediment. More than 10 metres of near-surface fine-grained, cohesive, soft sediment, or coarse-grained, non-cohesive loose to medium dense sediment. These materials comprise Holocene (less than 10000 years old) marine, terrestrial, and stream deposits, underlain by bedrock or a variable thickness, up to about 150 metres, of stiff sediment. Zone 5 materials have SPT values in the order of 10, ranging from 5 to 40 and shear wave velocities of 125 to 225 metres/second.