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Assessment and mapping of earthquake induced liquefaction hazards in the Wellington Region, New Zealand

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ABSTRACT The liquefaction hazards in the Wellington region have been systematically mapped. A study of the earthquakes and records of liquefaction in the region during the past 150 years confirmed the presence of significant liquefaction hazards. Two earthquake scenarios, a moderate distant event and a large event on the local Wellington Fault, were considered in the liquefaction assessment and mapping. The liquefaction hazard was mapped using a method specifically developed for the study, which comprised detailed liquefaction assessments at key locations where sufficient geotechnical information was available, followed by mapping using these point estimates and the near-surface geology of the area. Hazard maps for liquefaction susceptibility, potential and the consequent ground damage were prepared.

1 INTRODUCTION

The Wellington region, at the southern part of the North Island, is among the most seismically active areas in New Zealand. Past earthquakes and studies have shown that there is a high risk of damage from earthquakes in the region. The Wellington Regional Council is developing a strategy with an aim to achieving an acceptable level of risk from seismic and geological hazards in the region. Studies to date have involved mapping the surface geology and active faults of the region, and assessing the potential for ground shaking and liquefaction due to earthquakes.

Previous studies such as the Wellington Lifelines Study (Centre for Advanced Engineering, 1991) have highlighted the presence of a number of areas in the region, which have soils susceptible to earthquake induced liquefaction and consequent ground damage. Liquefaction can cause considerable damage to structures and services, and poses a significant hazard to the infrastructure of the region.

Liquefaction is a phenomena giving rise to a loss of shearing resistance or to the development of excessive strains as a result of transient or repeated disturbance of saturated cohesionless soils (National Research Council, 1985). It can be defined as the act

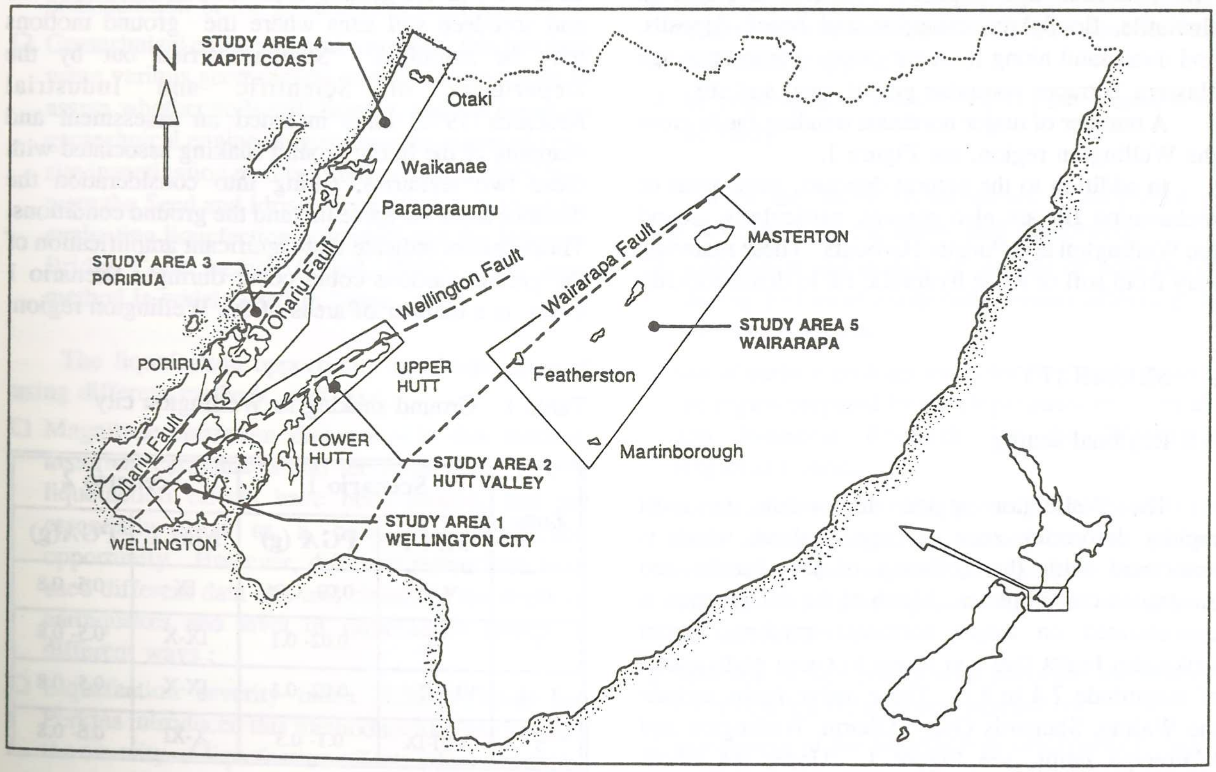

Figure 1 Wellington region and faults

or process of transforming cohesionless soils from a solid state to a liquefied state as a consequence of increased porewater pressure and reduced effective stress. Liquefaction most commonly occurs in loose sands and silty sands, but is also found to occur in loose sandy gravels, sandy silts and silts of low plasticity. Ground damage caused by liquefaction may be of the form of sand boils, subsidence, lateral spreading and flow slides.

'Liquefaction susceptibility' reflects the ground conditions in term of its vulnerability to liquefy when given sufficient ground shaking. 'Liquefaction opportunity' is the occurrence of earthquake shaking strong enough to generate liquefaction. 'Liquefaction potential' is the presence of both 'susceptibility' and 'opportunity' at a particular site, giving the likelihood that liquefaction could take place.

The liquefaction hazard study was carried out for the Wellington Regional Council (Works Consultancy Services, 1993). Five developed areas of the Wellington region, Wellington City, Hutt Valley, Porirua Basin, Kapiti Coast and Wairarapa (the "study areas"), were covered by the study, see Figure 1.

2 GEOLOGICAL SETTING

The Wellington region generally has a rugged terrain, predominantly composed of Wellington and Ruahine Greywacke of Triassic and Jurassic age, overlain by Holocene and Pleistocene age sediments. The Holocene age deposits comprise alluvium in fluviatile, floodplain, estuarine and beach deposits, and dune sand along the west coast. Pleistocene age Hawera Terraces comprise gravel, sand and silt.

A number of major northeast trending faults cross the Wellington region, see Figure 1.

In addition to the natural deposits, large areas of reclamation fill are also present, particularly around the Wellington and Porirua Harbours. These materials vary from soft or loose hydraulic fill to dense rockfill.

3 SEISMICITY

3.1 Regional setting

The Wellington region lies within the most rapidly deforming zone of New Zealand, which is associated with the collision of the Pacific and Australian crustal plates. Much of the deformation is concentrated on major northeast trending dextral strike-slip faults that can move to cause earthquakes of magnitude 7.4 to 8.0. These active faults include the Wairau, Shepards Gully, Ohariu, Wellington and Wairarapa faults, see Figure 1. Under the whole region, there is also a seismogenic zone where the Australian Plate overrides the subducting Pacific Plate.

3.2 Earthquake scenarios

Two earthquake scenarios were considered for the liquefaction hazard assessment. Scenario 1 is a large, distant, shallow (<60 km) earthquake that produces Modified Mercalli (MM) intensity shaking of V-VI in bedrock over the Wellington Region, with a return period of about 20 to 80 years. Such an event could be a magnitude 7 earthquake centred 100 km from the study area, at a depth of 15 km to 60 km.

A Scenario 2 event is 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 scenario approach was chosen by the Wellington Regional Council, given the potential for rupture of the Wellington fault to give a large magnitude 7.5 earthquake in close proximity to the developed areas of the region. The other scenario was chosen to represent ground shaking, from a distant earthquake with a higher probability of occurrence, which could be amplified by the soft soils present in some areas of the region.

3.3 Ground shaking

Observations during overseas earthquakes such as the 1989 Loma Prieta earthquake in California had shown that a large distant shallow earthquake (such as a Scenario 1 event) could result in a marked difference in the ground motions between rock sites and soft/deep soil sites where the ground motions may be amplified. Studies carried out by the Department of Scientific and Industrial Research (1992) have included an assessment and mapping of the likely ground shaking associated with these two scenarios, taking into consideration the distance from the epicentre and the ground conditions. These studies indicate that significant amplification of the ground motions could occur during a Scenario 1 event, in a number of areas of the Wellington region.

Table 1 Ground shaking in Wellington city

Zone	Scenario 1		Scenario 2	
	MM I	PGA (g)	MM I	PGA(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

(PGA - Peak Ground Acceleration)

Table 1 shows the peak ground accelerations and MM intensities assessed for the two scenarios, in the various ground shaking zones of the Wellington city study area. As shown in the table, there is a large difference between ground shaking in different zones during a distant Scenario 1 earthquake, while there is little variation in the ground shaking during an earthquake centred on the nearby Wellington fault.

4 LITERATURE REVIEW

Methods that have been used overseas to map liquefaction hazards are reported in the published literature. Youd (1991) presents a useful summary of the state-of-the art methods used by various people in different countries. A review of published literature showed that the following three approaches have been used by previous researchers for assessing liquefaction susceptibility :

- Historical liquefaction - this method involves mapping all historical records of liquefaction, and showing zones encompassing these previously liquefied areas as having a liquefaction hazard ;
- Geological mapping - while a number of variations to this method have been used, they essentially involved mapping the near-surface geology (and in some instances geomorphology), considering the age and type of soils contained in the deposits, and assigning a liquefaction hazard based on these parameters. Some studies have also included consideration of the groundwater level ;
- Geotechnical engineering assessment - this involves using various geotechnical engineering methods to assess whether soils will liquefy, and are based on geotechnical engineering parameters assessed from site investigation results. Methods commonly used were the Seed and Idriss' "simplified procedure for evaluating liquefaction potential" and the Japanese Bridge Code method (Youd, 1991). The latter method is widely used in Japan.

The liquefaction opportunity has been assessed using different methods, such as :

- Magnitude-maximum distance - in this method, historical earthquakes and the furthest distance of liquefaction effects have been plotted, and are essentially used as a basis for liquefaction opportunity. However, different researchers have used different data sets and classified the depth of earthquakes and level of liquefaction effects in different ways ;
- Liquefaction severity index (LSI) - Youd and Perkins introduced this method to take into account the severity of liquefaction effects which would be more important for engineering purposes (Youd, 1991). They correlated the maximum horizontal ground displacement of lateral spreading on liquefiable, gently sloping, late Holocene fluvial and deltaic deposits divided by 25, against the horizontal distance from the earthquake source ;
- Magnitude-peak acceleration criteria - this method involves the estimation of peak ground accelerations from seismic sources and attenuation models, taking into account the earthquake magnitude through magnitude scaling factors.

Past researchers have then derived liquefaction potential maps by the superposition of liquefaction opportunity and liquefaction susceptibility maps.

5 METHODOLOGY

A methodology was developed by the author for the liquefaction hazard study of the Wellington region. The methodology was tailored to suit :

- the requirement of the study to assess the hazard for two earthquake scenarios as discussed in section 3.2 above ;
- the variable ground conditions in the region, comprising soils which are clearly susceptible to liquefaction as well as many soils which are marginal ;
- the limited information available, both historical data on liquefaction and geotechnical data from site investigations ;
- the regional nature of the study, while requiring a reliability more than that which is achievable from geological mapping alone ;
- the constraints of resources and time available for the study.

Given the above requirements, a methodology was developed for the study, and comprised :

- compilation and review of records of liquefaction during historical earthquake events affecting the Wellington region ;
- use of surface geology maps for five study areas of the region prepared by the Department of Scientific and Industrial Research for the Wellington Regional Council ;
- compilation of accessible geotechnical information from site investigations carried out for various projects in the region, and carrying out some additional site investigations to fill in any gaps in the information ;
- selection of key points with adequate information for a detailed liquefaction assessment ;
- assessment of the liquefaction susceptibility based on the site investigation information collated and the surface geological map ;

- the ground shaking hazard maps with associated peak ground acceleration estimates prepared by the Department of Scientific and Industrial Research (1992) during previous studies for the Wellington Regional Council were used to represent liquefaction opportunity. This takes into account attenuation with distance, and amplification based on the ground conditions ;
- evaluation of the potential for liquefaction at the key points, using geotechnical methods ;
- extrapolation of the liquefaction assessment at the key points, based on the available site investigation information and the surface geology, to derive liquefaction hazard zones ;
- verification of the liquefaction assessment based on the available historical records of liquefaction ;
- assessment and mapping of ground damage due to liquefaction.

This methodology uses the combined information from historical liquefaction records, surface geology mapping, and geotechnical assessment. This is a better and more reliable approach than using only one of the three techniques used in overseas studies as discussed in section 4. This method particularly suits situations where only a limited amount of information is available.

The liquefaction opportunity from the ground shaking hazard study ensured that the magnitude, distance and soft soil amplification effects were taken into consideration. The liquefaction induced ground damage was assessed and shown on a separate map.

6 REVIEW OF HISTORICAL RECORDS

Given the uncertainties in the assessment of the potential for liquefaction, it is important to look at any evidence of liquefaction in the past. Further, overseas studies indicate that sites which had liquefied in the past could liquefy again during future earthquakes. Therefore, a comprehensive search and review of recorded instances of liquefaction was carried out.

6.1 Past earthquakes

Previous work on liquefaction case histories in New Zealand showed that liquefaction events were associated with a MM intensity of at least VII. The earthquakes which gave an MM intensity of VII or more in the Wellington Region, since 1840, are listed in Table 2. There appears to be little information prior to 1840 because most of the large scale settlement in New Zealand took place after this time. Many of the larger earthquakes in the Wellington region occurred before significant and widespread human settlement and development of the region.

Table 2 Earthquakes felt in the Wellington region with MM intensities of VII and above

Earthquake	Magnitude (Richter)	Max felt intensity (MM)
1848 Marlborough	7.1	X
1855 Wairarapa	8	XI+
1904 Cape Turnagain	7.5	IX
1914 Cook Strait	6	VIII+
1934 Pahiatua	7.5	VIII-IX
1942 June Masterton	7	VII-VIII
1942 August Masterton	7	VIII

6.2 Past records of liquefaction

Various sources of historical information were searched, collated and reviewed. Since liquefaction was not a recognised phenomenon until recent times, it was necessary to look for reports such as sand boils, subsidence and lateral spreading described by various people in different ways. Some 30 cases of liquefaction were identified from the records. Because many of the large earthquakes occurred in the last century, many instances of liquefaction would have either been not observed, or not recorded.

Some of the records are indicative of liquefaction, while others clearly show that liquefaction did occur. For example, records such as,
" In the lower part of the valley of the Hutt, numerous hillocks of sand were thrown up, forming cones, varying from 2 to 4 feet in height, and in many parts of the valley large fissures were formed, with partial subsidence in many places." (1855 Wairarapa Earthquake) and
" Opposite this building on the road, a considerable opening emitted slimy mud, and the main street was overflowing by inundation" (1855 Wairarapa Earthquake), are clear indications of sand boils observed during liquefaction. The reports such as,
" Between Paraparaumu and Waikanae 19 lengths of rails subsided, and between Waikanae and Te Horo 10 lengths had subsided" (June 1942 Masterton Earthquake) suggest liquefaction induced subsidence.

6.3 Geological evidence of liquefaction

In addition to the records of liquefaction observations during past earthquakes, there was an interesting geological observation of possible liquefaction (Brown - pers comm). It is reported that during excavation of trenches adjacent to the Melling

Railway Station in Lower Hutt, a surface silt layer underlain by sandy gravel was found to have about 5 mm diameter vents through the silt, filled with sand. This suggests that the underlying sandy gravel may have liquefied during some earthquake in the past, during which sand and water were ejected through the silt layer to the surface.

6.4 Conclusions from review of past liquefaction

The review of the historical records of liquefaction clearly demonstrated the occurrence of earthquake induced liquefaction damage.

Some of the reports of liquefaction (see Section 6.2 above) refer to ejection of "slimy mud" during the 1855 Wairarapa earthquake. While the descriptions in 1855 may be inaccurate, these reports do suggest that fine grained materials such as silt have liquefied in the past, substantiating such occurrences quoted in overseas published literature.

The geological evidence of liquefaction in the Hutt Valley (see Section 6.3 above), suggests that coarser grained soils such as sandy gravels could also liquefy.

There has been widespread development, including reclamation and development in areas such as Porirua and the Wellington harbour front, since the large earthquakes in the Wellington region occurred. Therefore, more widespread liquefaction, and hence ground damage can be expected from future large earthquakes.

7 COMPILATION OF GEOTECHNICAL DATA

Geotechnical information on the ground conditions were collated from site investigations and laboratory tests carried out for various projects in the region. The locations of the site investigation information collated were plotted, and where there were significant gaps in the information in areas considered to be susceptible to liquefaction, some additional investigations were carried out.

The information collated was reviewed, and together with the surface geology, was used to choose key locations. These key locations represent areas with different ground conditions which appeared to be vulnerable to liquefaction. The density of the key points depended on the variability of the ground conditions and the degree of surface development.

8 LIQUEFACTION HAZARD ASSESSMENT

8.1 Liquefaction susceptibility

The liquefaction susceptibility was assessed based on the groundwater level, soil type, particle size distributions, and a general consideration of the density of the soils as indicated by the geology and SPT 'N' values. Sands and silty sands below the groundwater level, with SPT 'N' values less than about 25 were generally considered to be susceptible. As discussed in section 6.4 above, historical evidence suggests silts to be also susceptible to liquefaction, and hence sandy silts and silts of low plasticity and SPT 'N' values less than about 20 were also classified as susceptible to liquefaction. These soils, when present within a depth of about 15 m of the ground surface were classified as being susceptible to liquefaction. Liquefaction susceptibility maps were prepared by considering this assessment and the surface geology.

8.2 Liquefaction opportunity

The liquefaction opportunity was directly obtained from the results of the ground shaking study carried out by the Department of Scientific and Industrial Research (1992).

8.3 Liquefaction potential

The liquefaction assessment was carried out mainly using the Seed and Idriss simplified procedure for evaluating liquefaction potential (National Research Council, 1985). This method takes into consideration the peak ground accelerations, the magnitude of the earthquake (which also allows for the effect of duration of shaking), the effective overburden stress, and the groundwater levels. The peak ground accelerations are based on the results of the ground shaking hazard study, which is summarised in Table 1, for the Wellington city study area. The cyclic stress ratio caused by a given earthquake scenario at a given location can be calculated.

For each key location, the cyclic stress ratio was calculated for the layers of soils which are susceptible to liquefaction, and the calculated values for the most critical layer at each key location were plotted against the SPT 'N' value corrected as described by the National Research Council (1985) to allow for the effect of overburden pressure. An example plot for a Scenario 1 event in the Wellington city study area is shown on Figure 2. Seed and Idriss have developed curves separating liquefiable and liquefaction resistant soils for different magnitude earthquakes, based on empirical correlations. A family of curves for fines contents of 5%, 15% and 35%, for a magnitude 7 event are shown on Figure 2.

The plot of cyclic stress ratio v corrected SPT 'N' values for the Wellington city study area shows that even a magnitude 7 earthquake at a distance of 100 km, can cause liquefaction in a number of areas of the Wellington city. This is because the soft soils could amplify the ground shaking from a distant earthquake, giving significant peak ground accelerations of up to about 0.1g to 0.3 g. Depending on the fines content, and the location of the plotted point relative to the curves, each key location is classified as liquefiable or liquefaction resistant, for each scenario.

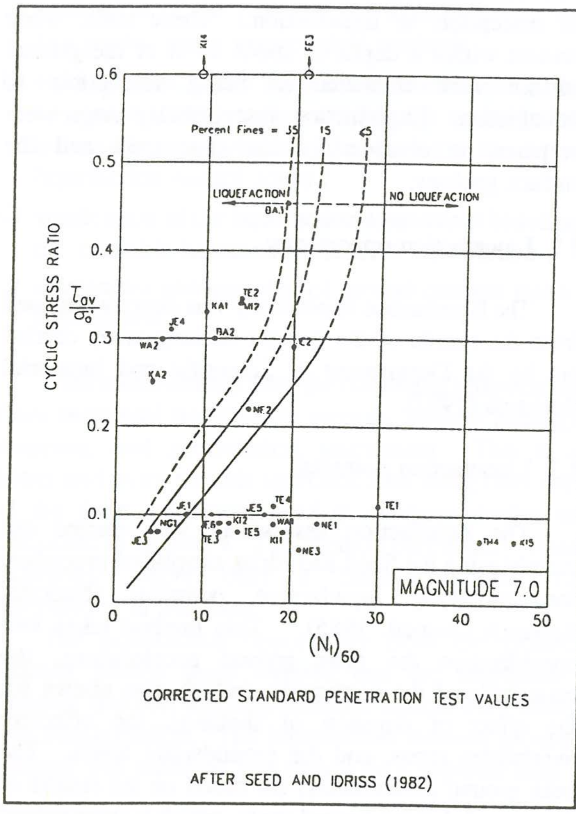

Figure 2 Liquefaction assessment for Wellington city

Where Static Cone Penetration Test results were available instead of SPTs, the method proposed by Sugawara (1989) was used.

The potential for liquefaction is classified as :

- ❑ High — liquefaction during both Scenarios 1 and 2
- ❑ Moderate — liquefaction unlikely or marginal during Scenario 1
- ❑ Low — liquefaction may occur only during Scenario 2
- ❑ Variable — liquefaction potential varies from low to high due to variable ground conditions

The liquefaction assessments at the key points were used to map the liquefaction potential zones, using the information from other site investigations, and the surface geology map. As an example of the hazard maps prepared, the liquefaction potential map for part of the Wellington city study area is shown on Figure 3.

9 GROUND DAMAGE

The likely type and order of magnitude of ground damage due to liquefaction were assessed. The estimates are considered to be only a rough order assessment of likely ground damage, as accurate methods of prediction are not currently available. The ground damage will depend on the ground conditions as well as the topography at each site. The main types of liquefaction induced ground damage are subsidence, slope failure, and lateral spreading of natural banks and embankments built on liquefiable ground. The presence of a liquefaction resistant surface layer could minimise ground damage, depending on the thickness of the surface layer relative to the thickness of the liquefiable layer below. However, where lateral instability is likely, the presence of a surface layer may not necessarily preclude ground damage.

The likely order of subsidence due to liquefaction was estimated from a chart proposed by Tokimatsu and Seed (1987) for a magnitude 7.5 earthquake. Therefore, the estimates may be somewhat conservative for a Scenario 1 event of magnitude 7.

Most of the areas susceptible to liquefaction in the Wellington region are in relatively flat areas between the foothills and the present coastline. Lateral spreading is likely to affect areas adjacent to stream / river banks and coastal areas.

In the absence of analytical methods which can be easily applied to assess the lateral spreading, the following simple rules have been formed to enable ground damage maps to be prepared :

- ❑ liquefiable areas within 50 m of water fronts and banks could be affected by lateral spreading during a Scenario 1 earthquake ;
- ❑ liquefiable areas within 200 m of water fronts and banks could be affected by lateral spreading during a Scenario 2 earthquake.

10 PREPARATION OF HAZARD MAPS

Hazard maps for liquefaction susceptibility, liquefaction potential and ground damage were prepared for the Wellington City, Hutt Valley, Porirua Basin and Kapiti Coast study areas. Maps were not prepared for the Wairarapa study area, because there were only localised areas which are susceptible to liquefaction.

The maps were produced to a scale of 1 : 20,000 to 1 : 25,000. For the Wellington City centre, a larger maps was also prepared to a scale of 1 : 10,000. The maps were digitised and produced using computer aided draughting techniques, and installed in the Wellington Regional Council's geographical information system.

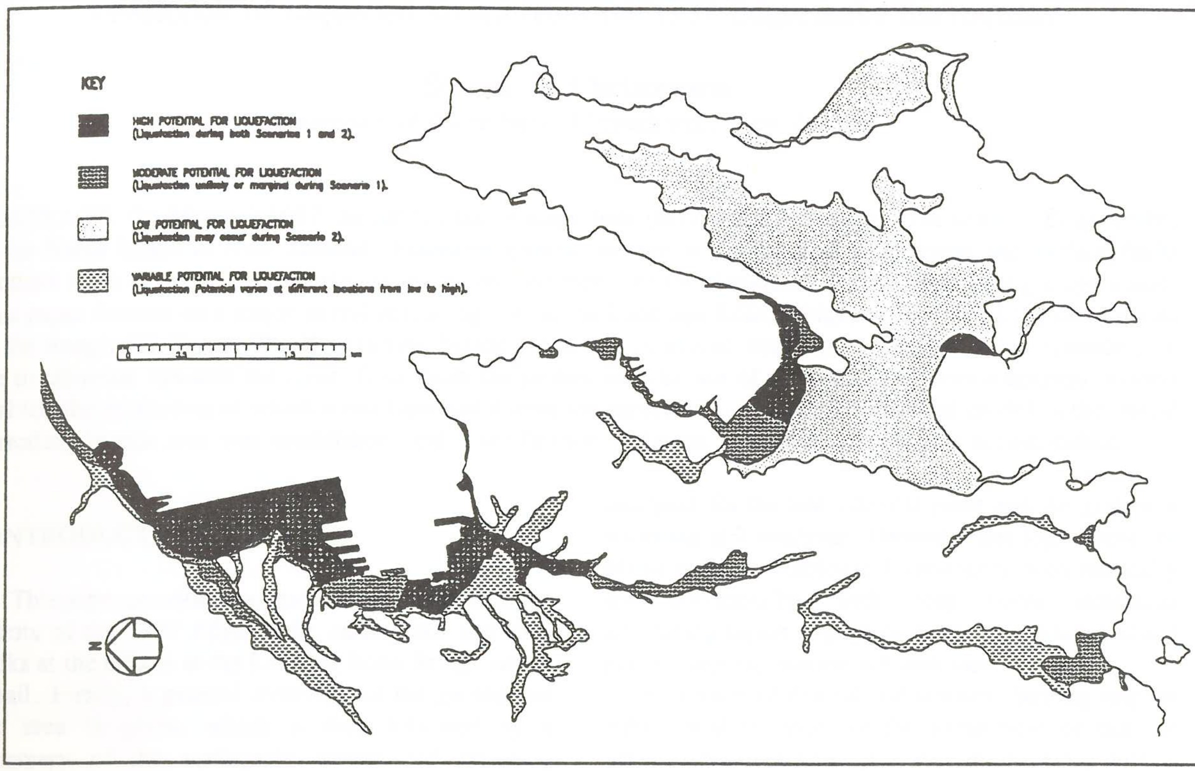

Figure 3 Liquefaction potential map, Wellington city

11 SUMMARY

A liquefaction hazard study has been carried out as part of the Wellington Regional Council's strategy for achieving an acceptable level of seismic and geological hazards in the region. The hazards were mapped using a method specifically developed, for two earthquake scenarios, a large distant event producing MM V-VI shaking in Wellington, and a large magnitude 7.5 event on the Wellington fault which runs through the region.

The liquefaction hazard was mapped using surface geological maps, historical records of liquefaction and geotechnical engineering methods. The study has confirmed significant liquefaction hazards in the Wellington Region. The maps have been published by the Wellington Regional Council, and will help in the recognition and mitigation of liquefaction hazards.

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