Liquefaction hazard in the Wellington Region

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ABSTRACT

The greater Wellington Region has a higher annual probability of damaging ground shaking than most of the rest of New Zealand. This means that the region is exposed to all of the effects of strong earthquake shaking including fault rupture, ground movement, liquefaction and landslides. This report deals specifically with the liquefaction hazard in the greater Wellington Region.

Liquefaction is a process that leads to a soil suddenly losing much of its strength, most commonly as a result of strong ground shaking during a large earthquake. Not all soils, however, can liquefy in an earthquake. The following are particular features of soils that potentially can liquefy:

- The soils need to be composed of loose sand and/or silt with very little or no clay. Such soils do not stick together the way clayey soils do.
- The soils need to be saturated (i.e. located below the water table) so all of the space between the grains of sand and silt is filled with water. Dry soils above the water table do not liquefy.

This simplifies the identification of sediments (soils) that are vulnerable to liquefaction. The sediments must be relatively young (less than ~10,000 years old) and deposited in a low energy environment (e.g. settle out of suspension). Thus the places most likely to accumulate sediments prone to liquefaction are lagoons and estuaries near the coastline where sand and silt suspended in flood waters can settle out of suspension. Other locations are overbank silt deposits (again silt settling out of suspension from floodwaters), and point bar and channel deposits in meandering river systems.

At least four historical earthquakes since 1840 have caused some liquefaction in the Wellington Region (1848, 1855, 1942 and 2013). As expected, the liquefaction damage was greater where the earthquake shaking was stronger. With regards to the likely severity of liquefaction in the Wellington Region, a key observation was made by Edward Roberts, a trained engineer who, after the 1855 earthquake, travelled extensively in the Lower North Island observing ground and building damage due to the earthquake. He observed that the “plains of the Manawatu” (i.e. between Tokomaru and Foxton) were affected by liquefaction “to a much greater degree” than anything in the Hutt. Liquefaction has also shown a tendency to recur in the same areas. In the Wellington Region, the sites most vulnerable to liquefaction have been the lower parts of the Wairarapa Plains from the northern (or inland) end of Lake Wairarapa to the coastline at Lake Onoke, the lower reaches of the Hutt River south of the Waterloo-Melling area, and reclaimed land around the margins of Wellington and Porirua harbours. Liquefaction has occurred elsewhere but has been limited in extent.

This report presents two liquefaction maps for each area studied. The first of these shows the assessed range of liquefaction susceptibilities. Five liquefaction susceptibility classes have been used, but not all are present in some areas. The second map shows areas where potentially destructively damaging liquefaction could occur. These maps are based on published geological maps, historical accounts of liquefaction during strong earthquake shaking and subsurface information from boreholes to identify materials, predominantly loose sand and silt that are most susceptible to liquefaction. The map scales range from 1:50,000 to 1:250,000 and reflect the scales of the source data. These maps are not intended to be used at a site specific or property level to describe the liquefaction hazard. A correct use of these maps is to identify areas where further, more detailed investigation of the liquefaction hazard is warranted. The more detailed investigations should include detailed geomorphic

mapping at larger scales (1:10,000 to 1:25,000), geotechnical characterisation of the subsurface materials to a depth of at least twenty metres and assessment of the shallow, unconfined groundwater surface and its seasonal and tidal variations. It is recommended that this more detailed work to assess and quantify the liquefaction hazard is undertaken before liquefaction hazard information is included on formal documents such as district plans and LIM (Land Information Memoranda).

The Wellington Region is less vulnerable to liquefaction than some other places in New Zealand (e.g. eastern Christchurch, Manawatu River between Tokomaru and Foxton), but liquefaction-induced ground damage still has the ability to disrupt and damage infrastructure in greater Wellington. A note of caution needs to be made with respect to the maps showing liquefaction susceptibility in the Wellington Region which although showing the liquefaction susceptibility in the same terms throughout the region the quality and quantity of data underpinning the maps ranges from good to poor and further effort by councils and other entities needs to be made to identify and refine the areas vulnerable to liquefaction where data are currently lacking.

KEYWORDS

Liquefaction, lateral spreading, sand boils, seismic hazard, Wellington Region, Wellington City, Porirua City, Hutt City, Upper Hutt City, Kāpiti District, Masterton District, Carterton District, South Wairarapa District, Wairarapa.

1.0 INTRODUCTION

Under the “It’s Our Fault” project, GNS Science has undertaken a regional assessment of liquefaction hazard in the Wellington Region. The purpose of undertaking the regional study was primarily to identify areas where further investigation of liquefaction hazard would be needed.

The greater Wellington Region has a higher annual probability of damaging levels of earthquake ground shaking than most of the rest of New Zealand (Stirling et al. 2012). As a consequence of this high seismic hazard the region is exposed to all of the effects of strong earthquake shaking including fault rupture, ground movement, liquefaction and landslides. This report deals specifically with the liquefaction hazard in the Wellington Region.

Assessing liquefaction hazard entails estimating the susceptibility of the region’s soils to liquefaction and determining the frequency (return time) of the different levels of strong earthquake shaking that trigger liquefaction. Combining soil liquefaction susceptibility with the return times of levels of earthquake shaking causing liquefaction allows an estimate of liquefaction hazard (or the probability of a stated level of liquefaction occurring in a given timeframe) to be made.

As demonstrated by the recent earthquake sequence in Christchurch, liquefaction has a devastating impact on affected buildings and buried infrastructure. The loss of amenity from liquefaction in Christchurch is costing billions of dollars to rectify, with remediation ranging from retiring land now recognised as unsuited to development through to the replacement of damaged infrastructure with more resilient forms.

This report examines the liquefaction hazard in the Wellington Region. The report first describes the liquefaction process and how this translates into different liquefaction hazards including water and sand ejection causing differential settlement (variations in vertical displacement), and lateral spreading causing variations in horizontal displacement. The risks to infrastructure and buildings in relation to the different liquefaction hazards are then outlined. The historical record is then reviewed describing liquefaction effects observed after historical earthquakes in the region that produced shaking strong enough to have caused liquefaction ground damage.

Previous work on mapping liquefaction hazards in the region is chronicled. Then data sources used in the current work are discussed including historical accounts, geological maps, borehole and limited geophysical and geotechnical data. Using these data, liquefaction hazard maps are prepared for five areas in the Wellington Region, Wellington City, Hutt Valley, Porirua City, Kāpiti Coast and the Wairarapa. Last, the liquefaction hazard maps are discussed in relation to each other in terms of data quality and quantity and their variability in uncertainty. This discussion leads to a series of recommendations for each area to improve knowledge of the liquefaction hazard.

Two maps of liquefaction hazard are presented for each area. The first map uses a deterministic method to rank the relative likelihood of liquefaction hazards in each area. Five categories of liquefaction hazard are used, ranging from no liquefaction through low, moderate, high and very high liquefaction susceptibility classes. Areas with greater liquefaction susceptibility are expected to have a higher frequency and extent of damaging liquefaction effects relative to those with a lower susceptibility.

The second map identifies those areas where liquefaction hazard may be considered to have damaging consequences, that is, areas where liquefaction susceptibility needs further quantitative investigation. If the quantitative measures of liquefaction hazard, such as cone penetrometer tests evaluated using the liquefaction severity number (van Ballegooy et al, 2014) show severe enough liquefaction susceptibility then actions to mitigate the effects of liquefaction could be considered.

It is after these next levels of investigation of the liquefaction hazard, such as detailed geomorphic mapping, geotechnical characterisation of subsurface materials and assessment of the shallow, unconfined groundwater surface that it may be appropriate to include liquefaction hazard on formal documents such as district plans and LIM's (Land Information Memoranda). Improving our understanding of liquefaction hazards, and their consequences, should lead to more reliable mitigation of liquefaction hazard, and a more resilient community.

2.0 THE LIQUEFACTION PHENOMENA

Earthquakes pose hazards to the built environment through five main types of processes. These include strong ground shaking (the most pervasive hazard), primary breakage of the ground surface (fault rupture), deformation of the ground surface due to fault rupture (tectonic tilting, differential uplift and subsidence), seismically-induced gravitational slope movements slope failures, and ground deformation resulting from soil liquefaction. This report focuses on documenting the nature and distribution of soils that are susceptible to soil liquefaction in the Wellington Region.

The section below has mostly been adapted from the Institution of Professional Engineers of New Zealand Liquefaction fact sheet (IPENZ) (Figure 2.1) and the GNS Science publication by Saunders and Berryman (2012) titled: “Just add water: when should liquefaction be considered in land use planning?”.

2.1 Background

In New Zealand, the most widespread observations of liquefaction since European was in the 2010-2011 sequence of Canterbury earthquakes (Cubrinovski et al, 2011b, Cubrinovski et al, 2012. However, earlier instances of significant liquefaction were documented after the 1848 Marlborough, 1855 Wairarapa, 1929 Murchison, 1931 Napier, 1968 Inangahua, and 1987 Edgecumbe earthquakes. Most of these events generated strong shaking in coastal regions with extensive deposits of recent, cohesionless, fine-grained, sedimentary deposits (Fairless and Berrill, 1984; Hancox et al. 1997). The effects of soil liquefaction during these earthquakes have been the ejection of water and sand (sand boils or earthquake fountains) and lateral spreading. These phenomena resulted in vertical and horizontal displacement of the ground surface which caused extensive damage to buildings, wharves, roads and bridges, embankments, and buried services (e.g. Hancox et al. 1997).

The Modified Mercalli (MM) intensity scale (Appendix 1) threshold for liquefaction in New Zealand is generally MM7 for sand boils, and MM8 for lateral spreading, but both may occur at one intensity level lower in highly susceptible materials (Hancox et al. 1997). Liquefaction-induced ground damage is most common at MM8-10 (Hancox et al. 1997). The minimum earthquake magnitude for liquefaction is magnitude 5 based on recent experience in Christchurch, but liquefaction is more common at magnitudes of 6 and greater. In terms of peak ground acceleration, a common instrumental measure of the strength of earthquake shaking at a site, the threshold for liquefaction in highly susceptible sediments is between 0.057g (Quigley et al, 2013) and 0.09 g (de Magistris et al, 2013) (where 1 g is the acceleration due to the force of gravity at the Earth’s surface).

2.2 What is Liquefaction?

Liquefaction is the phenomenon where a soil suddenly decreases in strength, most commonly as a result of strong ground shaking during an earthquake. Not all soils, however, can liquefy in an earthquake. The following are particular features of soils that can liquefy:

- The soils need to be composed of loose sands and silts. Such soils do not stick together the way clay soils do.
- •The soils need to be saturated (i.e. located below the water table) so all the space between the grains of sand and silt is filled with water. Dry soils above the water table will not liquefy.

When an earthquake occurs, strong shaking may cause the sand and silt grains to compress the spaces filled with water, but the water pushes back and pressure builds up until the grains 'float' in the water. When this happens the soil loses strength and it has liquefied. Soil that was once rigid now flows like a fluid.

Soils that cannot liquefy may be unsaturated, or cohesive (clay is present and binds the soil together) or dense (for example, gravels deposited in a high-energy environment). If any of these features are present in a soil it will not liquefy.

Liquefied soil, like water, cannot support the weight of whatever is lying above it – be it the surface layers of dry soil, or the concrete floors (or piles) of buildings. The liquefied soil under that weight is forced into any cracks and crevasses it can find, including those in the dry soil above, or the cracks between concrete slabs. It flows out onto the ground surface as sand boils and rivers of silt and water. In some cases the liquefied soil flowing up a crack erodes and widens the crack (even to a size big enough to accommodate a car). Some other consequences of the soil liquefying are:

- Differential settlement of the ground surface due to the loss of soil from underground;
- Loss of support to building foundations;
- Floating of manholes, buried tanks and pipes in the liquefied soil - but only if the tanks and pipes are mostly empty; and
- Near streams and rivers, the unsaturated surface soil layers can slide sideways on the liquefied soil towards the streams. This is called lateral spreading and can severely damage buildings and buried infrastructure such as buried water and wastewater pipes. It typically results in long tears and rips in the ground surface.

Not all of a building's foundations, buried pipe networks, road networks or flood protection stop-banks need be affected by liquefaction. An affected part may subside (settle) or be pulled sideways by lateral spreading, to severely damage the building. Buried services such as sewer pipes can be damaged when they are warped by lateral spreading, ground settlement or floatation.

2.3 Which Soils are Susceptible to Liquefaction?

Not all soils are susceptible to liquefaction. Generally, for liquefaction to occur there needs to be three soil preconditions (Tinsley et al. 1985; Youd et al. 1975; Ziony, 1985):

- Geologically young (less than ~10,000 years old), loose sediments, that are
- Fine-grained and non-cohesive (coarse silts and fine sands), and
- Saturated (below the water table).

When all three of these preconditions are met, an assessment of the liquefaction hazard is required. Assessment of liquefaction hazard can be on a regional or district scale, such as in this report, or it can be site specific using, for example, cone-penetrometer tests. Note that the ‘saturated’ condition may apply seasonally or only part of the time i.e. the potential for saturation must be assessed.

If one of these preconditions is not met, then soils are not susceptible to liquefaction. If soils are not susceptible to liquefaction then liquefaction potential does not need to be assessed in an urban or rural planning context.

2.4 Are the Consequences of Liquefaction Significant?

Once it has been ascertained that soils are susceptible to liquefaction, it needs to be determined if the seismic hazard is sufficient to warrant consideration of liquefaction as a hazard. This is done by considering the likelihood of earthquakes strong enough, and frequent enough, to warrant concern. Whether earthquake shaking is strong enough or frequent enough will in part depend on the type of facility or infrastructure being considered (e.g. for domestic dwellings the seismic hazard that can be expected to occur more frequently than once every 500 years should be considered, but for a critical facility, liquefaction should not impact on continued functionality of the facility in a 1 in 2500 year event).

If the seismic hazard is sufficient to warrant attention for the infrastructure or facility under consideration then an assessment of the consequences of liquefaction on that land use needs be undertaken. The primary impacts of liquefaction are to the built environment (e.g. buildings); infrastructure (i.e. underground pipes and services, roads); and to the socio-economic resilience if people are not able to live in their homes and/or attend places of education and employment. Photographs 2.1-2.7 show examples of liquefaction damage to a range of assets and infrastructure.

If the impacts of liquefaction are insignificant, then it may be appropriate that no planning actions are required. If, however, the potential consequences are more than insignificant, and a cost-benefit assessment indicates possible future losses can be mitigated, either by avoidance or by engineering solutions; then liquefaction should be a criteria assessed during land use planning. Saunders and Beban (2012) provide an explanation for how the consequences of liquefaction can be assessed in a risk-based planning context.

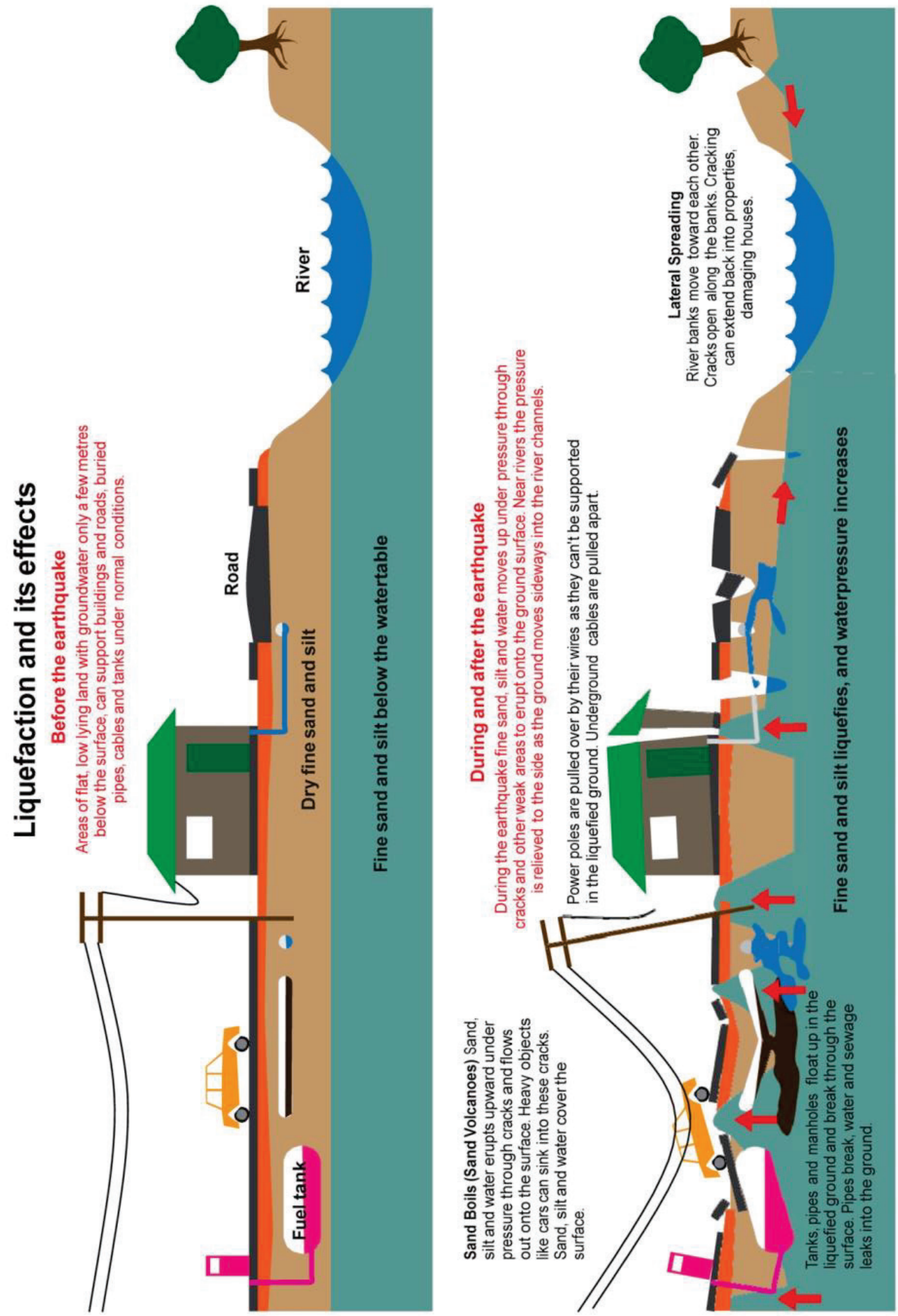

Figure 2.1 Diagramatic illustration of liquefaction and its effects (IPENZ).

Photograph 2.1 Sand boils caused by liquefaction in Kaiapoi 45 kilometres from the epicentre of the magnitude 7.1, 4 September 2010 Darfield earthquake. (Photo: N. Litchfield, GNS Science).

Photograph 2.2 Liquefaction ejecta in a suburban Christchurch Street. In the suburb of Bexley, approx. 10 km from the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011 (Photo NZ Herald).

Photograph 2.3 Buoyancy of a pump-station floated up to 500 mm out of the ground by liquefaction adjacent to the Avon River near the eastern end of Morris Street, approx. 10 km form the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011 (Photo D. Beetham, GNS Science).

Photograph 2.4 Lateral spreading fissures run parallel to the Avon River in Avonside Drive, Christchurch, approx. 10 km form the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011 (Photo D. Beetham, GNS Science).

Photograph 2.5 Compression-induced buckling of a bridge over the Avon River near Medway Street due to lateral spreading displacement of the abutments approx. 10 km form the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011 (Photo D. Beetham, GNS Science).

Photograph 2.6 Liquefaction-induced lateral spreading through the foundation of a house after the magnitude 6.3 Christchurch earthquake of 22 February 2011, location unknown.

Photograph 2.7 Damage to underground infrastructure from liquefaction, in this case lateral spreading has pulled a pipe joint apart in Avonside Drive after the magnitude 6.3 Christchurch earthquake of 22 February 2011.

3.0 HISTORICAL OCCURANCES OF LIQUEFACTION IN THE WELLINGTON REGION

Strong earthquake shaking in the Wellington Region caused liquefaction on five occasions since 1840. These were the 1848 Marlborough earthquake, the 1855 Wairarapa earthquake, the 1904 Cape Turnagain earthquake, the June 1942 Wairarapa earthquake and the 2013 Cook Strait earthquake. The sites where liquefaction was observed were a function of the location of the epicentre of the earthquake, and the strength of the shaking at susceptible sites. The sites where liquefaction has occurred in the past, provides information on where it is likely to occur in the future.

3.1 1848 Marlborough Earthquake

The Marlborough earthquake sequence of October 1848 shook the Wellington Region with shaking intensities of MM7 to MM8 estimated from interpretation of contemporary damage (Downes, 1995; Grapes et al. 1998; Grapes et al. 2003). Wellington City, Porirua City and the Hutt Valley all experienced MM8. The southern parts of both the Wairarapa and Kāpiti coast experienced MM8, while the northern parts of these areas experienced MM7.

Eiby (1980) notes a single observation of ground cracking in Wellington City in 1848, where a fissure with vertical displacement was observed at the beach (presumably in the Lambton Quay-Te Aro area). Newspaper reports in Grapes et al. (2003) describe “Several cracks or fissures were observed in the earth, the most remarkable being on the beach at Thorndon Quay a short distance beyond the Cottage of Content.” An additional report describes “The cracks in the ground at Wellington, at the mouths of some of the small rivers on the N.W coast” (presumably the Kāpiti Coast). Taylor (1855) travelled from Wanganui to Wellington after the earthquake and reported sand boils near the mouth of the Ohau River and fissures and sand boils near the mouth of the Waikanae River. The Lower Hutt area was settled at the time, with much of the flat land in the valley used for farming. The only report of damage sighted for the Hutt is damage to the bridge over the Hutt River and the origin of this damage is unknown.

The sparse nature of the reports of ground damage and liquefaction from the October 1848 earthquake in the Wellington Region make an accurate assessment of liquefaction impacts at MM8 difficult. However, the Wellington City central business district and the southern part of the Hutt Valley were both settled at the time of the earthquake so the observations (or lack of them) in these areas is informative. In both cases, it is the lack of reported liquefaction that stands out at both of these sites at this level of strong earthquake shaking (MM8).

3.2 1855 Wairarapa Earthquake

Liquefaction was reported from throughout the Wellington Region after the 1855 Wairarapa Earthquake (Grapes and Downes, 1997, Hancox et al. 2002). Most of the region lay within the MM9 isoseismal (Hutt Valley, Wellington City, Porirua City and the central plains of the Wairarapa) while the rest of the region lay within the MM8 isoseismal (Kāpiti Coast, eastern coastal regions of the Wairarapa (Grapes and Downes, 1997).

In Wellington City (MM9) fissures and sand and silt ejection were reported (Grapes and Downes, 1997). The fissuring was reported from near the mouths of several small streams between Tinakori Road and Willis Street. However at only one fissure, on the corner of Willis and Manners Street was sand and silt reported as being ejected. Numerous small sand boils were also reported in the post-earthquake tidal zone (the area had been raised about 1 m) between Lambton Quay and Pipitea Point. There were also reports of clumps of flax and toi-toi from the Te Aro swamp floating in the harbour after the earthquake, but it is uncertain if this was the result of liquefaction or seiching in the harbour immediately after the earthquake.

The 1855 earthquake occurred prior to harbour reclamation and filling of the small stream valleys in the central city. The relatively minor liquefaction reported in Wellington City at MM9 in natural ground provides some indication, in the central city at least, that liquefaction in the natural sediments is unlikely to cause widespread damage.

In the Hutt Valley (MM9) the effects of liquefaction were more severe, although reports of liquefaction were limited to the Lower Hutt area (Grapes and Downes, 1997). The bridge across the Hutt River was destroyed with the land on each side having sunk (lateral spreading). Large fissures were also reported along the banks of the rivers and creeks, some associated with subsidence probably due to lateral spreading. Sand boils from 0.6 to 1.2 m high were numerous in the lower part of the valley. The descriptions of liquefaction phenomena indicate that liquefaction was more extensive and more damaging than occurred in Wellington City at the same level of shaking (MM9). However, the exact location of the damage is not well documented.

It should also be noted that Roberts (1855) observed that in comparison with the Hutt Valley the “plains of the Manawatu” were affected “to a much greater degree” (Grapes and Downes, 1997). Given that the Hutt Valley experienced MM9 (the stronger shaking) compared to probably MM8 in the Manawatu, Roberts’ observation suggests the Hutt Valley may not be as vulnerable to liquefaction as some localities in the Manawatu.

On the Kāpiti Coast at Otaki and Waikawa, residents reported cracking of the surrounding hills (presumably the coastal sand dunes) and the draining of the Manga-pirau lagoon (Waikawa). The area was severely fissured and showed evidence of sand fountaining (Otaki) (Grapes and Downes, 1997). The MM intensity assigned to this area on the basis of chimney damage is MM7, but the lack of masonry structures other than chimneys means there is an inherent uncertainty in this assessment. The environmental damage described suggests MM8 may be a more appropriate intensity for this area. The lack of environmental damage in the 1942 Masterton earthquakes on the Kāpiti Coast at MM 7(see below) support MM8 as the more appropriate intensity in this area for 1855.

There is very little information on ground damage for the Porirua City area in the 1855 earthquake. The only reference in Grapes and Downes (1997) is the ‘the Porirua road is sunk in places’. This is not clearly attributable as liquefaction damage and could be the subsidence of road fills commonly observed in earthquakes.

In the Wairarapa, the attribution of liquefaction damage is a little more difficult as some of the fissuring reported is clearly related to the rupture of the Wairarapa Fault. However, liquefaction was unequivocally reported from the area around the confluence of the Ruamahanga and Waiohine Rivers. The other place where unequivocal liquefaction occurred was 4-5 kilometres west of Martinborough at Pahautea. The strength of shaking in the Wairarapa has been variously reported as MM9-10.

3.3 1904 Cape Turnagain Earthquake

The 9 August 1904 Cape Turnagain earthquake produced shaking intensities of MM5 to MM7 in the Wellington Region (Downes, 1996, Hancox et al, 1997, Downes, 2006). The MM7 isoseismal encompasses the eastern and northern parts of the Wairarapa, with most of the rest of the region experiencing MM6 ground shaking.

Liquefaction effects, most notably sand boils, were reported in the Wairarapa at Castlepoint, Whakataki (approximately 5 km north of Castlepoint), Gladstone and Waihakeke (approximately 5 km east of Greytown on the Ruamahanga River), all within the MM7 isoseismal. The liquefaction effects observed in the Gladstone-Waihakeke area is consistent with observed liquefaction effects in this area in 1855 (MM9-10) and 1942 (MM8).

No liquefaction effects were reported from within the MM6 isoseismal (Downes, 2006).

3.4 1942 Masterton Earthquakes

The 1942 Wairarapa earthquakes of 24 June and 1 August produced shaking intensities between MM6 and MM8 through the Wellington Region (Downes, 1995, Downes et al. 2001). The June earthquake produced MM8 in the Masterton and Carterton districts and MM7 in the rest of the Wairarapa, on the Kāpiti Coast and in the Hutt Valley. Downes et al. (2001) show the MM7 isoseismal passing through the centre of Wellington City and the western side of Porirua City. Individual values are MM7 in Porirua, and MM6 and MM7 in Wellington City. However, 20,000 chimneys were damaged in Wellington, liquefaction was reported from Aotea Quay and a moderate landslide was reported at Goat Point near Plimmerton in Porirua City. Such building and ground damage suggests that it is reasonable to assign MM7 to the Wellington City and Porirua City areas. The lack of similar building and ground damage at MM6 during the 2013 Cook Strait and Lake Grassmere earthquakes (see below) provide further support to assigning MM7 to Wellington City and Porirua City for the Masterton earthquake of 24 June 1942. In the 1 August 1942 earthquake MM7 has been assigned to most of the Wairarapa and the Kāpiti Coast from Paraparaumu north (Downes et al. 2001). At the southern end of the Wairarapa, in Porirua City, the Hutt Valley and Wellington City MM6 has been assigned (Downes et al. 2001).

In Wellington City, a few sand boils were reported in the vicinity of Aotea Quay (Murashev and Palmer, 1998, Downes et al. 2001) during the June earthquake (MM7). Subsidence of reclaimed land along the waterfront was also reported, with cracks appearing in many of the masonry structures built on reclaimed land. The June earthquake (MM7) resulted in larger subsidence than in the August earthquake (MM6) (Murashev and Palmer, 1998). No data have been found to establish the extent or the magnitude of the subsidence that occurred in either the June or August earthquakes.

No liquefaction was reported from the Porirua area, the Kāpiti Coast or the Hutt Valley, all with reported shaking intensities of MM7 for the June earthquake, and MM6 for the August earthquake (except for the Kāpiti Coast north of Paraparaumu where MM7 was reported). Extensive liquefaction, sand boils and fissuring, at MM7 were reported along the Manawatu River between Opiki and Foxton Beach but this was north of the Wellington Region. However, this observation supports the observations of Roberts (1855) that liquefaction damage was much greater on the plains of the Manawatu than it was in the Hutt Valley after the 1855 Wairarapa earthquake.

In the Wairarapa, in the MM8 shaking intensity zone of the June earthquake, isolated sand boils and an instance of lateral spreading along the Tauweru River were reported north of Tauweru, near Dalefield and more extensively in the vicinity of Gladstone (Downes et al. 2001). This liquefaction was relatively minor within the MM8 zone. After the June earthquake sand boils (Lake Ferry), cracks and fissures (near Martinborough), and one case of lateral spreading (near Tuhitarata) were reported from along the Ruamahanga River in the MM7 zone (Downes et al. 2001).

In the August earthquake the only liquefaction reported after the earthquake was in the lower reaches of the Manawatu River in the MM7 intensity zone, although this area lies outside the Wellington Region. No liquefaction in the Wairarapa was reported after this earthquake (Downes et al. 2001). The liquefaction reports for the 1942 earthquakes provide further evidence that the Holocene sediments in the Wellington Region are not as susceptible to liquefaction as those in Christchurch, and more locally, the lower reaches of the Manawatu River between Opiki and Foxton Beach.

3.5 2013 Cook Strait and Lake Grassmere Earthquakes

The Cook Strait and Lake Grassmere earthquakes of July and August 2013, respectively, produced maximum shaking intensities of MM7 in the southern and central suburbs of Wellington City (Hancox et al. 2013, Van Dissen et al. 2013). Both liquefaction and landslides were reported over an area of 1000 km^2 in the coastal Marlborough area between Blenheim and Ward for both earthquakes. Ground damage in the North Island was limited to two landslides reported in Wellington City and liquefaction ground damage observed only in the most recently reclaimed land within Wellington Harbour at Port Nicholson. No ground damage was reported in any other part of the Wellington Region.

The Wellington Harbour reclamation that experienced liquefaction in 2013 was constructed during the 1960's and 1970's (i.e. it did not exist in 1942). Areas of older reclaimed land adjacent to Aotea Quay where sand boils were reported in 1942 showed no surface manifestation of liquefaction in 2013. These observations suggest that the shaking experienced in 2013 was slightly less than the shaking experienced in 1942, even though the ground damage was more severe in 2013 because the area that liquefied did not exist in 1942.

The isolated and minor liquefaction in the Wellington Region during the 2013 earthquakes at up to MM7 shaking, provides further evidence that the Holocene sediments in the Wellington Region are not as susceptible to liquefaction as those of Christchurch, for example.

3.6 Summary of Historical Liquefaction in the Wellington Region

Liquefaction has occurred locally in the Wellington Region during strong earthquake shaking. The more severe the shaking, the more severe and extensive the liquefaction effects were. The locations where liquefaction occurred can be obtained from historical records of what has happened during previous strong ground shaking. Earthquakes in 1848, 1855, 1904, 1942 and 2013, all caused liquefaction at susceptible sites.

The threshold for liquefaction in the Wellington Region is MM7. At this level of shaking, the reclaimed land in Lambton Harbour has experienced liquefaction damage (June 1942; July 2013). Liquefaction in natural ground at this level of shaking has only been reported from Lake Ferry and near Pirinoa and Tuhitarata near the lower reaches of the Ruamahanga River (June 1942). This stands in stark contrast to the extensive liquefaction damage reported in the Horowhenua near the mouth of the Manawatu River at Foxton for MM7 shaking (June 1942, August 1942), which although outside the Wellington Region, provides a contrast with the lack of liquefaction of Holocene sediments at similar shaking levels (MM7) in the Wellington Region. Edward Roberts's observation in 1855 that the plains of the Manawatu were much more affected by liquefaction than the valley of the Hutt River is consistent with the observations made in 1942.

The Wellington Region has been subjected to earthquake shaking of MM8 at least once (southern and western parts of the region in 1848, and the Wairarapa in June 1942). At MM8, minor ground cracking was reported at sites along the original shoreline of Lambton Harbour in Wellington, between Thorndon and Te Aro, and sand boils and fissures were reported near the mouth of the Waikanae River, and possibly the Otaki River (October 1848). In the Wairarapa, sand boils and fissures were reported in the Gladstone area, near Dalefield and adjacent to the Ruamahanga River near Martinborough (June 1942). As expected at MM8 the liquefaction damage was a little more widespread and increased moderately in severity with the increased level of shaking. With regards to assessing liquefaction hazard in the region, the most striking observation from MM8 shaking is the lack of reported liquefaction damage in the lower parts of the Hutt Valley (October 1848), between Seaview/Petone and Waterloo/Melling, despite the area being settled at the time. However, this could be due to a lack of reporting rather than an absence of liquefaction effects.

Most of the Wellington Region experienced MM9 shaking during the 1855 Wairarapa earthquake (the exceptions being the strip of the west coast north of Paekakariki and the strip of the east coast between Cape Palliser and Castlepoint). Within ten to twenty kilometres of the fault rupture the shaking intensities may have reached MM10. It is at MM9 shaking that the first reports of liquefaction ejecta in Wellington City and Lower Hutt were recorded. In Wellington, liquefaction ejecta was recorded at the corner of Willis and Manners Streets, and below the low-water mark in Lambton Harbour (i.e. beneath what is today reclaimed land). Other fissures, without ejecta, were reported along the shoreline where small streams had their mouths between Hobson Street and Lambton Quay. Although not directly mentioned, the Te Aro swamp may be indirectly referred to in reports of ejecta being observed in places that were swampy.

In the Hutt Valley, there are reports of fissures and ejecta at MM9. These appear to be limited to the lower part of the valley, south of the Waterloo- Melling area and adjacent to the stream and river channels. A point of note from the 2010 Darfield earthquake in Christchurch is that liquefaction fissuring and ejecta were noticeable in the old (pre- European settlement) infilled channels of the Kaiapoi and Waimakariri Rivers (Wotherspoon et al 2013). This will probably hold true of the Hutt River as well, with the original courses of the Hutt River and Waiwhetu Stream liable to be the sites of liquefaction phenomena at MM9. North of the Waterloo-Melling area the reports of liquefaction are largely absent, although the behaviour of swamps at Naenae, Trentham and Mangaroa is not documented.

No unequivocal liquefaction effect is noted in the Porirua area at MM9 in 1855. And the Kāpiti Coast has not experienced MM9 at least since 1840.

The Wairarapa experienced MM9 during the 1855 Wairarapa earthquake. There are reports of widespread liquefaction in the southern Wairarapa area which is consistent with the observations of liquefaction around the shores of Lake Wairarapa and in the lower reaches of the Ruamahanga River in 1942 at MM8. Vulnerable sites near Dalefield (west of Carterton) and Gladstone (east of Carterton on the Ruamahanga River) probably also liquefied although it is not possible to accurately locate the liquefaction in the Wairarapa in the 1855 reports. Liquefaction was reported near Gladstone in 1904 (MM7) and 1942 (MM8).

4.0 PREVIOUS LIQUEFACTION WORK

The earliest work to look at micro-zoning effects in Wellington City, albeit indirectly, was Grant-Taylor et al. (1974). Although liquefaction was not specifically addressed in this work the areas mapped as “Zone 3 – High-porosity sediments” had an accompanying description that stated “some of these sediments are expected to flow under vibration”.

Further work was undertaken during the 1989-1993 period to underpin a regional natural disaster reduction plan for the Wellington Regional Council (now Greater Wellington) as part of a series of studies specific to seismic hazard. Geological data for these maps came from the 1:250,000 geological map of Kingma (1967) and more detailed mapping provided by Van Dissen (1992), Dellow et al. (1991, 1992), Heron and Van Dissen (1992), Read et al. (1991) and Begg and Van Dissen (1992). In addition, subsurface data for the studies came from geological, geotechnical and geophysical data from boreholes, standard penetrometer tests, cone penetrometer tests, seismic cone penetrometer tests and site investigation data held by Opus International Consultants, territorial authority records and GNS Science.

Following on from that work, a series of map sheets with accompanying booklets was published in 1993 by the Wellington Regional Council showing liquefaction hazard in Wellington, Porirua, Kāpiti and the Hutt Valley (Kingsbury and Hastie, 1993a; 1993b; 1993c; 1993d). A booklet only was produced describing the liquefaction hazard in the Wairarapa (Kingsbury and Hastie, 1993e). The maps show areas susceptible to liquefaction and the geographic variation in liquefaction susceptibility and liquefaction ground damage that could be expected during two earthquake scenarios, a large (magnitude 7), distant (100 km) shallow (15-60 km) earthquake producing MM5-6 on bedrock in the Wellington Region and a large (magnitude 7.5) earthquake on the Wellington-Hutt Valley segment of the Wellington Fault (Kingsbury and Hastie, 1993a; 1993b; 1993c; 1993d).

In addition to the work mapping the liquefaction hazard, historical studies were made to understand the performance of the sediments of the Wellington Region during historical earthquakes. The first report to address this is Fearliss and Berrill (1984) which lists liquefaction sites during historical earthquakes in New Zealand after 1840. This was followed with more detailed analysis of the historical records by Hancox et al. (1997, 2002) which establishes that liquefaction occurred in the Wellington Region in each of the 1848 Marlborough earthquake, 1855 Wairarapa earthquake, 1904 Cape Turnagain and 1942 Masterton earthquakes.

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5.0 LIQUEFACTION HAZARD

5.1 Introduction

Liquefaction hazard (the probability of liquefaction occurring) is a measure of the probability of the soils at a site liquefying when subjected to strong earthquake shaking. Certain soils are more susceptible to liquefaction than others. Generally, the assessment of liquefaction hazard involves two steps:

- First, evaluation of liquefaction susceptibility. This involves the identification of those layers at the site which have the physical characteristics of liquefiable soil; and
- Second, assessing the probability of strong ground shaking. This involves identifying seismic sources that are capable of generating moderate to large magnitude earthquakes and estimating the likelihood of ground shaking strong enough to cause liquefaction in the materials present at the site.

Liquefaction hazard at a site is assessed by estimating the extent and severity of liquefaction in response to different levels of shaking based on historical records and geological and geotechnical similarities in materials and their behaviour.

5.2 Liquefaction Susceptibility

The variation in liquefaction susceptibility was identified in the first instance using the historical response of the geological units present to strong ground shaking (Beetham et al. 1998; Dellow et al. 2003). For a given earthquake, with a known shaking intensity (derived from the Modified Mercalli intensity scale) a liquefaction-damage rating was applied using the scale in Table 5.1. Lateral spreading damage was assessed separately (Table 5.2 and Table 5.3) as the large horizontal displacements which occur are usually more damaging to buildings and other infrastructure than the differential settlements from liquefaction in confined areas.

Table 5.1 Descriptions of expected liquefaction induced ground damage for liquefaction damage ratings (after Dellow et al. 2003).

Liquefaction Damage Rating	Description of expected liquefaction induced ground damage
NONE	No liquefaction damage is seen.
MINOR	A few sand boils and minor fissures. Estimate up to 10% of total area affected.
MODERATE	Sand boils and moderate fissuring – more extensive near basin edges and in waterlogged areas: banks of rivers broken up, and embankments slumped. Settlements of up to 0.2 m. Estimate 10-20% of total area affected.
MAJOR	Lateral spreading common, with many fissures in alluvium (some large), slumping and fissuring of stop-banks, common sand boils. Settlements of up to 0.5 m. Estimate 20-50% of total area affected.
SEVERE	Lateral spreading widespread, with extensive fissures and horizontal (and some vertical) displacements of up to 10 m common especially near channel edges. Settlement of uncontrolled fills by up to 1.0m. Estimate >50% of total area affected.

The observations of liquefaction damage made after the 2010 Darfield earthquake and the 2011 Christchurch (Cubrinovski et al, 2011a) are in general agreement with these older tables. The limited distribution and relatively moderate severity of liquefaction after the Darfield earthquake was very different to the the more extensive and severe liquefaction recorded after the 2011 Christchurch earthquake (Cubrinovski et al, 2011a). Given the very general nature of these descriptions, the liquefaction damage after the 2010 Darfield earthquake is assessed as equivalent to the upper end of liquefaction damage rating 2 (Table 5.1 and Table 5.2), while after the 2011 Christchurch earthquake the liquefaction damage is assessed as being equivalent to the upper end of liquefaction damage rating 3.

Once the liquefaction damage rating has been assigned for known earthquakes, Table 5.4 is used to assign the liquefaction damage rating for intensities that are not represented in the historical record. If the liquefaction response of any geological units cannot be determined from historical data then a liquefaction damage rating is assigned by firstly considering any geotechnical data available for the unit and then by comparing the unit with similar materials in other areas where a liquefaction damage rating is available that has been assigned based on historical liquefaction.

Table 5.2 Liquefaction damage ratings for ground damage caused by lateral spreading.

Liquefaction damage rating (lateral spreading)	Description
NONE	No liquefaction damage is seen.
MINOR	Minor fissures. Horizontal displacements less than 0.5 m. Vertical displacements less than 0.1 m. Deformation (fissures) extend no more than 20 m from free face. Estimate up to 10% of total area affected.
MODERATE	Moderate fissuring – Horizontal displacements less than 2 m. Vertical displacements less than 0.2 m. Deformation (fissures) extend no more than 100 m from free face. Estimate 10-20% of total area affected.
MAJOR	Lateral spreading common - Horizontal displacements less than 5 m. Vertical displacements less than 0.5 m. Deformation (fissures) extend no more than 500 m from free face. Estimate 20-50% of total area affected.
SEVERE	Lateral spreading widespread - Horizontal displacements greater than 5 m. Vertical displacements greater than 0.5 m. Deformation (fissures) extend more than 500 m from free face. Estimate >50% of total area affected.

This method derives a liquefaction susceptibility class (Table 5.4) by assigning the highest liquefaction susceptibility class to the geological units where liquefaction is observed at the lowest shaking intensity (generally a Modified Mercalli Intensity of MM7; Appendix 1). As the shaking intensity increases, the severity and extent of liquefaction damage may increase in the very high liquefaction susceptibility class. The onset of liquefaction damage in the high liquefaction susceptibility class occurs at MM8. Thus using this method liquefaction susceptibility classes are assigned based on the level of shaking at which liquefaction damage first appears. This method is based on historical observations of liquefaction at the same site that report increasing severity and extent of liquefaction with increasing shaking intensity. However, these observations are limited because of the short historical record in New Zealand.

Table 5.3 Parameter values for lateral spreading liquefaction damage rating.

Liquefaction Damage Rating	Maximum horizontal displacement	Maximum vertical displacement	Maximum fissure distance from free face	Percentage area affected
MINOR	0.5 m	0.1 m	20 m	0-10%
MODERATE	2 m	0.2 m	100 m	10-20%
MAJOR	5 m	0.5 m	500 m	20-50%
SEVERE	> 5 m	> 0.5 m	1000 m	> 50%

Table 5.4 Liquefaction susceptibility classes and liquefaction damage ratings assigned at different Modified Mercalli shaking intensities (after Dellow et al. 2003). (*MOD = MODERATE as per Table 5.1, Table 5.2, Table 5.3).

Liquefaction Susceptibility Class	MM Intensity				
	MM6	MM7	MM8	MM9	MM10
	Liquefaction Damage Rating				
Very high	NONE	MINOR	MOD*	MAJOR	SEVERE
High	NONE	NONE	MINOR	MOD*	MAJOR
Moderate	NONE	NONE	NONE	MINOR	MOD*
Low	NONE	NONE	NONE	NONE	MINOR
None	NONE	NONE	NONE	NONE	NONE

Using the tables compiled from historical accounts, the liquefaction damage is described and labelled, in many cases based on quite limited descriptions, with respect to the severity of the damage (in terms of the measured displacements) and the extent of the liquefaction in terms of the percentage of the area of a susceptible unit that will visibly manifest liquefaction and lateral spreading.

At low levels of ground shaking, liquefaction will occur in only the most susceptible deposits, namely saturated, relatively uniform fine sands or coarse silts in a loose state, at depths less than 10 m, where the groundwater level is within about 2 m of the ground surface. However, liquefaction may occur in other less susceptible deposits during stronger ground shaking. Susceptibility to liquefaction may reduce if one or more of the following conditions apply: increasing depth to groundwater; increasing clay content in the sediments, increasing coarseness of the sediments (greater gravel content) or increasing variability in the grainsize of the sediments.

5.3 Frequency of Strong Ground Shaking

The other variable to consider besides the intensity of ground shaking is the frequency with which shaking of a given intensity occurs. The stronger the earthquake ground shaking the less frequently it will occur at a site. The frequency with which MM intensity shaking from MM6 to MM10 occurs in the urban centres of the Wellington Region is set out in Table 5.5.

From Table 5.5 it can be determined that land assessed as having a very high susceptibility to liquefaction will exhibit/experience liquefaction damage at the lowest severity (liquefaction damage rating 1) approximately once every 30 years throughout the region. But the same areas will only experience the severest liquefaction damage (liquefaction damage rating 4) once every 1500 to 3900 years depending on the location. In contrast, areas assigned low liquefaction susceptibility will only experience the lowest liquefaction damage (liquefaction damage rating 1) every 1500 to 3900 years depending on the location. This is consistent with the historical observations of liquefaction in the Wellington Region during strong earthquake shaking of the last 170 years.

Table 5.5 Annual return periods for different levels of MM shaking intensity for sites around the Wellington Region.

Location	nzmgE	nzmgN	MM6	MM7	MM8	MM9	MM10
Wellington City (Parliament)	2658869	5990550	7.6	29.3	120	400	1500
Porirua City (city centre)	2664444	6006288	7.6	30.1	120	470	2500
Kāpiti Coast (Coastlands)	2678863	6030331	7.5	29.6	120	600	3900
Lower Hutt (Queensgate)	2669818	5997971	7.7	29.8	120	400	1500
Upper Hutt (UHCC)	2683567	6006898	7.8	29.5	110	430	2800
Featherston	2705288	6007331	8.1	29.2	110	400	2700
Martinborough	2716198	5995787	8.8	31.2	120	440	2200
Greytown	2716766	6011160	8.1	28.7	110	400	2400
Carterton	2722502	6017105	8.0	28.0	100	380	2300
Masterton	2733910	6025072	7.8	27.3	99	350	1700

Assumptions:

1. MMI attenuation modelling as per Dowrick and Rhoades (2005) and Smith (2002).
2. No adjustments for ground class. Assumed ground class is Ground Class C – Shallow soil as per New Zealand Standard, 2004.
3. Long-term average recurrence intervals for known active fault sources.

6.0 EVALUATION LIQUEFACTION HAZARD IN THE WELLINGTON REGION

6.1 Introduction

The evaluation of the liquefaction hazard across the Wellington Region presented here has only used existing datasets to identify the materials that are susceptible to liquefaction and to spatially constrain their extent wherever possible.

6.1.1 Subsurface Information

The information available to assess the material properties of materials include data from boreholes, which may include standard penetrometer tests (SPT), cone penetrometer tests (CPT - the most common method of investigation for material properties used in Christchurch after the Canterbury earthquake sequence of 2010-2011), seismic cone penetrometer tests (SCPT) (which includes measured shear-wave velocities), and spatial auto-correlation of micro-tremors (SPAC) which provide a shear-wave velocity profile for a site where ground conditions are suitable.

The borehole data accessed is held by Greater Wellington and includes both geotechnical boreholes (boreholes drilled for the purpose of investigating geological and geotechnical conditions) and water-well boreholes drilled for the primary purpose of accessing underground water resources. The quality and quantity of information available varies between boreholes but the primary use made of these data was to obtain a description of material types in the upper 20 m of the borehole, as these are the materials that if susceptible, will liquefy. In most cases the soils in the upper 20 m of the boreholes match the material descriptions given for the corresponding geological units shown on the geological maps used in the study.

The data records including borehole, SPT, CPT, SCPT and SPAC data are variable in quality and quantity with regards to information used in assessing liquefaction hazard. Borehole data provides information on the types of material present in the subsurface, and their depths, but provides no direct information on properties such as strength and porosity. SPTs provide some data on soil strength but have a large uncertainty with respect to liquefaction assessment (Clayton, 2014).

Cone Penetration Test soundings (CPT) can provide far more accurate and continuous information on the soil properties than the SPT method for determination of liquefaction potential (Toprak and Holzer, 2003). CPTs provide a continuous record of soil properties (versus a single SPT result measured over 0.5 m every two to five metres) allowing both the soil properties and their thickness to be measured as a continuous record. CPTs are the preferred investigation method for liquefiable soils in Christchurch because of this. Although CPT's are the most reliable means of assessing liquefaction potential at a site, very few CPT records are publically available in the Wellington Region.

SCPT tests provide the shear-wave velocity of the shallow soil column in addition to the CPT record. The addition of the shear-wave velocity is helpful because Stephenson et al. (2011) identified a shear-wave velocity of 200 m/s as the upper threshold for liquefiable sediments in a series of SPAC tests in Christchurch. This also points to the value of SPAC results in the Wellington Region as the SPAC tests provide a shear-wave velocity profile and where this exceeds 200 m/s at the ground surface the site is unlikely to liquefy.

6.1.2 Geological map data

The data used to spatially constrain the liquefaction hazard were the most recent geological mapping at the most detailed scale available (Begg and Mazengarb, 1996; Begg and Johnston, 2000; Lee and Begg, 2002). This mapping is available digitally in a GIS, with the source data from Begg and Johnston (2000) and Lee and Begg (2002) mapped at a presentation scale of 1:250,000 for the entire region and more detailed mapping of Wellington City and large parts of the Hutt Valley and Porirua City available at a scale of 1:50,000 (Begg and Mazengarb, 1996).

The geological setting of the different areas within the Wellington Region varies with the shallow alluvial and marginal marine sediments of the Porirua Basin and Wellington City standing in contrast to the deep alluvial and marginal marine sediments of the wide and deep valleys of the Hutt and the Wairarapa formed in fault-angle depressions and the wedge of marginal-marine sediments present on the Kāpiti Coast.

6.1.3 Other data

Additional data used to validate the liquefaction hazard mapping and where necessary refine the spatial extent of liquefiable deposits were reports of liquefaction during historical earthquakes.

No effort was made to systematically use the depth to the unconfined groundwater surface in this analysis because these data are lacking for large areas of the region. However, the results of this study enable areas to be identified where an understanding of the unconfined groundwater surface would better quantify the liquefaction hazard.

6.1.4 Significant liquefaction

The liquefaction susceptibility is presented for each of the city and district councils (the three Wairarapa district councils are shown on a single map) using two maps. The first map uses a deterministic method to rank the liquefaction susceptibility in each area. Five categories of liquefaction susceptibility are used, ranging from no liquefaction through low, moderate, high and very high liquefaction susceptibility classes, with the areas ranked as having a very high liquefaction susceptibility expected to see liquefaction effects, albeit at a low level of damage at a Modified Mercalli shaking intensity of MM7 as per Table 5.1 to Table 5.4.

The second map identifies areas where liquefaction hazard may be considered significant, that is, areas where the liquefaction could be a danger and needs further quantitative investigation. If the quantitative measures of liquefaction hazard, such as cone penetrometer tests evaluated using the liquefaction severity number (van Ballegooy et al, 2014) show severe enough liquefaction then actions to mitigate the effects of liquefaction could be considered. Site-specific investigations would be required to determine both the extent and severity of liquefaction at a site in order to ensure the mitigation measures adopted are appropriate for the site’s current or future use. These site-specific investigations should be undertaken by a qualified geotechnical professional and include direct observation of the sub-surface ground conditions using approved tests.

The second map highlights the areas mapped as having a moderate, high or very high liquefaction hazard. Areas of low liquefaction hazard will experience liquefaction-induced ground damage no greater than liquefaction and lateral spreading with a minor damage rating (Table 5.1 and Table 5.2). For liquefaction this implies only a few sand boils and minor fissures with less than 10% of the total susceptible area affected (Table 5.1); and for lateral spreading minor fissures, horizontal displacements less than 0.5 m, vertical displacements less than 100 mm, fissures extend no more than 20 m from free face, less than 10% of total susceptible area affected (Table 5.2).

Areas with a low liquefaction hazard are only expected to experience visible liquefaction effects at MM10. As MM10 is only expected to occur with a frequency between 1500 and 3900 years depending on location within the region, areas of low liquefaction susceptibility have been excluded from the areas mapped as having potential for damaging levels of liquefaction. In areas where liquefaction is unlikely, the provisions in NZS 3604 for foundation investigations are likely to prove adequate for domestic house foundations.

The intent of the binary delineation of liquefaction hazard presented in the significant liquefaction maps is to identify those areas where liquefaction needs to be considered as a potential danger needing further investigation, planning and mitigation purposes (e.g. California Department of Conservation, 2000).

6.2 Wellington City

6.2.1 Data

The areal distribution of data used to determine the liquefaction hazard in Wellington City is summarised in Figure 6.1. The data comprise geological mapping from published sources and available in a GIS (Geographic Information System) format. Maps used to address the liquefaction hazard in Wellington City include Begg and Mazengarb (1996) and the Wellington Harbour Board reclamation map (Bastings, 1936). The Begg and Mazengarb (1996) map provides data on the spatial distribution of geological units at a scale of 1:50,000. The late Quaternary and Holocene geology was simplified to aid in the liquefaction assessment. Within the Wellington City area, four late Quaternary and Holocene units that could potentially liquefy are recognised. Some mapped late Quaternary sediments are included here because on the map legend the Holocene is not age differentiated from the late Quaternary for these sediments. These geological units are:

> Beach deposits: dominantly medium dense to dense fine to coarse sand (marginal marine sediments): around the original shoreline of Lambton Harbour, the Kilbirnie-Lyall Bay isthmus and the Worser Bay, Seatoun, Breaker Bay areas. This also includes two areas of mixed marginal marine sands and fan alluvium in southern Miramar - Strathmore and Island Bay.
>
> Recent alluvium: loose to dense fine sands to gravel in the small streams and valleys of the city, e.g. Karori, Makara, Tawa and Khandallah-Ngaio. An area of mixed Holocene and older gravels along the south-eastern side of Tinakori Hill is also included in this unit.
>
> Dunes: loose to medium dense fine sand - a small area of dunes is present in Miramar.
>
> Anthropogenic fills: divided into five separate units ranging from rock-fill – medium dense to dense coarse angular gravels (airport, stream and some harbour fills in the Lambton area) (Begg and Mazengarb, 1996) to hydraulic fill – very loose to loose silt and fine to medium sand (Aotea Quay area) (Bastings, 1936) to old refuse dumps – medium dense to dense mixed weathered gravel and human refuse (Wilton) (Begg and Mazengarb, 1996) to engineered fills dense angular gravel (motorway interchange at Tawa) (Begg and Mazengarb, 1996) and unrestrained fill at the southern end of the CentrePort container terminal (Van Dissen et al, 2013). The fills are subdivided into four separate units because it can be shown that they have responded very differently, from a liquefaction perspective, during historical earthquake shaking (Table 6.1).

Borehole data are available for some of the area. Over 800 boreholes were used to establish subsurface geology in the CBD (Semmens et al. 2010, Semmens et al, 2010a, Semmens et al, 2011). A few boreholes were available outside this area (Figure 6.1). The borehole data provide information on the distribution of subsurface sediments, as well as some geotechnical data where standard penetrometer tests (SPTs) were carried out in conjunction with drilling.

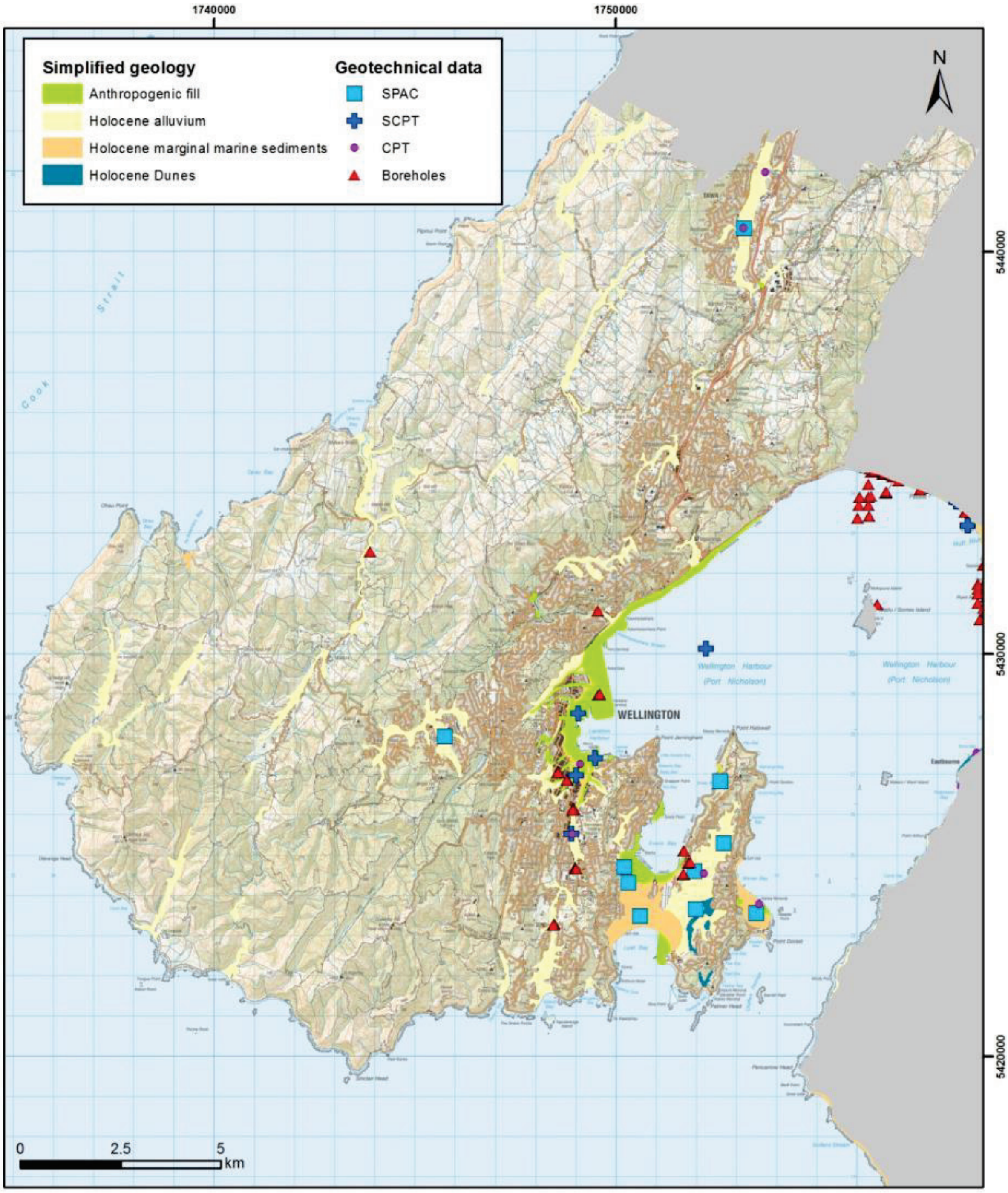

Figure 6.1 Simplified geology of Wellington City showing locations of sediments potentially susceptible to liquefaction. The locations and types of subsurface data used in the liquefaction assessment are also shown.

Available geotechnical data includes standard penetrometer test (SPT), cone penetrometer test (CPT) and seismic cone penetrometer test (SCPT) results. These data provide information on the material properties of the subsurface materials and indicate where the materials may be susceptible to liquefaction. Standard penetrometer test (SPT) results for Wellington City data are generally higher (SPT N counts >2) than the most susceptible sediments in Christchurch (SPT N counts <2). This is consistent with the observed liquefaction response during historical earthquakes for both Wellington (1855, 1942, 2013) (Hancox et al, 2002, Van Dissen et al, 2013) where liquefaction was limited and only minor damage occurred, and Christchurch (2010, 2011) where liquefaction was widespread and damaging at similar levels of shaking (Cubrinovski et al, 2013).

Geophysical data available for Wellington City includes SPAC data, a non-invasive technique that measured shear-wave velocities in the near surface materials. Shear-wave velocities of less than 200 m/s are generally required for a geological unit to be susceptible to liquefaction. The available SPAC data for Wellington (Barker et al. 2012) generally has shear wave velocities in excess of 200 m/s. There are some exceptions, with the Lambton Harbour reclamation fills having shear-wave velocities less than 200 m/s at two sites. At least three other sites around the city (Ebor St in the Te Aro area (4 m deep), Onepu Rd in Kilbirnie (1.6 m deep) and Miramar Park in Miramar (8 m deep)) have shear wave velocities less than 200 m/s but these are relatively shallow (<10 m) and therefore seasonal variations in the depth of the water table will strongly influence the occurrence of liquefaction at these sites if the sediments are susceptible to liquefaction.

A three-dimensional model of the geology is available for the CBD area (Semmens et al. 2010, Semmens et al, 2010a, Semmens et al, 2011). This model also characterises the geotechnical properties of the sediments beneath the CBD. This model has been used to help constrain the liquefaction hazards in the CBD.

There is no reliable shallow groundwater model for Wellington City.

6.2.2 Results

The liquefaction and lateral spreading assessment for the Holocene sediments (deposited in the last 10,000 years) of Wellington City are categorised in Table 6.1. The data in Table 6.1 are presented in two maps (Figure 6.2 and Figure 6.3). Figure 6.2 presents a map of liquefaction susceptibility for Wellington City. The severity of liquefaction and lateral spreading over varying levels of ground shaking is estimated using the five-fold scale outlined in Table 5.1 to Table 5.4.

Figure 6.3 presents a significant liquefaction hazard map for Wellington City where liquefaction and lateral spreading hazard is presented - areas where liquefaction is potentially significant versus areas where liquefaction will not occur or if it does it will be inconsequential (effects will not occur or will be minor in nature and occur infrequently). In Figure 6.3 areas where significant liquefaction is likely are the reclamations of Lambton Harbour and in-filled stream valley sediments of Thorndon and Te Aro and similar areas in the Kilbirnie-Lyall Bay-Miramar but including the marginal marine sediments such as are present in Seatoun.

The only areas assigned a very high liquefaction susceptibility are the hydraulic fill reclamation (pumped harbour muds) near Aotea Quay and the southern end of CentrePort's container port reclamation. Sand boils were reported in the hydraulic fill after the June 1942 Masterton earthquake which produced MM6-7 intensity shaking in Wellington City (Table 6.1). No other reports of liquefaction are known from Wellington City for this event. In both the July and August 2013 earthquakes, the unrestrained reclamation at the southern end of the container port slumped with ground cracking extending some 50 m inland from the slump failure (Hancox et al. 2013). Some cracks had sand and silt ejecta (Hancox et al. 2013).

Table 6.1 Liquefaction and lateral spreading damage ratings assessed using historical records and geological precedent for the Holocene sediments of Wellington City.

Geological Unit[1]	Modified Mercalli Intensity					Liquefaction Susceptibility (see Table 5.4)
	6[2]	7[3]	8	9[4]	10	
	Liquefaction Damage Rating (see Table 5.1)					
Q1n (hydraulic fill)	**none**	**minor**	*moderate*	*major*	*severe*	Very High
Q1n[5] (unrestrained fill)	**moderate**	*major*	*severe*	*severe*	*severe*	Very High
Q1n (un-engineered fill)	**none**	**none**	*minor*	*moderate*	*major*	High
Q1b (beach deposits)	**none**	**none**	*none*	**minor**	moderate	Moderate
Q1a (recent alluvium)	**none**	**none**	*none*	**none**	*minor*	Low
Q1d (dunes)	**none**	**none**	*none*	*none*	*none*	Low
Q1n (refuse fill)	**none**	**none**	*none*	*none*	*none*	none
Q1n (engineered fill)	**none**	*none*	*none*	*none*	*none*	none

Bold numbers are for historical observations, while the italic numbers are assessments made where no historical data exists.

1. Geological unit codes (e.g. Q1n) from Begg and Mazengarb, 1996. Q1 refers to oxygen isotope stage one and denotes that the unit has an age between 0 and 14,000 years old. Fills differentiated based on age and construction type (from Bastings, 1936; Begg and Mazengarb, 1996 and Van Dissen et al, 2013).
2. MM6 data based on the 2013 Cook Strait and Lake Grassmere earthquakes.
3. MM7 data based on the June 1942 Masterton earthquake.
4. MM9 data based on January 1855 Wairarapa earthquake
5. Unrestrained fill is limited to the southern end of the container terminal facilities of CentrePort Wellington.

The areas assigned a high liquefaction susceptibility at require least MM8 intensity shaking before any ground damage becomes significant. These areas are located on the harbour reclamations constructed using rock fill in Lambton Harbour, the harbour reclamations in Evans Bay, including Greta Point and Shelley Bay, and the reclamation for the southern extension to the airport in Lyall Bay. All these, with the exception of the airport fill and the container port reclamation, (both constructed after 1942) experienced the 1942 Masterton earthquakes at MM7 but with no ground damage in these areas.

It is anticipated that areas mapped as having moderate liquefaction susceptibility will require at least MM9 intensity shaking before significant ground damage occurs. In Wellington, these areas are located in in-filled valleys between Tinakori Hill and Mt Victoria, the marginal marine sediments of Lambton Harbour (the original shoreline) and the marginal marine sediments of the Lyall Bay – Evans Bay isthmus and Seatoun. The marginal marine sediments in the central city had sites with small scale fissuring and sand and silt ejection (liquefaction damage rating of 1; Table 5.1) at MM9 in the 1855 Wairarapa earthquake.

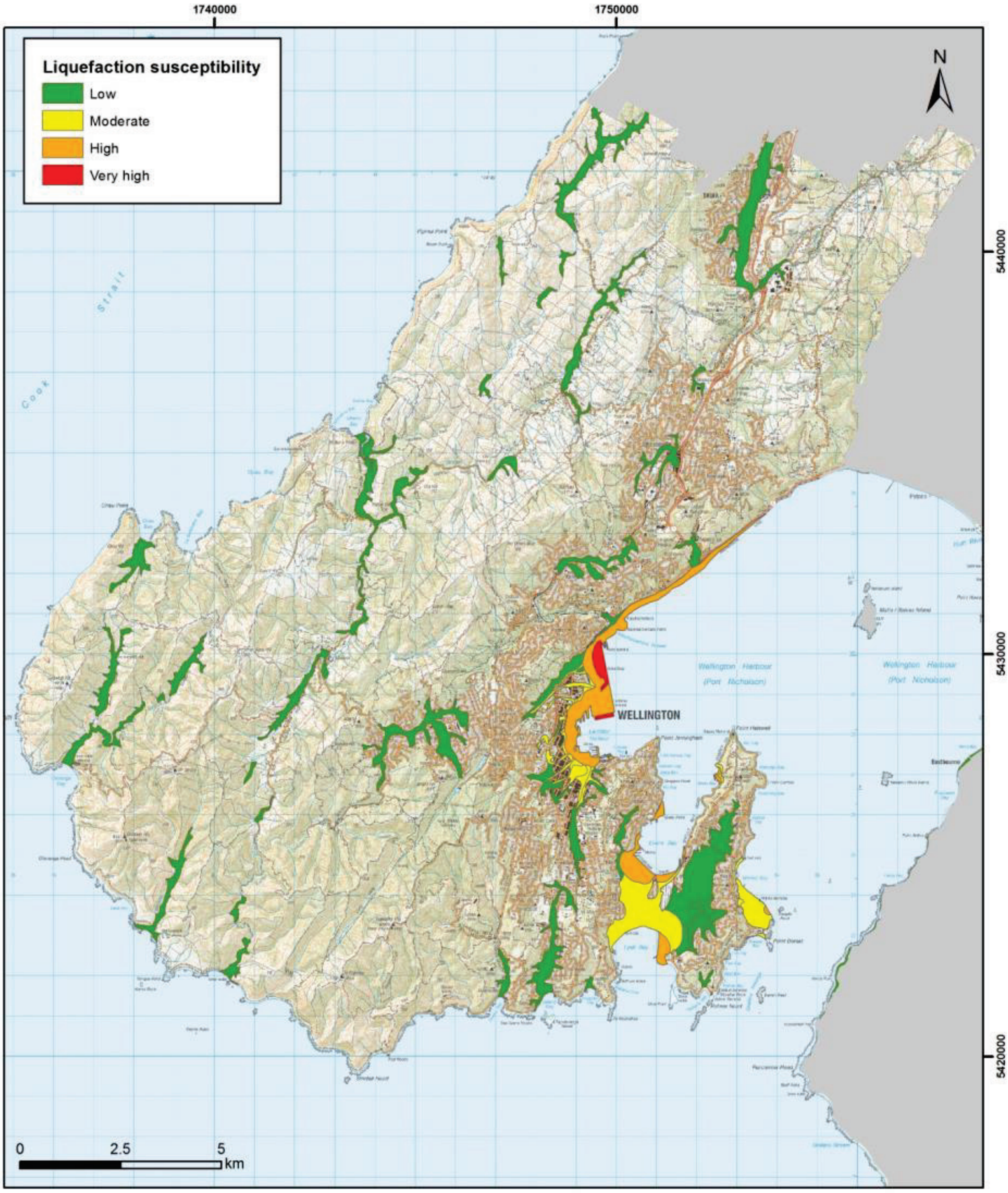

Figure 6.2 Liquefaction susceptibility of sediments in Wellington City. Table 5.1, Table 5.2, Table 5.3 and Table 5.4 define the expected liquefaction in each liquefaction-susceptibility class over a range of ground shaking intensities. Table 5.5 gives the expected return period of each of the assessed shaking intensities.

The low liquefaction susceptibility areas in Wellington are the remaining areas of Quaternary sediments, and it is anticipated that at least MM10 intensity shaking will be needed before any ground damage occurs, and if it does occur it is likely to be inconsequential. These areas include stream alluvium, refuse tips and engineered fills. There are no reports of liquefaction occurring in these areas in any historical earthquakes that have impacted Wellington. The old Wilton tip is assessed as having a low susceptibility to liquefaction because it was developed on top of bedrock (greywacke) and the water table within the refuse fill is unlikely to be within a few metres of the surface.

A couple of other factors to note in relation to liquefaction in Wellington are that the 1855 earthquake raised land in around the city by about 1 m. This would have had the effect of lowering the water table in some areas, reducing the opportunity for liquefaction to occur. Draining the Te Aro swamp would have had a similar effect. Another factor to consider is the infilling of stream valleys. In places this may have increased the depth to the water table but in other places may have impeded drainage, decreasing water table depth.

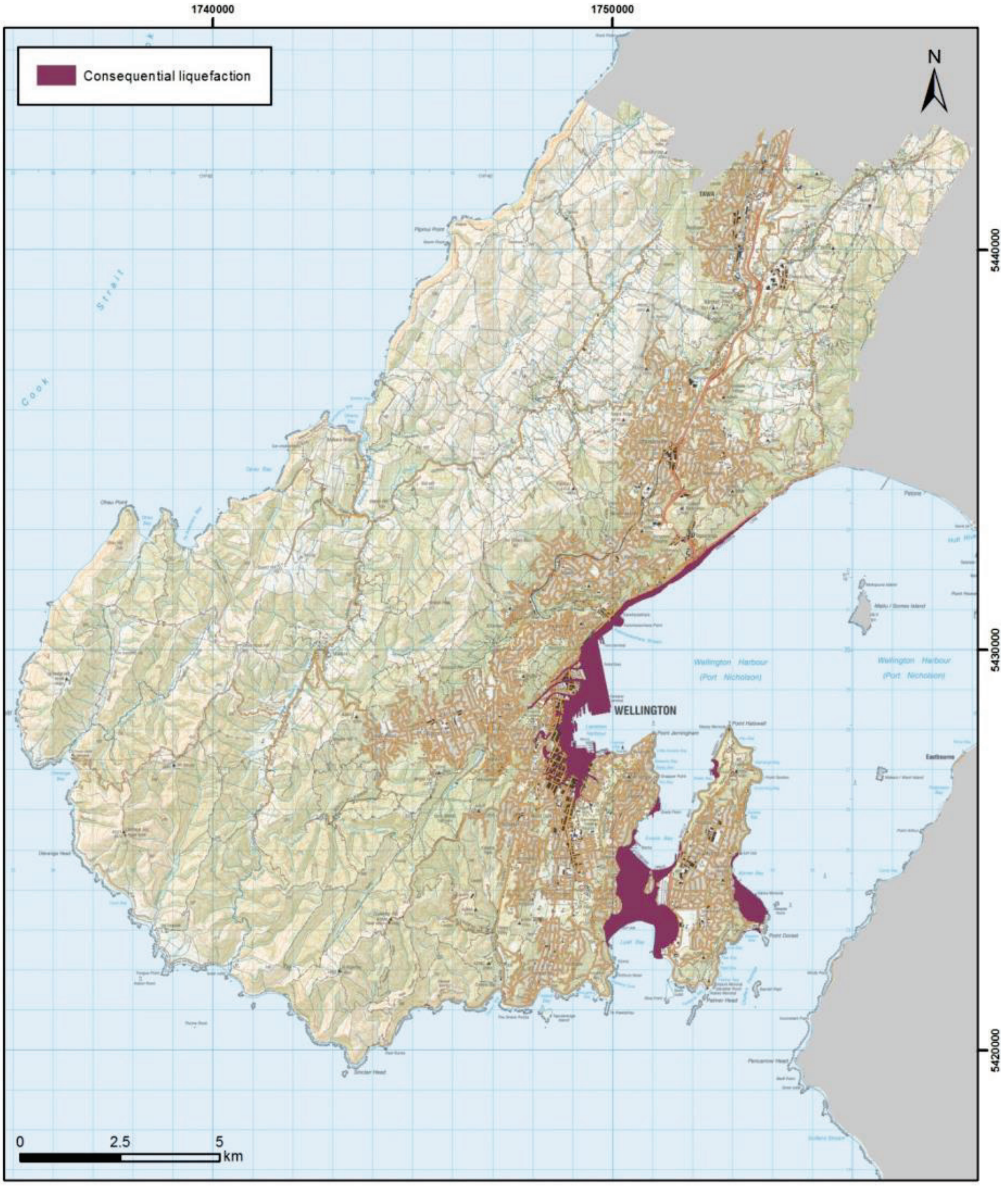

Figure 6.3 Map of Wellington City showing areas of potentially damaging liquefaction, where liquefaction is expected to damage infrastructure, if the shaking is strong enough (MM8 or greater).

6.2.3 Discussion

Historically ground damage from liquefaction in Wellington City has been of limited extent. This is due to a relative lack of highly susceptible sediments in the city. The lack of rivers and streams of significant size, and of estuaries and lagoons, with their low-energy fine-grained sedimentation processes, are the major factors contributing to the lack of liquefiable materials in Wellington City. This absence generally precludes lateral spreading occurring in the wider Wellington City area, except in specific circumstances associated with reclamation fills or where colluvial wedges extend onto poorly drained areas.

The fills associated with harbour reclamation and the infilling of stream valleys in the central city are potentially vulnerable to liquefaction induced-ground damage at shaking intensities of MM6-7 or greater. At lower levels of shaking, MM6 and MM7, liquefaction is confined to specific areas, namely the reclamation areas built by pumping harbour muds into a confined area, and the container terminal reclamation where an unconfined fill face is being suggested as the reason for lateral spreading during the Cook Strait earthquake of July 2013. The other fills around the harbour are predominantly end-tipped rock fills and as such have performed largely without damage at shaking levels in the MM6 to MM7 range. None of these fills has been tested at stronger shaking levels but the evidence from historical earthquakes both in New Zealand (Hawke's Bay, 1931; Canterbury 2010 and 2011) and overseas (1995 Kobe, Japan; 1964 Anchorage Alaska; 1960 Valdivia, Chile; and 1989 Loma Prieta, California) provide evidence that reclamations on shallow marine sediments are vulnerable to liquefaction ground damage at moderate to strong levels of earthquake shaking (MM8 – MM9).

The only areas of natural ground that may be vulnerable to liquefaction ground damage are the marginal marine sediments of the Evans Bay – Lyall Bay isthmus and Seatoun. The limited historical evidence indicates these areas are only vulnerable to liquefaction at shaking intensities of MM9 or greater. Available geotechnical data for these areas, mostly SPAC data (Barker et al, 2012) indicate shear-wave velocities in the near surface in excess of 200 m/s. Stephenson et al, 2010 suggest that such areas should not be particularly vulnerable to damaging liquefaction because areas that liquefied in the Darfield (2010) and Christchurch (2011) earthquakes had measured shear-wave velocities less than 200 m/s.

In the areas assessed as being vulnerable to damaging levels of liquefaction (Figure 6.3) additional information from two potential sources would help confirm the extent of vulnerable areas. The first source is further cone penetrometer (CPT) data for the marginal marine sediments of the Lyall Bay – Evans Bay isthmus and Seatoun. Existing SPAC data suggest that the large areas indicated as possibly vulnerable to liquefaction could be substantially reduced with if better data were available. The behaviour of the fills is more difficult to characterise because CPT probes are less likely to successfully penetrate the rock-fills overlying the shallow marine sediments that may be susceptible to liquefaction. The rock-fills also act to increase the depth to the liquefiable layers. This further reduces the likelihood of liquefaction manifesting at the ground surface in the areas of rock-fill. Another source of information that would enable better characterisation of the liquefaction hazard in the areas shown in Figure 6.3 as likely to experience damaging liquefaction is the depth below the ground surface of the shallow groundwater table and how this varies with both the tide and seasonally.

In the Canterbury earthquakes, extensive liquefaction occurred in eastern Christchurch at shaking intensities equivalent to MM8-MM9 (Bradley and Hughes, 2013; Wald et al, 1999). However, with regards to geological material types, there are no areas analogous to eastern Christchurch in Wellington City (Brown and Weeber, 1992; Begg and Mazengarb, 1996). The setting in Canterbury that is most analogous to Wellington City is Lyttelton Harbour. Liquefaction in Lyttelton Harbour was minor and limited to harbour reclamations at MM8–MM9 (Chalmers et al, 2013).

6.3 Porirua

6.3.1 Data

The data used to determine the liquefaction hazard in Porirua City are shown in Figure 6.4. Maps used to provide data on the spatial distribution of geological units for liquefaction hazard in Porirua City include Begg and Mazengarb (1996) and the 1;250,000 scale geological map of the Wellington Region (Begg and Johnston, 2000).

The late Quaternary and Holocene geology were simplified in the liquefaction assessment. Some mapped late Quaternary sediments are included here because on the map legends the Holocene is not age differentiated from the late Quaternary for these sediments. Within the Porirua City area four late Quaternary and Holocene (sediments deposited within the last 10,000 years) units that could potentially liquefy are recognised. These are:

Holocene marginal marine sediments (outer harbour): medium dense to dense, fine to coarse sand at Plimmerton and on the Mana isthmus.

Holocene marginal marine sediments (inner harbour): loose to medium dense silts, sands and gravels around the original shoreline of Porirua Harbour and Pauatahanui Inlet. These deposits are most extensive at the head of the Porirua Arm and at the head of Pauatahanui Inlet.

Holocene alluvium: medium dense to dense gravel, sand and silt in the small streams and valleys of the city, e.g. Porirua Stream, Duck Creek, Judgeford basin, Horokiri Stream and Kakaho Stream.

Holocene swamp: loose sands and silts of the Taupo Swamp, ponded behind the marginal marine deposits at Plimmerton.

Anthropogenic fill: medium dense to dense angular gravel and sand at the southern end of the Porirua Arm of the harbour and around the margins (State Highway 1 and Titahi Bay Road).

Borehole data available for this project was limited, with access to only seven boreholes within the boundaries of Porirua City, four in the city centre, two in the Judgeford basin and one in the Horokiri valley. The four boreholes in the city centre are all within the marginal marine sediments at the southern end of the Porirua Arm of Porirua Harbour. These boreholes are sited within tens of metres of each other and three of the four show sediments with a moderate to high clay content. The other three boreholes in the alluvium of the Pauatahanui Stream at Judgeford and the Horokiri Stream near Battle Hill Farm Park all show mixed alluvium dominated by gravel, and to a lesser extent clay, particularly in the top few metres.

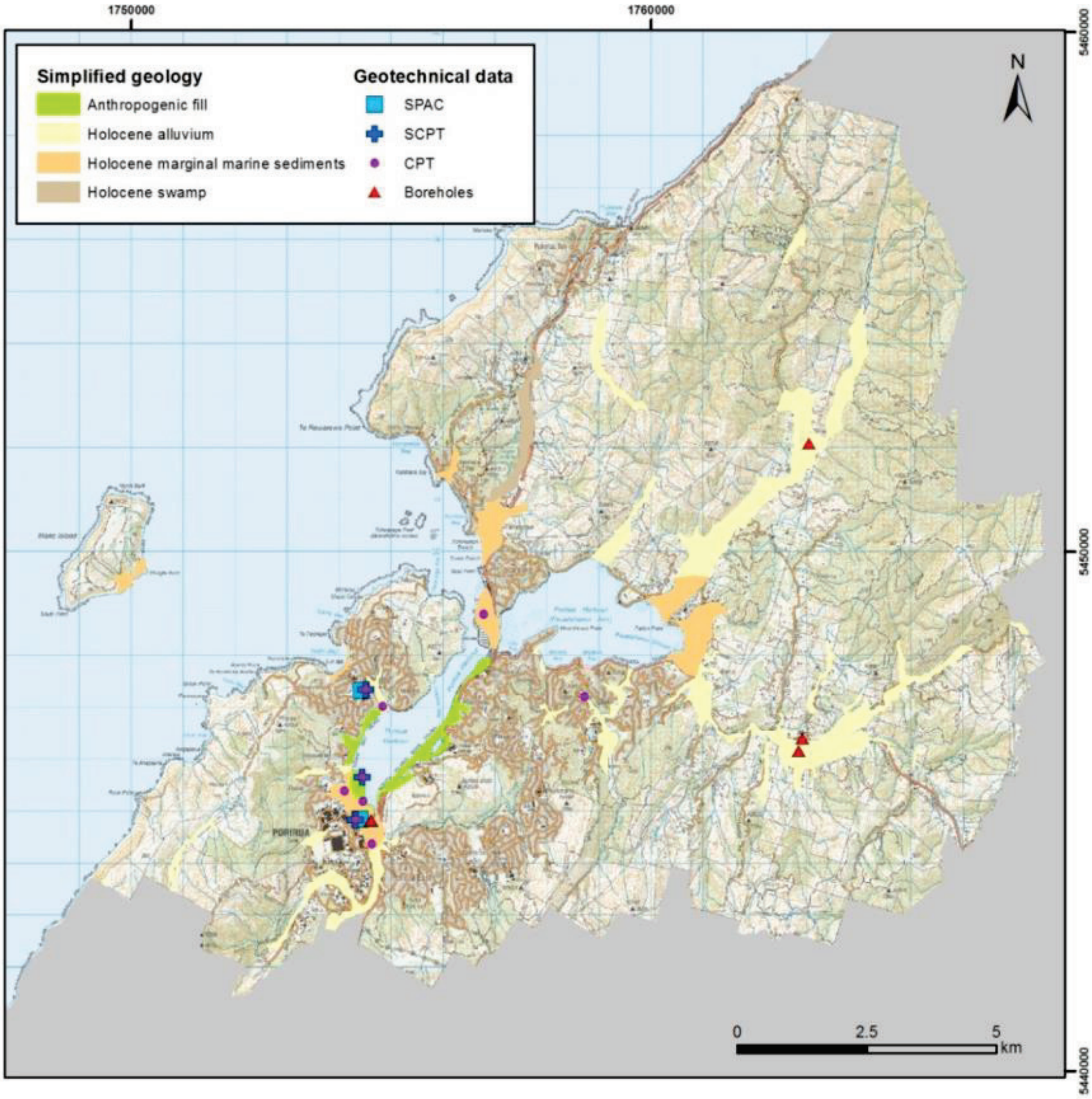

Figure 6.4 Simplified geology of Porirua City showing locations of sediments potentially susceptible to liquefaction. The locations and types of subsurface data used in the liquefaction assessment are also shown.

Nine cone penetrometer test (CPT) results within Porirua City have been accessed, two in Titahi Bay, one at Ngati Toa Domain in Mana, five in the city centre area and one in Whitby. The site at Kura Park in Titahi Bay is described as non-liquefiable in Stephenson and Barker (1991). An evaluation of micro-tremor data (SPAC measurements) acquired in 2012 for the Kura Park site indicate that the top 7.5 metres has a shear wave velocity of 117 m/s which, being below 200 m/s, which is in the liquefiable range (Barker et al. 2012). However, CPT results from Stephenson and Barker (1991) indicate that the top 7.5 metres of sediment is stiff with some clay present. There is no information available on the depth to the water table at this site. Collectively these data suggest that the site is unlikely to liquefy because of the stiff soil strength and the presence of cohesive clay in the sediment.

The CPT site at Onepoto Park in Titahi Bay shows up to six metres (in two layers) of materials with a point resistance ranging from 5 to 15 MPa, indicating materials that are either coarse grained or that are medium dense (non-cohesive) or stiff (cohesive) (Stephenson and Barker, 1992b). There are also two layers (from 4-6 metres and 8-14 metres of materials that have a point resistance of 1-2 MPa indicating loose, fine grained materials. It is not possible to determine the clay content from the available data. There are no groundwater data available for this site. Based on this information, Onepoto Park is assessed as having, at worst, a moderate liquefaction potential.

The CPT site in Whitby at Discovery School (Stephenson and Barker, 1991) shows four metres of dense silty sand overlying two metres of stiff clay and clayey silt. No information on the depth of groundwater at this site has been found. Based on these data (moderately dense surficial silty sand and clay-rich sediments below this) the site is assessed as unlikely to liquefy.

The CPT probe at Ngati Toa Domain met refusal at 0.4 metres depth in a layer of tightly packed gravels (Stephenson and Barker, 1992b).

There are five CPT tests in the central city area and one SPAC site. Two (Wi-Neera Drive and Semple Street) are located within the reclaimed area at the southern end of the Porirua Arm of the harbour and the other three CPT's and the SPAC site (Recreation Centre/Te Rauparaha Park, Newall Street and Elsdon Park) are located in an area mapped as Holocene marginal marine sediments. Both the CPT's on the reclamation show four to five metres of coarse-grained material interpreted as fill overlying seven to ten metres of material with a point resistance of 1-2 MPa. The CPT at Elsdon Park is similar to the reclamation fill CPT's while the Newall Street and Recreation Centre CPT's are more variable. The SPAC result at Te Rauparaha Park indicates up to 12 m of sediments with a shear wave velocity of 180 m/s, which being below 200 m/s, is in the liquefiable range (Barker et al. 2012). These results suggest that the original harbour sediments are liquefiable, but the thickness and strength of the overlying fill along with the depth to the surface of the unconfined groundwater surface will determine whether the liquefaction can be damaging at the ground surface.

6.3.2 Results

The liquefaction and lateral spreading hazards assessment for the Holocene sediments (deposited in the last 10,000 years) of Porirua City are categorised in Table 6.2. The data in Table 6.2 are presented in two maps (Figure 6.5 and Figure 6.6). Figure 6.5 presents a liquefaction susceptibility map for Porirua City. The severity of liquefaction and lateral spreading is estimated using a five-fold scale based on Table 5.1 to Table 5.4.

Figure 6.6 presents a liquefaction hazard map for Porirua City where liquefaction hazard is presented in two classes - areas where damaging liquefaction might occur versus areas where liquefaction will not occur or if it does it will be inconsequential (damaging effects will not occur). On Figure 6.6 areas where damaging liquefaction might occur are the sediments and fill that are marginal to the coast and the Taupo Swamp. This is consistent with observations from historical earthquakes that at MM7 (1942), liquefaction phenomena were not seen.

6.3.3 Discussion

The total area of possible liquefaction in Porirua is limited. However, the mapping is not well constrained due to a lack of subsurface geotechnical and geophysical data. Targeted acquisition of data in the areas marked as likely to experience liquefaction damage may enable the extent of the liquefaction to be further refined. Key areas that may be affected by liquefaction are the Porirua City central business district and the Mana isthmus. The Plimmerton beach ridge and Pauatahanui village are other areas where liquefaction damage is possible.

Table 6.2 Liquefaction and lateral spreading damage ratings assessed using historical records and geological precedent for the Holocene sediments of Porirua City.

Geological Unit[1]	**Modified Mercalli Intensity**					**Liquefaction Susceptibility (see Table 5.4)**
	6[2]	**7[3]**	**8**	**9[4]**	**10**	
	Liquefaction Damage Rating (Table 5.1)					
Q1n (anthropogenic fill)	**none**	*none*	*minor*	*moderate*	*major*	High
Q1b (marginal marine deposits: inner harbour)	**none**	**none**	*minor*	*moderate*	*major*	High
Q1b (marginal marine deposits : outer harbor)	**none**	**none**	*none*	*minor*	*moderate*	Moderate
Q1a (Holocene alluvium)	**none**	**none**	**none**	**none**	*minor*	Low
Q1s (Holocene swamp)	**none**	**none**	*none*	*minor*	*moderate*	Moderate

Bold numbers are for historical observations, while the italic numbers are assessments made where no historical data exists.

1. Geological unit codes (e.g. Q1n) from Begg and Mazengarb, 1996; Begg and Johnston, 2000. Q1 refers to oxygen isotope stage one and denotes that the unit has an age between 0 and 14,000 years old. Marginal marine deposits differentiated on basis of exposure to open ocean wave action producing denser sediments.
2. MM6 data based on the 2013 Cook Strait and Lake Grassmere earthquakes.
3. MM7 data based on the June 1942 Masterton earthquake.
4. MM9 data based on January 1855 Wairarapa earthquake

There is no historical record of liquefaction in the Porirua City area. In 1848 (MM8) and 1855 (MM9) the area was lightly settled but the overland road to the west coast of the North Island passed through the area following the Porirua Stream, around the eastern margin of the Porirua Arm of the harbour and the southern margin of the Pauatahanui Inlet before following the Paekakariki Hill Road route. In 1855, the road was reported as being sunk in places but this cannot be directly attributed to liquefaction as road fills commonly crack and subside during earthquake shaking and this is more likely to be what was observed. In 1942 (MM7) the area was more extensively settled but no reports of liquefaction damage in Porirua City have been found.

Cone penetrometer testing is recommended for investigating the potential liquefaction hazard at sites that are likely to experience liquefaction damage (Figure 6.6) but any CPT results need to be integrated with the historical records. For example, if the CPT tests, at say the site of the Pauatahanui staging post, show potentially liquefiable sediments this would need to be reconciled with the historical observation that no liquefaction effects were noted at MM9 in 1855 and there were numerous observers would have noted such occurrences (e.g. Edward Roberts).

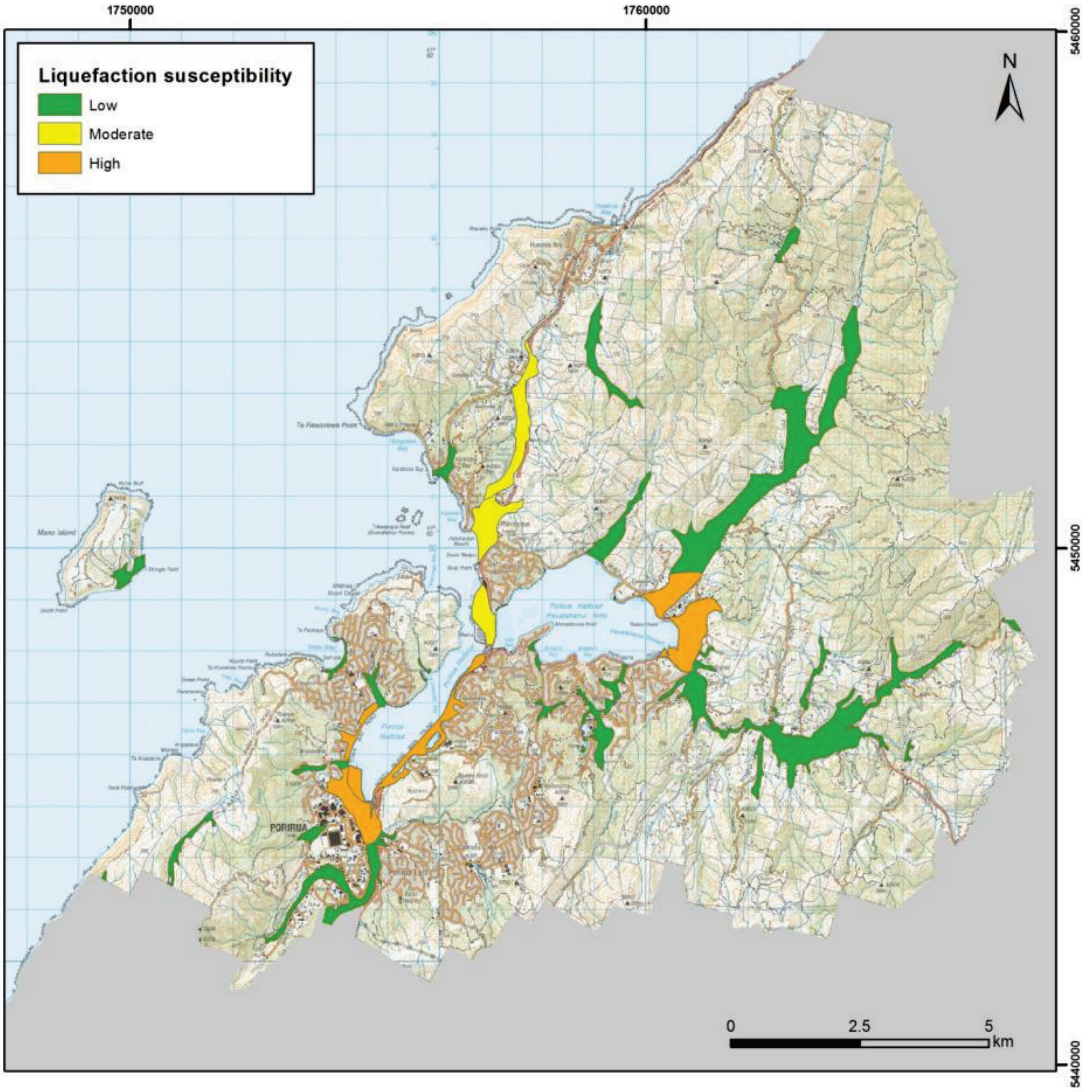

Figure 6.5 Lliquefaction susceptibility of sediments in Porirua City. Table 5.1, Table 5.2, Table 5.3 and Table 5.4 define the expected liquefaction in each liquefaction-susceptibility class over a range of ground shaking intensities. Table 5.5 gives the expected return period of each of the assessed shaking intensities.

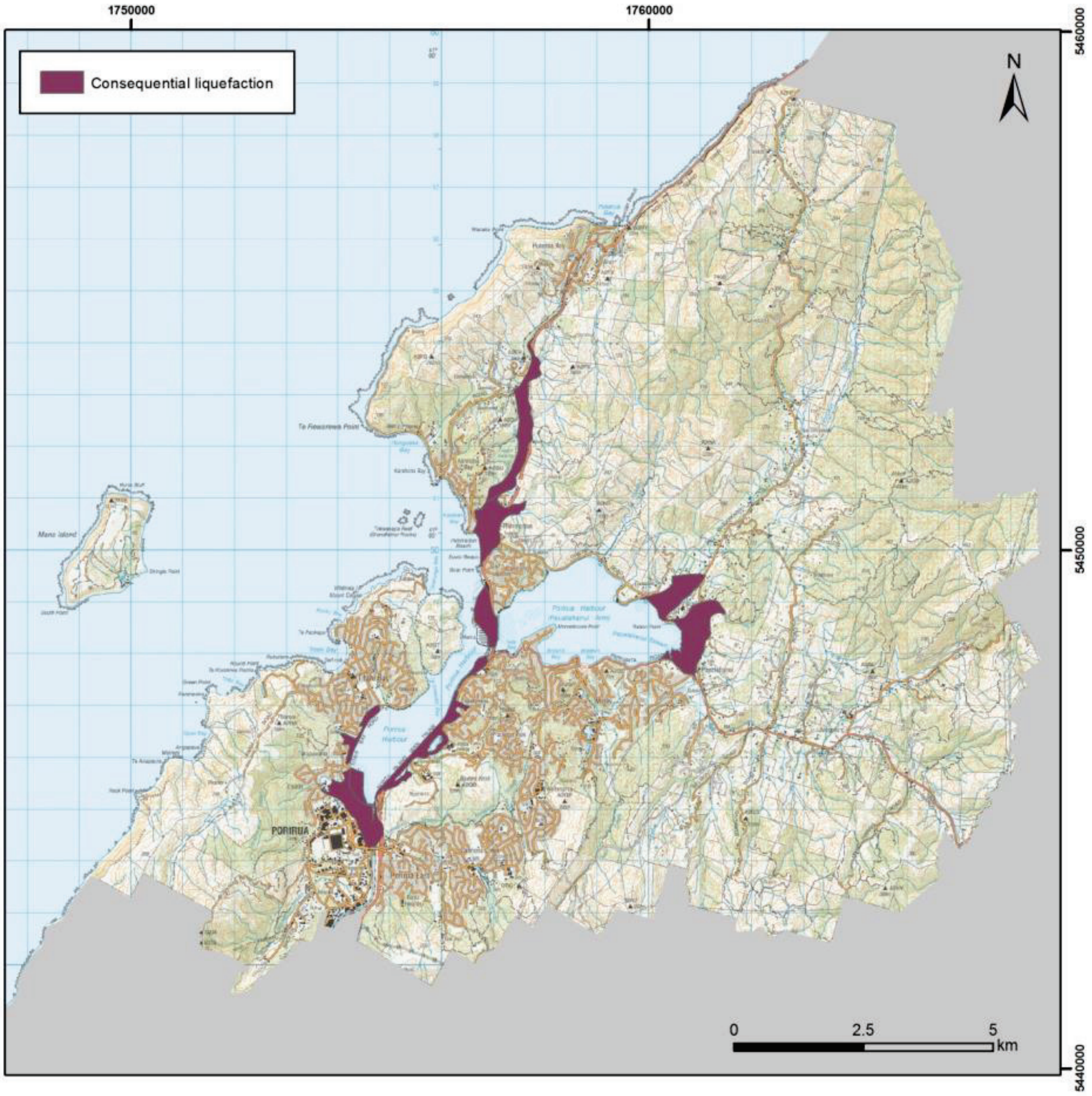

Figure 6.6 Map of Porirua City showing areas of potentially damaging liquefaction, where liquefaction is expected to damage infrastructure, if the shaking is strong enough (MM8 or greater).

6.4 Hutt Valley

6.4.1 Data

The data used to determine the liquefaction hazard in the Hutt Valley are shown in Figure 6.7. Maps used to provide data on the spatial distribution of geological units for liquefaction hazard in the Hutt Valley include the 1:50,000 scale geological map of Begg and Mazengarb (1996) and the 1;250,000 scale geological map of the Wellington region (Begg and Johnston, 2000). The late Quaternary and Holocene geology was simplified for the liquefaction assessment. Some mapped late Quaternary sediments are included here because on the map legends the Holocene is not age differentiated from the late Quaternary for these sediments. Within the Hutt Valley area four late Quaternary and Holocene (sediments deposited within the last 10,000 years) units that could potentially liquefy are recognised.

These are:

Holocene alluvium (Hutt Valley north of Hutt City CBD): medium dense to dense gravels and sandy gravels of the Taita alluvium. North of the Hutt City CBD the Taita alluvium is dominated by gravel.

Holocene alluvium (Hutt Valley south of Hutt City CBD): loose to medium dense silts, sands and sandy gravels mapped as part the Taita alluvium of the Hutt Valley. Although the alluvium has been mapped as a single unit, the sedimentary composition is variable, more notably in the lower reaches of the Hutt River in the Alicetown-Woburn-Moera-Gracefield area where the Taita alluvium is often finer-grained.

Holocene alluvium (Mangaroa, Akatarawa, Pakuratahi, Orongorongo, Wainuiomata Rivers (excluding Wainuiomata) and Gollans Stream): medium dense to dense gravels and sandy gravels of the named rivers and streams

Holocene alluvium (Wainuiomata): mix of cohesive clays and loose silts of the developed area of Wainuiomata where fine-grained lake sediments are present.

Holocene marginal marine sediments (Petone): loose to dense sands and silts present in the Petone-Gracefield area which extend inland to inter-finger with the Taita Alluvium in the Alicetown-Woburn-Moera-Gracefield area.

Holocene marginal marine sediments (coast from Seaview to Mukamuka Stream): medium dense to dense fine to coarse sand and gravels of beach deposits exposed to the open sea, gravel-dominated from Eastbourne to Turakirae Head.

Holocene swamps: loose silts, sands and gravels, often with inter-bedded peat are present in the Melling, Naenae, Trentham and Mangaroa areas.

Anthropogenic fill: medium dense to dense coarse angular gravels and sand at Seaview, near the mouth of the Hutt River.

Begg and Mazengarb (1996) mapped the Holocene Hutt River alluvium, (Taita Alluvium), as comprising 10 to 15 m of gravel, and sand and gravel that overlie swamp deposits which include the Melling Peat and contemporaneous marginal marine sediments including the Petone Marine Beds. The Petone Marine Beds are typically shelly, sometimes gravel rich sandy silt and silty sand (Stevens, 1956) and are c. 27 m thick in the Petone (Gear Meat) drillhole (#151). They are still being deposited off the Petone foreshore today. To the north and east of Melling Bridge, the Melling Peat forms the lateral equivalent of the Petone Marine Beds. It consists of sand, gravel, silt and peat beds with remnants of a fossil forest and is up to c. 4000 years old based on radiocarbon dating. The Melling Peat is younger towards the coast and probably thins to the southwest and northeast (Stevens, 1956; Begg and Mazengarb, 1996). An enclave of swamp deposits nestle between two alluvial fans at Naenae. A similar swamp is mapped in the Trentham area. The swamp deposits were penetrated by a drillhole at Naenae that recorded up to 30m of soft silt and inter-bedded peats. There are probably other deposits of soft organic silt and peat locally under the valley floor.

Borehole data are available for some of the area. 846 boreholes were used to establish geology in the Lower Hutt area (Boon et al. 2010). Only a few boreholes are available for outside the Lower Hutt area (Figure 6.7). The borehole data provides information on the distribution of subsurface sediments, as well as some geotechnical data where standard penetrometer tests (SPTs) were carried out in conjunction with drilling.

Available geotechnical data includes standard penetrometer test (SPT), cone penetrometer test (CPT) and seismic cone penetrometer test (SCPT) results. These data provide information on the material properties of the subsurface materials and indicate where the materials may be susceptible to liquefaction. Standard penetrometer test (SPT) results for Lower and Upper Hutt are generally higher (>2) than the most susceptible sediments in Christchurch (<2). This is consistent with the observed liquefaction response during historical earthquakes for both Wellington (1855, 1942, 2013) (Hancox et al, 2002; Van Dissen et al, 2013) where liquefaction was limited and only minor damage occurred, and Christchurch (2010, 2011) where liquefaction was widespread and damaging (Cubrinovski et al, 2013). SPT results in Wainuiomata are generally very low as reflects the sedimentary environment but the cohesion is likely greater than observed in Christchurch.

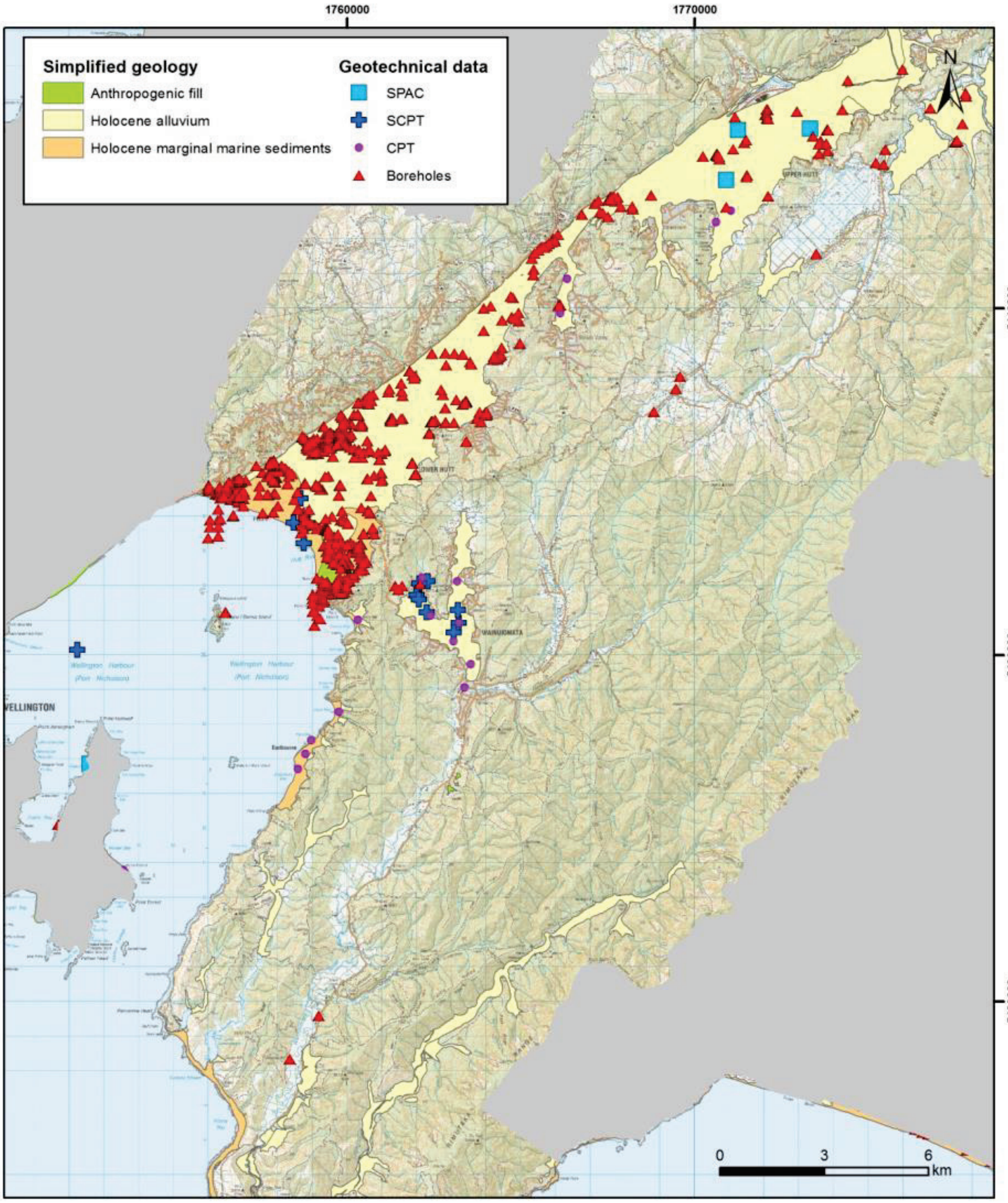

Figure 6.7 Simplified geology of the Hutt valley showing locations of sediments potentially susceptible to liquefaction. The locations and types of subsurface data used in the liquefaction assessment are also shown.

There are few CPT test results available for the Valley sediments (Stephenson and Barker, 1992a, 1992b). Correlations between SPT and CPT have been developed for assessing liquefaction potential. More CPT data are desirable to provide accurate strength profiles of the Lower Hutt Valley Holocene materials. There are thirteen seismic cone penetrometer records available for the Hutt Valley, five in the Petone area and eight in Wainuiomata.

There are three SPAC (spatial auto-correlation) test results available for the Hutt Valley, all in Upper Hutt (Barker et al. 2012). All the SPAC results suffered from poor coherency, but are consistent with shear wave velocities of 400-500 m/s. Shear wave velocities of this magnitude are inconsistent with liquefiable materials, which in Christchurch were shown to have shear wave velocities less than 200 m/s.

6.4.2 Results

The liquefaction and lateral spreading hazards assessment for the Holocene sediments (deposited in the last 10,000 years) of the Hutt Valley are categorised in Table 6.3. The liquefaction hazard in the Hutt Valley is then presented in two maps (Figure 6.8 and Figure 6.9). Figure 6.8 shows the areas where liquefaction is considered likely during strong ground shaking. This area is quite extensive in Lower Hutt and Wainuiomata with small areas identified in Stokes Valley and Upper Hutt. A large swamp in the Mangaroa valley is also identified as likely to liquefy. The limited infrastructure and buildings in this area are marginal to the swamp. No areas with very high liquefaction susceptibility have been identified in the Hutt Valley. This is based on the absence of reports of liquefaction after the 1942 Masterton earthquakes and the 2013 Cook Strait earthquake.

Areas with a high susceptibility to liquefaction are considered to be the lower part of the Lower Hutt valley, the Naenae swamp, the Mangaroa swamp and areas adjacent to waterways in Wainuiomata. Historical data available for Wainuiomata, Naenae and Mangaroa are limited to the fact that no liquefaction was reported from these areas in 1942. For the lower part of the Lower Hutt valley the reports from 1855 indicate sand boils and lateral spreading were common along the margins of the river (note the river channels in 1855 were different to the heavily modified course of the Hutt River in this area today (Figure 6.10). The high susceptibility area in Wainuiomata is assigned on the basis that the drains in the urban area are 2 to 5 m deep and potentially provide a ‘free face’ to facilitate lateral spreading.

The areas assessed as having a moderate susceptibility to liquefaction in the Hutt Valley are the marginal marine strip along the Petone Esplanade, river and stream channels, both current and old, in Lower Hutt, the Trentham swamp in Upper Hutt, the Wainuiomata valley north of Main Road intersection with Moore’s Valley Road and Gollans valley on the south coast.

Figure 6.9 presents a liquefaction hazard map for the Hutt valley where liquefaction hazard is in two classes - areas where liquefaction damage might occur versus areas where liquefaction will not occur or if it does it will be inconsequential (damaging effects will not occur). On Figure 6.9 areas where liquefaction damage is likely are the sediments and fill that are marginal to the coastline including the Petone, Alicetown, Moera and Woburn areas, the soft sediments of Wainuiomata and swamps at Naenae and Trentham. This is consistent with the observations from historical earthquakes that at MM7 (1942), liquefaction phenomena have not been observed, but at stronger shaking intensities (e.g. MM9 in 1855) liquefaction was reported in these areas.

Table 6.3 Liquefaction and lateral spreading damage ratings assessed using historical records and geological precedent for the Holocene sediments of the Hutt Valley.

Geological Unit[1]	**Modified Mercalli Intensity**					**Liquefaction Susceptibility (see Table 5.4)**
	6[2]	**7[3]**	**8**	**9[4]**	**10**	
	Liquefaction Damage Rating (see Table 5.1)					
Q1n (anthropogenic fill)	**none**	**none**	*minor*	*moderate*	*major*	High
Q1b (Holocene marginal marine deposits at Petone)	**none**	**none**	*minor*	*moderate*	*major*	High
Q1b (Holocene marginal marine deposits from Seaview to Mukamuka Stream)	**none**	**none**	*minor*	*moderate*	*major*	Moderate
Q1a (Holocene alluvium, Hutt Valley north of Hutt City CBD – gravel dominated)	**none**	**none**	**none**	**none**	*minor*	Low
Q1a (Holocene alluvium Hutt Valley south of Hutt City CBD – sand and silt dominated)	**none**	**none**	*none*	*minor*	*moderate*	Moderate
Q1a (Holocene alluvium of other rivers and streams)	**none**	**none**	*none*	*none*	*minor*	Low
Q1a (Holocene alluvium of Wainuiomata– fines dominated)	**none**	**none**	*none - minor*	*minor - moderate*	*moderate - major*	Moderate to high
Q1s (Holocene swamp)	**none**	**none**	*minor*	*moderate*	*major*	High

Bold numbers are for historical observations, while the italic numbers are assessments made where no historical data exists.

1. Geological unit codes (e.g. Q1n) from Begg and Mazengarb, 1996; Begg and Johnston, 2000. Q1 refers to oxygen isotope stage one and denotes that the unit has an age between 0 and 14,000 years old. Marginal marine deposits differentiated on basis of exposure to open ocean wave action producing denser sediments. Alluvial deposits differentiated on the basis of grain-size from subsurface data (boreholes, CPT and SPT probes).
2. MM6 data based on the 2013 Cook Strait and Lake Grassmere earthquakes.
3. MM7 data based on the June 1942 Masterton earthquake.
4. MM9 data based on January 1855 Wairarapa earthquake.

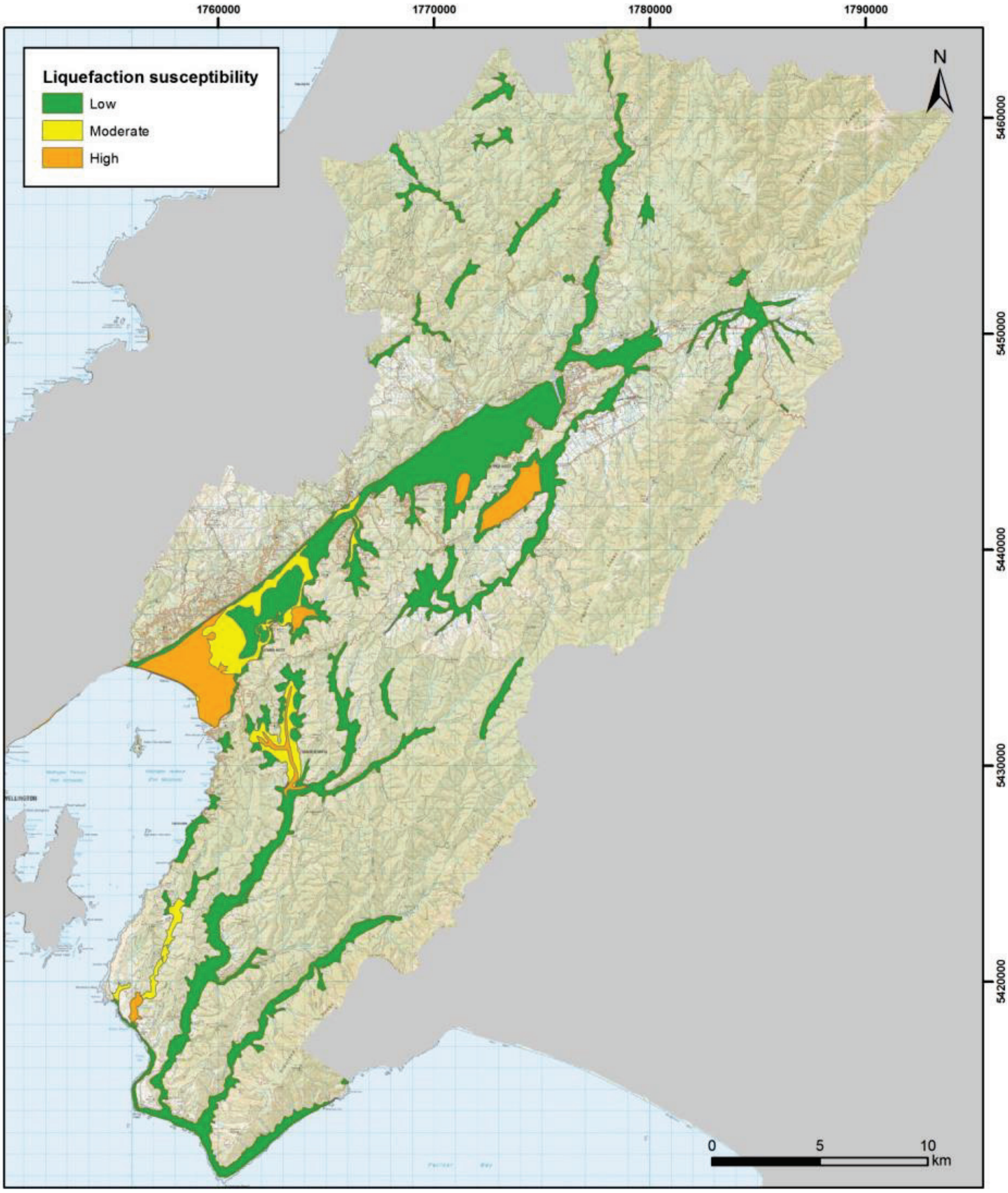

Figure 6.8 Liquefaction susceptibility of sediments in the Hutt valley area. Table 5.1, Table 5.2, Table 5.3 and Table 5.4 define the expected liquefaction in each liquefaction-susceptibility class over a range of ground shaking intensities. Table 5.5 gives the expected return period of each of the assessed shaking intensities.

The remaining sediments of the river and stream valleys are assigned a low susceptibility to liquefaction because although there is no historical evidence, isolated pockets of liquefiable sediments may be present. However, their extent and consequent ability to cause damage is probably quite limited. Of the two SPAC results in Upper Hutt one, at Upper Hutt College was inconclusive, and the other at Upper Hutt Primary School indicated relatively high shear-wave velocities and, accordingly, the sediments are interpreted as unlikely to be liquefiable.

The potential problem areas for liquefaction in the Hutt Valley are Lower Hutt and Wainuiomata. Further data are needed to better refine the extent and severity of the liquefaction hazard. A key location for this would be the Petone Esplanade which is a transit route for several lifelines (road, water and wastewater). Better understanding in the Naenae area would also help refine the earthquake hazards here as currently the liquefaction mapping is largely based on geological mapping and is poorly constrained due to the lack of relevant sub-surface data. The same applies to Wainuiomata.

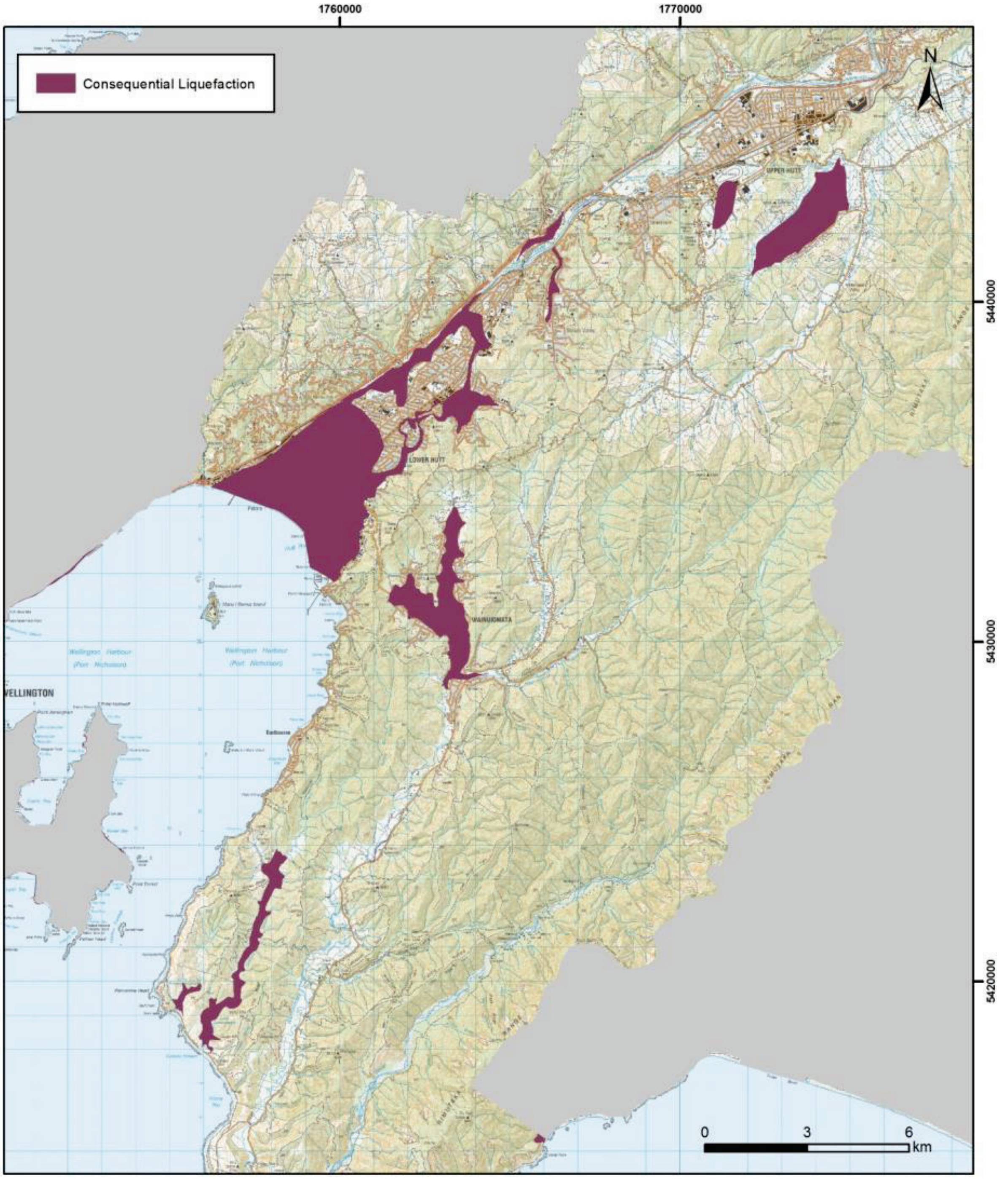

Figure 6.9 Map of the Hutt valley showing areas of potentially damaging liquefaction, where liquefaction is expected to damage infrastructure, if the shaking is strong enough (MM8 or greater).

6.4.3 Discussion

The reports of liquefaction damage from the Hutt Valley from historical earthquakes, particularly the 1855 Wairarapa earthquake, describe damage that appears to be extensive and widespread. However, the observation of Roberts (1855) that the Manawatu plains were much more affected than the Hutt Valley, particularly when the Hutt Valley appears to have been the more strongly shaken area (c.f. MM8 and MM9 respectively, Grapes and Downes,(1997)) points to a paucity of the more susceptible materials in the Hutt Valley. This observation is also supported by the lack of liquefaction in the 1942 Masterton earthquakes (MM6 (Lower Hutt) and MM7 (Upper Hutt)) and the 2013 Cook Strait earthquakes (MM6-7).

This raises issues about the extent and severity of the damaging liquefaction that occurred in 1855. Analysis of the contemporary reports in 1855 is mostly limited to the southern end of the Hutt Valley. The fissuring was mostly along the banks of the rivers and creeks according to one account (Grapes and Downes, 1997) which is where it was in Christchurch too.

There is no information available for Wainuiomata from 1855, so the behaviour of the soft sediments in the Parkway Stream above its junction with the Wainuiomata River can only be inferred. Also the effect of cutting drains through the soft sediment is difficult to evaluate as these post-date the 1855 earthquake. A study by Stephenson and Barker (1991) has shown that Wainuiomata is underlain by very soft, weak sediment. Low shear wave velocities suggest elevated liquefaction susceptibility, but fine-grained sediments indicate the possibility of cohesion thereby reducing the liquefaction susceptibility. We map the Wainuomata basin as having moderate liquefaction susceptibility but acknowledge the need to have this verified.

A constraint to defining the location of sites susceptible to liquefaction in the Hutt Valley is a lack of spatial control. The mapping for this project has relied on the 1:50,000 scale geological map of Begg and Mazengarb (1996) to provide spatial boundaries for the limited subsurface and geotechnical data that are available. It is also worth noting the since the earlier work undertaken in 1991-92 (Read et al. 1991; Dellow et al. 1991) very little new sub-surface information has become available. The most substantial improvements in quantifying the extent and severity of liquefaction hazards in the Hutt Valley over the next few years will be made by collecting geotechnical data (preferably cone penetrometer test results) and mapping the geomorphology using LiDAR topographic data as a base, and a model of the shallow unconfined groundwater surface including seasonal and tidal variations based on measured data.

6.5 Kāpiti Coast

6.5.1 Data

The data used to determine the liquefaction hazard on the Kāpiti Coast are shown in Figure 6.10. The data comprises geological mapping from published sources and available in GIS format. Maps used to address the liquefaction hazard in the Hutt Valley include the 1:50,000 scale geological map of Begg and Mazengarb (1996) and the 1;250,000 scale geological map of the Wellington Region (Begg and Johnston, 2000). The Begg and Mazengarb (1996) and Begg and Johnston (2000) maps provide data on the spatial distribution of geological units. The late Quaternary and Holocene geology was simplified for the liquefaction assessment. Some mapped late Quaternary sediments are included here because on the map legend the Holocene is not age differentiated from the late Quaternary for these sediments. Within the Kāpiti area three late Quaternary and Holocene (sediments deposited within the last 10,000 years) units that could potentially liquefy are recognised. These are:

Holocene aeolian dunes: are mapped as being present over the coastal strip from Paekakariki to north of Otaki. Although this area is mapped as a single unit, a number of geomorphic settings are present within it but cannot be differentiated on the basis of the available mapping.

Holocene alluvium: is present in the river valleys of the Tararua ranges and on the coastal strip deposited by the Otaki and Waikanae rivers on their way to the sea

Holocene marginal marine sediments: are limited to the active beach sediments which extend as a narrow strip (300-2100 metres wide) from Paekakariki to north of Otaki. The limited width of this unit means it does not show up at the scale of mapping used in this report.

The geological setting of the Kāpiti Coast is of a mountain range front with a coastal strip of dunes and swamps with two major rivers, the Waikanae and the Otaki, exiting the ranges before discharging into the sea. The alluvium in the Otaki and Waikanae Rivers is dominated by gravels derived from the greywacke ranges. The dune system between the ranges and the sea has a number of different environments ranging from foreshore dunes with inter-dune swamps and lagoons to the extensive back-dune peat swamps between the foredune system and the mountain range front.

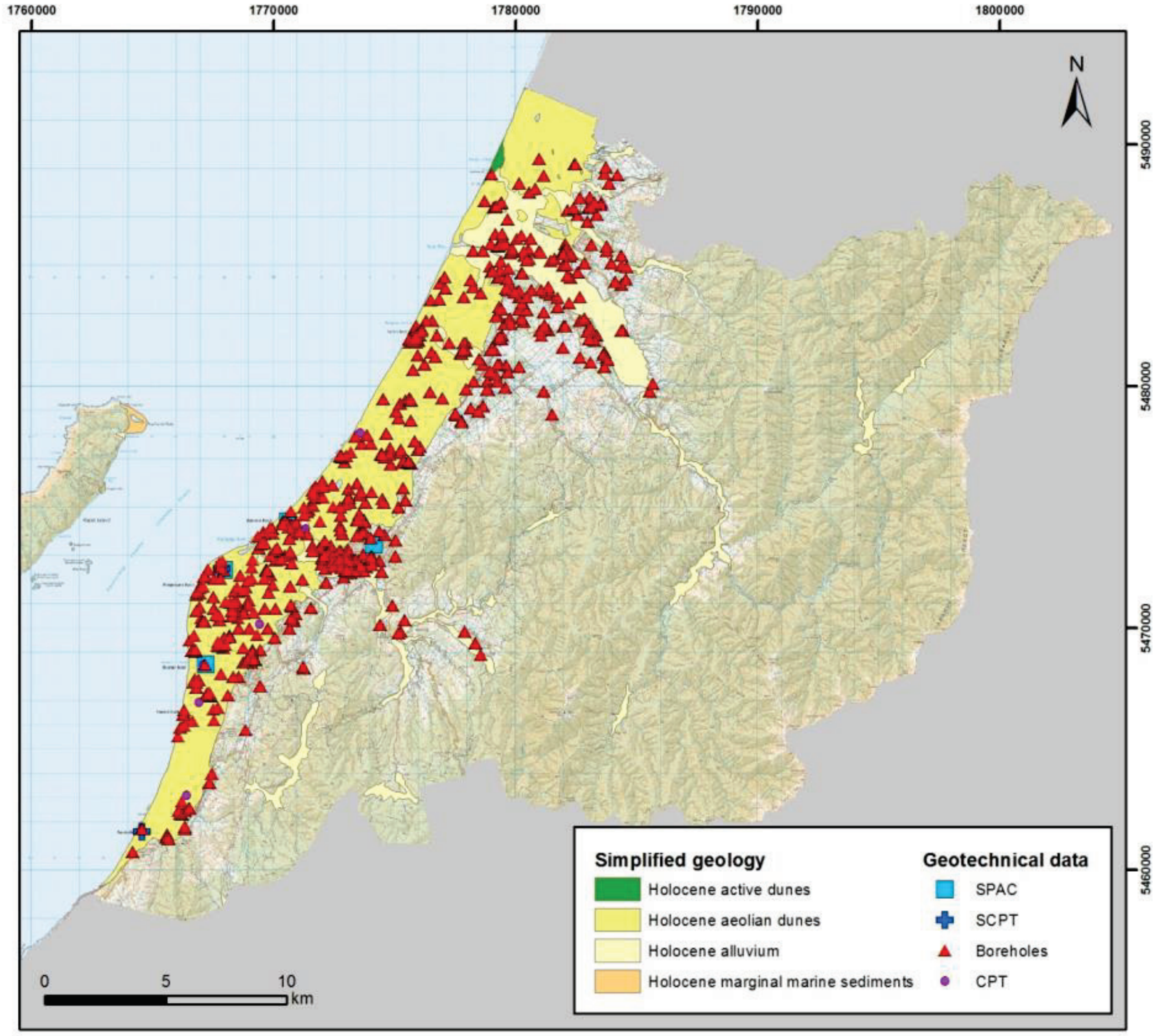

Figure 6.10 Simplified geology of Kāpiti District showing locations of sediments potentially susceptible to liquefaction. The locations and types of subsurface data used in the liquefaction assessment are also shown.

Borehole data are available for some of the area. 613 boreholes were used to establish geology in the Kāpiti area (Figure 6.7). The borehole data provided information on the distribution of subsurface sediments, as well as some geotechnical data where standard penetrometer tests (SPTs) were carried out in conjunction with drilling. No standard penetration test results were available with the Kāpiti Coast borehole data.

Nine cone penetrometer test results are currently available as public records for the Kāpiti Coast. These are all located in the southern part of the Kāpiti Coast between Paekakariki and Peka Peka.

Two seismic cone penetrometer test (SCPT) results are available for the Kāpiti Coast. Four SPAC results measuring shear-wave velocity are available, again between Paekakariki and Waikanae.

6.5.2 Results

The liquefaction and lateral spreading hazards assessment for the Holocene sediments (deposited in the last 10,000 years) of the Kāpiti Coast are categorised in Table 6.4. The liquefaction hazard on the Kāpiti Coast is presented in two maps (Figure 6.11 and Figure 6.12). Figure 6.11 shows total liquefaction susceptibility. The low liquefaction susceptibility areas include the gravel terraces within the valley systems of the greywacke ranges and areas of alluvium within the dune system. While these areas may experience some liquefaction during extreme shaking events (MM10) the liquefaction is anticipated to be limited in extent and lateral spreading is unlikely to occur (Table 5.1). The high liquefaction susceptibility areas on the Kāpiti Coast are the dune and inter-dune swamps of the fore-dune system. Experience from Christchurch in the New Brighton and Pines Beach areas suggest dunes are not as vulnerable to liquefaction because the sands are generally free-draining and have sufficient overburden pressure ('crust thickness') to prevent liquefaction from manifesting at the ground surface as fissures and ejecta. The inter-dune swamps may be more vulnerable because sand is below the water table, but the historical evidence also suggests that iron pans form in this environment and these may prevent liquefaction reaching the surface. Fracturing of iron-pans in a similar environment in Wanganui during strong earthquake shaking led to the draining of swamps (Beetham et al.1998).

Table 6.4 Liquefaction and lateral spreading damage ratings assessed using historical records and geological precedent for the Holocene sediments of the Kāpiti Coast.

Geological Unit[1]	**Modified Mercalli Intensity**					**Liquefaction Susceptibility (Table 5.4)**
	6[2]	**7[3]**	**8**	**9[4]**	**10**	
	Liquefaction Damage Rating (see Table 5.1)					
Q1b (Holocene marginal marine deposits)	**none**	**none**	**none**	*none*	*none*	Moderate
Q1a (Holocene alluvium)	**none**	**none**	**none**	**none**	*minor*	Low
Q1d (Holocene dunes)	**none**	**none**	*minor*	*moderate*	*major*	High

Bold numbers are for historical observations, while the italic numbers are assessments made where no historical data exists.

1. Geological unit codes (e.g. Q1a) from Begg and Johnston, 2000. Q1 refers to oxygen isotope stage one and denotes that the unit has an age between 0 and 14,000 years old.
2. MM6 data based on the 2013 Cook Strait and Lake Grassmere earthquakes.
3. MM7 data based on the June 1942 Masterton earthquake.
4. MM8 data based on January 1855 Wairarapa earthquake.

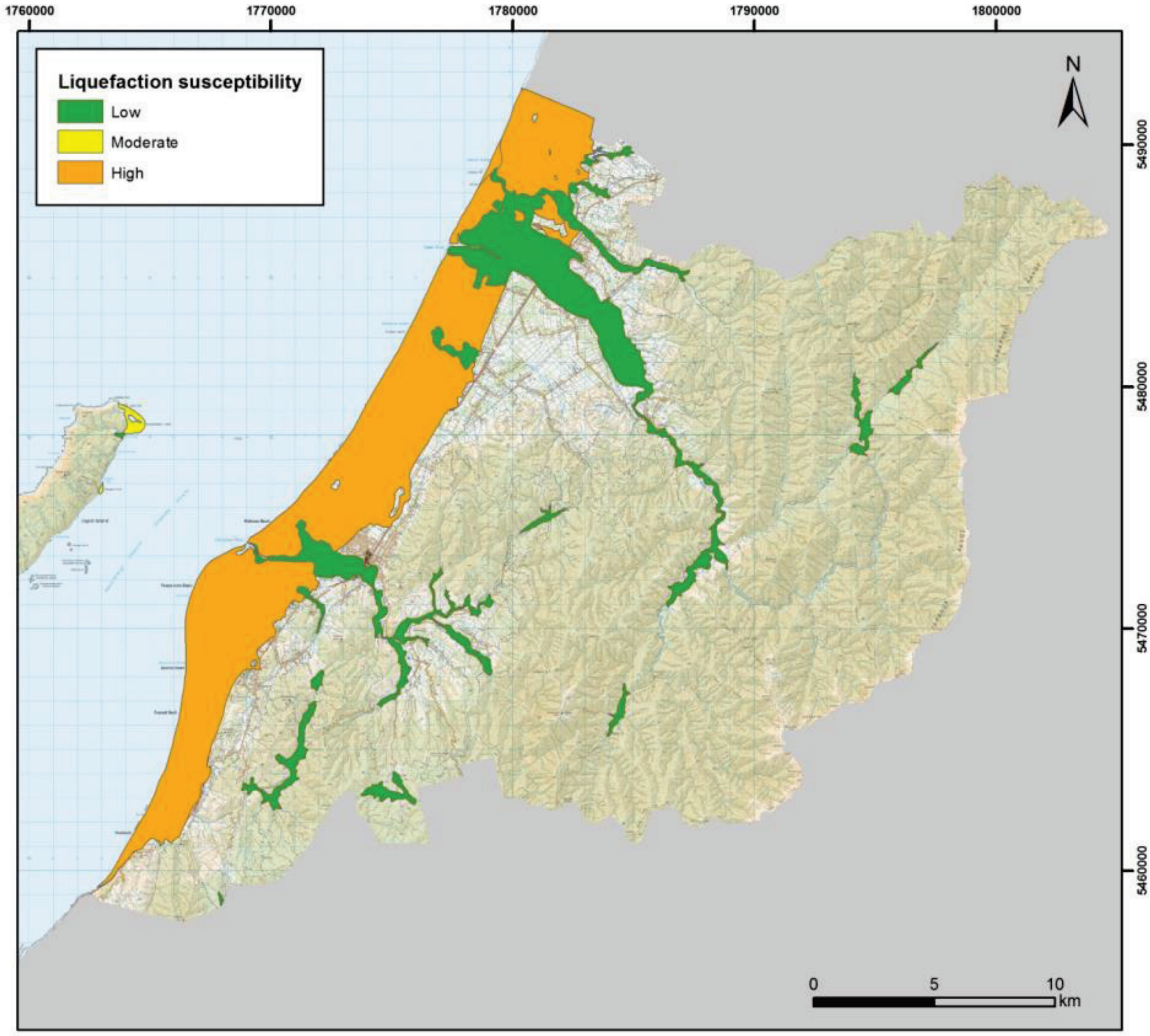

Figure 6.11 Liquefaction susceptibility of sediments on the Kāpiti Coast. Table 5.1, Table 5.2, Table 5.3 and Table 5.4 define the expected liquefaction in each liquefaction-susceptibility class over a range of ground shaking intensities. Table 5.5 gives the expected return period of each of the assessed shaking intensities.

Another area assessed as having a high susceptibility to liquefaction on the Kāpiti Coast is the extensive area of swamps behind the fore-dune system and at the mouths of the Otaki and Waikanae Rivers. Historical reports indicate the mouths of the Otaki and possibly the Waikanae River experienced liquefaction in 1855 at MM8 which fits the assessment of a high susceptibility to liquefaction as per Table 5.1. The susceptibility of the extensive areas of swamp to liquefaction remains an open question and although it is known that there are large areas of peat and peat swamps in the Kāpiti area there is no map that identifies these areas. Generally such areas are not susceptible to liquefaction but the scale of the available map data does not allow them to be differentiated. They do qualify as very soft ground if more than ten metres thick as per Standards New Zealand (2004:NZS 1170.5) and as such will amplify low to moderate levels of ground shaking.

There are no areas assessed as having a very high susceptibility to liquefaction on the Kāpiti Coast. This is consistent with the historical earthquake record where MM7 in 1942 did not cause any liquefaction on the Kāpiti Coast (or at least none that was reported). This is in contrast to the extensive liquefaction reported around the mouth of the Manawatu River and in the Opiki area at the same level of shaking (MM7) in the 1942 events.

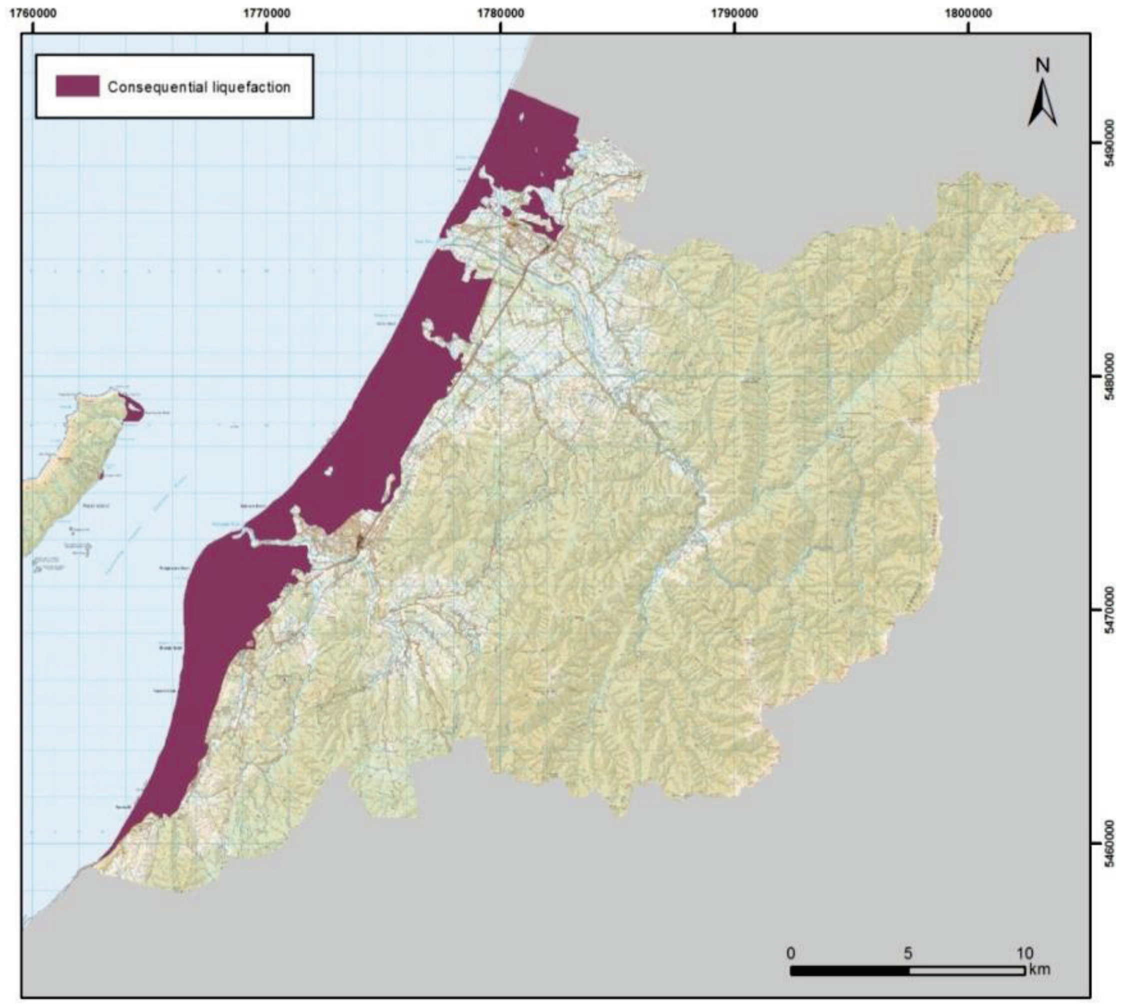

Figure 6.12 Map of Kāpiti District showing areas of potentially damaging liquefaction, where liquefaction is expected to damage infrastructure, if the shaking is strong enough (MM8 or greater).

Figure 6.12 presents a liquefaction hazard map for the Kāpiti Coast where liquefaction hazard is presented as two classes - areas where damaging liquefaction could occur versus areas where liquefaction will not occur or if it does it will be inconsequential (damaging effects will not occur). On Figure 6.12 areas where liquefaction is likely to be damaging are the marginal marine sediments of the coastal platform. This is consistent with the observations from historical earthquakes that at MM7 (1942), liquefaction phenomena have not been observed, but at stronger shaking intensities (e.g. MM8 in 1855) some liquefaction was reported in these areas.

6.5.3 Discussion

Historically very little liquefaction has occurred on the Kāpiti Coast. The key event is the 1855 Wairarapa earthquake where, at what was probably MM8 (Grapes and Downes, 1997), liquefaction effects were reported at the mouths of the Otaki River and possibly the mouth of the Waikanae River. At this time, the beach was the coach road and areas inland were not extensively settled by Maori or Pakeha. In the 1942 Masterton earthquakes, at MM7, no liquefaction was reported on the Kāpiti Coast which supports the 1855 observation of a few sand boils and fissures at MM8 (liquefaction damage rating 1 as per Table 5.1).

Although a liquefaction susceptibility map has been developed for the Kāpiti Coast, it is poorly constrained, both spatially and geotechnically. Two ways to improve understanding of liquefaction on the Kāpiti Coast are to improve the geological/geomorphic mapping, both at the ground surface and at depth. The development of a 3D geological model in conjunction with geotechnical characterisation of the different sediments would provide a more robust understanding of the extent and likely severity of liquefaction and other earthquake hazards on the Kāpiti Coast.

The development of a geotechnically characterised 3D geological model would also aid in understanding ground-shaking amplification behaviour and in developing a framework for understanding the unconfined groundwater surface which is an important component of liquefaction hazard.

6.6 Wairarapa

6.6.1 Data

The data used to determine the liquefaction hazard in the Wairarapa are shown in Figure 6.13. Maps used to address the liquefaction hazard in the Wairarapa include Begg and Johnson (2000) and Lee and Begg (2002), both at scales of 1:250,000. The geological maps provide data on the spatial resolution, at a generalised scale, of geological units. The late Quaternary and Holocene geology was simplified for the liquefaction assessment. Within the Wairarapa, area three Holocene (sediments deposited within the last 10,000 years) units that might contain liquefiable sediments are recognised. These are:

<u>Holocene alluvium</u>: is present throughout the river systems of the Wairarapa including the western hills (Tararuas and Rimutakas) and the eastern hill country as well as being associated with the active river channels. (Older terrace surfaces greater than ~10,000 years in age are present on the Wairarapa plains but these are not regarded as susceptible to liquefaction due to the higher degree of compaction of the sediments that comprise these older terraces.

<u>Holocene marginal marine sediments</u>: are present in the southern part of the Wairarapa plains between Lake Wairarapa and Lake Onoke.

<u>Holocene swamps: are present around the margins of Lake Wairarapa.</u>

Borehole data are available for some of the area. 1635 boreholes were used to establish geology in the Wairarapa area (Figure 6.13). The borehole data provided information on the distribution of subsurface sediments. No standard penetration test (SPT) results were available with the Wairarapa borehole data.

No cone penetrometer test results are currently available as public records for the Wairarapa area. No seismic cone penetrometer test (SCPT) results are available for the Wairarapa area.

Six SPAC results measuring shear wave-velocity are available, one each in Featherston, Greytown, Carterton and Martinborough and two in Masterton. All six SPAC results produced shear wave velocities in excess of 300 m/s indicating that at the SPAC sites liquefaction was unlikely.

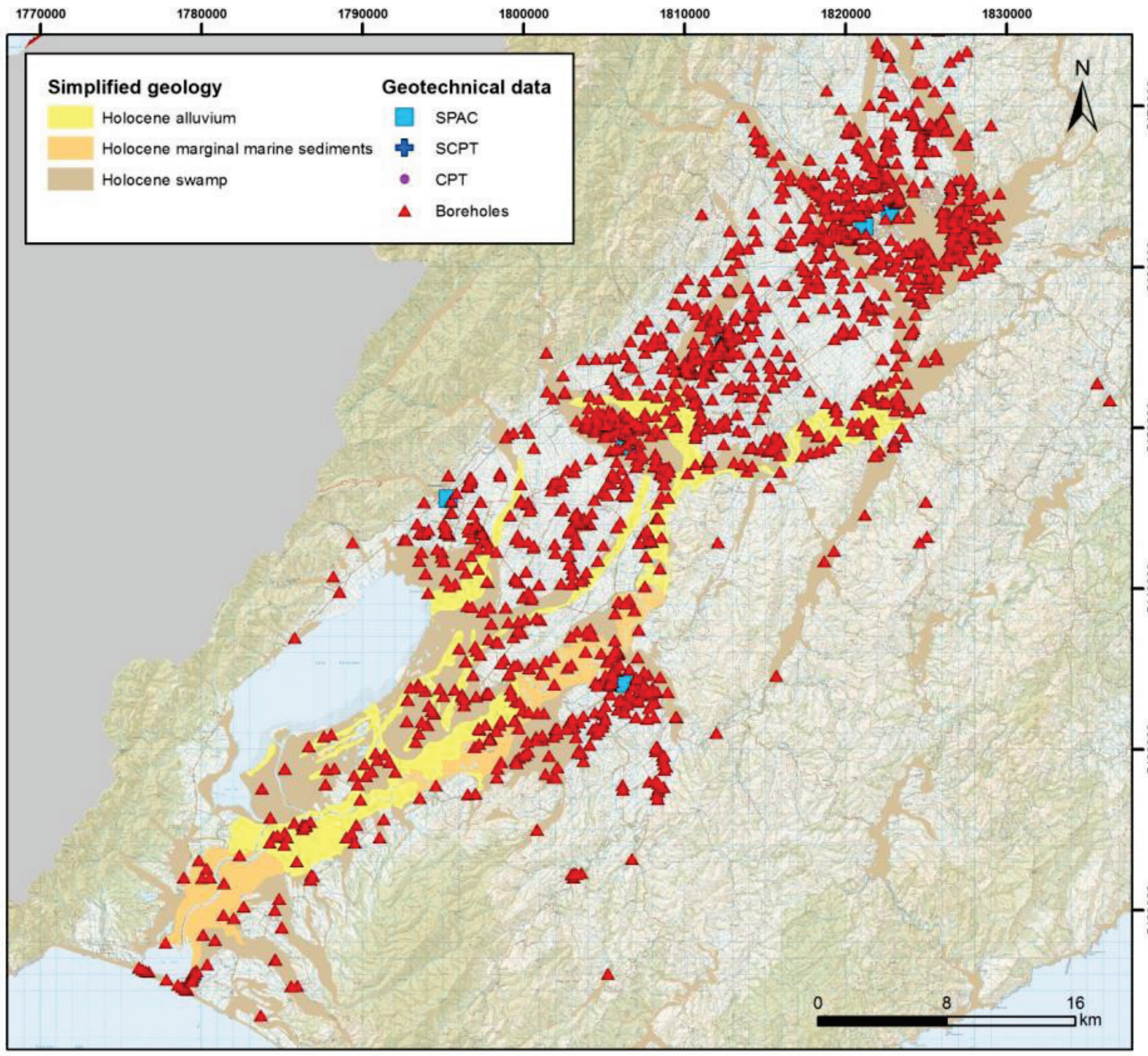

Figure 6.13 Simplified geology of the Wairarapa showing locations of sediments potentially susceptible to liquefaction. The locations and types of subsurface data used in the liquefaction assessment are also shown.

6.6.2 Results

The liquefaction and lateral spreading hazard assessment for the Holocene sediments (deposited in the last 10,000 years) of the Wairarapa are categorised in Table 6.5. The liquefaction hazard in the Wairarapa is presented in two maps (Figure 6.14 and Figure 6.15). On Figure 6.14 showing total liquefaction potential, the low liquefaction susceptibility areas can be divided into three distinct areas. These are the gravel dominated river systems of the greywacke ranges (the Tararua Ranges, the Rimutaka Ranges and the Aorangi Ranges), the alluvial gravels of the Wairarapa plains and the river systems of the Tertiary hill country of the eastern Wiararapa. While these areas may experience some liquefaction during extreme shaking events (MM10) the liquefaction is expected to be limited in extent and lateral spreading is unlikely to occur (Table 5.1). None of these areas are expected to experience damaging liquefaction and the lack of observed liquefaction during the 1942 Masterton earthquakes in the vicinity of Masterton which has been assigned MM9 supports this contention.

The Wairarapa plains contain the only areas where liquefaction damage is expected in the Wairarapa. However, the liquefaction hazard on the plains ranges from low to very high. Any alluvial surface on the Wairarapa plains with an age older than Holocene (i.e. older than 10,000 years) is assigned no liquefaction susceptibility (these surfaces are easily identified as they have a loess cap, Lee and Begg, 2002; Palmer, 1982). The areas of damaging liquefaction have been separated on the basis of likely sedimentation patterns and the historical locations of liquefaction during strong earthquake shaking. Thus north of the Carterton-Gladstone area areas of moderate liquefaction are confined to the active river channels. In the area bounded by Carterton-Gladstone-Featherston-Martinborough there are areas of high liquefaction susceptibility along the Raumahanga and Waiohine Rivers, with associated areas of moderate liquefaction susceptibility.

Table 6.5 Liquefaction and lateral spreading damage ratings assessed using historical records and geological precedent for the Holocene sediments of the Wairarapa.

Geological Unit[1]	**Modified Mercalli Intensity**					**Liquefaction Susceptibility (see Table 5.4)**
	6[2]	**7[3]**	**8**	**9[3]**	**10[4]**	
	Liquefaction Damage rating (see Table 5.1)					
Q1b (Holocene marginal marine deposits)	**none**	**minor**	*moderate*	*major*	**severe**	Very High
Q1a (Holocene alluvium – gravel dominated)	**none**	**none**	**none**	**none**	*minor*	Low
Q1a (Holocene alluvium – fines dominated)	**none**	**none - minor**	**minor - moderate**	**moderate - major**	*major - severe*	High to Very High
Q1s (Holocene swamp)	**none**	**none**	*minor*	*moderate*	*major*	High

Bold numbers are for historical observations, while the italic numbers are assessments made where no historical data exists.

1. Geological unit codes (e.g. Q1a) from Begg and Johnston, 2000 and Lee and Begg, 2002. Q1 refers to oxygen isotope stage one and denotes that the unit has an age between 0 and 14,000 years old.
2. MM6 data based on the 2013 Cook Strait and 2014 Eketahuna earthquakes.
3. MM8-9 data based on the June 1942 Masterton earthquake.
4. MM9-10 data based on January 1855 Wairarapa earthquake.

Additional areas of moderate and high liquefaction susceptibility occur in association with the active river channels of the Ruamahanga, Waiohine and Tauherenikau Rivers, where they enter Lake Wairarapa and along the eastern shores of Lake Waiararapa. Areas of very high liquefaction susceptibility are confined to the lower reaches of the Ruamahanga River south of Martinborough and the marginal marine sediments between Lake Wairarapa and Lake Onoke.

Figure 6.15 presents a liquefaction hazard map for the Wairarapa where liquefaction hazard is presented in two classes - areas where liquefaction damage may occur versus areas where liquefaction will not occur or if it does it will be inconsequential (damaging effects will not occur). On Figure 6.15 areas where liquefaction damage is likely are on the marginal marine sediments of the coastal platform and on the fine-grained, non-cohesive sediments of the lower reaches of the major rivers of the alluvial plains. This is consistent with the observations from historical earthquakes that at MM7 (1942) and MM 10 (1855) liquefaction phenomena have been observed in these areas.

6.6.3 Discussion

Reports of the distribution of liquefaction during historical earthquakes, notably the 1855 Wairarapa earthquake (MM9-10) and the 1942 Masterton earthquakes (MM7-8) indicate that large parts of the Wairarapa plains are not overly susceptible to liquefaction. North of the Carterton-Gladstone area very little liquefaction is expected to occur. There are no reports of liquefaction from the 1855 or 1942 earthquakes in this area despite shaking intensities of MM8-9 (Hancox et al, 2002).

Reports of liquefaction during the 1855 and 1942 earthquakes come consistently from the immediate vicinity of the Raumahanga River between Gladstone and the confluence with the Waiohine River, with additional reported occurrences of liquefaction further to the west of Carterton at Dalefield in both 1855 and 1942. The intensity of ground shaking in these areas was MM8-9 during both earthquakes, adding further evidence that damaging liquefaction on the Wairarapa plains is quite limited in its extent.

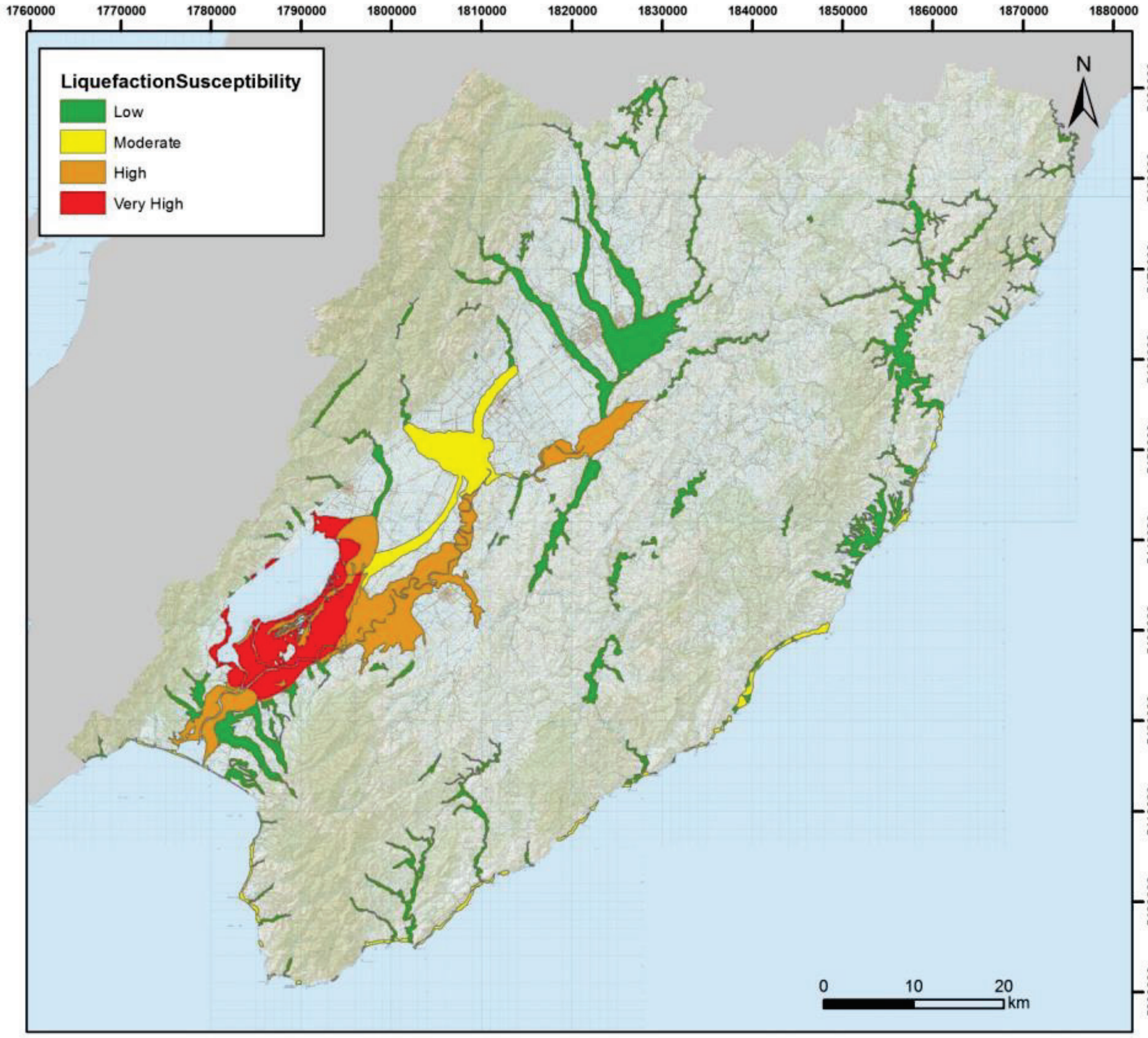

Figure 6.14 Liquefaction susceptibility of sediments in the Wairarapa. Table 5.1, Table 5.2, Table 5.3 and Table 5.4 define the expected liquefaction in each liquefaction-susceptibility class over a range of ground shaking intensities. Table 5.5 gives the expected return period of each of the assessed shaking intensities.

Further south the gradient of the plains reduces as evidenced by the meandering form of the Raumahanga River. It is in this area that isolated occurrences of liquefaction were reported along the Ruamahanga River south of Martinborough and in Lake Onoke at MM7 in the June 1942 Masterton earthquake. One contemporary account from 1855 in this area reports more extensive liquefaction in this area at MM9.

Overall the plains of the Wairarapa appear less susceptible to liquefaction than previously thought. However, on reflection the liquefaction observations in the Wairarapa are consistent with the recent observations from Christchurch. Areas where the alluvial sediments are gravel dominated and are more than 10,000 years old are unlikely to liquefy. Areas where sediment is finer-grained, because of reduced river gradients and gentler flow regimes, have increased reports of liquefaction. The area in the Wairarapa most vulnerable to liquefaction is along the Ruamahanga River south of Martinborough and the delta areas where the Ruamahanga and Tauherenikau Rivers enter Lakes Wairarapa and Onoke.

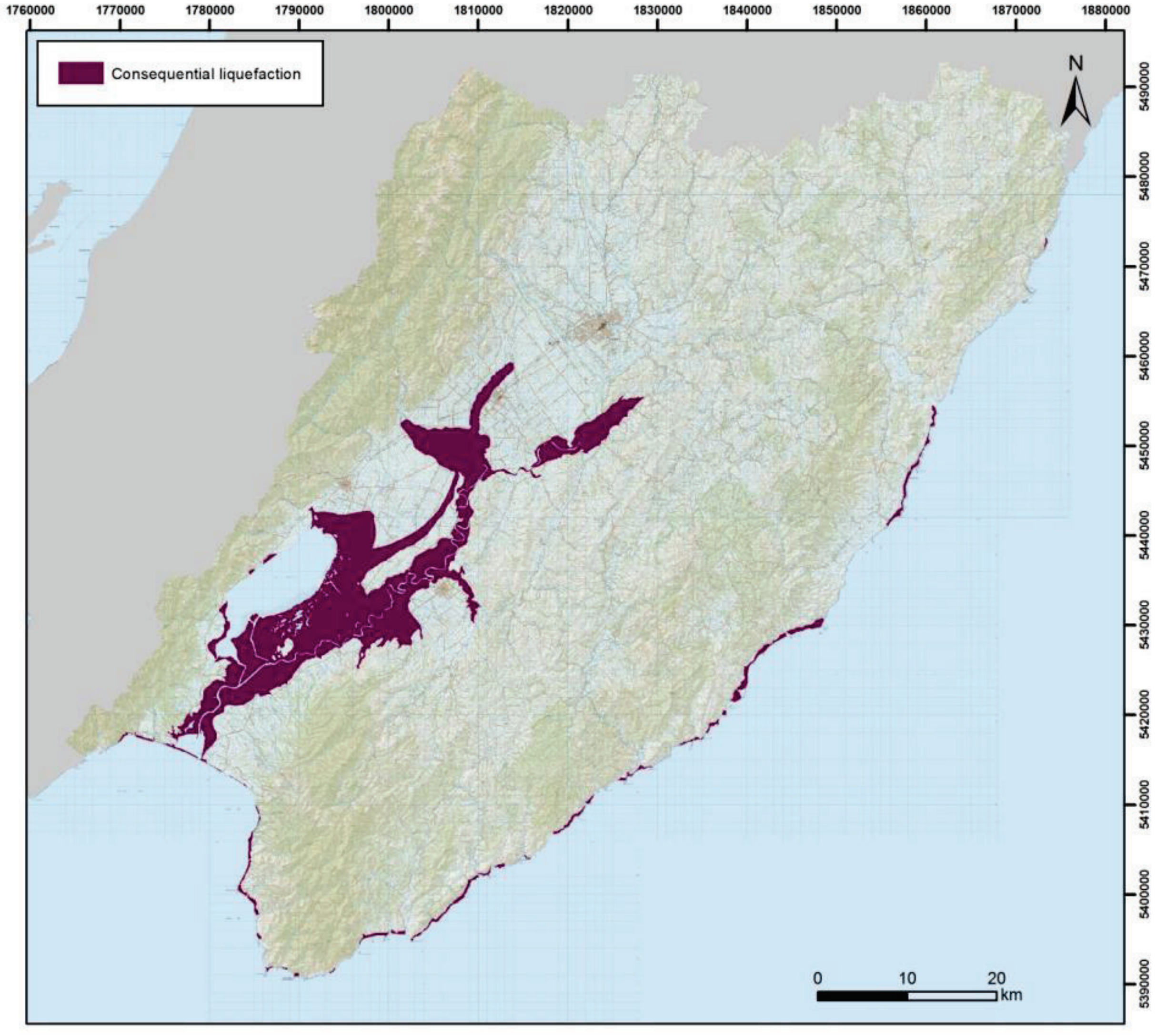

Figure 6.15 Map of the Wairarapa showing areas of potentially damaging liquefaction, where liquefaction is expected to damage infrastructure, if the shaking is strong enough (MM8 or greater).

7.0 LIMITATIONS

Although the maps showing liquefaction susceptibility and where liquefaction is likely to cause damage have been prepared using the same process, the quality and quantity of data that underpin the maps are highly variable. As an illustration of this, Table 7.1 shows the number of CPT and SPT tests available for different areas in the Wellington Region (and Christchurch for comparison). When these tests are compared on an equal area basis the results are informative as data density varies across five orders of magnitude. So although on the face of it the maps all display the results of the same compilation process the uncertainty inherent in the maps is highly variable. The extent these maps can be used to support planning and/or engineering decisions is directly linked to the quality and quantity of data used in their compilation. The quantity of the underpinning data also points to areas where data acquisition would provide the greatest benefit in terms of improving these liquefaction hazard maps.

Table 7.1 The numbers of standard penetration tests and cone penetration tests for different areas in the Wellington Region compared with Christchurch.

Location	Area (km^2)	Total CPT and SPT tests	CPT and SPT per km^2
Wellington CBD	10	439	44
Porirua		9	
Hutt City	30	243	8
Kāpiti District	150	9	0.06
Wairarapa	1100	0	0
Christchurch	100	12000	200

The process undertaken to arrive at the liquefaction susceptibility maps presented in this report is a qualitative one. The maps utilise descriptions of liquefaction, including both severity and extent, to identify sites where liquefaction has occurred in the past. These liquefaction occurrences are then located with respect to geological units on existing geological maps to delimit the areas that are susceptible to liquefaction.

As such the liquefaction susceptibility maps presented in this report should be used to identify those areas where a quantitative investigation into liquefaction hazard is warranted. Liquefaction hazard, as distinct from liquefaction susceptibility, is where the consequences of the liquefaction process are quantified in terms of the expected vertical and horizontal displacements at a given level of ground shaking (as specified by peak ground acceleration).

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8.0 SUMMARY AND CONCLUSIONS

Liquefaction is a damaging effect of strong earthquake shaking. The stronger the earthquake shaking the more damaging the liquefaction effects in terms of both severity and extent. The effects of liquefaction include vertical ground displacement due to material being ejected from below the ground surface and horizontal ground displacement due to lateral spreading when the liquefaction occurs near a stream or river bank. The Wellington Region has experienced earthquake shaking strong enough to cause liquefaction on at least four occasions (1848, 1855, 1942 and 2013). The extent and severity of the liquefaction in these earthquakes was proportional to the level of shaking experienced at a site.

The sites where liquefaction occurs always meet three criteria. The source material must be non-cohesive fine-grained sediment, the sediment must be loosely packed, in effect less than 10,000 years old (i.e. Holocene age) to negate the effects of consolidation that occurs over longer time periods, and the sediments must be below the water table. The sites where these criteria are invariably met are the sites of low-energy deposition (silts and sands settling out of suspension) where overbank flood deposits accumulate or where rivers and streams form lagoons and estuaries prior to discharge into the sea (or lakes). This is consistent with the observations of liquefaction in the Wellington Region.

This report has used historical accounts of liquefaction during strong ground shaking, the most up-to-date publically available geological maps and limited subsurface data (including boreholes, SPT, CPT and SCPT probes and SPAC) to derive a series of liquefaction susceptibility maps for the Wellington region. The liquefaction susceptibility maps are consistent with the methodology used in other areas of New Zealand to investigate and map liquefaction susceptibility at the regional or district level (Beetham et al, 1998; Dellow et al, 2003; Dellow and Ries, 2013).

The liquefaction susceptibility maps in this report are presented in two forms, the first displaying a scaled representation of liquefaction susceptibility, and the second a two-fold classification of where liquefaction damage is likely to occur and where damage is unlikely or inconsequential. The intent of the two-fold classification of liquefaction hazard presented is to identify those areas where liquefaction should be considered as a hazard for further investigation, planning and mitigation purposes (e.g. California Department of Conservation, 2000). The accuracy with which a region's liquefaction susceptibility can be determined is dependent on the quality of the data available for input. Liquefaction susceptibility maps produced using the same methodology can have different reliability because of variations in the quality and quantity of data available for use in the compilation of the maps.

The process undertaken to arrive at these liquefaction susceptibility maps as presented in this report is a qualitative one. The maps utilise descriptions of liquefaction, including both severity and extent, to identify sites where liquefaction has occurred in the past. These liquefaction occurrences are then located with respect to geological units on existing geological maps to spatially limit the areas that are susceptible to liquefaction. As such the liquefaction susceptibility maps presented in this report are intended to be used to identify those areas where a quantitative investigation into liquefaction hazard would be necessary. Liquefaction hazard, as distinct from liquefaction susceptibility, is where the consequences of the liquefaction process can be quantified in terms of the expected vertical and horizontal displacements at a given level of ground shaking (as specified by peak ground acceleration).

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9.0 RECOMMENDATIONS

The maps of liquefaction susceptibility presented in this report are regional scale maps based on a subjective analysis of available information. The maps highlight areas that are either known to be susceptible to liquefaction based on observations during historical earthquakes or are probably susceptible to liquefaction based on a combination of surface geological mapping, subsurface borehole and probing information, available geotechnical properties and depth to unconfined groundwater surface.

These maps may be used as a guide to where more detailed investigations of the liquefaction hazard is needed in order to provide the certainty required for inclusion in formal documents such as district plans, building regulations and land information memorandums (LIM reports).

More detailed studies are able to quantify the liquefaction hazard such as those that have been carried out in Christchurch and the Heretaunga Plains. Therefore the following recommendations are made with regard to quantifying the liquefaction hazard in the Wellington region. These recommendations apply to the areas identified in this report as having a likelihood of liquefaction damage.

1. Prepare geomorphic maps, based on LiDAR topographic data, at a scale of 1:25,000 or greater. This will provide a basis for differentiating the area into units of similar origin and properties with the inclusion of already available subsurface data.
2. Compile dataset of the unconfined shallow groundwater surface and its seasonal and tidal variation. It is important to understand the variation in the shallow groundwater surface as the extent and severity of liquefaction varies with the thickness of the unsaturated sediments above the groundwater surface.
3. Compile and/or acquire cone penetrometer test (CPT) data throughout the area of interest. Geotechnical consultancies may have existing data that can be utilised. Alternatively, CPT data can be acquired through a purpose-designed investigation program. CPT data is inexpensive relative to borehole data. The recommended CPT density in an area under investigation is at least one CPT per square kilometre.
4. Analysis the CPT data using the groundwater data, including the seasonal and tidal variations, using standard geotechnical liquefaction software (e.g. cLiq) to determine the liquefaction severity number (LSN). Determine the horizontal and vertical settlements associated with the LSN and correlate to structural damage from Christchurch.
5. Check that the distribution of LSN values is consistent with the geomorphic map units. Each geomorphic unit, or combination of geomorphic units, should have LSN's distributed over a relatively small range (e.g. ±5 LSN units) indicating that the geomorphic unit will behave consistently with respect to liquefaction.

If these recommendations are followed then the quantitative evaluation of liquefaction hazard will provide a robust and defendable basis on which to include liquefaction hazard information in formal documents such as district plans, building regulations and LIM reports.

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11.0 REFERENCES

Barker, P.R.; Stephenson, W.R.; Perrin N.D and Bruce, Z.R. 2012. It's Our Fault – Using microtremors (SPAC measurements) to assess some geotechnical parameters at 25 sites in the Greater Wellington Region Wellington, GNS Science Consultancy Report 2012/176.

Bastings L 1936. A subsoil survey of Wellington City. NZ Inst Archit 15(5): 75-78.

Beetham, R.D.; Dellow, G.D.; Barker, P.R. 1998. Assessment of liquefaction and related ground failure hazards in Wanganui City area. Institute of Geological and Nuclear Sciences client report 43705B.10.

Begg, J.G., Johnston, M.R., (compilers) 2000. Geology of the Wellington area. Institute of Geological and Nuclear Sciences 1:250,000 geological map10. 1 sheet + 64p. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited.

Begg, J.G.; Mazengarb, C. 1996. Geology of the Wellington area : sheets R27, R28, and part Q27, scale 1:50,000. Lower Hutt: Institute of Geological and Nuclear Sciences. Institute of Geological and Nuclear Sciences geological map 22. 128 p. + 1 fold. Map

Begg, J.G.; Van Dissen, R.J. 1992. Regional Natural Disaster Reduction Plan - seismic hazard. Geology and earthquake ground shaking hazard assessment of the Upper Hutt Basin, New Zealand (Part 5 of 1991/92 study). DSIR Geology and Geophysics contract report 1992/5. 36 p.

Boon, D.P.; Perrin, N.D.; Dellow, G.D.; Lukovic, B. 2010 It's Our Fault. Geological and geotechnical characterisation and site class revision of the Lower Hutt Valley. GNS Science consultancy report 2010/163. 56 p. http://www.gns.cri.nz/Home/IOF/It-s-Our-Fault/Publications/Effects-Phase

Boon, D.; Perrin, N.D.; Dellow, G.D.; Van Dissen, R.J.; Lukovic, B. 2011 NZS1170.5:2004 site subsoil classification of Lower Hutt. paper 013 In: Ninth Pacific Conference on Earthquake Engineering : building an earthquake resilient society, April 14-16, 2011, University of Auckland, Auckland, New Zealand. Auckland, NZ: 9PCEE.

Brown, L.J.; Weeber, J.H. 1992 Geology of the Christchurch urban area. Scale 1:25,000. Lower Hutt: Institute of Geological & Nuclear Sciences. Institute of Geological & Nuclear Sciences geological map 1. 1 map + 104 p.

California Department of Conservation, Division of Mines and Geology, 2000 Seismic Hazard Zone Report for the City and County of San Francisco, California, Seismic Hazard Zone Report 043

Chalmers, G., McLennan, N., and Barsanti, L. (2013) Lyttelton Port of Christchurch Seismic Resiliance from an Owner's Perspective. Ports 2013: pp. 1405-1414.

Clayton, P. 2014 Repeatability of SPT testing in Christchurch soils with reference to the liquefaction potential. p. 23-32 In: Orense, R.P.; Towhata, I.; Chouw, N. (eds) Soil liquefaction during recent large-scale earthquakes. The Netherlands: CRC Press.

Cubrinovski, M., Green, R.A., Wotherspoon, L. 2011a Geotechnical Reconnaissance of the 2011 Christchurch, New Zealand Earthquake; GEER Association Report No GEER-027.

Cubrinovski, M.; Bray, J.D.; Taylor, M.; Giorgini, S.; Bradley, B.A.; Wotherspoon, L.; Zupan, J. 2011b Soil liquefaction effects in the central business district during the February 2011 Christchurch Earthquake. Seismological Research Letters, 82(6): 893-904; doi: 10.1785/gssrl.82.6.893

Cubrinovski, M.; Robinson, K.; Taylor, M.; Hughes, M.; Orense, R. 2012 Lateral spreading and its impacts in urban areas in the 2010-2011 Christchurch earthquakes. New Zealand Journal of Geology and Geophysics, 55(3): 255-269; doi: 10.1080/00288306.2012.699895

Dellow, G.D.; Barker, P.R.; Beetham, R.D.; Heron, D.W. 2003. A deterministic method for assessing the liquefaction susceptibility of the Heretaunga Plains, Hawke's Bay, NZ. p. 111-120 In: Crawford, S.; Baunton, P.; Hargraves, S. Geotechnics on the volcanic edge, Tauranga, March 2003. Wellington: Institution of Professional Engineers New Zealand. Proceedings of technical groups / Institution of Professional Engineers New Zealand 30(1 GM)

Dellow, G.D.; Read, S.A.L.; Begg, J.G.; Van Dissen, R.J.; Perrin, N.D. 1992. Distribution of geological materials in Lower Hutt and Porirua, New Zealand : a component of a ground shaking hazard assessment. Bulletin of the New Zealand National Society for Earthquake Engineering, 25(4): 332-344

Dellow, G.D.; Read, S.A.L.; Van Dissen, R.J.; Perrin, N.D. 1991. Regional natural disaster reduction plan - seismic hazard. Geological setting of the Porirua basin, including distribution of materials and geotechnical properties (Part 6 of 1990 study). DSIR Geology and Geophysics contract report 1991/46. 18 p.

Dellow, G.D.; Ries, W. 2013 Liquefaction hazard in the Taranaki region. *GNS Science consultancy report 2013/57.* 34 p.

de Magistris, F.S., Lanzano, G., Forte, G., Fabbrocino, G., 2013. A database for PGA threshold in liquefaction occurrence. Soil Dynamics and Earthquake Engineering, 54 (Nov): 17-19.

Downes, G.L. 1995. Atlas of isoseismal maps of New Zealand earthquakes. Institute of Geological and Nuclear Sciences monograph 11, 304 p., Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences.

Downes, G.L. 2006 The 1904 MS6.8 Mw 7.0-7.2 Cape Turnagain, New Zealand, earthquake. Bulletin of the New Zealand Society for Earthquake Engineering, 39(4): 182-207.

Downes, G.L.: Dowrick, D.J.; Van Dissen, R.J.; Taber, J.J.; Hancox, G.. Smith, E.G.C. 2001. The 1942 Wairarapa, New Zealand, Earthquakes: Analysis of Observational and Instrumental Data. Bulletin of the New Zealand Society for Earthquake Engineering, 34 (2): 125-157.

Dowrick, D.J.; Hancox, G.T.; Perrin, N.D.; Dellow, G.D. 2008. The Modified Mercalli intensity scale : revisions arising from New Zealand experience. Bulletin of the New Zealand Society for Earthquake Engineering, 41(3): 193-205

Dowrick, D.J.; Rhoades, D.A. 2005. Revised models for attenuation of Modified Mercalli Intensity in New Zealand earthquakes. Bulletin of the New Zealand Society for Earthquake Engineering, 38(4): 185-214.

Eiby, G.A. 1980. The Marlborough Earthquakes of 1848. Department of Scientific and Industrial Research Bulletin 225, 82 p. DSIR, Wellington, New Zealand

Fairless, G.J.; Berrill, J.B. 1984. Liquefaction during historic earthquakes in New Zealand. Bulletin of the New Zealand National Society for Earthquake Engineering, 17(4): 280-291.

Grant-Taylor, T.L.; Adams, R.D.; Hatherton, T.; Milne, J.D.G.; Northey, R.D.; Stephenson, W.R. 1974. Microzoning for earthquake effects in Wellington. Wellington: DSIR. DSIR Bulletin 213. 61 p.

Grapes, R.; Downes, G. 1997. The 1855 Wairarapa, New Zealand, Earthquake – Analysis of Historical Data. Bulletin of the New Zealand National Society for Earthquake Engineering, 30(4): 271-369

Grapes, R.; Downes, G.; Goh, A. 2003. Historical documents relating to the 1848 Marlborough earthquakes, New Zealand. Institute of Geological and Nuclear Sciences science report 2003/34: 231p.

Grapes, R.; Little T.; Downes, G. 1998. Rupturing of the Awatere Fault during the 1848 October 16 Marlborough earthquake, New Zealand: Historical and present day evidence. New Zealand Journal of Geology and Geophysics, 41 (4); 387-399.

Hancox, G.T.; Archibald, G.C.; Cousins, W.J.; Perrin, N.D.; Misra, S. 2013. Reconnaissance report on liquefaction effects and landslides caused by the M_L 6.5 Cook Strait earthquake of 21 July 2013, New Zealand. Lower Hutt, NZ: GNS Science. GNS Science report 2013/42. 20 p.

Hancox, G.T.; Perrin, N.D.; Dellow, G.D. 1997. Earthquake-induced landsliding in New Zealand and implications for MM intensity and seismic hazard assessment. Institute of Geological and Nuclear Sciences client report 43601B. 85 p., apps

Hancox, G.T.; Perrin, N.D.; Dellow, G.D. 2002. Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand. Bulletin of the New Zealand Society for Earthquake Engineering, 35(2): 59-95

Heron, D.W.; Van Dissen, R.J. 1992. Regional Natural Disaster Reduction Plan - seismic hazard. Geology of the Kāpiti Coast (Pukerua Bay to Otaki), Wellington (Part 4 of 1991/92 study). DSIR Geology and Geophysics contract report 1992/19. 18 p.

IPENZ. Liquefaction. Retrieved 18 July 2012, from http://www.ipenz.org.nz/ipenz/forms/pdfs/ChChFactSheets-Liquefaction.pdf

Kingma, J.T. 1967. Geological map of New Zealand 1:250,000 Sheet 12 Wellington. 1st ed. Wellington: Department of Scientific and Industrial Research. Geological map of New Zealand 1:250,000 12. 1 fold. Map

Kingsbury, P.A.; Hastie, W.J. 1993a. Sheet 1 Wellington (1st Ed.) Liquefaction Hazard Map 1:20,000. With notes. Wellington Regional Council, Wellington, New Zealand.

Kingsbury, P.A.; Hastie, W.J. 1993b. Sheet 2 Porirua (1st Ed.) Liquefaction Hazard Map 1:50,000. With notes. Wellington Regional Council, Wellington, New Zealand.

Kingsbury, P.A.; Hastie, W.J. 1993c. Sheet 3 Hutt Valley (1st Ed.) Liquefaction Hazard Map 1:75,000. With notes. Wellington Regional Council, Wellington, New Zealand.

Kingsbury, P.A.; Hastie, W.J. 1993d. Sheet 4 Kāpiti (1st Ed.) Liquefaction Hazard Map 1:100,000. With notes. Wellington Regional Council, Wellington, New Zealand.

Kingsbury, P.A.; Hastie, W.J. 1993e. Liquefaction hazard Wairarapa, Seimic hazard map series: Liquefaction Hazard. Wellington Regional Council, Wellington, New Zealand.

Lee, J.M.; Begg, J.G. (comps) 2002. Geology of the Wairarapa area : scale 1:250,000. Lower Hutt: Institute of Geological and Nuclear Sciences Limited. Institute of Geological and Nuclear Sciences 1:250,000 geological map 11. 66 p. + 1 fold. Map

Murashev, A.; Palmer, S., 1998. Geotechnical issues associated with development on Wellington's waterfront. IPENZ Transactions, 25(1)/CE 38-46

Palmer, A.S. 1982 Kawakawa Tephra in Wairarapa, New Zealand, and its use for correlating Ohakea loess. *New Zealand Journal of Geology and Geophysics, 25(3):* 305-315

Quigley, M.C.; Bastin, S.; Bradley, B.A. 2013 Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. Geology, 41(4): 419-422.

Read, S.A.L.; Begg, J.G.; Van Dissen, R.J.; Perrin, N.D.; Dellow, G.D. 1991. Regional natural disaster reduction plan - seismic hazard. Geological setting of the Lower Hutt Valley and Wainuiomata, including distribution of materials and geotechnical properties. (Part 7 of 1990 study). DSIR Geology and Geophysics contract report 1991/45. 23 p.

Roberts, E. 1855. Memorandum the earthquake in the islands of New Zealand, January 23, 1855. Te Ika a Maui, or New Zealand and its inhabitants. Wertheim and MacIntosh, London, England.

Saunders, W. S. A.; Beban, J. G. 2012. A framework for risk-based land use planning for natural hazards. In GNS Science (Ed.), 6th Australasian Natural Hazards Management Conference. Christchurch: GNS Science.

Saunders, W.S.A.; Berryman, K.R. 2012. Just add water: when should liquefaction be considered in land use planning?. Lower Hutt: GNS Science. GNS Science miscellaneous series 47. 13 p. http://www.gns.cri.nz/Home/IOF/It-s-Our-Fault/Publications/Impacts-phase

Semmens, S.; Perrin, N.D.; Dellow, G.D. 2010. It's Our Fault: geological and geotechnical characterisation of the Wellington central business district. GNS Science consultancy report 2010/176. 48 p. + 1 CD http://www.gns.cri.nz/index.php/Home/IOF/It-s-Our-Fault/Publications/Effects-Phase

Semmens, S.; Perrin, N.D.; Barker, P.R. 2010a What lies beneath : geological and geotechnical characterisation of the Wellington central commercial area. p. 659-666 (paper 078) In: Williams, A.L.; Pinches, G.M.; Chin, C.Y.; McMorran, T.J.; Massey, C.I. (eds) Geologically active : delegate papers 11th Congress of the International Association for Engineering Geology and the Environment, Auckland, Aotearoa, 5-10 September 2010. Boca Raton, Fla: CRC Press. http://www.gns.cri.nz/index.php/Home/IOF/It-s-Our-Fault/Publications/Effects-Phase

Semmens, S.; Perrin, N.D.; Dellow, G.D.; Van Dissen, R.J. 2011 NZS 1170.5:2004 site subsoil classification of Wellington City. paper 007 In: Ninth Pacific Conference on Earthquake Engineering : building an earthquake resilient society, April 14-16, 2011, University of Auckland, Auckland, New Zealand. Auckland, NZ: 9PCEE. http://www.gns.cri.nz/index.php/Home/IOF/It-s-Our-Fault/Publications/Effects-Phase

Smith, W.D. 2002. A model for MM intensities near large earthquakes. Bulletin of the New Zealand Society for Earthquake Engineering, 35(2): 96-107.

Standards New Zealand 2004. NZS 1170.5:2004 Structural Design Actions - Earthquake Actions. Section 3 - Site Hazard Spectra, Standards New Zealand. Pp. 81.

Stirling, M.W.; McVerry, G.H.; Gerstenberger, M.C.; Litchfield, N.J.; Van Dissen, R.J.; Berryman, K.R.; Barnes, P.; Wallace, L.M.; Villamor, P.; Langridge, R.M.; Lamarche, G.; Nodder, S.; Reyners, M.E.; Bradley, B.; Rhoades, D.A.; Smith, W.D.; Nicol, A.; Pettinga, J.; Clark, K.J.; Jacobs, K. 2012. National seismic hazard model for New Zealand : 2010 update. Bulletin of the Seismological Society of America, 102(4): 1514-1542.

Stephenson, W.R.; Barker, P.R. 1991. Regional Natural Disaster Reduction Plan - Seismic Hazard. Report on cone penetrometer probing in Wainuiomata, Eastern Harbour Bays, Stokes Valley, Kura Park (Titahi Bay) and Whitby (Parts 4 and 5 of 1990 study). DSIR Geology and Geophysics contract report 91/21. 20 p. + figs

Stephenson, W.R.; Barker, P.R. 1992a. Regional Natural Disaster Reduction Plan - Seismic Hazard. Report on cone penetrometer and seismic cone penetrometer probing in Wellington City, Kāpiti Coast and Upper Hutt valley (Part 4.2 of the 1991 study). DSIR contract report 92/14. 21 p. + figs

Stephenson, W.R.; Barker, P.R. 1992b. Evaluation of sediment properties in the Lower Hutt and Porirua areas by means of cone and seismic cone penetration tests. Bulletin of the New Zealand National Society for Earthquake Engineering, 25(4): 265-285

Stephenson, W.R.; Barker, P.R.; Bruce, Z.; Beetham, R.D. 2011. Immediate report on the use of microtremors (SPAC measurements) for assessing liquefaction potential in the Christchurch area. Lower Hutt: GNS Science. GNS Science report 2011/25. 28 p.

Taylor, R., 1855: Te Ika a Maui, or New Zealand and its inhabitants. Wertheim and Macintosh, London

Stevens, G.R. 1956. Stratigraphy of the Hutt Valley, New Zealand. New Zealand journal of science and technology. B, General section, 38(3): 201-235

Tinsley, J.C.; Youd, T.L.; Perkins, D.M.; Chen, A.F.T. 1985. Evaluating Liuefaction Potential: in Evaluating earthquake hazards in the Los Angeles Region, J.I. Ziony ed: US Geological Survey Professional Paper 1360: 263-316

Toprak, S.; Holzer, T.L. 2003. Liquefaction potential index: Field assessment: Journal of Geotechnical and Geoenvironmental Engineering, 129(4): 315-322.

van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M.E., Cubrinovski, M., Bray, J.D., O'Rourke, T.D., Crawford, S.A., and Cowan H. (*2014*) Assessment of Liquefaction-Induced Land Damage for Residential Christchurch. Earthquake Spectra: February 2014, Vol. 30, No. 1, pp. 31-55.

Van Dissen, R.J.; McSaveney, M.J.; Townsend, D.B.; Hancox, G.T.; Little, T.A.; Ries, W.; Perrin, N.D.; Archibald, G.C.; Dellow, G.D.; Massey, C.I.; Misra, S. 2013. Landslides and liquefaction generated by the Cook Strait and Lake Grassmere earthquakes: a reconnaissance report. Bulletin of the New Zealand Society for Earthquake Engineering, 46(4): 196-200

Van Dissen, R.J.; Taber, J.J.; Stephenson, W.R.; Sritherani, S.; Read, S.A.L.; McVerry, G.H.; Dellow, G.D.; Barker, P.R. 1992. Earthquake ground shaking hazard assessment for the Lower Hutt and Porirua areas, New Zealand. Bulletin of the New Zealand National Society for Earthquake Engineering, 25(4): 286-302

Wotherspoon, L.M.; Pender ,M.J.; Orense, R.P. 2013 Correlations between liquefaction induced damage and former river channels in Kaiapoi. p. 179-186 In: Chin, C.Y. (ed) 19th New Zealand Geotechnical Society 2013 Symposium : Hanging by a thread? : lifelines, infrastructure and natural disasters, Queenstown, November 2013 : [proceedings]. Wellington, NZ: Institute of Professional Engineers New Zealand. Proceedings of technical groups (Institution of Professional Engineers New Zealand) 38(1)GM

Youd, T.L.; Nichols D.R.; Halley, E.J.; Lajoie, K.R.;1975. Liquefaction Potential; in Studies for Seismic Zonation of the San Francisco Bay Region, U.S. Geological Survey, Professional Paper 941-A: A68-A74.

Ziony, J.I., 1985. Evaluating earthquake hazards in the Los Angeles Region. US Geological Survey Professional Paper 1360: 1360 pgs

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APPENDICES

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A1.0 MODIFIED MERCALLI INTENSITY SCALE (NEW ZEALAND)

The New Zealand Modified Mercalli Intensity Scale (includes felt effects and damage to buildings and structures), based on information in Downes (1995), Dowrick (2008) and Hancox et al. (2002).

The Modified Mercalli intensity scale (MM)

The Modified Mercalli intensity scale (summarised from Downes (1995), Dowrick (1996) and Hancox et al. (2002)) is a descriptive scale used to rank the intensity of an earthquake at a particular location. The intensity of any earthquake will vary from place to place, because of factors such as distance from the epicentre and localised differences in ground conditions (for example, shaking will be much greater on swampy ground than on solid rock).

MM 2 *Felt by people at rest, on upper floors or favourably placed.*

MM 3 *Felt indoors; hanging objects may swing, vibration similar to passing of light trucks.*

MM 4 *Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration like passing of heavy traffic. Doors and windows rattle. Walls and frames of buildings may be heard to creak.*

MM 5 *Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Some glassware and crockery may be broken. Open doors may swing.*

MM 6 *Felt by all. People and animals alarmed. Many run outside. Furniture or objects may move on smooth surfaces. Objects fall from shelves. Glassware and crockery broken. Slight damage to some types of buildings. A few cases of chimney damage. Loose material may be dislodged from sloping ground. A few very small (e.g. <1000 m^3) shallow landslides and rockfalls occur.*

MM 7 *General alarm. Furniture and appliances may be shifted and unstable items overturned. Unreinforced stone and brick walls cracked. Some pre-earthquake code buildings damaged. Roof tiles may be dislodged. Many domestic chimneys broken. Small falls of sand and gravel banks. Some fine cracks appear in sloping ground and ridge crests. Rockfalls from steep slopes and cuttings are common. A few small to moderate landslides (e.g. 1 000 to 10 000 m^3) occur on steeper slopes. Some instances of liquefaction at susceptible sites.*

MM 8 *Alarm may approach panic. Steering of cars greatly affected. Some serious damage to pre-earthquake code masonry buildings. Most reinforced domestic chimneys damaged, many brought down. Monuments and elevated tanks twisted or brought down. Some post-1980 brick veneer dwellings damaged. Houses not secured to foundations may move. Cracks may appear on slopes and in wet ground. On slopes in steep or weak ground, numerous small to moderate landslides and some large landslides (e.g. 100 000 m^3). Collapse of roadside cuttings and unsupported excavations. Small sand fountains and other instances of liquefaction.*

MM 9 *Very poor quality unreinforced masonry destroyed. Pre-earthquake code masonry buildings heavily damaged or collapse. Damage or distortion to some pre-1980 buildings and bridges. Houses not secured to foundations shifted off. Brick veneers fall and expose framing. Conspicuous cracking of flat and sloping ground. On steep slopes, many small to large landslides and some very large (>1 000 000 m^3) landslides and rock avalanches that may block narrow valleys and form lakes. Liquefaction effects intensified, with large sand fountains and extensive cracking or settlement of weak ground.*

MM 10 *Most unreinforced masonry structures destroyed. Many pre-earthquake code buildings destroyed. Many pre-1980 buildings and bridges seriously damaged. Many post-1980 buildings and bridges moderately damaged or permanently distorted. Widespread cracking of flat and sloping ground. Widespread and severe landsliding on sloping ground. Very large landslides (>$10^6 m^3$) from steep mountain faces and coastal cliffs. Widespread and severe liquefaction.*

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