Liquefaction hazard in the Taranaki Region

G. D. Dellow

W. Ries

GNS Science Consultancy Report 2013/57
April 2013

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EXECUTIVE SUMMARY

The four local authorities in Taranaki have engaged GNS Science to undertake an assessment of the liquefaction hazard in the Taranaki Region. Liquefaction hazard includes the susceptibility of the soils of the region to liquefaction and the likelihood of different levels of strong earthquake shaking occurring that can potentially trigger liquefaction. Combining soil susceptibility to liquefaction with seismic hazard (i.e. the return time of various levels of earthquake shaking) allows an assessment of liquefaction hazard (or the probability of the severity of liquefaction occurring in a given timeframe) to be made.

Significant liquefaction hazard in the Taranaki Region is limited to only a few areas. The primary reasons for this are the fortuitous lack of young, non-cohesive fine-grained sediments in areas where the groundwater table is close (within 1-5 metres) of the ground surface.

The highest liquefaction hazard in the Taranaki Region has been assigned to the reclaimed land at Port Taranaki. This is based on historical precedent because reclaimed harbour land is commonly affected by liquefaction during strong earthquake shaking. Earthquake shaking strong enough to cause liquefaction-induced land damage to the reclaimed land, such as a few sand boils or fissures, can be expected, on average, every 120 years. More extensive damage can be expected during stronger, but less frequent, ground shaking (e.g. sand boils and moderate fissuring damage to reclaimed land every 980-1070 years).

The areas where the liquefaction hazard in Taranaki is assessed as high are the lower reaches of the Mohakatino, Rapanui, Tongaporutu, Mimi, Urenui Onaero and Waitara Rivers in north Taranaki and the Waitotara, Whenuakura and Patea Rivers in south Taranaki, and their tributaries. Earthquake ground shaking strong enough to cause a few sand boils and fissures can be expected, on average, every few hundred years (980-1070 years). More extensive damage can be expected during stronger, but less frequent (9500 to 14,300 years), ground shaking.

The areas where the liquefaction hazard in Taranaki is assessed as moderate or low are the upper reaches of the larger rivers in the region and the mouths of the rivers draining the Mount Taranaki ring-plain. Earthquake ground shaking strong enough to cause a few sand boils and fissures can be expected, on average, every few thousand years (9500-14,300 years). More extensive damage can be expected during stronger, but less frequent (very rare MM10) ground shaking.

The liquefaction hazard has been mapped principally based on geological data derived from 1:250,000 scale geological maps which were compiled from 1:50,000 geological maps. The liquefaction hazard maps presented here are suitable for use at the same scale, 1:50,000, showing where liquefaction hazard potentially exists at a regional level or district level. The maps are not suitable for use at scales less than 1:30,000 (as per the contract for this work) and the geological boundaries retain an uncertainty on their location of ± 100 metres.

The liquefaction classifications assigned to the different map units were tested through the analysis of geological information contained in 900 boreholes. The liquefaction hazard derived from the borehole and the geological map are generally in agreement. However, in some cases there are discrepancies between the borehole interpretation and the liquefaction hazard assigned on the basis of map units. The liquefaction hazard interpretation from the

geological map has been preferred in these cases because the geotechnical information in the borehole records is insufficient to accurately determine the liquefaction hazard.

The liquefaction hazard maps presented are not suitable for use at a suburb or site specific level to determine liquefaction hazard. It is strongly recommended that site specific investigations, such as cone penetrometer tests, be carried out to confirm or discount the liquefaction hazard at sites of key infrastructure in areas identified as having a high, or very high, liquefaction hazard.

1.0 INTRODUCTION

The New Plymouth District Council has engaged GNS Science to undertake an assessment of the liquefaction hazard in the Taranaki Region on behalf of the other local authorities (Stratford District Council and the South Taranaki District Council) and the Taranaki Regional Council. Liquefaction hazard includes the susceptibility of the soils of the region to liquefaction and the likelihood of different levels of strong earthquake shaking occurring that can trigger liquefaction. Combining soil susceptibility to liquefaction with seismic hazard (i.e. the return time of various levels of earthquake shaking) allows an assessment of liquefaction hazard (or the probability of the severity of liquefaction occurring in a given timeframe) to be made.

The scope of work and deliverables agreed to between GNS Science and the four Taranaki councils provide for the following work to be completed:

- To assemble, review, summarise and assess available subsurface information and historical liquefaction data from the Taranaki region, and assess the applicability of relevant geological and engineering data towards the assessment of liquefaction hazard.
- To carry out a geotechnical assessment using existing information assembled under a) above of the typical ground material to determine the scale of liquefaction and ground damage that might occur during strong (MM Intensity 7 to 10) earthquake shaking.
- If it is found that significant liquefaction and associated ground damage could occur, then measures that would help to investigate and mitigate the damage will be identified, together with comments on their applicability and likely costs.

Information from the study will be used by the four councils for:

- Hazard mapping in the district plan for guiding land use and development, and
- Hazard mapping for Taranaki Civil Defence and Emergency Management purposes.

The report follows the methodology used in Beetham et al (1998) (Wanganui), Dellow et al (1999) (Hawke's Bay) and work currently in preparation for Wellington region (Dellow et al in prep). The methodology uses datasets including geology, groundwater, geotechnical, boreholes and topography. These datasets are combined to identify areas where young (or loose), fine grained, non-cohesive sediments are present within 20 metres of the ground surface and where the groundwater is shallow. In areas where groundwater data is lacking topography is used instead, with the assumption made that low areas will have groundwater close to the ground surface, while for high areas the groundwater will be deep.

The report initially provides a brief description of liquefaction including answering the questions: What is liquefaction? What makes soils susceptible to liquefaction? And, when is liquefaction significant? The report then goes on to describe the key datasets in terms of their relevance to characterising liquefaction hazard including the geology and geomorphology of Taranaki, the historical earthquake and liquefaction record in Taranaki and the level of seismic hazard present in the region. The subsurface data is discussed and how this was analysed to extract the liquefaction relevant information presented.

Following that, the liquefaction hazard of Taranaki is then presented as three maps, to be used at scales between 1: 30,000 and 1:250,000, based on district council boundaries. The maps show the extent of geological materials that may be prone to liquefaction and an interpretation of potential liquefaction hazard based on an analysis of borehole data.

2.0 THE LIQUEFACTION PROCESS

This section is adapted from the Institution of Professional Engineers of New Zealand Liquefaction fact sheet (IPENZ) (Figure 1) and the GNS Science publication by Saunders & Berryman (2012) titled: "Just add water: when should liquefaction be considered in land use planning?"

2.1 WHAT IS LIQUEFACTION?

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

- Loose sands and silts. Such soils do not stick together the way clay soils do.
- Saturated, 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, the shaking may be so strong that the sand and silt grains try to compress the spaces filled with water, but the water pushes back and pressure builds up until the grains 'float' in the water. Once that happens the soil loses its strength and it has liquefied. Soil that was once solid now behaves like a fluid.

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 surface as boils, sand volcanoes and rivers of silt. In some cases the liquefied soil flowing up a crack can erode and widen the crack 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 dry surface soil layers can slide sideways on the liquefied soil towards the streams. This is called lateral spreading and can severely damage a building 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 might be affected by liquefaction. The affected part may subside (settle) or be pulled sideways by lateral spreading, which can severely damage the building. Buried services such as sewer pipes can be damaged as they are warped by lateral spreading, ground settlement or floatation.

2.2 WHEN ARE SOILS 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).

If all three of these preconditions are met, then an assessment of the liquefaction hazard is required. Assessment of liquefaction hazard can be on a regional or district scale, such as this report, or it can be site specific using, for example, cone penetrometer tests. It is important to 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 does not need to be assessed in an urban or rural planning context.

2.3 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 if earthquakes are 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 consideration 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 on to socio-economic resilience if people are not able to live in their homes and/or attend places of education and employment.

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.

Photo 1 Lateral spreading fissures running parallel to the Avon River in Avonside Drive, Christchurch, February 2011 (Photo D. Beetham, GNS Science).

Photo 2 Fissure and associated sand and silt ejecta in Kaiapoi, Christchurch, September 2010 (Photo N. Litchfield, GNS Science).

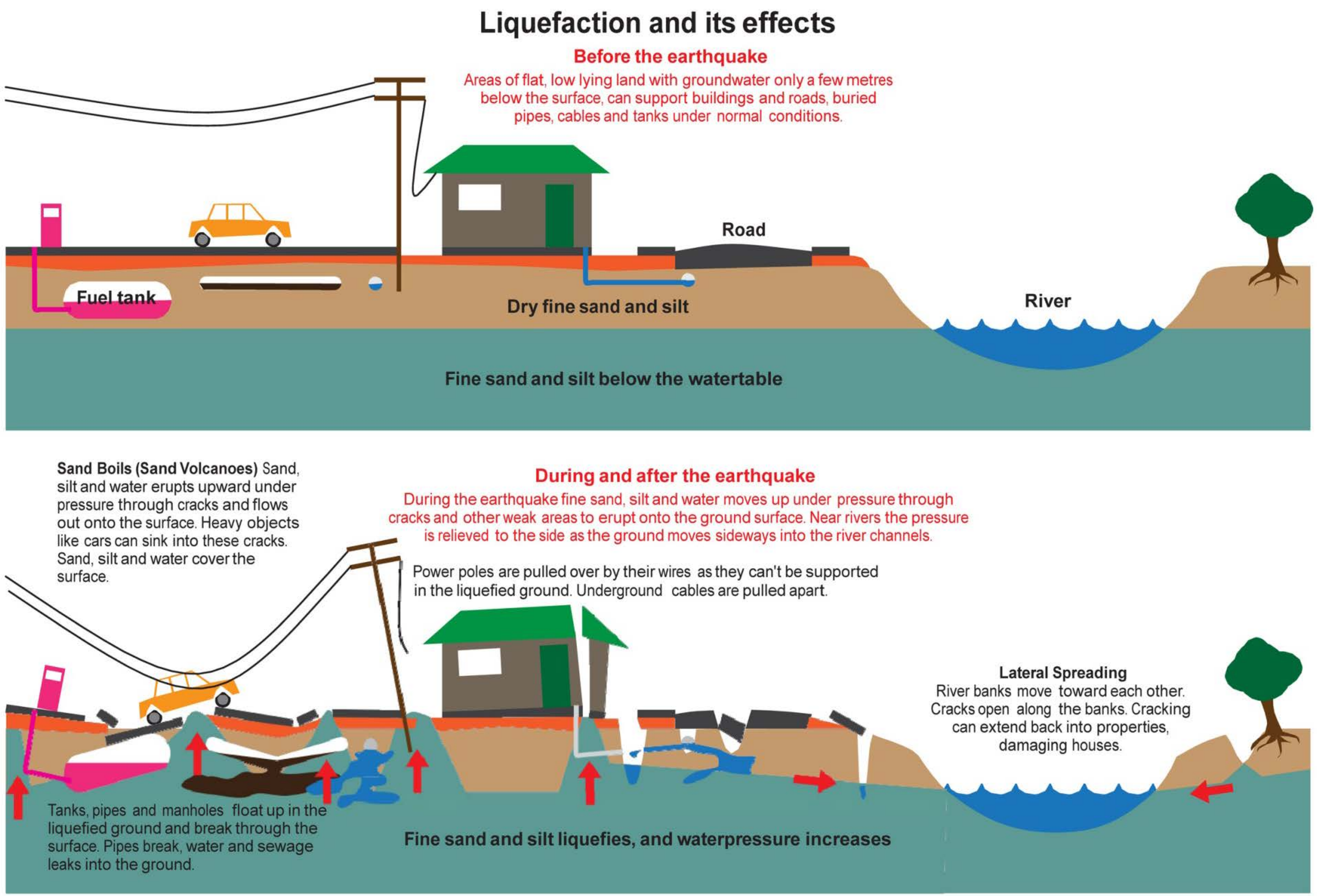

Figure 1 Liquefaction and its effects (IPENZ).

3.0 GEOLOGY OF TARANAKI

The geology of the Taranaki Region (Townsend et al, 2008; Edbrooke, 2005) has three main components:

- to the west the Quaternary volcanic and volcaniclastic rocks of Mt Taranaki and its associated ring-plain;
- to the east Neogene (2-24 Ma (million years old)) marine sedimentary rocks; and
- to the south a strip of coastal lowlands between Waitotara and Hawera covered with Quaternary marginal marine sediments.

In terms of liquefaction susceptibility, these three geological settings provide three distinct provinces. Associated with all three of these geological settings are young Quaternary sediments (0-2 Ma), including even younger Holocene sediments (<10 ka (thousand years old)) including beach deposits, dunes, alluvium, fan deposits and swamps.

3.1 MOUNT TARANAKI AND THE RING-PLAIN

The geology of the Egmont Volcanic Centre is dominated by lavas, breccias, lahars and pyroclastic materials derived from the several andesitic volcanic vents active over the last two million years (Townsend et al, 2008). None of these materials are susceptible to liquefaction.

The only potentially liquefiable material in this setting is the alluvium of the rivers draining from the edifice of Mt Taranaki. Because these rivers have their sources on Mt Taranaki and the other volcanic edifices they do not carry a lot of fine-grained (sand and silt) sediment. However where these rivers approach the coast the steep gradient of the ring-plain may abate (i.e. the river flow is no longer capable of transporting boulders and gravel) and small estuaries may form. In these areas it may be possible for small areas of liquefiable sediments (fine-grained, non-cohesive sands and silts) to accumulate. The potential extent of liquefiable areas is constrained because river incision into the ring-plain limits the lateral extent of potentially liquefiable materials. The presence of low coastal cliffs (c. 10-20 m high) also constrains the areas available for the deposition of young, fine-grained, non-cohesive sediments.

In some areas beach and/or dune deposits are present and these may also be susceptible to liquefaction in rare circumstances. Mostly the dunes are located on the top of the ring-plain above the low coastal cliffs. In this position they are unlikely to have shallow water table depths, precluding liquefaction. Beach environments are generally high-energy environments, especially if they are exposed to the open sea, which compact the beach sands in a denser arrangement that inhibits liquefaction. The exception would be the landward side of small sand spits of the larger rivers and streams as described above.

3.2 NEOGENE HILL COUNTRY

The Neogene rocks (ages between 2 and 24 Ma) of the hill country to the east of Mt Taranaki are not susceptible to liquefaction but the sediments derived from these rocks and deposited as alluvium on the river floodplains in places probably are. The Neogene rocks are sandstones, siltstones and occasional limestone deposited in a shallow marine environment (Townsend, 2008). The derived alluvium varies in age from Holocene (deposited in the last 10,000 years and therefore young) through too late Quaternary (deposited sometime in the last one million years). Where the alluvium is of Holocene age it is more likely to liquefy provided it is non-cohesive and fully saturated. Older alluvium is less likely to liquefy as it is more consolidated and higher above current stream and river levels.

3.3 COASTAL LOWLANDS

The coastal lowlands between Hawera and Waitotara are dominated by Holocene dune fields and older beach deposits on former marine terraces. These dunes are composed of non-cohesive fine-grained (sands) sediments that could potentially liquefy. The extent of the liquefaction is likely to be limited where the dune-fields have some relief (i.e. a variation in height of over five metres). Depth to the groundwater table will be variable in these areas and consequently the extent of liquefaction is also likely to be variable.

The beach deposits on the marine terrace surface are unlikely to liquefy because they were deposited in a high energy environment, are older than 10,000 years and are often isolated on uplifted surfaces reducing the possibility of the groundwater surface being close to the ground surface.

3.4 SWAMPS

Several large swamps have been identified in the Taranaki region. The swamps occur in a variety of settings, but the most extensive occur where rapid sedimentation from the Mt Taranaki edifice has blocked or dammed valleys draining from the inland Neogene hill country.

While swamps seldom liquefy because of the presence of cohesive materials (volcanic ash), non-cohesive materials (that have settled out from suspension) and large amounts of organic material they can expel water under strong earthquake shaking as well as settle differentially. Swamps may also amplify low to moderate levels of earthquake shaking and where their depth is greater than 10 metres they fall into Ground Class E (soft soil) of the ground classification scheme used in NZS 1170.5 – the structural design code used for building design in New Zealand.

4.0 HISTORICAL EARTHQUAKES AND LIQUEFACTION IN TARANAKI

Hancox et al (2002) in a study of the largest earthquakes in New Zealand since 1840 identify a minimum level of shaking of Modified Mercalli Intensity (Appendix 1) of MM7 as necessary for liquefaction to occur in the most susceptible sediments.

Table 1 lists earthquakes in the Taranaki region where earthquake shaking was MM 5 or greater (Downes and Dowrick, 2012) at four urban sites within the Taranaki region (New Plymouth, Stratford, Hawera and Opunake). Earthquake shaking at or above the threshold identified by Hancox et al (2002) is bolded in the table.

Based on the Hancox et al (2002) threshold no shaking strong enough to initiate liquefaction in the most susceptible deposits has occurred at either Stratford or Opunake since 1840 (Table 1). Near New Plymouth and Hawera two or three earthquakes have generated shaking that would have been strong enough to initiate liquefaction in the most susceptible deposits (Table 1). However, no historical reports of liquefaction have been found to date for either location.

The New Zealand National Seismic Hazard Model (Stirling et al, 2002; Stirling et al, in press) is a fundamental component of the New Zealand Structural Design Standard (NZS 2004). The National Seismic Hazard Model provides estimations of the level (strength) of earthquake ground shaking throughout the country at various return times. These ground motion estimations are then used to derive earthquake loadings for the design, construction and/or retrofit of buildings and other important structures (e.g. bridges, dams) to comply with, or exceed, specified operational and life-safety performance objectives. Figure 2 shows the seismic hazard for the 475 year return period peak ground acceleration for shallow soil sites (ground shaking subsoil class C; NZS 1170.5) throughout New Zealand and highlights the relatively moderate to low seismic hazard present in the Taranaki Region (Stirling et al, 2012).

The lack of reported liquefaction in Taranaki during strong ground shaking probably reflects two things – the low seismic hazard in Taranaki relative to the rest of New Zealand (Stirling et al, 2012) and the lack of materials that are susceptible to liquefaction (this report).

Table 1 A list of historical earthquakes in Taranaki and the corresponding MM intensities felt at four localities within the region. Highlighted (bold) numbers are where the MM intensity was at, or exceeded, the threshold for liquefaction in susceptible sediments.

Historic Earthquake	**MM Intensity felt in Taranaki urban areas**			
	New Plymouth	**Stratford**	**Hawera**	**Opunake**
1848 Marlborough	6		**7**	
1855 Wairarapa	**6-7**			
1868 Cape Farewell	**7-8**		**7-8**	
1929 Buller	5-6	6	**7**	
1931 Hawke's Bay	5	5	5	4-5
1932 South Taranaki Bight	6	5	5	
1934 Hororeka	5	5	5	5
1942 Wararapa 1	4	5	5	5
1942 Wararapa 2	4-5	4-5	6	4
1974 Opunake	5	5	5	6

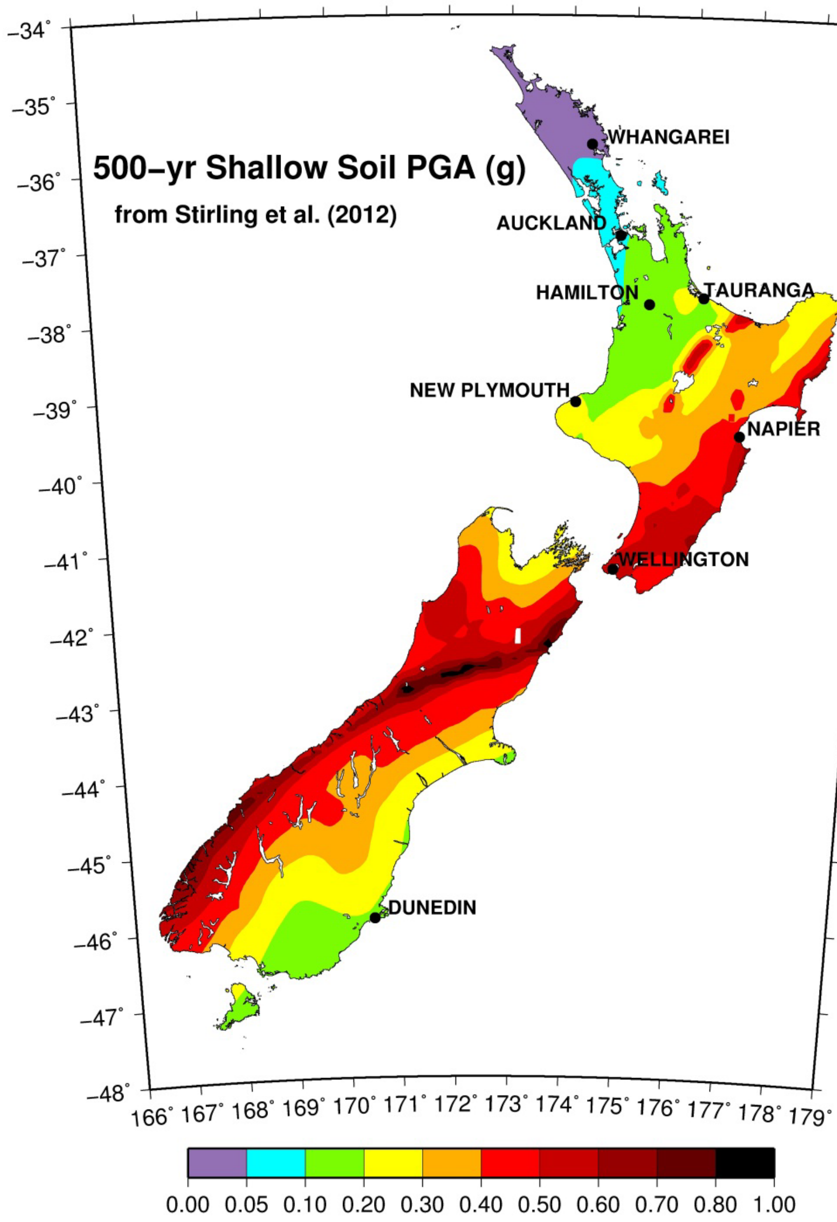

Figure 2 Probabilistic seismic hazard map from the National Seismic Hazard Model of Stirling et al (2012). The map shows the peak ground acceleration expected with a return period of 475 years (10% probability in 50 years) for shallow soil sites (subsoil class C).

5.0 KNOWN FAULTING AND ESTIMATED RECURRENCE INTERVALS OF SHAKING OF SUFFICIENT STRENGTH TO CAUSE LIQUEFACTION.

There are a number of known active faults in the Taranaki Region (Table 2, Figure 3). The mapped fault traces have been aggregated to produce a number of discrete sources in the National Seismic Hazard Model (Stirling et al, 2012). These known faults, other known faults outside the region and a distributed seismicity model allow the seismic hazard in Taranaki to be determined (Stirling et al, 2012).

The seismic hazard for the Taranaki Region can be expressed in a number of ways but for the purposes of this report it has been expressed as the mean return period expected for different levels of earthquake shaking as expressed by the Modified Mercalli Intensity scale (Table 3).

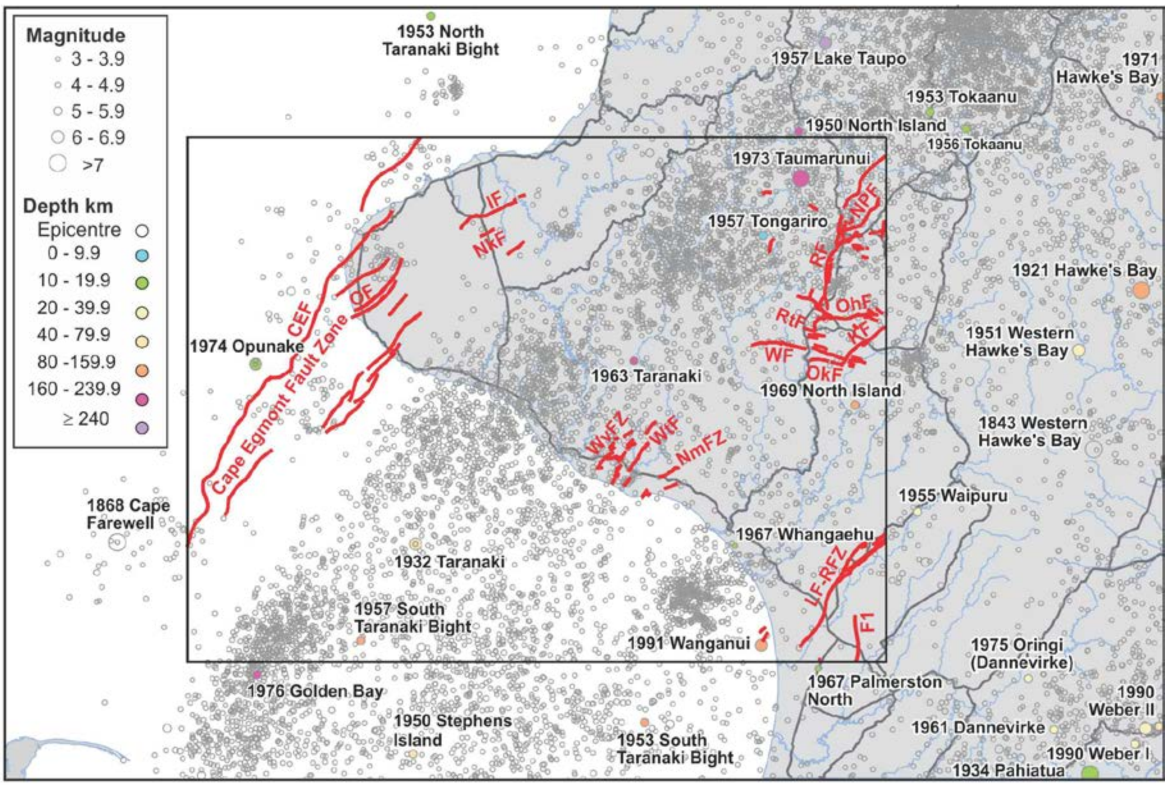

Figure 3 Active faults (http://data.gns.cri.nz/af) within QMAP Taranaki (red lines) and epicentres of large historical earthquakes in the surrounding central North Island region (http://www.geonet.org.nz). Grey dots represent earthquakes (>M3) between 1992 and 2007 and historical earthquakes from Downes and Dowrick (2012). CEF: Cape Egmont Fault, OF: Oaonui Fault, IF: Inglewood Fault, NkF: Norfolk Fault, WvFZ: Waverley Fault Zone, WF: Waitotara Fault, NmFZ: Nukumaru Fault Zone.

Table 2 Fault length, slip rate, timing of last rupture, recurrence interval and probable earthquake magnitude of significant active faults and associated earthquakes in the Taranaki area. Data from: [1] Townsend 1998; [2] Neall 1979; [3] Hull 1996; [4] Nodder 1993; [5] Stirling et al, 1998; [6] Pillans 1990; [7] Townsend et al, 2008). [a]) Minimum length of demonstrably active trace, limited by faults going offshore and/or being obscured by younger lahars from Egmont or Ruapehu volcanoes; [b]) vertical slip rate. (From Townsend et al, 2008).

Fault name	Fault strike	Minimum length (km) [a]	Slip rate (mm/yr) [b]	Age of last event (ka)	Recurrence interval (ka)	Possible max. EQ mag.
Waverley	NE-SW	7+	-	>1 [1]	7 - 11 [1]	6.4-6.5 [1,5]
Moumahaki	NE-SW	10+	-	-	-	-
Waitotara	NE-SW	14+	0.71 [5, 6]	-	0.694 [5]	6.1 [5]
Nukumaru	NE-SW	6+	0.07 [5, 6]	-	5 - 20 [5]	6.2 [5]
Ararata	NE-SW	1?	0.02 [3, 6]	-	-	6.2 [5]
Cape Egmont	NE-SW	200+	0-1 [4]	<10-11 [4]	-	7.1 M [5]
Turi	NE-SW	105	-	-	-	-
Rahotu[7]	NE-SW	1.8+	0.06	<7	-	6.1[7]
Oaonui	NE-SW	14+	0.7v [2, 3]	<8.5[7]		7.1 M [3]
Kina[7]	NE-SW	4.5+	0.36	<4	-	6.1[7]
Ihaia[7]	NE-SW	5+	0.41	<5	-	6.1[7]
Kiri[7]	NE-SW	6+	0.71	<10?	-	6.1[7]
Pihama[7]	NE-SW	4+	0.22	<<6.2	-	6.1[7]
Inglewood	NE-SW	20	0.5 [5]	3.3-3.5 [3]	31.552 [5]	6.5 Mw [3, 5]
Norfolk	NE-SW	4.7	-	-	-	-

Table 3 Mean return period for earthquake shaking intensity at selected locations within the mapped area, derived using the seismicity model of Stirling et al 2012.

Intensity	Mean return period (years)	
	New Plymouth	Hawera
MM6+	32	21
MM7+	150	120
MM8+	980	1070
MM9+	9500	14300
MM10+		

6.0 SUB-SURFACE DATA

The New Plymouth District Council, Stratford District Council, South Taranaki District Council and the Taranaki Regional Council supplied the location of 1733 boreholes (Table 4). Of these boreholes, 955 contained logged descriptions of stratigraphy. The descriptions were analysed to determine if non-cohesive fine sands and silts were present. If fine sands and silts were present (and were not overlain by cohesive clays) then the materials were treated as liquefiable. If information on the water table was available and showed a static water table above or within the liquefiable layer then the liquefaction potential was assessed as ‘Probable’. If no water table data was available then a ‘Possible’ liquefaction potential was assigned. If non-liquefiable material (cohesive clays or gravels) was present in the top 20 m or the static water table was below 20 m then the borehole was assessed as having ‘No Potential’ for liquefaction.

These data were imported into a GIS and classified with regards to liquefaction potential:

- Probable – Presence of liquefiable material (with no layer above likely to inhibit liquefaction) within 20 m of ground surface and a static water table within this layer.
- Possible - Liquefiable material (with no layer above likely to inhibit liquefaction) within 20 m of the top of the borehole and no information regarding water table.
- No Potential – Non liquefiable material present in the top 20 m of the borehole or the static water table below 20 m.
- Data insufficient – The description of material in the log was insufficient to determine the presence or absence of liquefiable material.
- No Log – The borehole had no stratigraphic log.

Table 4a Boreholes supplied by the New Plymouth District Council, Stratford District Council, South Taranaki District Council and the Taranaki Regional Council and the number of boreholes classified into each liquefaction potential category where sufficient data was available to do so.

Borehole Liquefaction Potential	Number of Boreholes
Probable	19
Possible	37
No Potential	802
Data insufficient	97
No Log	778
	1733

Table 4b The liquefaction potential of boreholes supplied by the New Plymouth District Council, Stratford District Council, South Taranaki District Council and the Taranaki Regional Council by local authority area.

Territorial Authority	No log	Data insufficient	No Potential	Possible	Probable	Total boreholes
NPDC	336	45	301	11	13	706
SDC	145	26	162	4	0	337
STDC	297	26	339	22	6	690
						1733

The descriptions of stratigraphy varied considerably between boreholes with single word descriptions (i.e. sand) through to very detailed (i.e. minor sand, light brown, soft/moist/loose, clayey below 1.4m). The lack of detail in some of the stratigraphic descriptions makes it likely that some of these boreholes may have been classified incorrectly. Where the description was not detailed enough to confirm the presence or absence of a liquefiable material or the borehole was classified as 'data insufficient'. These data are summarised in Table 4a and 4b.

7.0 LIQUEFACTION IN TARANAKI

7.1 GEOLOGICAL MAP DATA

The three requirements for liquefaction are:

- Loose sediments (i.e. young and therefore seldom older than Holocene and deposited in a low energy environment e.g. settling out of suspension);
- Fine-grained non-cohesive sediments
- Fully saturated (i.e. below the water table).

The geological base maps used to assess the regional liquefaction in Taranaki are Edbrooke (2005) and Townsend et al (2008). These maps present geological data at a scale of 1:250,000 and are based on maps compiled at a scale of 1:50,000. On both these maps Holocene age (less than 10,000 years old) sediments have ‘Q1’ as part of their unit code on the maps. Therefore all geological units that are sediments and have ‘Q1’ as part of their code are potentially liquefiable. All the ‘Q1’ age sediments are listed in Table 7. The only geological unit that does not have ‘Q1’ as part of its code that is assessed for liquefaction susceptibility is late Quaternary alluvium (lQa on the Townsend et al, 2008 and Edbrooke, 2005 maps). This unit is assessed because it includes the Holocene time period and therefore some areas within this unit may be potentially liquefiable. All the other geological units on the Townsend et al (2008) and Edbrooke (2005) maps are considered to be non-liquefiable because they are too old.

The geological maps do not include cover deposits which are thin (> 5metres thick) and may be extensive throughout a region. For Taranaki there are two cover deposits that are widespread through the region. The oldest is loess (wind-blown sand and silt) deposited during the last ice age (30,000 to 10,000 years ago). The younger deposit is Holocene age (10,000 to 300 years old) volcanic ash, otherwise known as Taranaki Brown Ash. Both these deposits are potentially liquefiable in the right conditions. However, the variability of the landscape onto which these materials have been deposited inhibits the easy identification of areas where these materials may be susceptible to liquefaction. The other feature of these materials is that because of the variability in the pre-existing landscape onto which they were deposited, areas that are potentially susceptible to liquefaction are unlikely to be extensive. At worst liquefaction is likely to affect only a few properties in small discrete areas and is highly unlikely to affect whole suburbs as was seen in Christchurch.

Liquefaction susceptibility in each of the geological units below (listed in Table 5) is assessed in terms from the historical record (Section 4), analogous geological units elsewhere in New Zealand that have experienced strong earthquake shaking and physiographic location. The physiographic location is considered because the historical occurrence of liquefaction in New Zealand has dominantly occurred within 10 km of the coastline (Hancox et al, 2002).

Holocene age (Q1) volcanic materials are often coarse (debris flow deposits), cohesive (volcanic ash) or strong rock (lava) which are deposited by high energy processes. There is no evidence of primary volcanic materials liquefying in New Zealand (Hancox et al, 2002). So although these materials are Holocene they are treated as non-liquefiable.

The only geological unit assessed as having a very high potential for liquefaction is Q1n, anthropogenic fill and reclaimed land (Townsend, 2008). The only Q1n in the Taranaki

Region is located in Port Taranaki. Historically port facilities are extremely vulnerable to liquefaction. New Zealand examples include damage to the port facilities at Napier in the 1931 Hawke's Bay earthquake (Marshall, 1933) and in Lyttelton after both the 2010 Darfield and 2011 Christchurch earthquake.

The Q1a (Holocene) alluvium of the Mohakatino, Rapanui, Tongaporutu, Mimi, Urenui Onaero and Waitara Rivers in north Taranaki and the Waitotara, Whenuakura and Patea Rivers in south Taranaki, and their tributaries, are sourced from sediments derived from the Neogene sediments and as such are dominated by non-cohesive sands and silts (Townsend et al, 2008; Edbrooke, 2005). A close geological analogy would be the sediments of the Waipaoa River near Gisborne. However, the historical record suggests these sediments have been shaken to at least MM7 without liquefaction occurring unlike in the Gisborne area where these sediments have been known to liquefy in some circumstances at MM6. Two possible scenarios exist to explain this – the Taranaki sediments have higher clay content due to volcanic ashes making them more cohesive and therefore more resistant to liquefaction or alternatively liquefaction occurred but was not recorded after the strongest earthquake shaking in this area (1868). Also deforestation is far greater in the Waipaoa catchment with consequently greater sedimentation rates (i.e. lots of very young sediment).

The liquefaction susceptibility of the Q1a alluvium (Townsend et al, 2008; Edbrooke, 2005) is further subdivided by considering proximity to the coast. Q1a alluvial river terraces below 20 m (i.e. closer to the coast) are given a high susceptibility rating because river gradients are lower nearer the coast, and therefore lower energy environments, compared with the slightly steeper river gradients, and therefore higher energy environments further inland. This is supported by the historical occurrence of liquefaction in New Zealand which is dominantly within 10 km of the coastline (Hancox et al, 2002). In this instance 'coastal ' is defined as less than 20 m above mean sea level (i.e. the alluvial terrace surface is below the 20 m contour on the NZMS 260 map series). It is expected that at MM8 intensity shaking affecting these sediments will cause a few sand boils and minor fissures every 980-1070 years (Table 2). Moderate liquefaction in these sediments (sand boils and moderate fissuring, banks of rivers broken up and embankments slumped) is only expected to occur every 9500-14,300 years (Table 2).

Q1a (Townsend et al, 2008; Edbrooke, 2005) alluvium of the rivers draining Mt Taranaki ring-plain is assigned a low liquefaction susceptibility, where the alluvium is less that 20 metres above mean sea level. It is expected that MM10 shaking, which is expected every few ten thousand years, might cause a few sand boils and fissures in these sediments.

lQa (late Quaternary alluvium; Townsend et al, 2008; Edbrooke, 2005) sediments are assigned a low liquefaction hazard rating because they range in age from a few thousand years (<12,000) up to 780,000 years old. Generally they will be sufficiently consolidated that liquefaction is unlikely but some areas may be Holocene in age (young) and isolated pockets of liquefaction may occur.

Q1a (fan deposits; Townsend et al, 2008; Edbrooke, 2005) are considered non-liquefiable because the steeper gradients of the fan surfaces. These steeper stream gradients on fans are indicative of a higher energy process operating in this geomorphic setting when compared to the settling out of suspension in estuarine environments.

Q1a (swamps; Townsend et al, 2008; Edbrooke, 2005) are mapped separately as swamp deposits. Swamps are not usually susceptible to liquefaction because they are often sites where clays and organic material accumulate. However, they are identified on the map because areas of wet, swampy ground can deform during strong earthquake shaking with differential settlements and water ponding. These areas should be picked up by NZS 1170.5 (if the ‘soft’ ground is greater than 10 m thick) or foundation investigations under NZS 3604 where scala penetrometer values less than 2 may indicate unsuitable foundation conditions for light-weight timber-framed construction.

Q1h (Townsend et al, 2008) lahar deposits are not considered liquefiable because they emplaced in a high-energy process of debris flows or debris floods and they also contain a range of grain-sizes. There are no known instances of lahar deposits liquefying during strong earthquake shaking.

Q1b beach deposits (Townsend et al, 2008; Edbrooke, 2005) - exposed beaches are high-energy environments (from the waves) and as such although beach sediments meet the grain-size and water table criteria the grains are often densely packed and therefore do not liquefy easily (c.f. the exposed ocean beach side of Brighton Spit in Christchurch where very little liquefaction was observed or reported with the estuary side where liquefaction was often extensive and highly damaging as in the suburb of Bexley). Young beach sediments are assessed as having a very low susceptibility to liquefaction meaning liquefaction could occur in exceptional circumstances – very strong (MM10 or greater) shaking or on the landward side of beach barriers.

Q1d dune sand deposits (Townsend et al, 2008; Edbrooke, 2005) are often located on old marine terraces and although they are deposited in a low energy environment (wind-blown sand) the sands themselves are free-draining and unlikely to sustain the saturated condition necessary for liquefaction to occur. Young dunes, active or fixed, are assessed as having no susceptibility to liquefaction meaning liquefaction could occur in exceptional circumstances – very strong (MM10 or greater) shaking in conjunction with a high-intensity rainstorm.

7.2 LIQUEFACTION SUSCEPTIBILITY

Sand boils and water ejections are the most common and unambiguous historical evidence of liquefaction in New Zealand. However, it is likely that other types of ground damage such as the settlement and spreading of embankments and river banks, have been caused by liquefaction, but have not always been recognised as such. In historical records, emphasis has been placed on recording the more obvious effects of earthquakes on buildings, although the unusual and often spectacular earthquake fountains (sand boils or `volcano' features), so common in the epicentral areas of large earthquakes, were usually noticed and reported. On alluvial plains, such features are often the only visible manifestation of liquefaction on areas that appear otherwise undamaged.

Generally, the intensity threshold (Modified Mercalli (MM) Intensity) for liquefaction in New Zealand was found to be MM7 for sand boils, and MM8 for incipient lateral spreading (Hancox et al, 2002). Liquefaction-induced ground damage is most common at MM8-10, at epicentral distances of 10-100 km (Hancox et al, 2002). As the shaking intensity increases at the most susceptible sites, the severity of the reported liquefaction also increases. Also, as the shaking intensity increases less susceptible sites will reach the threshold for initiating liquefaction. These observations are used as the basis for classifying the type and extent of liquefaction-induced ground-damage in terms of a liquefaction damage rating (Table 5).

Table 5 Descriptions of expected liquefaction induced ground damage for liquefaction damage ratings.

Liquefaction Damage Rating	Description of expected liquefaction induced ground damage
0	No liquefaction damage is seen.
1	A few sand boils and minor fissures. Estimate up to 10% of total area affected.
2	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.
3	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.
4	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 liquefaction damage ratings in Table 5 are used to develop criteria for liquefaction susceptibility classes (Table 6). The higher the Modified Mercalli shaking intensity needed at a site for the liquefaction threshold to be reached the lower the susceptibility class. At the triggering threshold for a geological unit, ground damage is generally minimal (damage rating 1 – see Table 5 above). Table 6 sets out the liquefaction damage ratings associated with each liquefaction susceptibility class for a range of MM shaking intensities.

Table 6 Liquefaction damage ratings assigned to liquefaction susceptibility classes at different MM shaking intensities.

Liquefaction Susceptibility Class	MM Intensity				
	MM6	**MM7**	**MM8**	**MM9**	**MM10**
Very high	0	1	2	3	4
High	0	0	1	2	3
Moderate	0	0	0	1	2
Low	0	0	0	0	1
None	0	0	0	0	0

Each geological unit that is potentially liquefiable in the Taranaki region is listed in Table 7. Using the geological map data described above (Section 7.1) and the historical data presented in Section 4.0 liquefaction damage ratings (Table 5) are assigned to each geological unit potentially susceptible to liquefaction in the Taranaki region for a range of MM intensities. Table 7 has been populated using a combination of historical data in the Taranaki region, an assessment of the liquefaction potential from borehole data and knowledge of the performance of similar geological units elsewhere in New Zealand (e.g. Wanganui, Christchurch, Wellington, Gisborne).

Table 7 Liquefaction damage ratings as assessed using historical records and geological precedent for the Holocene sediments of the Taranaki Region.

Geological Unit	**Modified Mercalli Intensity**					**Liquefaction Susceptibility (see tables 5 & 6)**
	6	7	8	9	10	
Q1n (fill)	*0*	*1*	*2*	*3*	*4*	Very High
Q1a (coastal)	**0**	**0**	*1*	*2*	*3*	High
Q1a (inland)	**0**	**0**	*0*	*1*	*2*	Moderate
Q1a (ring-plain)	**0**	**0**	*0*	*0*	*1*	Low
lQa (alluvium)	**0**	**0**	*0*	*0*	*1*	Low
Q1a (fan deposits)	**0**	**0**	*0*	*0*	*0*	none
Q1a (swamp)	**0**	**0**	*0*	*0*	*0*	none
Q1h (lahar)	**0**	**0**	*0*	*0*	*0*	none
Q1b (beach)	**0**	**0**	*0*	*0*	*0*	none
Q1d (dune)	**0**	**0**	*0*	*0*	*0*	none
Bold numbers are for historical observations, while the italic numbers are assessments made where no historical data exists.						

Using the liquefaction susceptibility classes assigned to each of the geological units in Table 7 every geological unit on the geological base maps (Edbrooke, 2005; and Townsend et al, 2008) can be assigned a liquefaction susceptibility class. Figure 4, Figure 5 and Figure 6 show the liquefaction susceptibility classes in each of the three districts in the Taranaki Region.

If the liquefaction susceptibility classes are analysed in terms of the seismic hazard information presented in Table 3 then liquefaction in the very high liquefaction susceptibility class can be expected, on average, every 120-150 years. Liquefaction in the high liquefaction susceptibility class can be expected, on average, every 980-1070 years. Liquefaction in the moderate liquefaction susceptibility class can be expected, on average, every 9500-14,300 years. And liquefaction in the low liquefaction susceptibility class can be expected, on average, every few tens of thousands of years.

Table 8 Number of boreholes in each borehole liquefaction class located within the mapped liquefaction susceptibility classes.

Borehole Liquefaction Potential	Number of Boreholes	Liquefaction Susceptibility Class				
		Very High	High	Moderate	Low	Outside
Probable	19	3	0	0	0	16
Possible	37	1	2	0	0	34
No Potential	802	0	14	17	12	759

Three of the 19 boreholes classified as ‘Probable’ were located in the very high liquefaction susceptibility areas and the remaining 16 in areas were located where no liquefaction susceptibility has been identified. Three of the 37 boreholes classified as ‘Possible’ were located in the very high or high liquefaction susceptibility areas and the remaining 34 in areas were located where no liquefaction susceptibility has been identified. Forty-three of the 802 boreholes classified as ‘No Potential’ were located in the high, moderate or low liquefaction susceptibility areas and the remaining 759 in areas were located where no liquefaction susceptibility has been identified.

The comparison between the sub-surface data and the liquefaction susceptibility areas identified through analysis of geological units do not completely support each other.

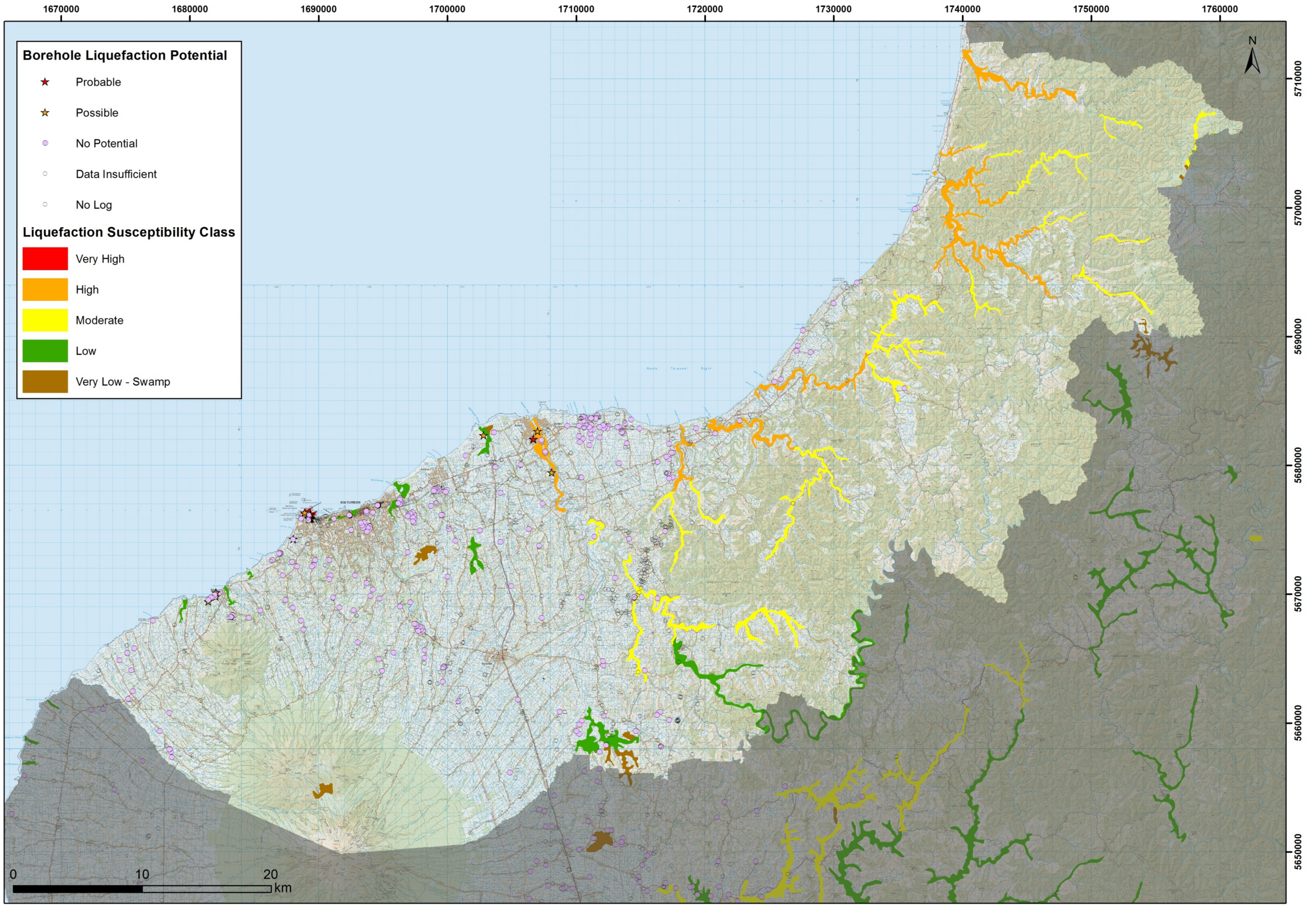

Figure 4 Liquefaction susceptibility in New Plymouth District.

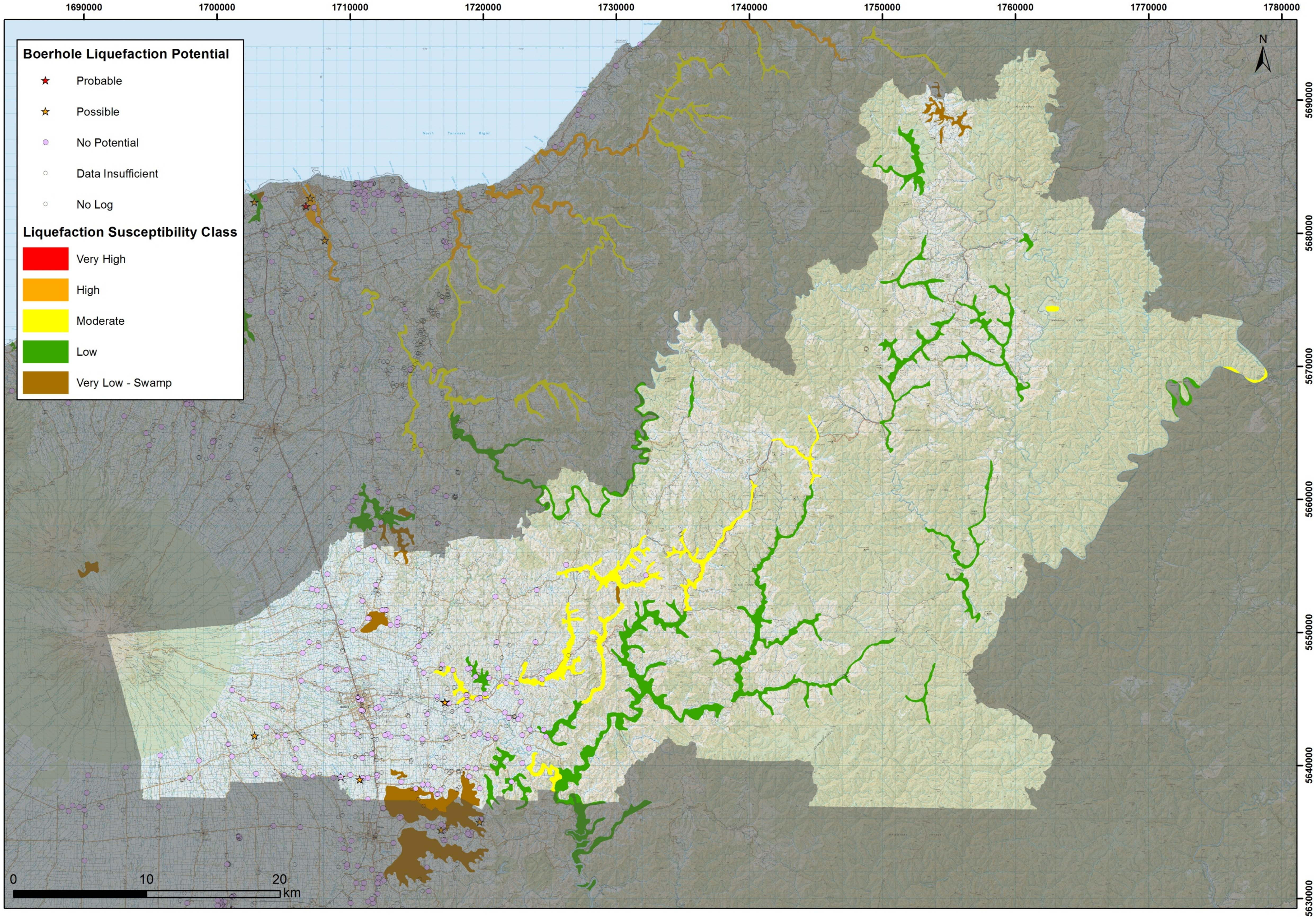

Figure 5 Liquefaction susceptibility in Stratford District.

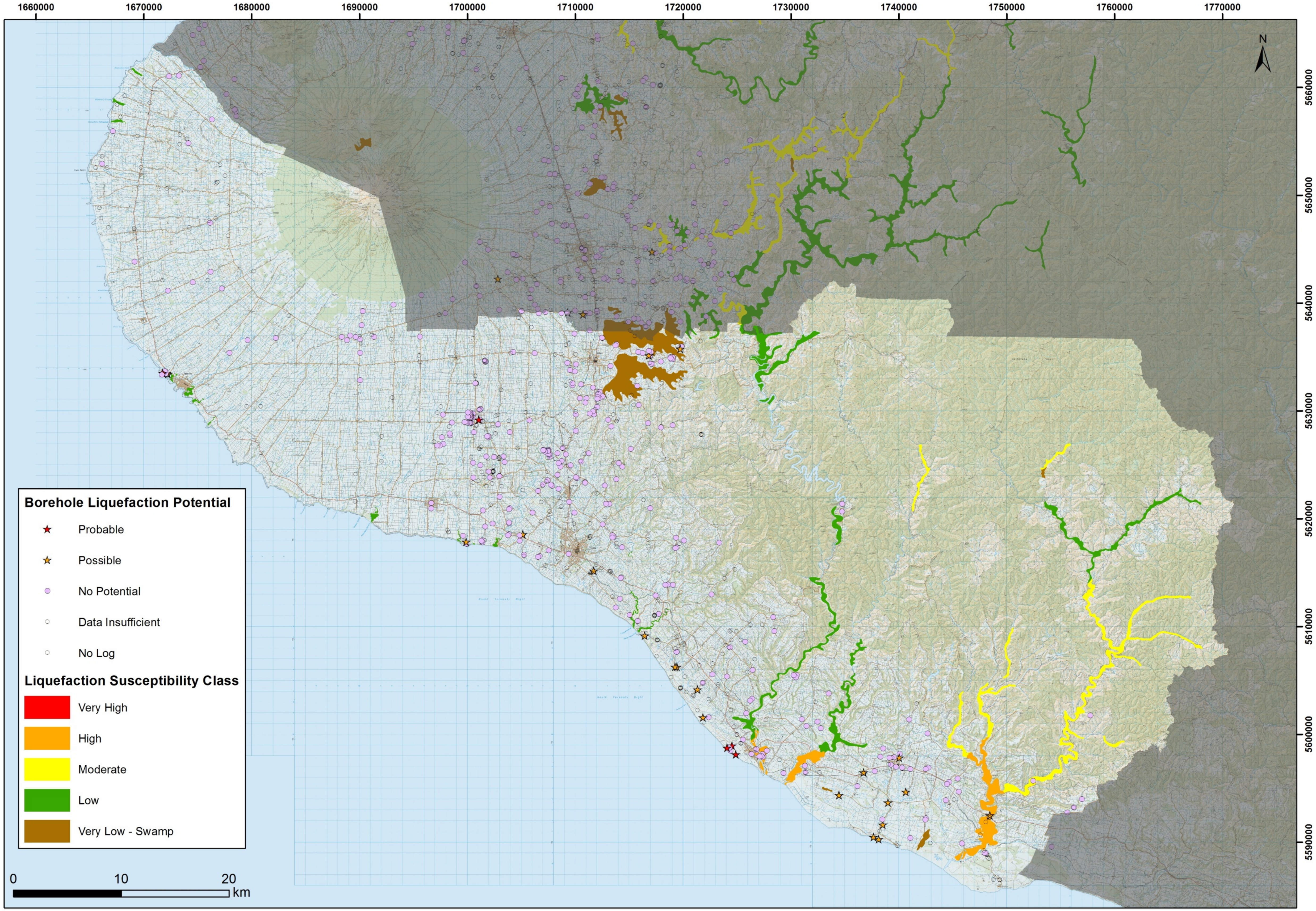

Figure 6 Liquefaction susceptibility in South Taranaki District.

8.0 MITIGATION OPTIONS

Liquefaction hazards can be mitigated in two principle ways, avoidance or using engineered solutions. Avoiding areas prone to significant liquefaction hazards can be put in place at the development planning stage (Saunders and Beban, 2012). In the Taranaki Region many of the areas susceptible to liquefaction are also flood prone. Mitigation of the flooding hazards using stopbanks and preventing development inside the stopbanks will also help to mitigate lateral spreading close to river banks. However, flood protection works, such as stopbanks, are vulnerable to liquefaction-induced ground damage.

Engineering solutions are possible in most circumstances to mitigate liquefaction effects but these are usually specific to the type of infrastructure being protected. For example, domestic housing might require piled foundations rather than a concrete slab-on-grade in high liquefaction hazard areas. For other types of infrastructure point solutions such as ground densification (e.g. stone piles, ground compaction) or ground replacement are possible. For linear infrastructure such as pipe networks, the choice of pipe material (ductile plastic pipes versus brittle concrete pipes) may provide a mitigation option.

9.0 CONCLUSIONS

Significant liquefaction hazard in the Taranaki Region is limited to only a few areas. The primary reasons for this are the lack of young, non-cohesive fine-grained sediments in areas where the groundwater table is close (within 1-5 metres) of the ground surface.

The highest liquefaction hazard (in the Taranaki Region has been assigned to the reclaimed land at Port Taranaki. This is based on historical precedent because reclaimed harbour land is commonly affected by liquefaction during strong earthquake shaking. Earthquake shaking strong enough to cause liquefaction-induced land damage to the reclaimed land, such as a few sand boils or fissures, can be expected, on average, every 120 years. More extensive damage can be expected during stronger, but less frequent, ground shaking.

The areas where the liquefaction hazard in Taranaki is assessed as high are the lower reaches of the Mohakatino, Rapanui, Tongaporutu, Mimi, Urenui Onaero and Waitara Rivers in north Taranaki and the Waitotara, Whenuakura and Patea Rivers in south Taranaki, and their tributaries. Earthquake ground shaking strong enough to cause a few sand boils and fissures can be expected, on average, every few hundred years (980-1070 years). More extensive damage can be expected during stronger, but less frequent (9500 to 14,300 years), ground shaking.

The areas where the liquefaction hazard in Taranaki is assessed as moderate are the upper reaches of the larger rivers in the region. Earthquake ground shaking strong enough to cause a few sand boils and fissures can be expected, on average, every few thousand years (9500-14,300 years). More extensive damage can be expected during stronger, but less frequent (very rare MM10) ground shaking.

Elsewhere the hazard is sufficiently low that it could be treated as inconsequential (i.e. areas where there are beach sediments or dune sands.

The liquefaction hazard has been mapped principally based on geological map data from 1:250,000 scale geological maps. The liquefaction classifications assigned to the different map units were tested through the analysis of geological information contained in 900 boreholes. The liquefaction hazard derived from the borehole and the geological map are generally in agreement. However, in some cases there are discrepancies between the borehole interpretation and the liquefaction hazard assigned on the basis of map units. The liquefaction hazard interpretation from the geological map has been preferred in these cases because the geotechnical information in the borehole records is insufficient to quantify the liquefaction hazard.

It is recommended that site specific investigations be carried out to confirm or discount the liquefaction hazard at sites of key infrastructure in areas identified as having a high or very high liquefaction hazard.

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APPENDIX

APPENDIX 1: MODIFIED MERCALLI SEISMIC INTENSITY SCALE FOR NZ

Modified Mercalli Intensity scale is a measure of how ground shaking from an earthquake is perceived by people and how it affects buildings and the environment at a particular location. In any given large earthquake, the Mercalli Intensity will depend on the location of the observer and will usually be greatest nearer to the earthquake's hypocentre.

MM1 ***People***

- Not felt except by a very few people under exceptionally favourable circumstances

MM2 ***People***

- Felt by persons at rest, on upper floors or favourable placed.

MM3 ***People***

- Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

MM4 ***People***

- Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic or to the jolt of a heavy object falling or striking the building.

Fittings

- Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures

- Walls and frames of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.

MM5 ***People***

- Generally felt outside, and by almost everyone indoors.
- Most sleepers awakened.
- A few people alarmed

Fittings

- Small unstable objects are displaced or upset. Some glassware and crockery may be broken.
- Hanging pictures knock against the wall.
- Open doors may swing.
- Cupboard doors secured by magnetic catches may open.
- Pendulum clocks start, stop, or change rate (H).

Structures

- Some Windows Type I cracked.
- A few earthenware toilet fixtures cracked (H).

MM6 ***People***

- Felt by all.
- People and animals alarmed.
- Many run outside.
- Difficulty experienced in walking steadily.

Fittings

- Objects fall from shelves.
- Pictures fall from walls (H).
- Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved.
- Glassware and crockery broken.
- Very unstable furniture overturned.
- Small church and school bells ring (H).
- Appliances move on bench or table tops.
- Filing cabinets or “easy glide” drawers may open (or shut).

Structures

- Slight damage to Buildings Type I.
- Some stucco or cement plaster falls.
- Windows Type I broken.
- A few cases of Chimney damage.
- Damage to a few weak domestic chimneys, some may fall.

Environment

- Trees and bushes shake, or are heard to rustle.
- Loose material dislodged on some slopes, e.g. existing slides, talus and scree slopes.
- A few very small (≤103 m3) soil and regolith slides and rock falls from steep banks and cuts.
- A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.

MM7 ***People***

- General alarm.
- Difficulty experienced in standing.
- Noticed by motorcar drivers who may stop.

Fittings

- Large bells ring.
- Furniture moves on smooth floors, may move on carpeted floors.
- Substantial damage to fragile contents of buildings.

Structures

- Unreinforced stone and brick walls cracked.
- Buildings Type I cracked, some with minor masonry falls.
- A few instances of damage to Buildings Type II.
- Unbraced parapets, unbraced brick gables, and architectural ornaments fall.
- Roofing tiles, especially ridge tiles may be dislodged.
- Many unreinforced domestic chimneys damaged, often falling from roof line.
- Water tanks Type I burst.
- A few instances of damage to brick veneers and plaster or cement-based linings.
- Unrestrained water cylinders (Water Tanks Type II) may move and leak.
- Some Windows Type II cracked.
- Suspended ceilings damaged.

Environment

- Very small (≤10^3 m^3) disrupted soil slides and falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings are common.
- Fine cracking on some slopes and ridge crests.
- A few small to moderate landslides (10^3-10^5 m^3), mainly rock falls on steeper slopes (> 30˚) such as gorges, coastal cliffs, road cuts and excavations.
- Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places.
- A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.

MM8 ***People***

- Alarm may approach panic.
- Steering of motorcars greatly affected.

Structures

- Buildings Type I heavily damaged, some collapse.
- Buildings Type II damaged, some with partial collapse.
- Buildings Type III damaged in some cases.
- A few instances of damage to Structures Type IV.
- Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down
- Some pre-1965 infill masonry panels damaged.
- A few post-1980 brick veneers damaged.
- Decayed timber piles of houses damaged.
- Houses not secured to foundations may move.
- Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment

- Cracks appear on steep slopes and in wet ground.
- Significant landsliding likely in susceptible areas.
- Small to moderate slides (10^3-10^5 m^3) widespread; mainly rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc.).
- Significant areas of shallow regolith landsliding, and some reactivation of scree slopes.
- A few large (10^5-10^6 m^3) landslides from coastal cliffs, and possibly large to very large (≥10^6 m^3) rock slides and avalanches from steep mountain slopes.
- Larger landslides in narrow valleys may form small temporary landslide-dammed lakes.
- Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills.
- Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes and canals etc.

MM9 ***Structures***

- Many Buildings Type I destroyed.
- Buildings Type II heavily damaged, some collapse.
- Buildings Type III damaged, some with partial collapse.
- Structures Type IV damaged in some cases, some with flexible frames seriously damaged.
- Damage or permanent damage to some Structures Type V.
- Houses not secured to foundations shifted off.
- Brick veneers fall and expose frames.

Environment

- Cracking on flat and sloping ground conspicuous.
- Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20˚.
- Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate to steep slopes (20˚-35˚ or greater), cliffs, escarpments, gorges and man-made cuts.
- Many small to large (10^3-10^6 m^3) failures of regolith and bedrock, and some very large landslides (10^6 m^3 or greater) on steep susceptible slopes.
- Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys
- Damage to road and rail infrastructure widespread with moderate to large failures of road cuts and slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries
- Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc. Spreading and settlement of river stopbanks likely.

MM10 ***Structures***

- Most Buildings Type I destroyed.
- Many Buildings Type II destroyed.
- Many Buildings Type III heavily damaged, some collapse.
- Structures Type IV damaged, some with partial collapse.
- Structures Type V moderately damaged, but few partial collapses.
- A few instances of damage to Structures Type VI.
- Some well-built timber buildings moderately damaged (excluding damage from falling chimneys)

Environment

- Landsliding very widespread in susceptible terrain.
- Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines.
- Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharves, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.

MM11 ***Structures***

- Most Buildings Type II destroyed.
- Many Buildings Type III destroyed.
- Structures Type IV heavily damaged, some collapse.
- Structures Type V damaged, some with partial collapse.
- Structures Type VI suffer minor damage, a few moderately damaged.

MM12 ***Structures***

- Most Buildings Type III destroyed.
- Many Structures Type IV destroyed.
- Many Buildings Type V heavily damaged, some with partial collapse.
- Structures Type VI moderately damaged.

Categories of Construction

Buildings Type I:

Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Types I-III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II:

Buildings of ordinary workmanship, with mortar of average quality. No extreme weaknesses, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III:

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Structures Type IV:

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930's to c. 1970 for concrete and to c.1980 other materials).

Structures Type V:

Buildings and bridges designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c.1980 other materials.

Structures Type VI:

Structures, dating from c. 1980, with well-defined foundation behaviour, which have been specially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low-damage structures.

Windows Type I:

Large display windows, especially shop windows.

Windows Type II:

Ordinary sash or casement windows.

Water Tanks Type I:

External, stand mounted, corrugated iron water tanks

Water Tanks Type II:

Domestic hot-water cylinders unrestrained except by supply and delivery pipes.

H (Historical):

Important for historical events. Current application only to older houses, etc.

General Comments

- "Some" or "a few" indicates that the threshold of a particular effect has just been reached at that intensity.
- "Many run outside" (MM6) variable depending on mass behaviour, or conditioning by occurrence or absence of previous quakes, i.e. may occur at MM5 or not until MM7.
- "Fragile contents of buildings". Fragile contents include weak, brittle, unstable, unrestrained objects in any kind of building.
- "Well-built timber buildings" have: wall openings not too large; robust piles or reinforced concrete strip foundations; superstructure tied to foundations.
- Buildings Type III-V at MM10 and greater intensities are more likely to exhibit the damage levels indicated for low-rise buildings on firm or stiff ground and for high-rise buildings on soft ground. By inference lesser damage to low-rise buildings on soft ground and high-rise buildings on firm or stiff ground may indicate the same intensity. These effects are due to attenuation of short period vibrations and amplification of longer period vibrations in soft soils.

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www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657