LIQUEFACTION HAZARD WELLINGTON

NOTES TO ACCOMPANY

SEISMIC HAZARD MAP SERIES: LIQUEFACTION HAZARD MAP SHEET 1 WELLINGTON (FIRST EDITION) 1:50000

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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 purpose 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 the earthquake hazard.

1.2 PURPOSE OF MAP AND BOOKLET

A series of four map sheets, with accompanying booklets, has been compiled to describe the liquefaction and ground damage hazard for the main metropolitan areas in the western part of the Region (refer to Index Map on accompanying map sheet):

- Sheet 1 - Wellington.
- Sheet 2 - Porirua.
- Sheet 3 - Hutt Valley.
- Sheet 4 - Kapiti.

The liquefaction hazard in the Wairarapa is summarised in booklet form only.

The purpose of the maps is to show the areas susceptible to liquefaction, and the geographic variation in liquefaction potential and liquefaction ground damage that can be expected during two earthquake scenarios (refer Part 7). The map sheets and booklets have been compiled from detailed reports prepared for the Wellington Regional Council by **Works Consultancy Services Ltd.** Substantial parts of this booklet are taken directly from a report prepared by Brabhaharan and Jennings (1993) of Works Consultancy Services Ltd. Geology information from studies by the **Institute of Geological and Nuclear Sciences Ltd** for the Regional Council was used for the liquefaction hazard assessment.

In recognition of earthquake hazards in the Region, the Wellington Regional Council is developing a strategy aimed at achieving an *acceptable level of risk* from earthquake and geologic hazards. The Regional Council's strategy will promote the use of seismic and geologic hazard information in planning and development, and for civil defence. The strategy will also help to raise public awareness of such hazards.

Studies on surface fault rupture, ground shaking hazard and tsunami hazard have been completed by the Regional Council. Information on active faults in the Region was published in a series of maps by the Regional Council (McMenamin and Kingsbury, 1991a, b and c). A series of six maps and booklets describing the ground shaking hazard in the Region was published by the Regional Council in 1992 (Kingsbury and Hastie, 1992a, b, c, d, e and f). Tsunami hazard information for Wellington Harbour is also available from the Regional Council.

1.3 BOOKLET STRUCTURE

This booklet is divided into eight main parts. Part 1 provides background information on the study. Part 2 describes the liquefaction hazard maps and the hazard classifications used. The types of ground damage from liquefaction and the liquefaction assessment methodology adopted are outlined in Parts 3 and 4 respectively. Part 5 states the qualifications and limitations that determine the certainty with which the liquefaction hazard information can be used. The sources of information and type of field investigations carried out are summarised in Part 6. Part 7 defines the two earthquake scenarios used in the study. Background geology information and ground conditions in 13 subareas of the Wellington study area are described in Part 8.

Appendix 1 lists the contributing reports and references. Technical words and terms are defined in Appendix 2. The Modified Mercalli Intensity scale is given in Appendix 3. The classification of masonry structures referred to in the Modified Mercalli Intensity scale is given in Appendix 4.

2. LIQUEFACTION HAZARD MAPS

2.1 LIQUEFACTION POTENTIAL MAP

The potential for liquefaction during two earthquake scenarios (refer Part 7) is shown on the accompanying map sheet (Map A) at a scale of 1:50000. The potential zones are based on surface geology and sediment distribution information (Perrin and Campbell, 1992), the assessed ground shaking hazard (Van Dissen et al., 1992), the liquefaction assessment (refer Part 4) and a review of historical records of liquefaction (McMinn et al., 1993).

The potential for liquefaction in the Wellington study area has been classified into the following zones:

- **High** potential for liquefaction. Liquefaction during both Scenarios 1 and 2.
- **Moderate** potential for liquefaction. Liquefaction unlikely or marginal during Scenario 1.
- **Variable** potential for liquefaction. Liquefaction potential varies at different locations from low to high. This zone includes areas where the available information suggests soils have a variable potential for liquefaction or soils are unlikely to liquefy at some locations within the same general area.
- **Low** potential for liquefaction. Liquefaction may occur during Scenario 2. This zone includes areas where the soils are considered to be susceptible but may or may not liquefy because of their density, fines content or gravel content.
- **No liquefaction.** Area(s) not susceptible to liquefaction.

The liquefaction potential information was compiled at a scale of 1:10000 for the central business district and 1:20000 for the remainder of the Wellington study area.

2.2 LIQUEFACTION INDUCED GROUND DAMAGE MAP

The likely ground damage arising from liquefaction of the soils in the Wellington study area is shown on the accompanying map sheet (Map B) at a scale of 1:50000.

The ground damage potential has been classified into the following zones:

- Potential for lateral spreading and large subsidence during both Scenarios 1 and 2.
- Potential for lateral spreading during Scenario 2 only, and subsidence during both Scenarios 1 and 2.
- Potential for subsidence during both Scenarios 1 and 2.
- Potential for subsidence during Scenario 2 and only minor subsidence during Scenario 1.
- Potential for subsidence during both Scenarios 1 and 2, but not widespread.
- Potential for minor subsidence during Scenario 2 only.
- Area(s) not susceptible to liquefaction. No ground damage expected.

The liquefaction ground damage information was compiled at a scale of 1:10000 for the central business district and 1:20000 for the remainder of the Wellington study area.

3. LIQUEFACTION INDUCED GROUND DAMAGE

3.1 INTRODUCTION

The nature and extent of ground damage was assessed for two earthquake scenarios (refer Part 7) based on available literature and engineering judgement.

The main types of ground damage due to liquefaction are subsidence, slope failure of sloping ground, and lateral spreading of natural banks and embankments built on liquefiable ground. Where a non-liquefiable surface layer overlies material susceptible to liquefaction, liquefaction induced ground damage at the ground surface will be minimal. Where lateral spreading is likely, the presence of a non-liquefiable surface layer will not necessarily preclude ground damage.

3.2 GROUND SUBSIDENCE

The magnitude of liquefaction induced ground subsidence was estimated for key boreholes (refer Part 8.2), based on the thickness of soils likely to liquefy, and earthquake Scenarios 1 and 2 (refer Part 7). During a Scenario 1 event subsidence is likely to range from 50 to 100 mm, and 25 to 150 mm for a Scenario 2 event. The estimated subsidence values for specific locations in the Wellington study area are given in Brabhaharan and Jennings (1993). The assessment of subsidence is based on a method proposed by Tokimatsu and Seed (1987) and is modelled on an earthquake of Richter magnitude 7.5. The estimated subsidence values for the Wellington study area are therefore conservative for a Scenario 1 event.

3.3 SLOPE FAILURES

Most of the areas susceptible to liquefaction in the Wellington study area are located in the relatively flat area between the present reclaimed coastline and the hills. Liquefaction could cause failure of the slopes, banks and seawalls along the harbour/waterfront.

3.4 LATERAL SPREADING

Lateral spreading is likely to affect areas adjacent to stream banks and coastal areas.

For the purpose of this study the following assumptions were made for the preparation of the ground damage maps:

(1) Areas within 50 metres of the harbour waterfront are affected by lateral spreading, where liquefaction occurs following a Scenario 1 earthquake.

(2) Areas within 200 metres of the harbour waterfront are affected by lateral spreading, where liquefaction occurs following a Scenario 2 earthquake.

Embankments or abutments constructed on liquefiable ground can also undergo lateral spreading. However, this will depend on construction details and ground improvement measures carried out during construction. Ground damage of embankments and other earth structures was not assessed in this study.

3.5 DISCUSSION

The soils in the Wellington study area have a variable potential for liquefaction during a Scenario 1 event. During a Scenario 2 event the majority of the soils have a high potential for liquefaction.

In the Ngauranga interchange area the soils are likely to liquefy in a Scenario 2 event, but may be resistant to liquefaction during a Scenario 1 event. In the reclamation area between Kaiwharawhara and Bunny Street, liquefaction of the fill material and sediments beneath are likely to under Scenarios 1 and 2. The reclaimed area along Featherston Street/Lambton Quay appears to be resistant to liquefaction during a Scenario 1 event. However, the sediments beneath the fill material are likely to liquefy during a Scenario 2 event. The reclaimed areas along Jervois Quay, Wakefield Street and Oriental Bay are susceptible to liquefaction during both Scenario 1 and 2 events.

The unreclaimed areas of Thorndon and Te Aro have a variable potential for liquefaction, with greater potential along old stream courses. The Cambridge Terrace/Kent Terrace corridor and the Basin Reserve area are likely to liquefy in both Scenarios 1 and 2. The soils in the Newtown area are generally resistant to liquefaction in a Scenario 1 event but are likely to liquefy during a Scenario 2 event. The southern upper part of the Newtown Valley is likely to have a lower and variable potential for liquefaction.

The potential for liquefaction in the Evans Bay reclamation area is high. The potential increases from west to east. In the eastern part liquefaction is likely during both Scenarios 1 and 2, while the western end is unlikely to liquefy in a Scenario 1 event. The Lyall Bay/airport area also has potential for liquefaction under both Scenarios 1 and 2. The Rongotai, Lyall Bay, Miramar and Seatoun areas have a low potential for liquefaction.

4. LIQUEFACTION ASSESSMENT

4.1 DEFINITION AND EXPLANATION

Earthquake induced liquefaction of soils is caused by ground shaking, giving rise to an increase in porewater pressure in loose, mainly cohesionless, soils. When porewater pressures cannot dissipate rapidly and become equal to the overburden stress, the soil liquefies and looses most of its shear strength. This state is known as *initial liquefaction.*

Liquefaction most commonly occurs in loose sands and silty sands, but may also occur in loose sandy gravels and low plasticity sandy silts and silts. Soft cohesive soils such as clays and silty clays do not strictly undergo liquefaction. However, lateral spreading, flow slides or failure of structures due to a significant loss of undrained shear strength may result from strong ground shaking.

4.2 METHODOLOGY

The following methodology was used to assess liquefaction hazard in the Wellington study area:

(1) Identification of areas vulnerable to liquefaction based on the geology and selection of key boreholes.

(2) Assessment of the liquefaction susceptibility of soils based on soil descriptions and particle size distributions.

(3) Assessment of liquefaction potential using a variety of techniques based on available information.

(4) Evaluation of expected ground damage for two earthquake scenarios based on the assessed potential for liquefaction, thickness of liquefiable and overlying liquefaction resistant layers, and topography.

(5) Consideration of past earthquake events and any observed liquefaction and ground damage, to confirm assessment.

4.3 LIQUEFACTION SUSCEPTIBILITY

Soils susceptible to liquefaction were identified based on the description of the soils in key boreholes and, where available, particle size distribution analyses.

Generally, loose to medium dense sand and silty sand were identified as susceptible to liquefaction. Loose sands with more than 35 percent fines (low plasticity sandy silts or silts) or more than 35 percent gravel (sandy gravels) were identified as possibly susceptible to liquefaction. *Fines* are defined as the percentage of soil fraction having a grain size of less than 63 um.

4.4 LIQUEFACTION POTENTIAL

Soils in areas considered to be susceptible to liquefaction were assessed using liquefaction evaluation procedures developed by Ambraseys (1988), and Seed and Idriss (1982). Details of the procedures are given in Brabhaharan and Jennings (1993). The potential for liquefaction was evaluated for two earthquake scenarios (refer Part 7) using information from the key boreholes.

4.5 HISTORICAL EVIDENCE

A review of historic records of liquefaction was carried out as part of the study (McMinn et al., 1993). Liquefaction may have occurred in the Wellington study area during the 1848 Marlborough earthquake, 1855 Wairarapa earthquake, and the 1942 June and August Masterton earthquakes.

5. QUALIFICATIONS AND LIMITATIONS

The liquefaction hazard assessment used for the study and the map compilation procedures impose the following qualifications and limitations on the use of the information:

(1) The liquefaction hazard information is regional in scope and should not be considered as a substitute for site specific investigations and/or geotechnical engineering assessment for any project.

(2) The liquefaction hazard information given in this booklet and on the accompanying map sheet is based on the best information available at the time of the study and was supplied to the Regional Council under specific financial constraints. The liquefaction hazard information may be liable to change or review if new information is made available.

(3) While zones of liquefaction potential have been shown on the accompany map sheet, there is no certainty that liquefaction will occur in a particular area due to an earthquake of any size.

(4) Liquefaction could occur in some isolated areas not shown to be susceptible to liquefaction, for example, near streams.

(5) In areas of reclamation, the liquefaction potential and ground damage hazards include the related effect of densification of loose granular deposits during earthquake shaking.

(6) Ground damage due to densification of dry sand during earthquake shaking was identified for sand dune areas, but has not been assessed or shown on the accompanying map.

(7) There is limited information for parts of the study area. Therefore, the estimated lateral extent and the potential for liquefaction are indicative only.

(8) The boundaries between the various liquefaction and ground damage zones are approximate and indicative only.

(9) The classification of liquefaction potential and ground damage is indicative only, and does not imply any level of damage to particular structures or services.

6. COMPILATION OF DATA

Existing site investigation data was compiled for the Wellington study area from published reports, in-house records from past engineering projects and from information held by the Wellington City Council, Maritime Museum and New Zealand Rail Limited. A lack of information was identified in the Newtown, Miramar, Kilbirnie, Rongotai, Lyall Bay and Seatoun areas. Potentially liquefiable soils were considered to be present in these areas. Site investigations comprising two boreholes and Standard Penetration Tests (SPT), five Static Cone Penetration Tests (SCPT) and laboratory tests were carried out in these areas. Although there was a lack of data in other parts of the Wellington study area, no further investigations were carried out in these areas because of the limited urban development or the improbability of liquefaction occurring.

7. EARTHQUAKE SCENARIOS

7.1 THE SCENARIOS

No single earthquake event adequately describes the potential liquefaction hazard in the Region. Therefore, two earthquake scenarios were used to define the hazard:

Scenario 1: A large, distant, shallow (<60 km) earthquake that produces Modified Mercalli (MM) intensity of V-VI on bedrock over the Wellington Region. An example of such an event would be a magnitude (M) 7 earthquake centred 100 km from the study area at a depth of 15-60 km, perhaps similar to the 1848 Marlborough earthquake. The return period of a Scenario 1 event is 20-80 years.

Scenario 2: A large earthquake centred on the Wellington - Hutt Valley segment of the Wellington Fault. Rupture of this fault segment is expected to be associated with a magnitude 7.5 earthquake at a depth less than 30 km. The average recurrence interval for such an event is about 600 years and the probability of it occurring in the next 30 years is estimated to be 10 percent.

7.2 GROUND MOTION PARAMETERS

The large, distant, shallow Scenario 1 earthquake resulting in MM V-VI shaking on bedrock will be of sufficient duration and contain sufficient low period energy to allow long-period response to develop at deep (or soft) sediment sites (Van Dissen et al., 1992). This will result in a marked difference in the earthquake ground motions between rock sites and soft/deep soil sites. Van Dissen et al. (1992) have estimated the likely level of ground shaking for the various zones depending on the ground conditions (Table 1). As shown in the table, a Scenario 1 event is capable of producing a felt intensity of MM VIII-IX and peak ground acceleration of up to 0.3g in Zone 5 areas.

The large, local Wellington Fault event (Scenario 2) will give a higher level of ground shaking hazard throughout the Region but with smaller differences in average shaking between the different zones in comparison to a Scenario 1 event. The distance from the source is also important for this earthquake scenario. In general, shaking decreases with increased distance from the source. Most of the Wellington study area is within 5 km of the Wellington-Hutt Valley segment of the Wellington Fault, with the Miramar Peninsula within 10 km from the Wellington Fault. The predicted felt intensity in Zone 5 areas of the Wellington study area is MM X-XI and peak ground acceleration about 0.6 to 0.8g (Table 1).

Zones	Scenario 1		Scenario 2	
	MM Intensity	Peak Ground Acceleration (g)	MM Intensity	Peak Ground Acceleration (g)
1	V-VI	0.02-0.06	IX	0.5-0.8
2	VI	0.02-0.1	IX-X	0.5-0.8
3-4	VI-VII	0.02-0.1	IX-X	0.5-0.8
5	VIII-IX	0.1-0.3	X-XI	0.6-0.8

Table 1: Ground motion parameters for the ground shaking hazard zones in the Wellington study area.

8. GEOLOGY AND GROUND CONDITIONS

8.1 GEOLOGY

The New Zealand Geological Map, 1:250000, Sheet 12 Wellington (Kingma, 1967) shows the Wellington study area to be Wellington Greywackes of Triassic age and Ruahine Greywackes of Jurassic age, overlain by

Holocene and Pleistocene age sediments. The Wellington and Ruahine Greywackes comprise alternating dark grey argillite and sandstone. The Holocene age deposits comprise undifferentiated alluvium in fluviatile, floodplain, estuarine and beach deposits. Pleistocene age gravels, are also present. In addition to these natural deposits, large areas of reclamation fill are present. The fill materials vary from dense rockfill to soft hydraulic fill.

A more detailed description of the surface geology of the Wellington study area is given by Perrin and Campbell (1992).

8.2 GROUND CONDITIONS

The Wellington study area was divided into 13 subareas based on location, surface geology and topography. The subareas are underlain by soils which may have potential for liquefaction during earthquake shaking. These areas are:

- Ngauranga-Kaiwharawhara
- Kaiwharawhara-Thorndon Reclamation
- Thorndon
- Waterloo Quay Reclamation
- Featherston Street Reclamation
- Jervois Quay/Wakefield Street/Oriental Bay Reclamation
- Te Aro Flats
- Basin Reserve/Te Aro Swamp
- Newtown
- Kilbirnie/Lyall Bay
- Miramar/Airport
- Seatoun
- Island Bay

The northern and western suburbs and other hillside suburbs are generally underlain by rock. It is possible that alluvial deposits along stream valleys, and terrace and fan deposits contain sand and silty sand which are susceptible to liquefaction. However, the deposits are likely to be predominantly gravel and there is unlikely to be any significant risk of liquefaction.

One or more key boreholes in each subarea was chosen, based on the available geology information and geotechnical properties, to represent the ground conditions in each area. Where available, boreholes with soils susceptible to liquefaction were chosen to enable a liquefaction assessment to be carried out. The key boreholes were used for the assessment of the potential for liquefaction (refer Part 4). Static Cone Penetration Tests were used for liquefaction assessment where borehole information with geotechnical information was unavailable.

The ground conditions in each subarea are briefly discussed below.

The Ngauranga to Kaiwharawhara waterfront area, carrying the motorway and railway lines, is underlain by reclamation fill with soft/loose sediments in the lower part of Ngauranga Gorge. Boreholes indicate the area to be underlain by about 2 to 4 metres of fill, variable thickness of estuarine sediments and alluvium. The ground water level was recorded at about 4 metres depth in one borehole.

The Kaiwharawhara to Thorndon subarea covers the land to the seaward side of the Wellington Fault scarp and Thorndon Quay, between the Kaiwharawhara Stream and Pipitea Stream. The area is underlain mainly by reclamation fill with some soft/loose sediments near the Fault scarp. The reclamations consist of rockfill and hydraulic fill. The rockfill is probably Wellington Greywacke rock and the hydraulic fill is probably from dredging operations in Wellington Harbour. The ground water level is about 2 metres below ground surface.

The Thorndon subarea includes the inland (non-reclaimed) areas between Thorndon Quay, Bowen Street and the Tinakori hills. The Thorndon subarea is predominantly underlain by stiff sediments. Areas of soft/loose sediments exist along Tinakori Road and the old stream courses crossing the area. Ground water levels are at depths of about 2 metres or more below ground surface.

The Waterloo Quay reclamation covers the near-shore areas near Thorndon Quay and the reclaimed area to the seaward side of Thorndon Quay, between Davis Street and Bunny Street, and includes the container terminal. A historic plan shows the area to be reclaimed using rockfill. The rockfill is likely to be Wellington Greywacke rock. The ground water level is about 2.4 metres below the ground surface.

The Featherston Street reclamation covers the area to the seaward side of Lambton Quay, between Bunny Street and Willeston Street. A historic plan shows the northern part of the area to be reclaimed with rockfill but does not indicate the materials used for other parts of the reclamation.

The Jervois Quay/Wakefield Street/Oriental Bay reclamation subarea covers the waterfront reclamation along Jervois Quay, and the Wakefield Street area between Willeston Street and Oriental Bay. Fill materials overlie marine deposits on bedrock. The ground water level in this area is likely to be close to sea level and is likely to vary with the tide. In general, the ground water level is about 1 to 3 metres below ground surface.

The Te Aro Flats subarea covers the unreclaimed land approximately between Willis Street, Manners Street, Taranaki Street, Vivian Street, Cambridge Terrace, and Buckle Street/Webb

Street. This area is shown to be predominantly underlain by stiff sediments with fill and loose/soft sediments along old stream courses. The Basin Reserve and Te Aro Swamp areas are excluded from this subarea. Boreholes indicate ground water levels to be about 1 to 4 metres below ground surface.

The Basin Reserve/Te Aro Swamp subarea includes areas of poorer ground conditions in the Basin Reserve, along Cambridge/Kent Terraces and the Te Aro Swamp, approximately bounded by Vivian Street, Taranaki Street, Wakefield Street and Cambridge Terrace. These areas are underlain by soft/loose sediments and fill. Part of this area, including the Basin Reserve, was a swamp. The swamp drained following uplift during the 1855 Wairarapa earthquake. The ground water level is at a depth of about 1.5 to 1.8 metres below ground surface. In the Basin Reserve area the ground water level is at ground surface.

The Newtown valley extends south of the Basin Reserve. The area is underlain by soft/loose sediments in the middle of the valley, with stiffer sediments along the sides of the valley. The ground water level is at 2.2 metres depth below ground surface.

The Kilbirnie/Lyall Bay subarea includes Greta Point, Evans Bay, Hataitai, Rongotai, Kilbirnie and Lyall Bay. The Evans Bay area comprises fill and the remaining areas soft/loose sediments. The Kilbirnie, Rongotai and Lyall Bay areas are underlain by sands. Ground water level at Greta Point and Evans Bay is at a depth of about 2 to 2.5 metres below ground surface and is probably related to tide levels. At Lyall Bay ground water level was recorded at 3.6 metres depth and is likely to vary with the tide.

The Miramar/Airport subarea includes the central depression of the Miramar Peninsula and extends south to Lyall Bay. The area comprises soft/loose sediments, mainly sands. Ground water level at the Miramar Polo Ground is at a depth of 1.1 metres below ground surface and 1.5 metres depth at the airport.

The Seatoun area is located on the east coast of the Miramar Peninsula and is underlain by soft/loose sediments with some localised areas of fill.

The Island Bay valley comprises soft/loose sediment. Some stiff sediments and fill exist in the upper part of the valley.

APPENDICES

APPENDIX 1: CONTRIBUTING REPORTS AND REFERENCES

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Kingsbury P A and Hastie W J (1992a). Sheet 1 Wellington (1st ed.) Ground Shaking Hazard Map 1:20000. With notes. Wellington Regional Council, Wellington.

Kingsbury P A and Hastie W J (1992b). Sheet 2 Porirua (1st ed.) Ground Shaking Hazard Map 1:25000. With notes. Wellington Regional Council, Wellington.

Kingsbury P A and Hastie W J (1992c). Sheet 3 Lower Hutt (1st ed.) Ground Shaking Hazard Map 1:25000. With notes. Wellington Regional Council, Wellington.

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APPENDIX 2: GLOSSARY OF TECHNICAL WORDS AND 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.

Holocene The last 10000 years.

Jurassic The period of time that lasted from about 190 million years ago to 135 million years ago.

Lateral spreading The lateral extension and fracturing of a mass of surface rock and/or soil resulting from liquefaction or plastic flow of subjacent material.

Liquefaction Process by which water-saturated sediment temporarily loses strength, usually because of strong shaking and behaves as a fluid (refer to Part 4.1 of booklet for a more detailed definition).

Pleistocene The *Ice Age*. The period of time that lasted from about 2 million years ago to 10000 years ago.

SCPT Static cone penetration test. A cone is pushed into the ground. Penetration resistance (cone tip and friction sleeve) is recorded. Soil type can be interpreted from the penetration resistance.

SPT Standard penetration test. A tube is driven with hammer blows into the ground. For a standard depth of penetration the number of blows is recorded. Soil type can be interpreted from the penetration resistance. A sample of the ground is also recovered.

Seismicity Ground shaking due to release of energy by earthquake.

Triassic The period of time that lasted from about 235 million years ago to 190 million years ago.

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: CATEGORIES OF NON-WOODEN CONSTRUCTION

Masonry A. Structures designed to resist lateral forces of about 0.1 g, such as those satisfying the New Zealand Model Building Bylaws, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workmanship is good. Few buildings erected prior to 1935 can be regarded as in category A.

Masonry B. Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C. Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D. Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.