REPORT

Tonkin+Taylor

TC52/19 Liquefaction Analysis and Hazard Mapping for Eastern Zone

Liquefaction Vulnerability Study Report

Prepared for
Tauranga City Council

Prepared by
Tonkin & Taylor Ltd

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LIQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Assessment of Liquefaction-induced Ground Damage to Inform Planning Processes' published by the Ministry for the Environment and the Ministry of Business, Innovation and Employment in 2017. https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land/	
Client	Tauranga City Council (TCC)
Assessment undertaken by	Tonkin & Taylor Ltd, PO Box 317, Tauranga 3140
Extent of the study area	The area of the TCC territorial boundary defined as the Eastern Zone in Figure 1.1 in Section 1.
Intended RMA planning and consenting purposes	To provide TCC with a district-wide liquefaction vulnerability assessment to help inform spatial planning and assessment of land use, subdivision and building consents.
Other intended purposes	To provide TCC with an understanding of expected land performance for a range of potential future earthquake and groundwater scenarios.
Level of detail	Predominantly undertaken to a Level A (desktop assessment) and Level B (calibrated desktop assessment) with some smaller areas at Level C (detailed area-wide assessment). The level of detail is dependent on the available information and the degree of residual uncertainty in the assessment.
Notes regarding base information	The assessment leverages previous high-level work conducted over the study area which includes: • Area-wide groundwater models developed by T+T. • Models of likely shaking intensities in future earthquakes developed by Bradley Seismic Ltd. • Geotechnical investigation data available on the NZ Geotechnical Database and available in T+T and Aurecon's private database's as at November 2019.
Other notes	This assessment has been made at a broad scale across the Eastern Zone of Tauranga City, and is intended to approximately describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g. for design of building foundations). A key consideration of the liquefaction vulnerability categorisation undertaken in accordance with the MBIE/MfE Guidelines (2017) is the degree of uncertainty in the assessment. Discussion about the key uncertainties in this study is provided in Sections 4.1 and 5.1 of this report.

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1 Introduction

Tonkin & Taylor Ltd (T+T) and Aurecon New Zealand Ltd (Aurecon) were engaged by Tauranga City Council (TCC) in June 2019 to undertake risk identification and analysis of liquefaction hazard in accordance with the Ministry of Building, Innovation and Employment (MBIE) and the Ministry for the Environment (MfE) *Planning and engineering guidance for potentially liquefaction-prone land* (MBIE/MfE, 2017) to help inform various future activities.

T+T and Aurecon were engaged to undertake risk identification and analysis of liquefaction hazard in the Eastern and Western Zones respectively. As part of those engagements consultants undertook a preliminary risk identification and analysis of the Calibration Zone[1] assessment to enable "calibration" to be undertaken such that the different methodologies adopted, and outcomes produced by T+T and Aurecon can be compared and moderated by TCC and the Peer Reviewer (Wentz Pacific Ltd). The extent of the study area covered by the wider liquefaction risk identification and analysis, including relevant zones described above, is shown in Figure 1.1.

Figure 1.1: Map showing the location and extent of the TCC Liquefaction hazard study area and the relevant zones

The Eastern Zone is located to the East of the Tauranga City Central Business District (CBD) and covers approximately 5,800 ha of land. It is bounded by the open coast to the north, inner Tauranga Harbour to the south west, Western Bay of Plenty District along its southern boundary and the Kaituna River to the south east. The land in the Eastern Zone is currently used for a range of different purposes including: residential, commercial, industrial, recreational and rural uses.

[1] The Calibration Zone is wholly located within the Eastern Zone. The preliminary liquefaction risk identification and analysis of the Calibration Zone that was undertaken by T+T and Aurecon is superseded by the results of the liquefaction risk identification and analysis that are presented in this report.

Note that land development is ongoing in the Eastern Zone. For example TCC and the main landowners of the land within and to the east of the Calibration Zone are currently progressing the development of a structure plan and rezoning to convert the land from predominantly agricultural use to predominantly residential use. If that development proceeds it is likely that significant landform changes will occur and the results of this liquefaction risk identification and analysis may no longer be applicable. This would also apply to other areas where land development is ongoing or occurs in the future.

The purpose of this report is to summarise the general approach adopted for the assessment of liquefaction vulnerability in the Eastern Zone by T+T and the subsequent results. The model developed for this study provides a risk-based estimate of how the liquefaction vulnerability varies across the Eastern Zone. This report includes:

- The context in which this study has been undertaken and the intended purposes for its use and a summary of previously-collated information about the liquefaction hazard across the study area (Section 2)
- A summary of previously-collated information about the geological, groundwater, and seismic conditions for the study area (Section 3)
- Analysis of the uncertainty associated with the collated information (Section 4)
- The delineation of the study area into zones of similar expected ground performance and the groundwater levels and earthquake scenarios assessed in order to develop the model (Section 4)
- The determination of the expected degree of liquefaction-induced ground damage for the chosen groundwater levels and earthquake scenarios (Section 4)
- Liquefaction vulnerability measured against the performance criteria in MBIE/MfE Guidance (2017) (Section 4)
- Discussion about the results of this study and a summary of the key conclusions (Section 5).

The liquefaction vulnerability assessment and the layout of this report follows the risk management process recommended in ISO 31000:2009, as shown in Figure 1.2.

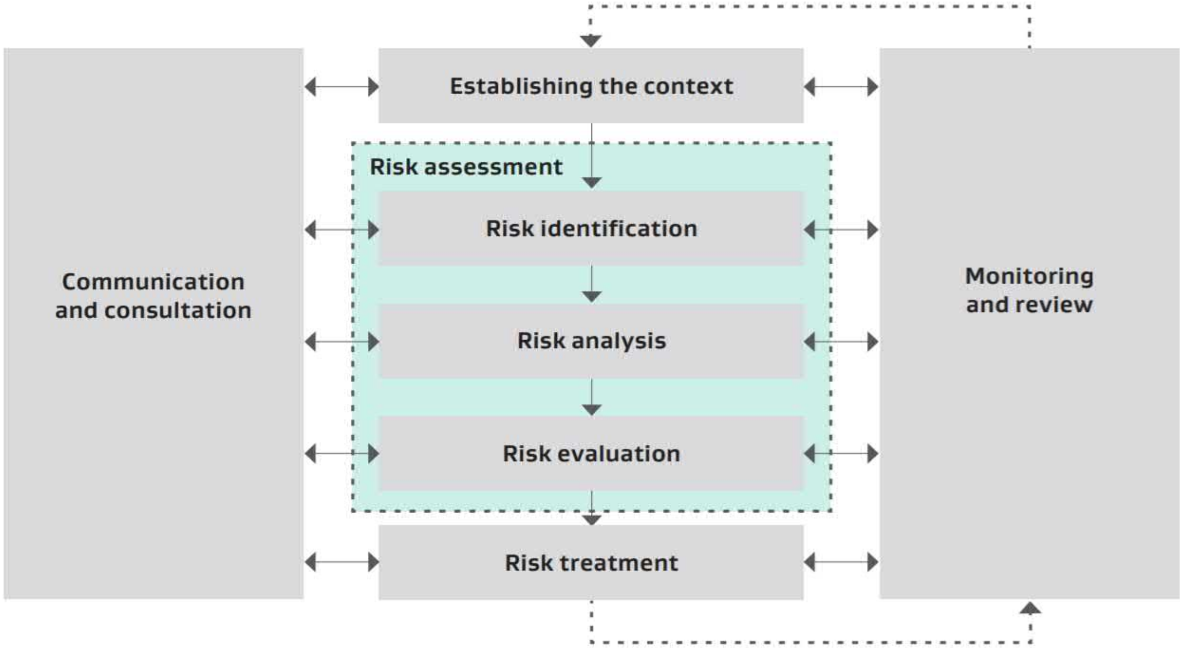


Figure 1.2: Risk management process defined in ISO 31000:2009, which has been used to guide the liquefaction vulnerability assessment and the layout of this report - from MBIE/MfE Guidance (2017)

The MBIE/MfE Guidance (2017) presents a risk-based approach to the management of liquefaction-related risk in land use planning and development decision-making. The guidance was developed in response to the Canterbury Earthquake Sequence 2010-2011 as a result of recommendations made by the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes.[2]

The focus of the MBIE/MfE Guidance (2017) is to assess the potential for liquefaction-induced ground damage to inform Resource Management Act (RMA) and Building Act planning and consenting processes. However, there are a number of ways in which liquefaction information may be used which are outside of the planning and consenting process and the following is a non-exhaustive list that is provided in Section 1.2 of the guidance:

- Long term strategic land use and planning
- Developing planning processes to manage risks and the effects of natural hazard events
- Design of land development, building and infrastructure works
- Informing earthquake-prone building assessments
- Improving infrastructure and lifelines resilience
- Civil defence and emergency management planning
- Catastrophe loss modelling for insurance, disaster risk reduction and recovery planning.

While there may be specific additional information required to inform the uses above that are outside of the planning and consenting process, many of the concepts presented in the MBIE/MfE Guidance (2017) are likely to be relevant and provide useful information to support these uses.

[2] The MBIE/MfE Guidance (2017) does not provide technical guidance on liquefaction analysis or earthquake engineering. Detailed information about this topic can be found in the NZGS/MBIE Earthquake Geotechnical Engineering Practice series (NZGS/MBIE, 2016; NZGS/MBIE, 2017a – 2017f).

The MBIE/MfE Guidance (2017) includes the overview of the recommended process for categorising the potential for liquefaction-induced ground damage shown in Figure 1.3. That figure shows the key steps in this categorisation process, namely establish the *Context, Risk Identification* and *Risk Analysis*, broken down into high level tasks. Comparison of Figure 1.3 with Figure 1.2 also demonstrates how the process maps to the risk management process defined in ISO 31000:2009.

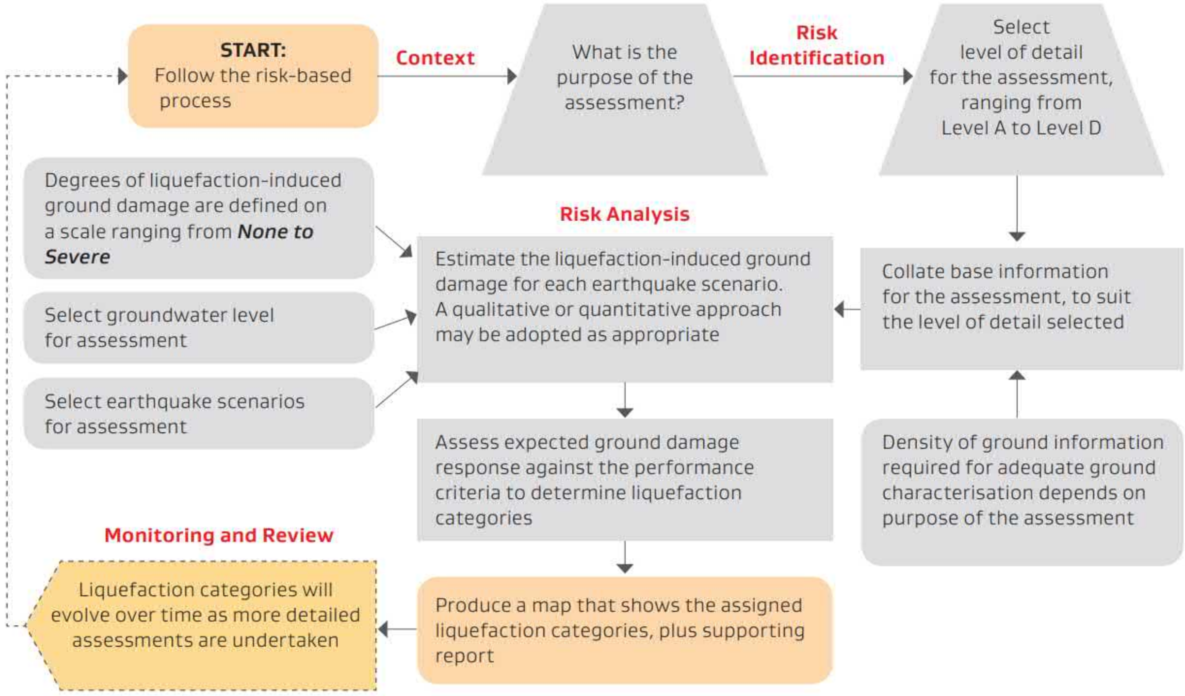


Figure 1.3: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage - from MBIE/MfE Guidance (2017)

The MBIE Guidance (2017) provides a performance-based framework for categorising the liquefaction vulnerability of land to inform planning and consenting processes. That framework is based on the severity of liquefaction-induced ground damage that is expected to occur at various intensities of earthquake shaking. Figure 1.4 shows the recommended liquefaction vulnerability categories for use in that performance-based framework. The categorisation of the liquefaction vulnerability of the land within the Eastern Zone into one of these seven categories is one of the key deliverables of this study. However, regional scale studies such as this one typically result in categorisation of the land into one of the top three vulnerability categories of “Liquefaction Category is Undetermined” or “Liquefaction Damage is Unlikely” or “Liquefaction Damage is Possible”.

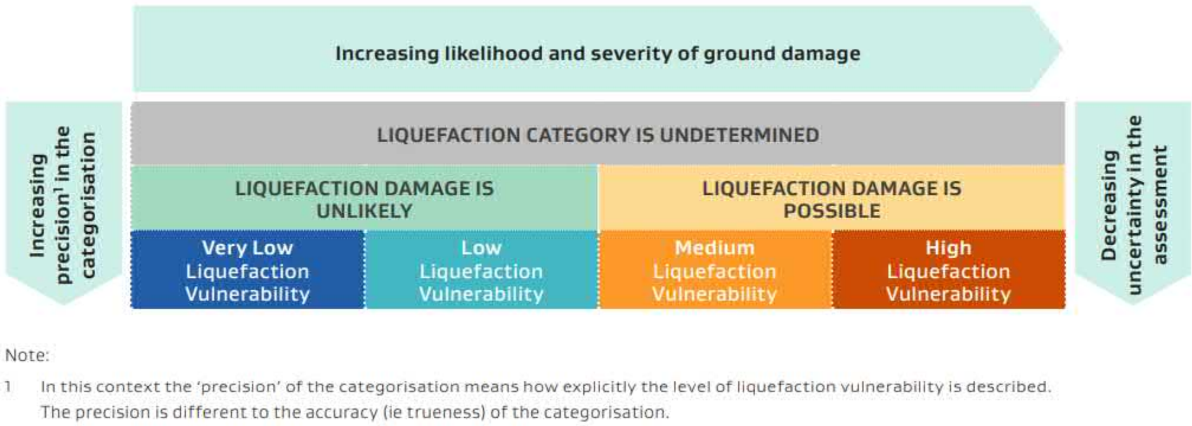


Figure 1.4: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes - from MBIE/MfE Guidance (2017)

As shown in Figure 1.4 the liquefaction vulnerability categories established in the MBIE Guidelines (2017) are a function of both the precision in the categorisation and the degree of uncertainty in the assessment. To provide guidance on how to manage these aspects, recommendations are provided in the MBIE Guidelines (2017) for the minimum level of detail required in the liquefaction assessment for specific applications. Figure 1.5 shows the categories used to define the levels of detail for liquefaction vulnerability studies.

LEVEL OF DETAIL
Level A – Basic Desktop Assessment
Level B – Calibrated Desktop Assessment
Level C – Detailed Area-Wide Assessment
Level D – Site-Specific Assessment

Figure 1.5: Categories of level of detail used to define the levels of detail for liquefaction vulnerability studies - from MBIE/MfE Guidance (2017)

Regional scale studies such as this one are typically undertaken to a Level A or Level B level of detail. Level C and Level D studies are typically associated with site specific development to support subdivision and building consent applications.

The key feature defining each level of detail is the degree of "residual uncertainty" in the assessment, such that the residual uncertainty is reduced as the level of detail in the liquefaction assessment increases. It is likely that substantial residual uncertainty will remain in some locations, so this should be acknowledged, recorded and clearly conveyed. Further information about the level of detail hierarchy and residual uncertainty is provided in Section 3.1.1. Section 4.1 and 5.1 provide discussion about the key sources of uncertainty associated with this assessment.

2 Context

2.1 Background to this project

In 2018 Tauranga City Council (TCC) embarked on a significant project to better understand risk and resilience issues across the city. Of specific consideration was the application of these issues to infrastructure and urban planning. As part of the risk and resilience project TCC engaged T+T to undertake a review of the current information available to assess risk and resilience issues across the city (T+T, 2018). One of the highest priority recommendations of that review was for TCC to commission an update to the available liquefaction hazard information such that mapping is undertaken in accordance with the MBIE/MfE Guidance (2017).

In response to this recommendation, TCC issued a Request for Proposal (RFP) for a liquefaction hazard assessment to be undertaken to which a number of different consultants responded. Aurecon was commissioned to undertake the assessment for the Western Zone and T+T was commissioned to undertake the assessment for the Eastern Zone (refer Figure 1.1).

TCC's primary objective in commissioning this study was to ensure that buildings and infrastructure are located and built with appropriate consideration of the land conditions. The primary deliverable from this study is to provide an updated liquefaction hazard layer for the city's GIS system. Their expectation is that this study will provide a significant refinement to the current liquefaction hazard understanding and mapping. To support this refinement TCC commissioned Bradley Seismic Ltd. (BSL) to undertake a regional ground motion seismic hazard assessment (BSL, 2019). Additional geotechnical investigations have also been funded by both TCC and the Earthquake Commission (EQC) as part of this study.

2.2 Liquefaction hazard

Liquefaction is a natural process where earthquake shaking increases the water pressure in the ground in some types of soil, resulting in temporary loss of soil strength.

The following three key elements are all required for liquefaction to occur:

1. Loose non-plastic soil (typically sands and silts, or in some cases gravel)
2. Saturated soil (i.e. below the groundwater table)
3. Sufficient ground shaking (a combination of the duration and intensity of shaking.

These elements are shown in Figure 2.1.

Figure 2.1: Three key elements required for liquefaction to occur - reproduced from MBIE/MfE Guidance (2017)

Figure 2.2 summarises the process of liquefaction with a schematic representation. For a more detailed explanation of the liquefaction process, refer to the MBIE/MfE Guidelines (2017).

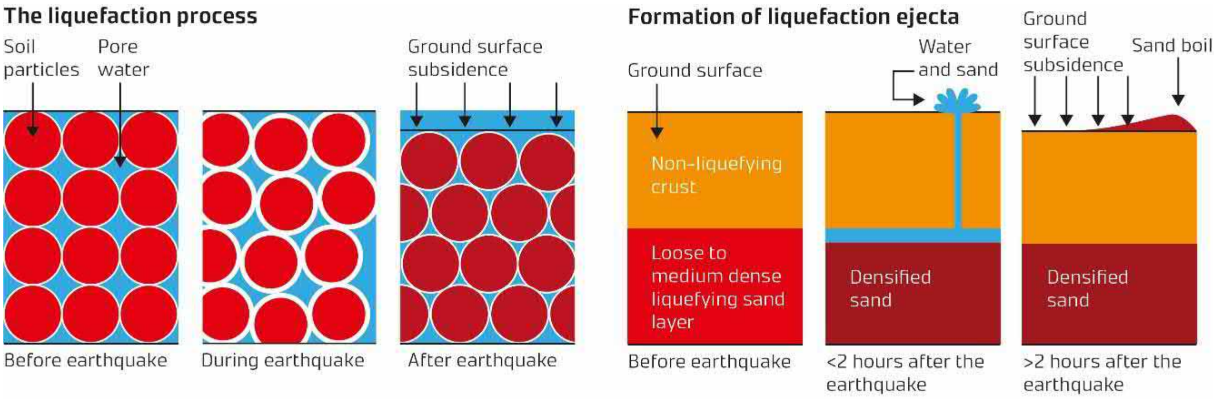


Figure 2.2: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta - reproduced from MBIE/MfE Guidance (2017)

Liquefaction can give rise to significant land and building damage through, for example, the ejection of sediment to the ground surface, differential settlement of the ground due to volume loss in liquefied soil and lateral movement of the ground (known as lateral spreading). These effects are schematically presented in Figure 2.3 and summarised in Table 2.1.

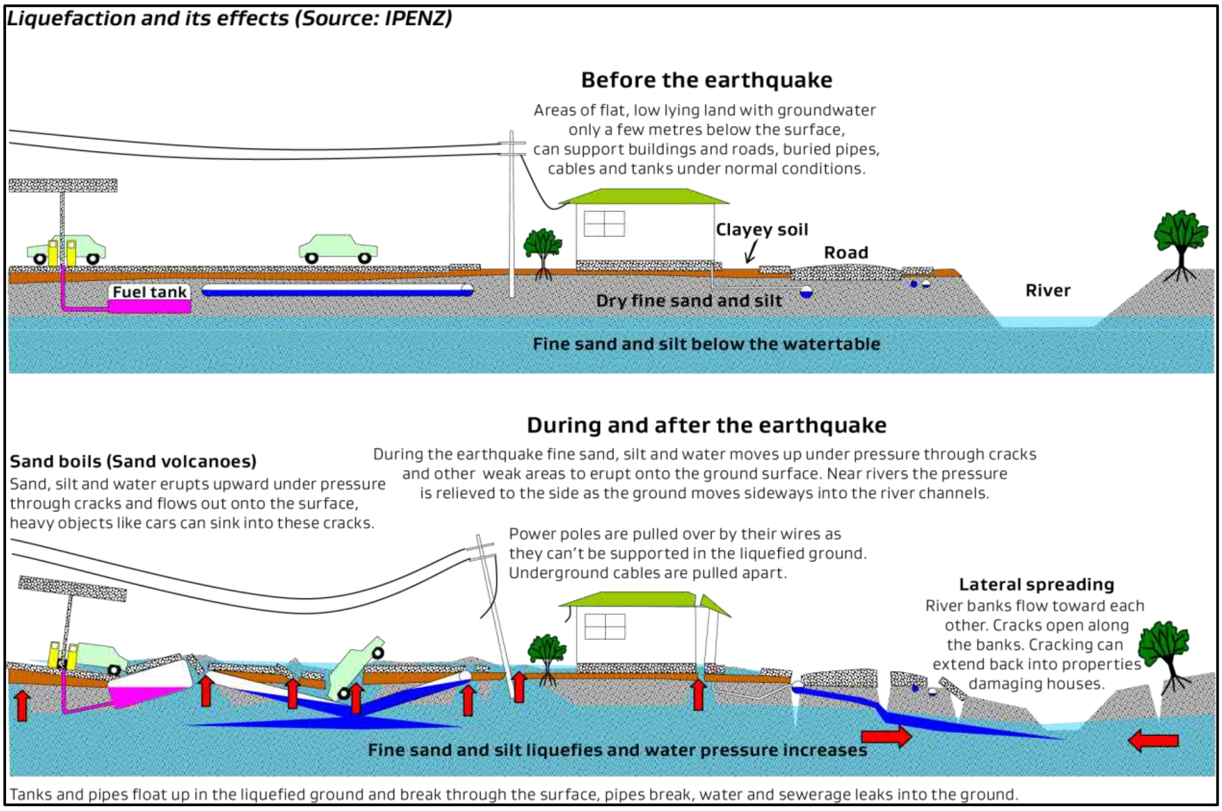


Figure 2.3: Visual schematic of the consequences of liquefaction - reproduced from the MBIE/MfE Guidance (2017)

Table 2.1: Overview of potential consequences of liquefaction (reproduced from MBIE/MfE (2017))

Land	• Sand boils, where pressurised liquefied material is ejected to the surface (ejecta). • Ground settlement and undulation, due to consolidation and ejection of liquefied soil. • Ground cracking from lateral spreading, where the ground moves downslope towards an unsupported face (e.g. a river channel or terrace edge).
Environment	• Discharge of sediment into waterways, impacting water quality and habitat. • Fine airborne dust from dried ejecta, impacting air quality. • Potential contamination issues from ejected soil. • Potential alteration of groundwater flow paths and formation of new springs.
Buildings	• Distortion of the structure due to differential settlement of the underlying ground, impacting the amenity and weather tightness of the building. • Loss of foundation-bearing capacity, resulting in settlement of the structure. • Stretch of the foundation due to lateral spreading, pulling the structure apart. • Damage to piles due to lateral ground movements, and settlement of piles due to downdrag from ground settlement. • Damage to service connections due to ground and building deformations.
Infrastructure	• Damage to road, rail and port infrastructure (settlement, cracking, sinkholes, ejecta). • Damage to underground services due to ground deformations (e.g. 'three waters', power, and gas networks). • Ongoing issues with sediment blocking pipes and chambers. • Uplift of buoyant buried structures (e.g. pipes, pump stations, manholes and tanks). • Damage to port facilities. • Sedimentation and 'squeezing' of waterway channels, reducing drainage capacity. • Deformation of embankments and bridge abutments (causing damage to bridge foundations and superstructure). • Settlement and cracking of flood stopbanks, resulting in leakage and loss of freeboard. • Disruption of stormwater drainage and increased flooding due to ground settlement.
Economic	• Lost productivity due to damage to commercial facilities, and disruption to the utilities, transport networks, and other businesses that are relied upon. • Absence of staff who are displaced due to damage to their homes or are unable to travel due to transport disruption. • Cost of repairing damage.
Social	• Community disruption and displacement – initially due to damage to buildings and infrastructure, then the complex and lengthy process of repairing and rebuilding. • Potential ongoing health issues (e.g. respiratory and psychological health issues).

These consequences can have severe impacts that range from land damage through to social disruption as seen in the 2010-2011 Canterbury Earthquake Sequence.

The risk identification and analysis undertaken for this study considered how the severity of these consequences at any particular location can vary depending on a range of factors, such as:

- **Soil condition –** Liquefaction typically occurs in loose non-plastic soils i.e. silts and sands and in some cases loose gravels. Liquefaction does not typically occur soils with higher plasticity such as clay and does not occur in rock or dense gravel.
- **Depth to groundwater –** Soil can only liquefy if it is below the groundwater table, so deeper groundwater can mean there is a thicker surface "crust" of non-liquefied soil at the ground surface that helps to reduce the consequences from liquefaction below.
- **Strength of earthquake shaking –** Stronger shaking can mean that greater thickness of the soil profile liquefies, resulting in more severe consequences.
- **Layering of the soil profile –** The way in which a soil was deposited (e.g. by a river, an estuary, or the sea) can influence how the soil profile is layered. If there are thick continuous layers of liquefied soil then this can have more severe consequences than if there are thinner isolated layers of liquefied soil interbedded between layers of non-liquefied soil.
- **Proximity to free faces or sloping ground –** For lateral spreading to occur liquefiable soils must be within close proximity to a free face (such as a river channel or a road cut) or sloping ground. Typically a location that is closer to these topographic features will sustain more severe consequences than a location that is further away.

2.3 Intended purpose and scope of works

TCC's primary objective in commissioning this study was to ensure that buildings and infrastructure are located and built with appropriate consideration of the land conditions. TCC intends to use this information for two main purposes:

1. To inform policy, planning and consenting processes.
2. To enable assessment of the risk of liquefaction related land damage to roads, bridges, pipelines and other city owned infrastructure.

The specific scope of T+T's risk identification and analysis of the Eastern Zone is described in detail in the TCC contract *TC52/19 Liquefaction Hazard Study Eastern Region* dated June 2019. The key outputs are as follows:

- A geomorphological map of the Eastern Zone study area with a target scale of 1:25,000;
- Assessment of the likely liquefaction related land damage and the production of associated maps for Scenarios 1-2, 4-7 and 9-10 listed in Table 2.2;
- Categorisation of the land in accordance with the MBIE/MfE Guidance (2017) into the liquefaction vulnerability categories shown in Figure 1.4;
- Assessment and production of an associated map of the level of detail supported by the currently available base information; and
- Preparation of a report to accompany the liquefaction hazard risk identification and analysis.

The following variations also apply to *TC52/19 Liquefaction Hazard Study Eastern Region* dated June 2019:

- *TC52/19 Variation 01* dated 2 December 2019 – This variation covers assessment of the likely liquefaction related land damage and the production of associated maps for Scenarios 3 and 8 listed in Table 2.2
- *TC52/19 Variation 02* dated 6 December 2019 – This variation covers peer review of the geomorphic map and includes the following main tasks:
  - Preparation of a standalone report for the geomorphic assessment of the Eastern Zone
  - Peer review of Aurecon's geomorphic assessment of the Western Zone
  - Response to Aurecon's peer review of the geomorphic assessment of the Eastern Zone
  - Finalisation of the Eastern Zone geomorphic map.

Table 2.2: Seismic hazard and groundwater model scenarios

Scenario number	Seismic hazard ARI (yrs)	Groundwater model
1	25	Current day groundwater median
2	100	
3	250	
4	500	
5	1,000	
6	25	Groundwater 1.25m shallower than current day median
7	100	
8	250	
9	500	
10	1,000	

2.4 Previous information about liquefaction in the Eastern Zone

Table 2.3 shows previous liquefaction hazard studies that have been undertaken in the Eastern Zone. Figure A1 in Appendix A shows the mapped results of the Opus 2002 study and the approximate extents of the land area covered by each of the T+T reports shown in Table 2.3.

Table 2.3: Previous liquefaction hazard studies

Title	Author(s)	Published date	Coverage of study area
Microzoning for Earthquake Hazards for the Western Bay of Plenty	Opus International Consultants	December 2002	Entire
Te Tumu Natural Hazard Risk Assessment – Liquefaction	T+T	June 2018	Partial
Eastern Corridor Wastewater – Liquefaction Desktop Study	T+T	April 2018	Partial

Considerable advances in liquefaction science since publication of the Opus 2002 study mean that an update to this information is warranted. Furthermore, both the quantity and quality of geotechnical investigations within the area has improved.

The two studies T+T undertook in 2018 represent current industry standard approaches for liquefaction assessment. However, they do not include mapping in accordance with the liquefaction vulnerability categories provided in the MBIE/MfE Guidance (2017). All three sources of information provide useful reference information however, they do not satisfy the key requirements as described in the scope.

3 Risk identification

The following sections outline the risk identification that has been carried out for the liquefaction hazard assessment for the Eastern Zone.

The first task is the determination of the level of detail required for the intended purposes (refer to Section 3.1). This requires consideration of the key features associated with each level of detail as established by the MBIE/MfE Guidance (2017) and consideration of TCC's intended purposes for undertaking the liquefaction hazard assessment.

The second task is review of the base information currently available for this liquefaction hazard assessment (refer to Section 3.2). The base information that has been reviewed for this Eastern Zone includes the following:

- Ground surface levels (refer to Section 3.2.1)
- Geology and geomorphology (refer to Section 3.2.2)
- Geotechnical investigations (refer to Section 3.2.3)
- Groundwater (refer to Section 3.2.4)
- Seismic hazard (refer to Section 3.2.5)
- Historical observations of liquefaction (refer to Section 3.2.6).

3.1 Level of detail

3.1.1 Level of detail hierarchy

The MBIE/MfE Guidance (2017) provides recommendations for four different levels of detail ranging from the least detailed (Level A) to the most detailed (Level D). Figure 3.1 shows the key features associated with each level of detail.

LEVEL OF DETAIL	KEY FEATURES
Level A **Basic desktop assessment**	Considers only the most basic information about geology, groundwater and seismic hazard to assess the potential for liquefaction to occur. This can typically be completed as a simple 'desktop study', based on existing information (eg geological and topographic maps) and local knowledge. **Residual uncertainty:** The primary focus is identifying land where there is a ***High*** degree of certainty that ***Liquefaction Damage is Unlikely*** (so it can be 'taken off the table' without further assessment). For other areas, substantial uncertainty will likely remain regarding the level of risk.
Level B **Calibrated desktop assessment**	Includes high-level 'calibration' of geological/geomorphic maps. Qualitative (or possibly quantitative) assessment of a small number of subsurface investigations provides a better understanding of liquefaction susceptibility and triggering for the mapped deposits and underlying ground profile. For example, the calibration might indicate the ground performance within a broad area is likely to fall within a particular range. It may be possible to extrapolate the calibration results to other nearby areas of similar geology and geomorphology, however care should be taken not to over-extrapolate (particularly in highly variable ground such as alluvial deposits), and the associated uncertainties (and potential consequences) should be clearly communicated. Targeted collection of new information may be very useful in areas where existing information is sparse and reducing the uncertainty could have a significant impact on objectives and decision-making. **Residual uncertainty:** Because of the limited amount of subsurface ground information, significant uncertainty is likely to remain regarding the level of liquefaction-related risk, how it varies across each mapped area, and the delineation of boundaries between different areas.
Level C **Detailed area-wide assessment**	Includes quantitative assessment based on a moderate density of subsurface investigations, with other information (eg geomorphology and groundwater) also assessed in finer detail. May require significant investment in additional ground investigations and more complex engineering analysis. **Residual uncertainty:** The information analysed is sufficient to determine with a moderate degree of confidence the typical range of liquefaction-related risk within an area and delineation of boundaries between areas, but is insufficient to confidently determine the risk more precisely at a specific location.
Level D **Site-specific assessment**	Draws on a high density of subsurface investigations (eg on or very close to the site being assessed), and takes into account the specific details of the proposed site development (eg location, size and foundation type of building). **Residual uncertainty:** The information and analysis is sufficient to determine with a ***High*** degree of confidence the level of liquefaction-related risk at a specific location. However, the scientific understanding of liquefaction and seismic hazard is imperfect, so there remains a risk that actual land performance could differ from expectations even with a high level of site-specific detail in the assessment.

Increasing level of detail and decreasing degree of uncertainty

Figure 3.1: Levels of detail for liquefaction assessment studies and the defining key features - from MBIE/MfE Guidance (2017)

As highlighted in Figure 3.1 the key feature of the level of detail assessment is the degree of residual uncertainty in the assessment. This refers to the uncertainty which remains after the available information has been analysed. The concept of residual uncertainty is important because it informs the suitability of the information for the intended purpose.

There are two key parts to the determination of the level of detail as follows:

1 **Determination of the level of detail required for the intended purpose.** This step involves consultation with the key stakeholders and a review of the different applications to which this information will be applied (refer to this Section 3.1.2 of this report); and

2 **Determination of the level of detail supported by the currently available base information.** This step involves collation and review of the base information available for the assessment (refer to Section 3.2 of this report) including consideration of the uncertainty associated with that information (refer to Section 4.1 of this report).

3.1.2 Level of detail required for intended purposes

The MBIE/MfE Guidance (2017) provides recommendations about the minimum level of detail likely to be appropriate for a liquefaction assessment, depending on the intended purpose, likelihood/severity of ground damage and the development intensity. Refer to Section 3.5 of the MBIE/MfE Guidance (2017) for further detail.

The target level of detail in the assessment (in accordance with MBIE Guidelines (2017)) that is required for TCC’s intended purposes was developed in a workshop held on 26 February 2019 (T+T, 2019). This establishment of the target level of detail included consideration of the following:

- The range of intended purposes for the liquefaction assessment
- The target level of detail required for those intended purposes
- The availability and spatial density/extent of data required for assessment at the selected level of detail
- Whether a better overall outcome could be achieved by adopting a higher target level of detail than the minimum requirements.

Figure 3.2 shows the target level of detail in the liquefaction assessment for the Eastern Zone with a larger version of the map provided in Figure A2 in Appendix A.

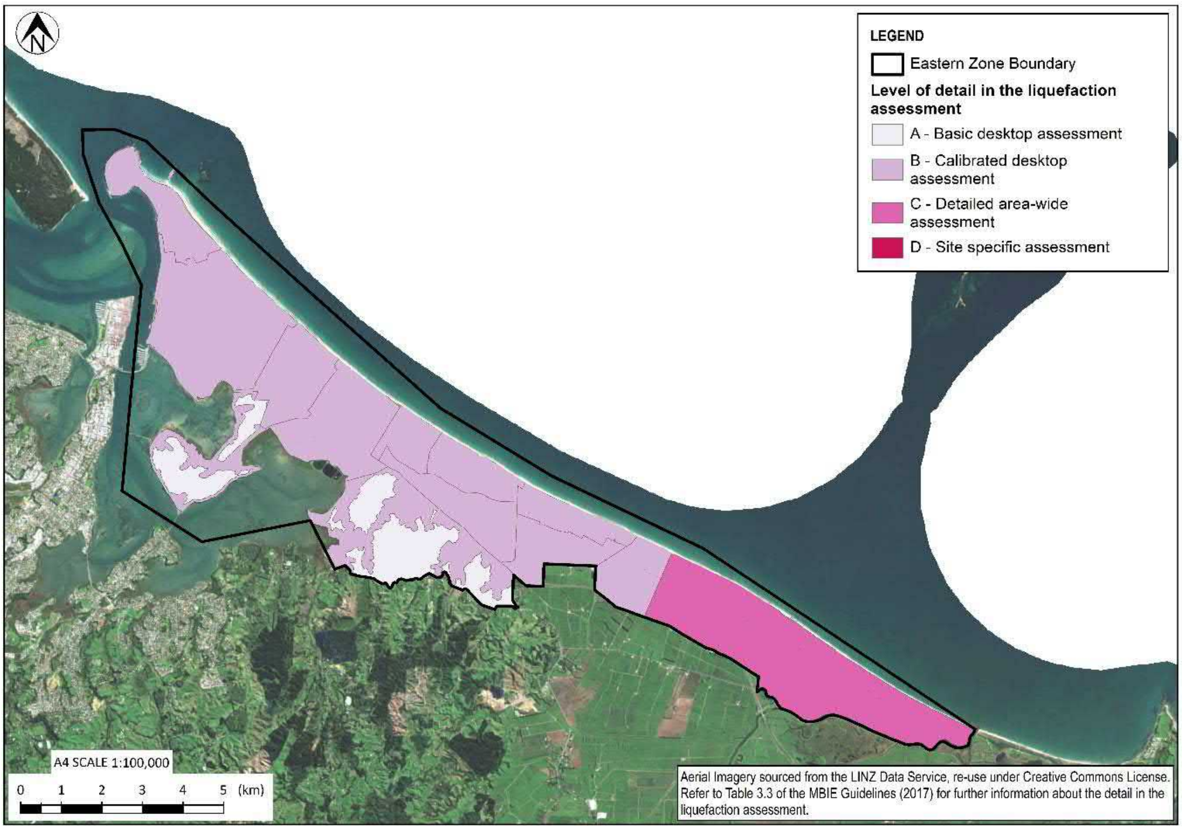


Figure 3.2: Target level of detail in the liquefaction assessment for the Eastern Zone

3.2 Base information currently available

3.2.1 Ground surface levels

The ground surface level of the Eastern Zone is characterised by a high resolution LIDAR derived Digital Elevation Model (DEM). Table 3.1 provides information about the LiDAR data acquisition that was used for this liquefaction assessment.

Table 3.1: Recent LiDAR data acquisitions for the Eastern Zone

Commissioning agency	Year of acquisition	Acquisition by	DEM resolution (m)	Coverage of study area
Bay of Plenty Local Area Shared Services	2019	Aerial surveys	1.0	Entire

The ground surface elevation within the Eastern Zone varies from approximately 0 to 230 m RL (NZVD 2016)[3] across the area although the majority of the study area is between 2 and 10 m RL. There are three areas where the majority of the land lies above 10 m RL: Mauao[4] to the North West; Matapihi Peninsula to the South West; and Kairua along the southern boundary with the Western Zone. The low-lying portions of the study area include: the open coast along the North Eastern boundary; the inner harbour to the South West and the land adjacent to the Kaituna River to the South East. Figure 3.3 shows the ground surface elevation over the Eastern Zone as represented by the 2019 LiDAR Survey. A larger version of this map is included as Figure A3 in Appendix A.

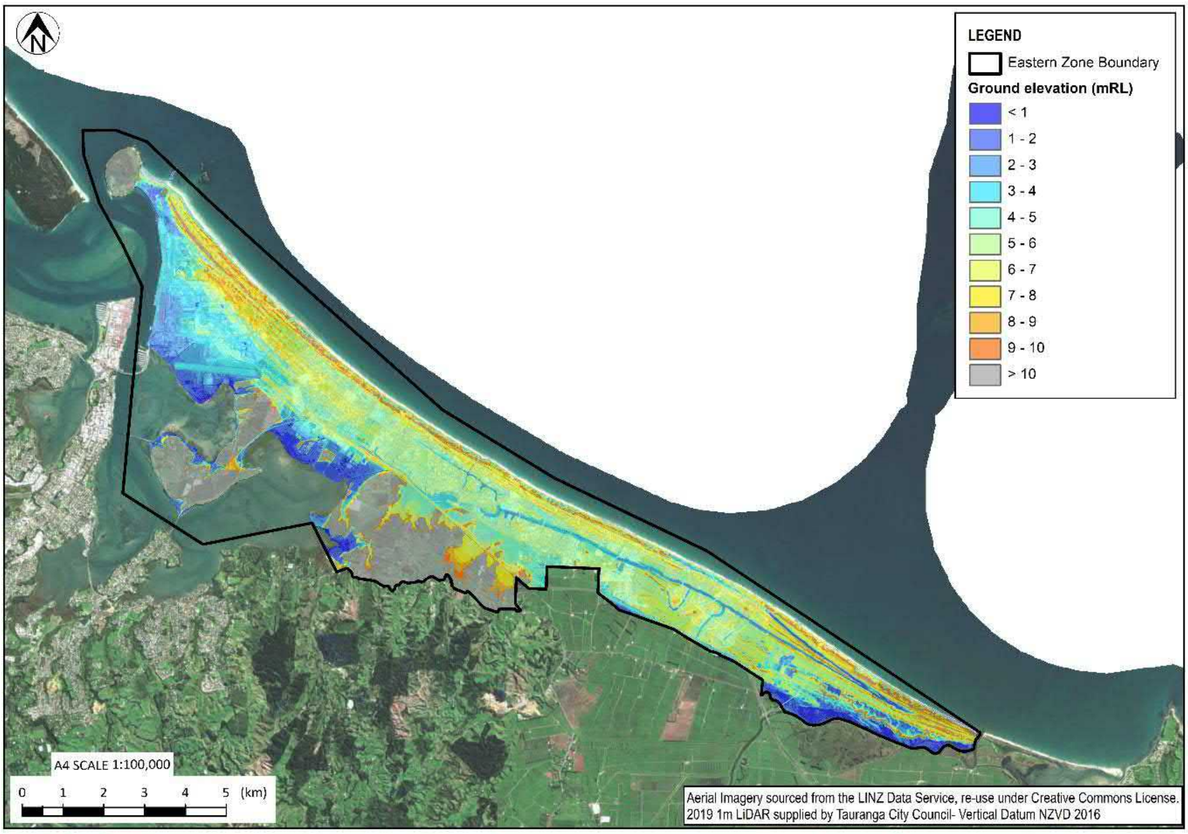


Figure 3.3: Ground surface elevation over the Eastern Zone as represented by the 2019 LiDAR Survey

[3] All elevations are provided to New Zealand Vertical Datum 2016 unless otherwise stated.

[4] Mauao is commonly referred to as Mount Maunganui which is also the name of a suburb in the Eastern Zone. In this report we will refer to the mountain as Mauao and the suburb as Mount Maunganui.

3.2.2 Geology and geomorphology

Geology

The geology of the Eastern Zone is represented by two published geological maps. As summarised in Table 3.1 below, the first map was published by Briggs *et al* in 1996 (Geology of the Tauranga Area) and the second map was published by GNS Science in 2010 (Geology of the Rotorua Area).

Table 3.2: Published geological maps that cover the Eastern Zone

Title	Authors	Published date	Scale
Geology of the Rotorua Area (QMAP)	Leonard, Begg & Wilson (compilers)	2010	1:250,000
Geology of the Tauranga Area	Briggs et al	1996	1:50,000

The geological map produced by Briggs *et al* (1996) was the original geological map produced for the Tauranga Area. This map was amalgamated with several other maps to produce the GNS Science Map produced by Leonard, Begg and Wilson (2010). For the purposes of this project, the 1:50,000 geological map published by Briggs *et al* (1996) will be referenced in this report. Figure 3.4 shows the Eastern Zone overlain on the Briggs et al (1996) geological map.

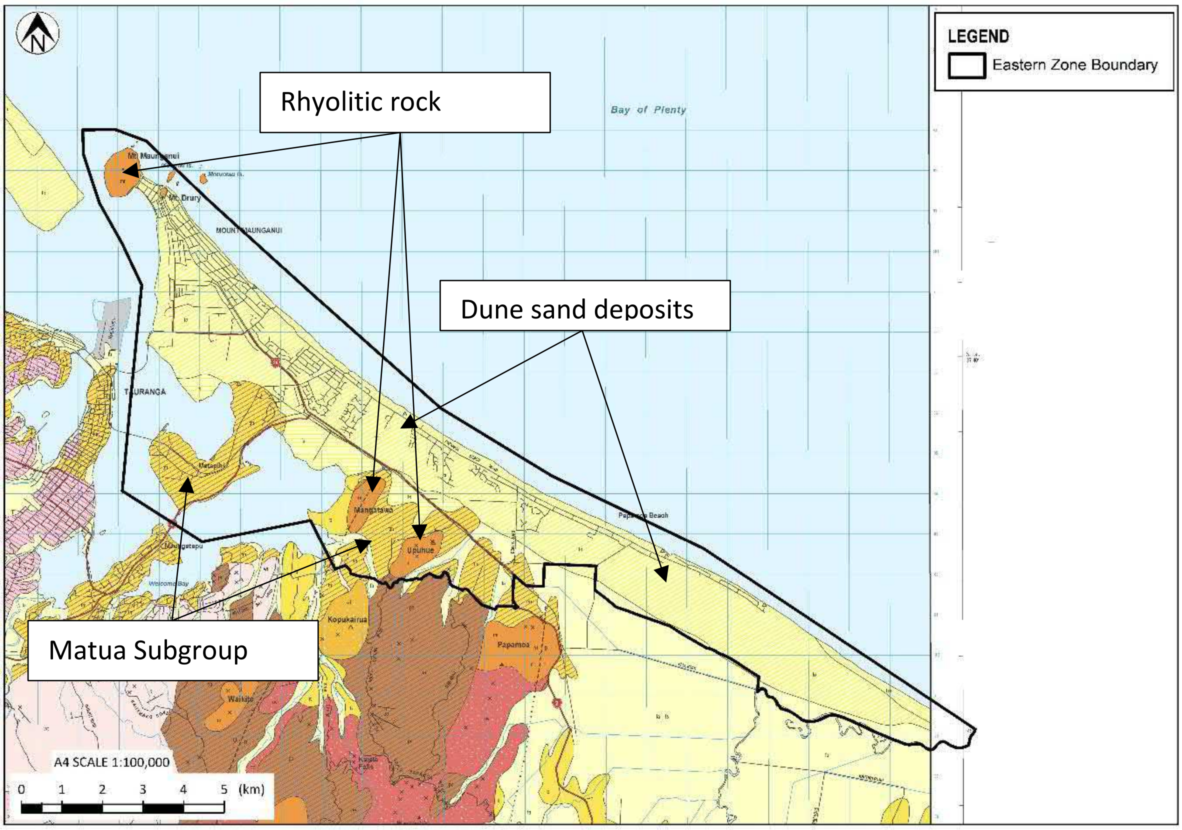


Figure 3.4: Eastern Zone overlain on the Briggs et al (1996) geological map - note as shown on the figure a small portion of the Eastern Zone is not included in the figure. This was mapped in the QMAP geological map series (2010) and in Briggs et al. (2006)

The geological map published by Briggs *et al* (1996) was accompanied by a report which detailed the geological setting and geological deposits of the Tauranga area. The majority of these geological terrains were deposited in Middle to Late Quaternary Period. However there are a few geological features in the Eastern Zone of Pliocene age.

The following is a summary of the geological terrains that comprise the study area:

- The oldest geological terrain in the Study Area comprises igneous Rhyolitic rocks of Pliocene age, significantly older than the other geological terrains in the Eastern Zone. This terrain is represented by Mauao, Drury, Mangatawa and Hikurangi. Briggs *et al* (1996) describes this terrain as being Minden Rhyolite, which is a cream to grey to pink, spherulitic and flow banded rhyolite lava with phenocrysts of plagioclase, quarts, hornblende, biotite and hypersthene.
- Matua Subgroup (Tauranga Group) deposits typically form the elevated terraces in the Eastern Zone. These sediments are of Late Pleistocene age and comprise a wide variety of lithologies which vary laterally and vertically. The Matua Subgroup sediments include fluvial pumiceous silts, sands and gravels, lacustrine and estuarine muds, lignites, peats, air fall volcanic deposits and distal ignimbrites.
- The remainder of the geological terrains extending across the Eastern Zone are all Holocene aged. The most extensive terrain across the study area consists of fixed dune sand deposits associated with post-glacial marine transgression. GNS Science (2019) describes these deposits as consisting of marine gravel, sand and mud. Stream deposits consisting of sand, silt and gravel also become more apparent along the eastern extent of the study area. Localised peat deposits are also identified by Briggs *et al* (1996) within the study area.

Geomorphology

As described in Section 2.3 of this report, one of the key tasks of this project was undertaking geomorphic mapping of the study area. The following is a summary of the methodology applied and outcome of this task for the Eastern Zone. A separate report providing further information about the geomorphic mapping undertaken for both the Eastern and Western Zones has been prepared and will be published.

The geomorphic mapping process undertaken for the Eastern Zone utilised two different mapping methods, these being digital and field-based methods. Initially, aerial imagery was used to identify visual geomorphic changes in the study area. Visual changes in vegetation, elevation and erosional processes/patterns were several of the features used to inform this mapping process. Historical aerial images were also utilised to assess the study area before developments had altered the landscape. A digital elevation model (DEM) was also used in conjunction with the aerial images to differentiate between topographical changes across the study area and to analyse topographical trends and patterns.

During the digital mapping process, a literature review was undertaken to provide further information for the geomorphic mapping process. Scientific papers were reviewed to provide information regarding historical shorelines in the study area and information about the Tauranga Harbour development. Geotechnical reports were also reviewed to provide further information about land reclamation around the Port of Tauranga.

The information obtained during the digital geomorphic mapping process was then ‘field-truthed’ across the Eastern Zone. This involved visually assessing the landscape in the field to determine if the correct features were identified during the digital mapping process. The geomorphic map was then revised if any changes were observed whilst out in the field.

The final geomorphic map was then reviewed by several senior engineering geologists/geotechnical engineers at T+T who have significant experience within the Tauranga Area. Discussions with these senior staff then provided further information to fine tune the geomorphic map. Following the completion of the internal T+T process, Aurecon undertook a Peer Review of the map and recommended changes resulting from this peer review have been incorporated as appropriate.

Figure 3.5 shows the completed geomorphic map. A larger version of this map is included as Figure A4 in Appendix A.

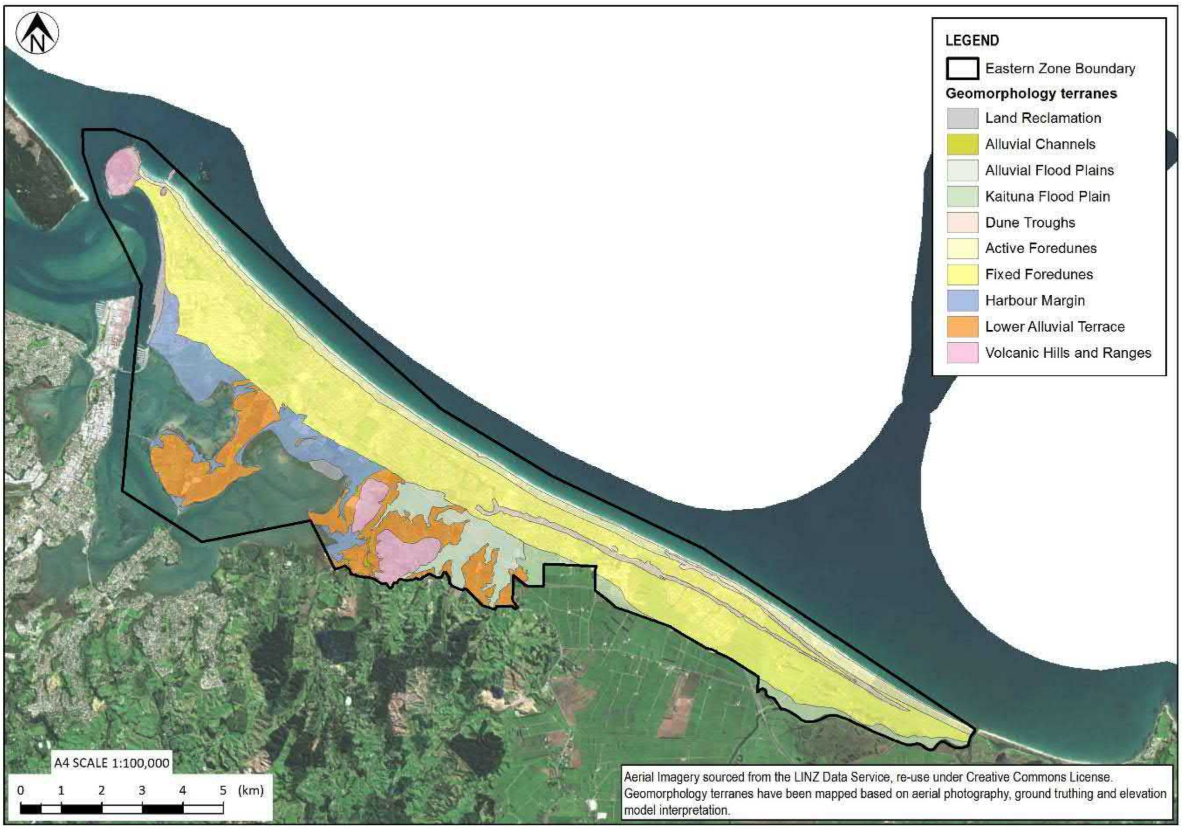


Figure 3.5: Geomorphic map of the Eastern Zone

The geomorphic mapping process identified several different geomorphic terrains across the study area. These geomorphic terrains are described briefly below:

- The most extensive geomorphic terrain across the Eastern Zone was defined as **Fixed Foredunes**. This terrain covered approximately 2,954 Ha (51% of the study area) and represents historical coastal dune systems associated with the fluctuating shoreline.
- **Lower Alluvial Terrace** was the second largest geomorphic terrain in the Eastern Zone, covering an area of approximately 782 Ha (13% of the study area). This geomorphic terrain comprises steep-sided terraces and sea cliffs located around the Tauranga Harbour and the southern boundary of the study area.
- The **Harbour Margin** geomorphic terrain covers an area of approximately 544 Ha (9% of study area) and is associated with the low-lying land surrounding the present day Tauranga Harbour.
- The present day shoreline along the suburbs of Mount Maunganui and Papamoa represents the third largest geomorphic terrain in the Eastern Zone which is defined as **Active Foredunes**. This terrain, which covers approximately 441 Ha (8% of the study area) represents the coastal dune system that is actively subject to windblown and coastal processes.
- **Alluvial Flood Plains** represent fluvial systems within the south-eastern extent of the Eastern Zone. This geomorphic terrain covers an area of approximately 333 Ha (6% of study area). This terrain is typically the product of alluvial/colluvial depositional processes.
- **Volcanic Hills and Ranges** covers an area of approximately 288 Ha (5% of the study area). This geomorphic terrain represents volcanic deposits throughout the Eastern Zone. This geomorphic terrain is mostly located along the southern edge of the study area with the exception of several volcanic domes throughout the study area (Mauao, Drury, Mangatawa and Upuhue). This geomorphic terrain also represents ignimbrite deposits forming terraces above the lower alluvial terrace geomorphic terrain.
- The present day Kaituna River flows into the very eastern extent of the Eastern Zone and is the main defining feature of the **Kaituna Flood Plain** geomorphic terrain. This geomorphic terrain covers approximately 212 Ha (4% of the study area) and represents the historical river channels and associated fluvial deposits of the Kaituna River.
- **Dune Troughs** represent low-lying dune troughs and narrow stream valleys within the fixed foredunes geomorphic terrain. This terrain covers an area of approximately 171 Ha (3% of the study area).
- **Land Reclamation** comprises approximately 66 Ha of the Eastern Zone (1% of the study area) and is typically associated with the land around the Port of Tauranga.
- The smallest geomorphic terrain mapped within the Study area has been defined as **Alluvial Channels**, covering an area of approximately 9 Ha (0.2% of the Study area). The alluvial channels terrain represent active fluvial systems eroding the older volcanic terraces.

Table A1 in Appendix A defines and describes these geomorphic terrains in detail. Note there are additional geomorphic terrains in Table A1 that are present in the Western Zone but not present in the Eastern Zone.

3.2.3 Geotechnical investigations

Existing geotechnical investigations from the publicly available New Zealand Geotechnical Database (NZGD) and from T+T's and Aurecon's records have been considered for this study, including 1,394 Cone Penetration Tests (CPT), 234 Boreholes (BH), 174 Test Pits (TP), 338 Hand Augers (HA) and 6 Laboratory Tests (LT). The number of CPT, BH, TP, HA and LT within each geomorphic terrain is shown in Table 3.3.

Table 3.3: Geotechnical investigation count by geomorphic terrain as at November 2019

Geomorphic terrain	CPT count (No.)	BH count (No.)	TP count (No.)	HA count (No.)	LT count (No.)
Fixed Foredunes	818	83	77	192	0
Lower (Alluvial) Terrace	32	1	31	11	3
Active Foredunes	32	0	0	11	0
Harbour Margin	189	35	32	12	0
Alluvial Flood Plain	166	23	14	1	1
Kaituna Flood Plain	43	6	3	23	0
Volcanic Hills and Ranges	0	0	0	3	0
Dune Troughs	25	0	0	3	0
Land Reclamation	5	3	1	0	0
Alluvial Channels	0	0	0	0	0
Outside study area	167	83	16	21	2
Total	1,394	234	174	338	6

Figure 3.6 shows the location of the geotechnical investigations available on the NZGD as at November 2019 with Figure A3 in Appendix A showing a larger version of this map.

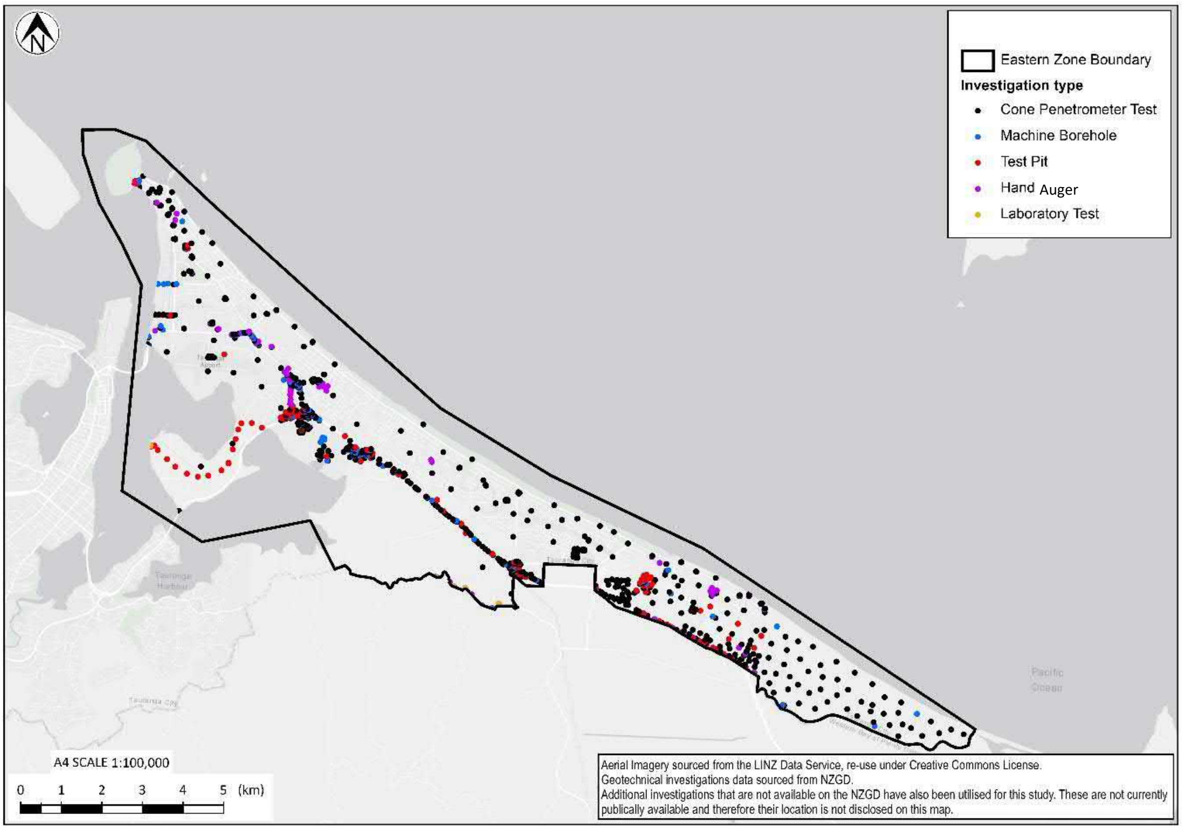


Figure 3.6: Geotechnical investigations available on the NZGD as at November 2019

3.2.4 Groundwater

TCC installed 67 piezometers across the Eastern Zone at varying dates to record the depth to the groundwater surface. The primary purpose of the piezometer installation was to ascertain how rising sea-levels may affect groundwater levels and in turn the possible problems this presents to Council infrastructure, and what associated inundation effects may occur within the City. For this reason the piezometers have been located to enable modelling of the groundwater depth in the coastal and harbour margins below approximately 10 m RL.

The piezometers used for the sea level rise study were installed in phases at different times and therefore the length of monitoring record for each piezometer installation phase is varied. The number of piezometers installed in the Eastern Zone and the approximate length of monitoring record for each of the phases is shown in Table 3.4. Table 3.5 shows the relevant groundwater studies that summarise groundwater information that was utilised for the Eastern Zone assessment.

Table 3.4: Sea level rise study piezometer count and approximate monitoring record length for each phase of installation

Phase	Piezometer count (No.)	Monitoring record length
1	25	August 2015 – present
2	26	October 2016 – present
3	12	October 2017 – present
4	4	July 2018 - present

Table 3.5: Groundwater studies summarising the extent of the groundwater modelled

Title	Author(s)	Published date	Coverage of Study Area
Effects of Sea Level Rise on Groundwater level Mount Maunganui North Pilot Study	T+T	May 2015	Partial
Effect of Sea Level Rise on Groundwater Levels Tauranga Study	T+T	July 2016	Full
Groundwater Effects of Sea Level Rise in Tauranga	T+T	April 2017	Full

In July 2019, T+T supplied TCC with an updated version of the current day median depth to groundwater model and this updated version has been used for this liquefaction hazard assessment. Figure 3.7 shows the current median depth to groundwater model for the Eastern Zone. A larger version of this map is shown in Figure A6 in Appendix A.

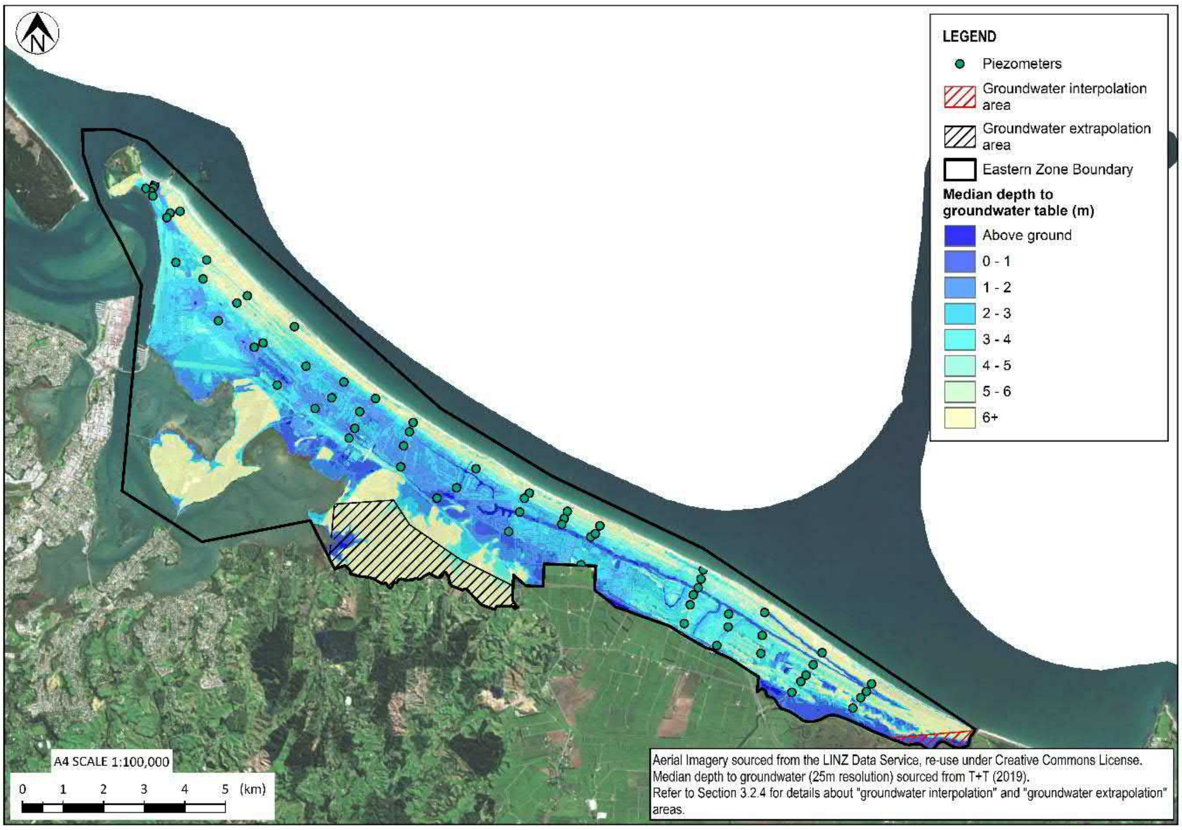


Figure 3.7: Current day median depth to groundwater model

When this model was supplied there were several areas within the Eastern Zone which were not modelled. Therefore, to estimate the depth to groundwater simple extensions to the model[5] were applied as follows:

- **Groundwater interpolation area** – In this area the groundwater surface was extended by interpolation between the original model boundary and the Kaituna River.
- **Groundwater extrapolation area** – In this area the groundwater surface was extended predominantly by extrapolation from the both the inner harbour and the original model boundary. In some areas close to the inner harbour, the extension involves interpolation between points.

Refer to Figure 3.7 and Figure A6 in Appendix A for the location of these areas of groundwater model extensions.

Despite the data in these two areas of extension being represented on the map in the same manner it is important to recognise the uncertainty associated with the methods used to extend it. The groundwater interpolation area is across a relatively low-lying area that interpolates to a location where the groundwater depth can be estimated with less uncertainty. This is because it is governed by the Kaituna River level which is tidal and therefore relatively predictable. However, the groundwater extrapolation area is across a relatively elevated area with significant topographic changes and extrapolates to an area where the groundwater level is not monitored and likely fluctuates significantly in response to rainfall events. Therefore there is more uncertainty associated with the estimation of the groundwater depth in the groundwater extrapolation area relative to the groundwater interpolation area.

In order to assess the potential increase in liquefaction vulnerability as a result of sea level rise, a scenario representing the potential future groundwater depth following 1.25 m of sea level rise was applied to the median model as requested by TCC. This level is in accordance with the local sea level rise projection provided in NIWA study (NIWA, 2017) and is representative of a 100 year timeframe as required by Bay of Plenty Regional Policy Statement (RPS) Policy NH11B (BoPRC, 2016).

The complexities associated with how sea level rise would influence the hydrological mechanics of the region are largely unknown. Given the site’s proximity to the coast, the inland damping effects of sea level rise are expected to be minor. Therefore, to model sea level rise, the current day median groundwater surface level was simply raised by a uniform of 1.25 m. Figure 3.8 shows the groundwater 1.25 m shallower than the current day median depth. A larger version of this map is shown in Figure A7 in Appendix A.

[5] Note that this was only undertaken in areas where this information would be used as inputs to the analytical liquefaction damage model. For example, the nature of soil conditions in Mauao meant that it was not necessary to extend the groundwater model in this area.

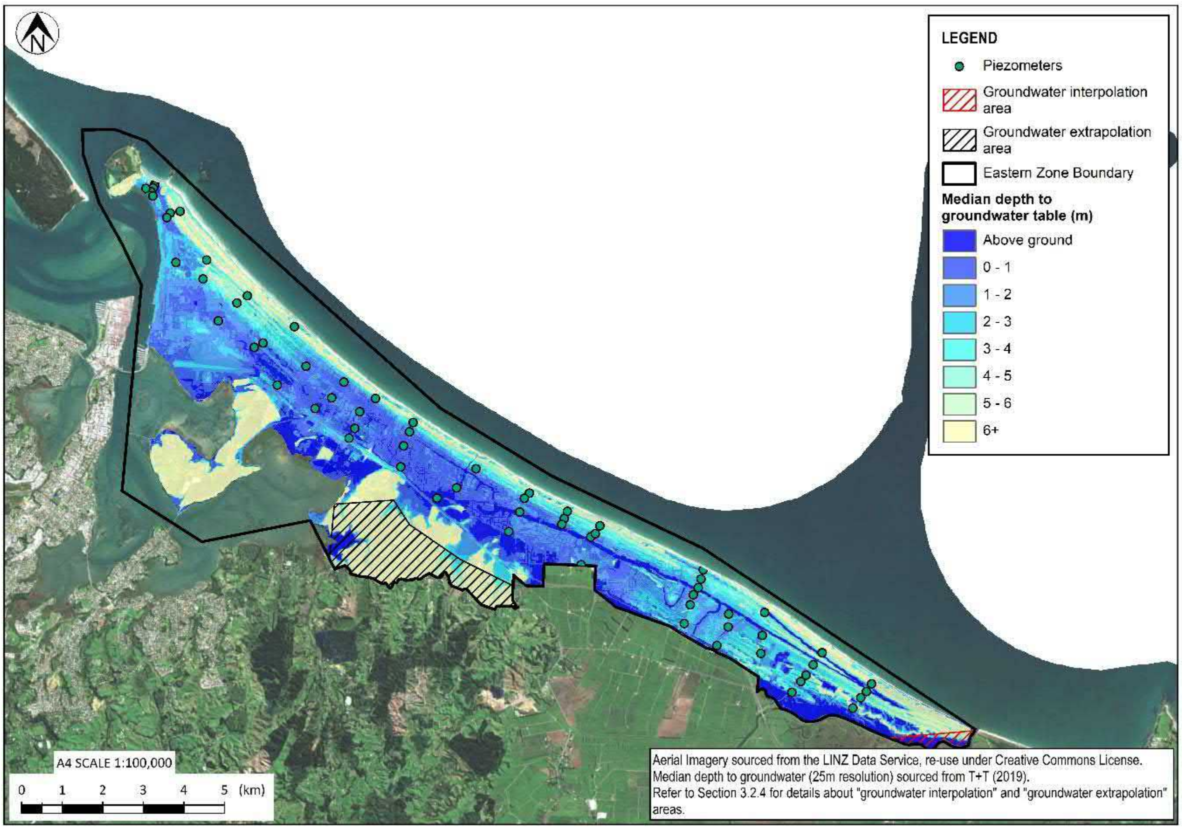


Figure 3.8: Groundwater 1.25m shallower than current day median depth to groundwater model

3.2.5 Seismic hazard

Soils that are susceptible to liquefaction require a certain level of earthquake shaking (duration and intensity of ground shaking) to cause them to liquefy. A key source of uncertainty in the liquefaction analysis is the intensity of shaking that will occur at a particular location in future earthquake events. The following seismic hazard information is provided as background to the triggering component of the liquefaction analysis.

Tectonic setting

There are a significant number of known active faults within close proximity of the Eastern Zone. Identified faults are shown in Figure 3.9 which has been taken from the National Seismic Hazard Model (NSHM) for New Zealand: 2010 Update (Stirling, 2012).

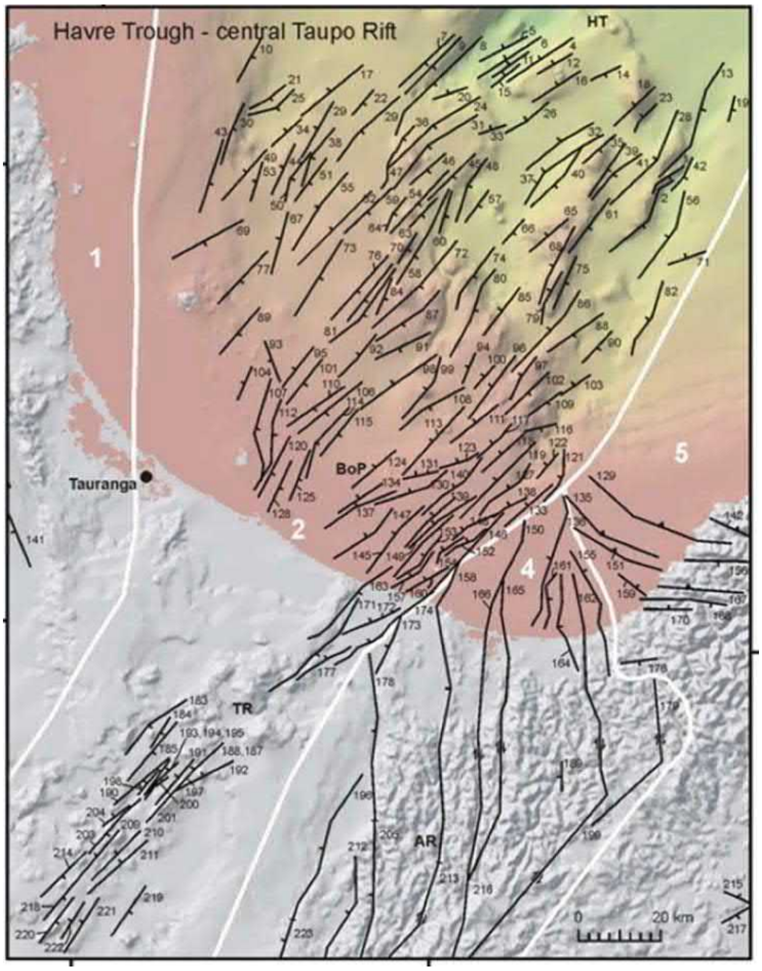


Figure 3.9: Active faults in the Bay of Plenty and Taupo Rift. The fault sources are shown as black lines and Area 2, which is bounded by the white lines, identifies the Bay of Plenty and Taupo Rift

The majority of the identified active faults in the Bay of Plenty are north of the study area (in the Bay of Plenty) and in the Taupo Rift to the south and southeast. The closest active fault is identified as Fault No. 128 which is about 20 km north east of the study area. This fault is assessed as being capable of a moment magnitude (M_w) of 6.3 and has an average recurrence interval of 1,360 years (Stirling, et al., 2012). Larger faults further away in the Waikato basin and Taupo volcanic zone also contribute to the seismic hazard of the area.

Seismic hazard information available for this study

For routine engineering projects the NZTA Bridge Manual (NZTA, 2018) is the commonly accepted method for determination of seismic hazard for liquefaction analysis in New Zealand in the absence of a site specific assessment or regional study. However, Module 1 of the NZGS Earthquake Geotechnical Engineering Practice Guidelines (NZGS/MBIE, 2016) notes the following issues have been identified with this approach:

1 Compatibility issues between the magnitude weighting factors embedded in the hazard evaluation and the magnitude scaling factors in the liquefaction evaluation procedures adopted in this guideline series;
2 The use of an "effective earthquake magnitude"; and
3 The need to incorporate updates in the NSHM[6].

For purposes of obtaining ground motion parameters based on the most recent version of the NSHM and utilising more current and applicable Ground Motion Prediction Equations (GMPEs), TCC engaged Bradley Seismic Limited (BSL) to undertake a high-level regional seismic hazard assessment (BSL, 2019). This regional seismic hazard assessment was undertaken for the purposes of informing the seismic hazard component of the TCC liquefaction assessment. A brief summary is provided below of the BSL report and information from a meeting with BSL, Aurecon, TCC and Wentz Pacific Ltd. on 18 November 2019:

- Peak ground accelerations (PGA's) and magnitudes have been determined spatially for the Tauranga City area.
- The spatial location relative to seismic sources is not a significant source of variability in the seismic hazard across the study area. For example if the ground conditions and topography were the same across Tauranga, the modelled ground motion intensity would be more or less consistent across the whole City.
- Shallow ground conditions have the most significant effect on the spatial variability of expected ground motion intensity across the study area. The primary parameter used in the BSL report (BSL, 2019) to characterise the impact of ground conditions on site response is the 30 m averaged shear wave velocity (Vs30). This parameter varies depending on the stiffness and composition of soil or rock.
- The BSL report (BSL, 2019) uses the regional model of Foster et al. (2019) to estimate the Vs30 values across the study area. The Foster model is shown in Figure 3.10 and this data is also provided in Figure A8 of Appendix A. The Foster model is based on surficial geology, topographic terrain and geotechnical and geophysical measurements.
- Seismic hazard curves for peak ground acceleration (PGA) for a number of Vs30 profiles presented in the BSL report (BSL, 2019) are shown in Figure 3.11. The hazard curve using the NZTA Bridge Manual (2018) methodology is also provided on this figure for reference.
- It is important to note that the BSL study is a regional seismic hazard assessment. It is not intended as a substitute for a site-specific probabilistic seismic hazard assessment.

[6] The NZTA Bridge Manual methodology is based on the Stirling (2002) NSHM and not the updated Stirling et al (2012) NSHM

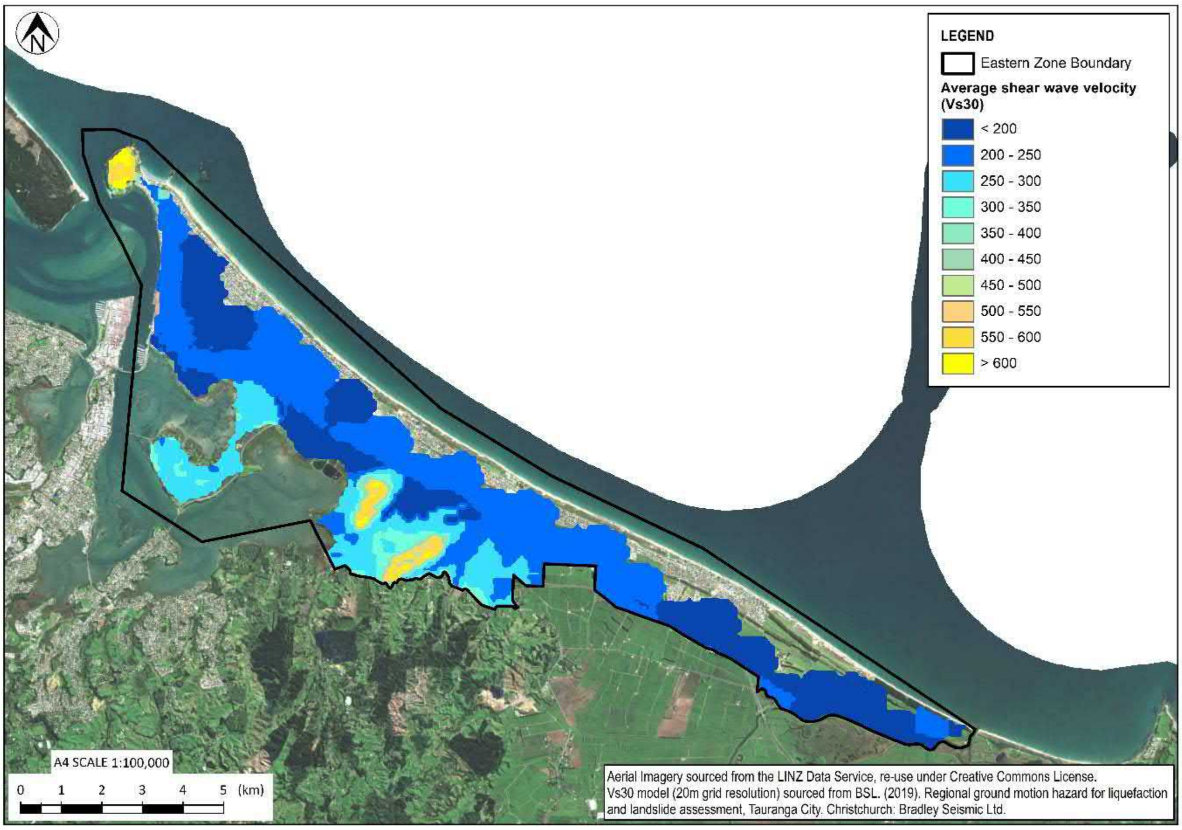


Figure 3.10: Foster model (2019) for the Eastern Zone

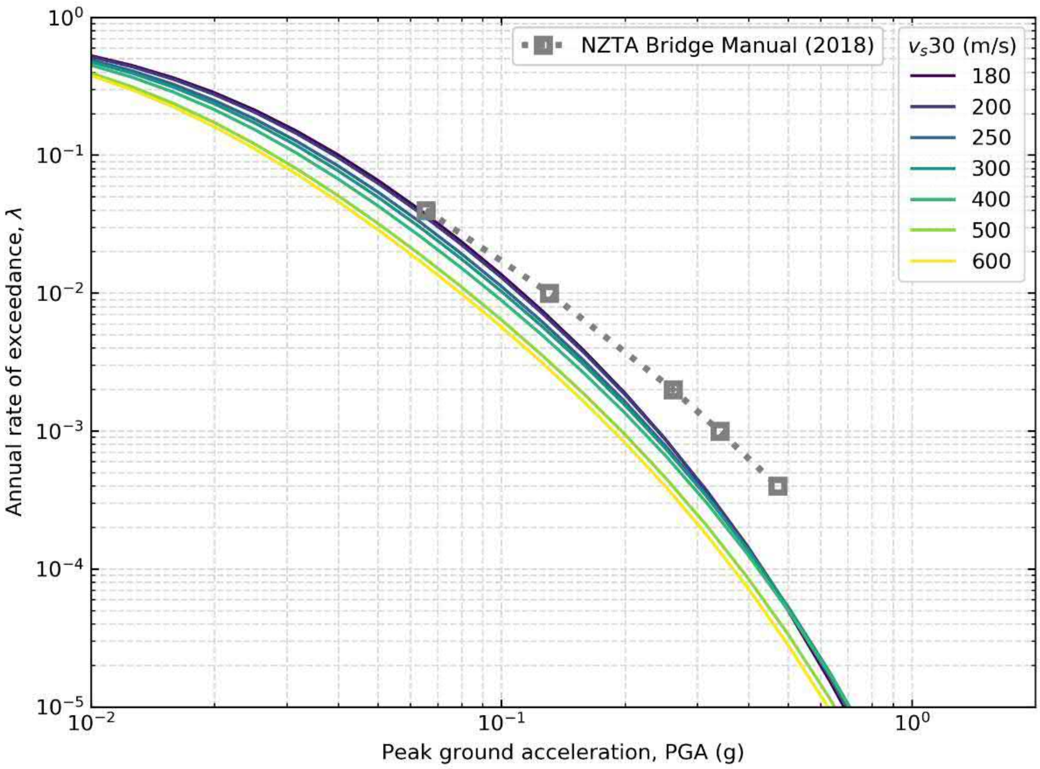


Figure 3.11: Seismic hazard curves for peak ground acceleration (PGA) from BSL (2019) illustrating the effect of soil conditions as quantified through Vs30. The hazard curves using the NZTA Bridge Manual (2018) methodology for site subsoil class D are also provided for reference

Table 3.6 provides a comparison of the BSL regional seismic hazard model with the NZTA Bridge Manual (2018).

Table 3.6: Ground seismic hazard: comparison between NZTA Bridge Manual (2018) and the BSL Report (2019)

Return period (years)	NZTA Bridge Manual (2018)[7]		BSL Regional Seismic Hazard Model	
	PGA (g)	Magnitude (M_{eff})	PGA (g)[8]	Mean Magnitude (M)
25	0.07	6.0	0.04 to 0.07	6.1
100	0.13	6.0	0.08 to 0.12	6.1
250	0.20	6.0	0.12 to 0.17	6.2
500	0.27	6.0	0.15 to 0.20	6.2
1,000	0.35	6.0	0.19 to 0.25	6.3

Note:

Bridge Manual values have been assessed based on the Bridge Manual SP/M/022 Third Edition, Amendment 3, for the following:

Return period factor, Ru	0.25 for 25yr; 0.5 for 100yr; 0.75 for 250 yr, 1.0 for 500yr; 1.3 for 1,000yr return period (NZS 1170.5:2004, Table 3.5)
Subsoil class	D (Deep soil)
Return period PGA coefficient, $C_{0,1000}$	0.35 for Te Puke (Bridge Manual Figure 6.1(b))
Site subsoil class factor, f	1.0 (Bridge Manual Section 6.2)
PGA	$C_{0,1000}$ x Ru/1.3 x f x g (Bridge Manual Section 6.2)
Effective Magnitude, M_{eff}	6.0 for Te Puke (Bridge Manual Table 6.2(d))

As shown in Figure 3.11 and Table 3.6 the BSL model (BSL, 2019) provides a range of PGA values, which is dependent on Vs30 at a given location. Figure 3.11 and Table 3.6 also show that independent of the Vs30 value, the BSL model predicts a lower PGA and slightly higher magnitude than the NZTA Bridge Manual (2018). While the difference in magnitude is likely to have a relatively minor effect on the liquefaction analysis, the PGA is up to 30% lower for similar expected ground conditions and this is likely to have a significant effect on the liquefaction analysis.

Further analysis is provided in Section 4.1.5 of this report to evaluate the uncertainty associated with the seismic hazard information available for this study and determine a suitable Vs30 range and triggering parameters (PGA, M) to apply to the liquefaction triggering analysis.

[7] Note that the PGA and Magnitude values calculated using NZTA Bridge Manual (2018) are shown for Te Puke which is to the South and West of the Eastern Zone. Slightly lower PGA and Magnitude values are calculated for Tauranga City which is to the West of the Eastern Zone. We note that the northern part of the Eastern Zone is closer to Tauranga City however, the differences in PGA at longer return period events are very small when compared to the differences between the BSL (2019) and NZTA Bridge Manual (2018) methods.

[8] The lower and upper PGA values presented in Table 3.6 for the BSL Regional Seismic Hazard Model correspond to Vs30 values of approximately 600 and 180 m/s respectively.

3.2.6 Historical observations of liquefaction

Review of the national catalogue of earthquakes (GNS, 2019), indicates that there have been no earthquakes of M_W 5 or greater at depths shallower than 100km in the historical record within approximately 50 km of the Tauranga CBD.

The 1987 M_w 6.5 Edgecumbe earthquake is the most significant nearby earthquake in the historical record with the epicentre located approximately 60 km from the Tauranga CBD. Downes & Dowrick (2014) estimate felt shaking intensity from the Edgecumbe earthquake of Modified Mercalli Index (MMI) 5 – 6 within the Eastern Zone.

A literature review of historical earthquake studies indicated that there are no recorded observations of liquefaction related land damage in the Eastern Zone. Ogden (2018) provides an overview of land damage observations from the Edgecumbe earthquake. This shows that observations of liquefaction related land damage were limited to the land within and proximal to Edgecumbe and Whakatane.

It is important to note that the observation of no liquefaction damage during the Edgecumbe earthquake does not provide conclusive evidence that liquefaction is not possible in the Eastern Zone. Given the distance from the Eastern Zone to the epicentre of the Edgecumbe earthquake we would not expect extensive and severe liquefaction-induced damage in this area even for susceptible soils. Furthermore, liquefaction triggering may have occurred in soils at depth without any significant surface manifestation, and minor liquefaction-induced ground damage may have occurred but not been recognised or documented at that time.

4 Risk analysis

The following sections outline the risk analysis that has been carried out for the liquefaction hazard assessment for the Eastern Zone.

The first task is the identification and assessment of uncertainty (refer to Section 4.1). This is achieved by describing the various elements that contribute to uncertainty and, where feasible, representing these uncertainties in a spatial format. The key output from this process is determination of the level of detail in the assessment supported by the currently available base information.

The second task is the liquefaction analysis process (refer Section 4.2). To do this an analytical model was developed which estimated the severity of liquefaction-induced ground damage. The sensitivity of this model to groundwater and earthquake shaking was considered as part of this process. In conjunction with engineering judgement to evaluate the available information and uncertainties, this model was then used to categorise expected land performance relative to the criteria recommended in the MBIE/MfE Guidance (2017).

4.1 Uncertainty assessment

We have considered the uncertainties in the liquefaction assessment as they relate to the following:

- Base information currently available (refer to Sections 4.1.1 to 4.1.5)
- Estimation of liquefaction-induced ground damage (refer to Section 4.1.6)
- Assessment of ground damage response against the performance criteria (refer to Section 0)
- Determination of the level of detail supported by the currently available (refer to Section 4.1.8).

4.1.1 Ground surface levels

As described in Section 3.2.1 the available information to define the ground surface levels is high resolution LiDAR DEM. This data is used in this study in a number of ways such as the development of the geomorphic map and the depth to groundwater model. The key uncertainties associated with the ground surface levels are discussed below.

Uncertainty due to the accuracy and limitations of LiDAR derived DEM

While the available LiDAR derived DEM is relatively high resolution and considered fit for the purposes of this liquefaction assessment, the following accuracy issues should also be acknowledged:

- Measurement error associated with the LiDAR point cloud collection method
- Localised error due to interpolation in areas with low density of ground classified points
- Spatial resolution of the DEM and the accuracy and appropriateness in representing the ground surface elevation.

In most cases these limitations will have a relatively minor effect on the representation of the ground surface. However there are some specific limitations which result in significant uncertainty in the assessment. A key example of this is the inability of LiDAR to penetrate water bodies. This limits the usefulness of LiDAR data for mapping free faces in water features because, when water bodies are present at the invert of free faces, the height of the free-face may be under-estimated resulting in under prediction of the extent and severity of lateral spreading.

Uncertainty due to temporal changes in ground surface elevation

To a greater or lesser extent, any ground surface will be undergoing change in elevation. These changes may be attributable to natural processes (e.g. earthquake induced ground deformation) or anthropogenic (man-made) changes (e.g. land development activities).

It is not feasible to predict with any reasonable degree of accuracy the extent and degree of future changes in ground surface elevation. However, by reviewing historical aerial imagery it is possible to map areas of historical change in ground surface elevation. Those anthropogenic features identified as part of this study are shown on Figure B1 in Appendix B.

To manage this source of uncertainty geotechnical investigations have been screened to identify and remove CPT that are not considered representative of the natural ground conditions prior to incorporation in the analytical ground damage model. The screening of geotechnical investigations is discussed further in Section 4.1.3.

4.1.2 Geology and geomorphology

As discussed in Section 3.2.2 the geology and geomorphology of the Eastern Zone is presented in the form of maps. This mapped information is used in the liquefaction assessment to group the geotechnical investigation data into areas of similar expected performance. The key uncertainties associated with the geology and geomorphology are discussed below.

Uncertainty due to the precision of mapping and the accuracy of boundaries between terrains

This can result in the incorrect categorisation of the land (if placed into the wrong geomorphology type) and hence incorrect estimation of ground performance. The specification of a scale of approximately 1:25,000 for the geomorphic mapping provides an indication of the degree of uncertainty and areas where there is more uncertainty associated with the location of the boundary have been identified.

Uncertainty due to anthropogenic landform changes

Some anthropogenic landform changes, in particular those associated with large infrastructure or land development projects, can result in changes to the severity of liquefaction related land damage under seismic load. In some cases these changes will result in an improvement of liquefaction performance (e.g. ground improvements such as dynamic compaction or stone columns) or in some instances there will be a degradation in liquefaction performance (e.g. reduction of the ground surface elevation resulting in a reduced depth to ground water).

In either case, if the ground investigations are undertaken prior to the anthropogenic landform change being made, these investigations may not be representative of the expected liquefaction performance of the final landform. However, these investigations still provide useful information as they are representative of the natural state of the ground. The areas where these changes are possible are indicated by the anthropogenic features shown on Figure B1 in Appendix B.

4.1.3 Geotechnical investigations

As discussed in Section 3.2.3, there is a range of geotechnical investigations available within the Eastern Zone, the most predominant of which are CPT and Borehole data. These geotechnical investigations, in particular the CPT, are used to estimate (both quantitatively and qualitatively) the expected liquefaction related performance of the land. The key uncertainties associated with the geotechnical investigations are discussed below.

Uncertainty due to geotechnical investigation data quality

Each geotechnical investigation has inherent issues in data quality. Some of these are readily identifiable, are logged as part of the investigation and can be allowed for in the analysis (e.g. post-ground improvement investigations and portions of predrilled CPT). Others are not readily identifiable without being able to refer to the data source and must be considered as part of engineering judgement (e.g. incorrectly logged BH data).

To provide a consistent basis for quantitative analysis, an initial filtering process was applied to the CPT dataset used for calculation of liquefaction vulnerability index parameters. This involved only selecting CPTs for analysis that have a depth of investigation greater than 5 m, depth of pre drill that does not intersect the groundwater table, and no known data issues or prior ground improvement works. However, the full unfiltered dataset was utilised for qualitative assessment purposes.

Uncertainty due to variability in ground conditions within geomorphic terrains

Within each geomorphic terrain there is a degree of natural variability in ground conditions that results in a degree of variability in expected liquefaction related performance. Some geomorphic terrains, such as the Active Foredunes in the Eastern Zone, have a low degree of variability and this is reflected in a relatively uniform estimate of liquefaction related performance for a constant depth to groundwater. Other geomorphic terrains, such as the Kaituna Flood Plain, are much more variable in the soil conditions encountered and this is reflected in a relatively variable estimate of liquefaction related performance for a constant depth to groundwater.

To demonstrate this variability, Figure 4.1 shows representative cone tip resistance (q_C) vs depth plots from the Active Foredune and Kaituna Flood Plain. The q_C parameter provides an indication of the relative density of the soil the CPT has been undertaken in. The Active Foredune shows a steady increase in relative density with depth with relatively little variability to a depth of approximately 6 m.[9] Beyond 6 m depth some of the traces hit a denser layer and others continue the steady increase in density. The Kaituna Flood Plain shows some increase in relative density with depth but a relatively high degree of variability for the full length of 10 m.

Figure 4.2 shows the soil behaviour type index (I_c) vs. depth for the same two geomorphic terrains. I_C provides an indication of the type of soil the CPT has been undertaken in. The Active Foredune has a uniform I_C value with depth, typically at or below 1.8 which is indicative of a clean sandy soil. The Kaituna Flood Plain I_C value is highly variable ranging from below 1.8 to above 2.6. An I_C value of 2.6 is indicative of silty to clay like soil behaviour.

[9] Note that the measured increase in cone tip resistance (q_c) with depth may also be attributable to an increase in confining pressure due to the weight of soil above. Regardless of the mechanism that causes this increase in the raw q_C values the figures provided illustrate the differences in variability between the Active Foredune and the Kaituna Flood Plain.

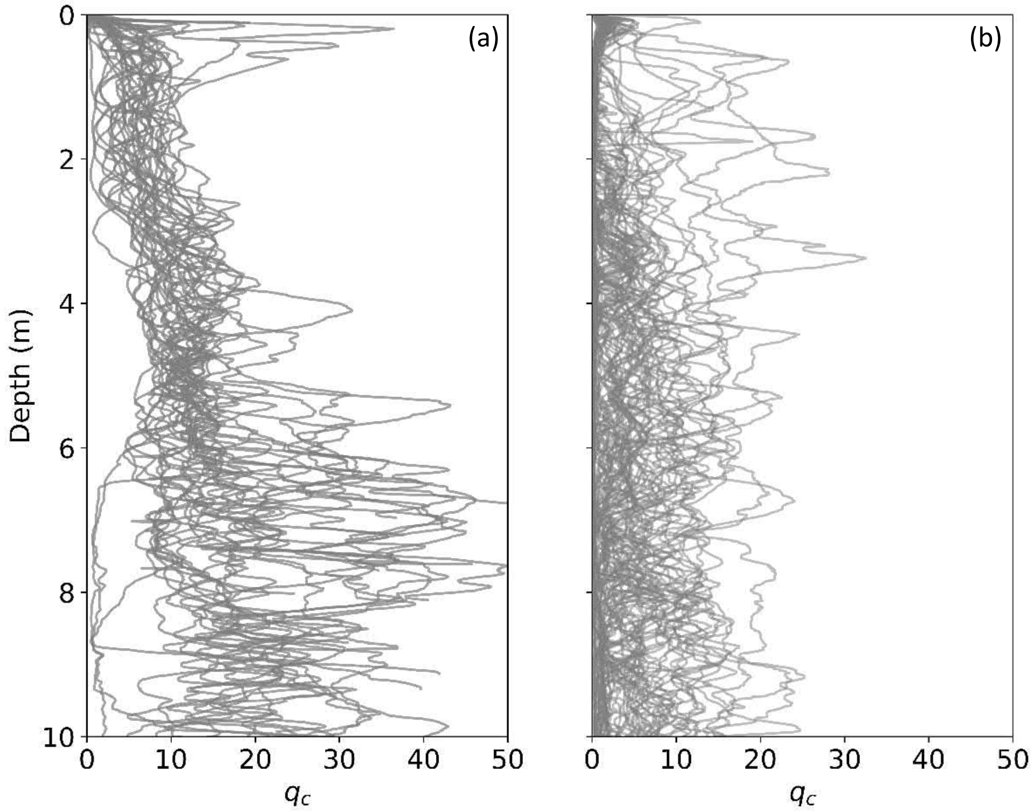


Figure 4.1: CPT cone tip density (q_c) vs. depth from the (a) Active Foredune and (b) Kaituna Flood Plain

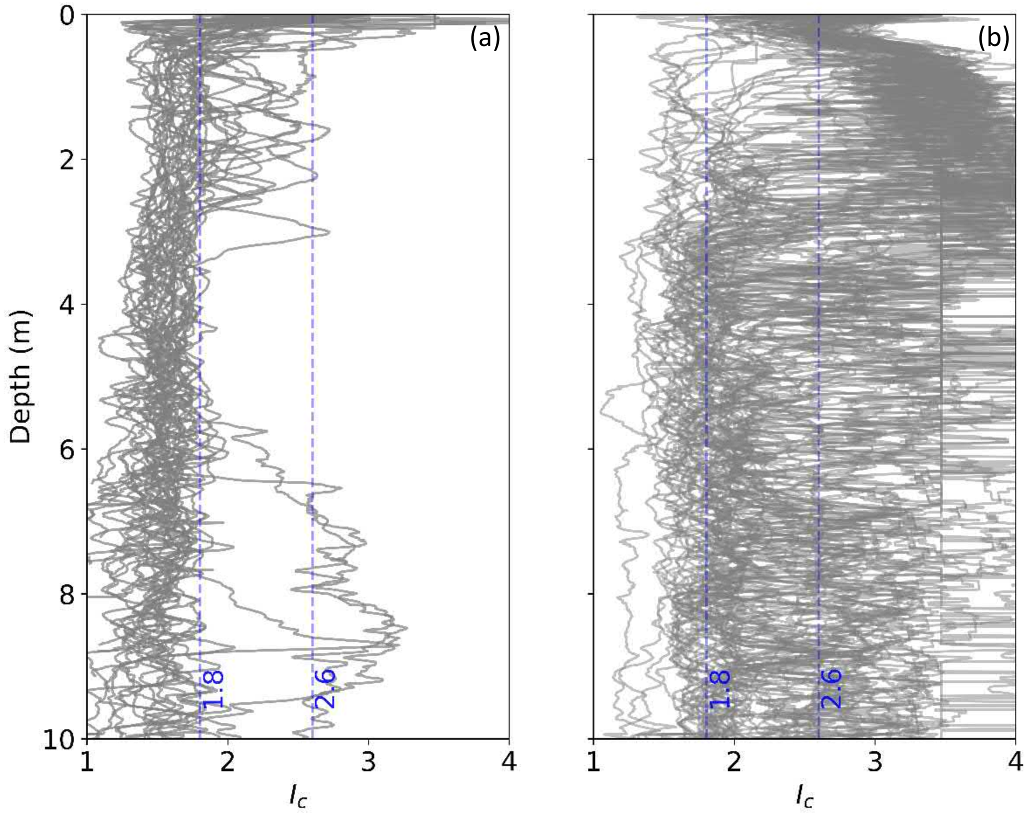


Figure 4.2: CPT soil behaviour type(I_c) vs. depth from (a) Active Foredune and (b) Kaituna Flood Plain

Uncertainty due to CPT cone sensitivity

CPT cones are calibrated to be operated up to a maximum value of q_C with 25, 50 and 100 MPa being typical. CPT cones that have lower maximum operating values are more sensitive to small changes in the soil conditions, however due to the restricted range of operation these cones should only be used in relatively softer/less dense soils. If the maximum operation value of q_C is exceeded recalibration of the cone may be required to ensure it is reading accurately. Conversely, CPT cones that have higher maximum operating values are less sensitive to small changes in the soil conditions, however these can be used in firmer/more dense soils.

Due to the relatively dense soil conditions in the majority of the Eastern Zone, the majority of CPT available in the study area were undertaken using cones calibrated for use up to a maximum q_C of 100MPa. For the relatively dense sandy soils in the Active Foredunes and Fixed Foredunes that cover 58% of the study area and the vast majority of the developed land, this choice has a relatively small impact on the accuracy of the liquefaction analyses. Any benefit from undertaking the analyses using a more sensitive cone is offset by the limitations on the depth of penetration (as these soils typically get denser with depth) and the additional costs associated with using a more sensitive cone. However for the soils where relatively soft/less dense soils are likely to be found, such as the Lower Alluvial Terraces and Harbour Margins, it is useful to understand the uncertainty that using a 100 MPa cone in place of a 50 MPa cone may have.

To understand this issue further, T+T commissioned 50 MPa cones to be undertaken adjacent to 100MPa cones in two locations within the Harbour Margin geomorphic terrain on the Matapihi Peninsula. Refer to Figure 4.3 for the two locations where these investigations were undertaken. It was necessary to undertake multiple CPT using the 50 MPa cone in each location in order to reach the required target depth because denser soils were encountered in multiple locations. This highlights one of the key limitations of using the higher sensitivity 50 MPa cone discussed above.

Figure 4.3: Two locations on Matapihi shoreline where 50MPa cones were undertaken adjacent to 100MPa cones

Figure 4.4 and Figure 4.5 show plots of the q_C and I_C from location one and location two respectively. Inspection of both figures indicates a relatively consistent result for each cone type such that the degree of variability between the results of each of the cones could be attributable to minor differences in ground conditions that can be observed between locations that have been offset by a small distance.

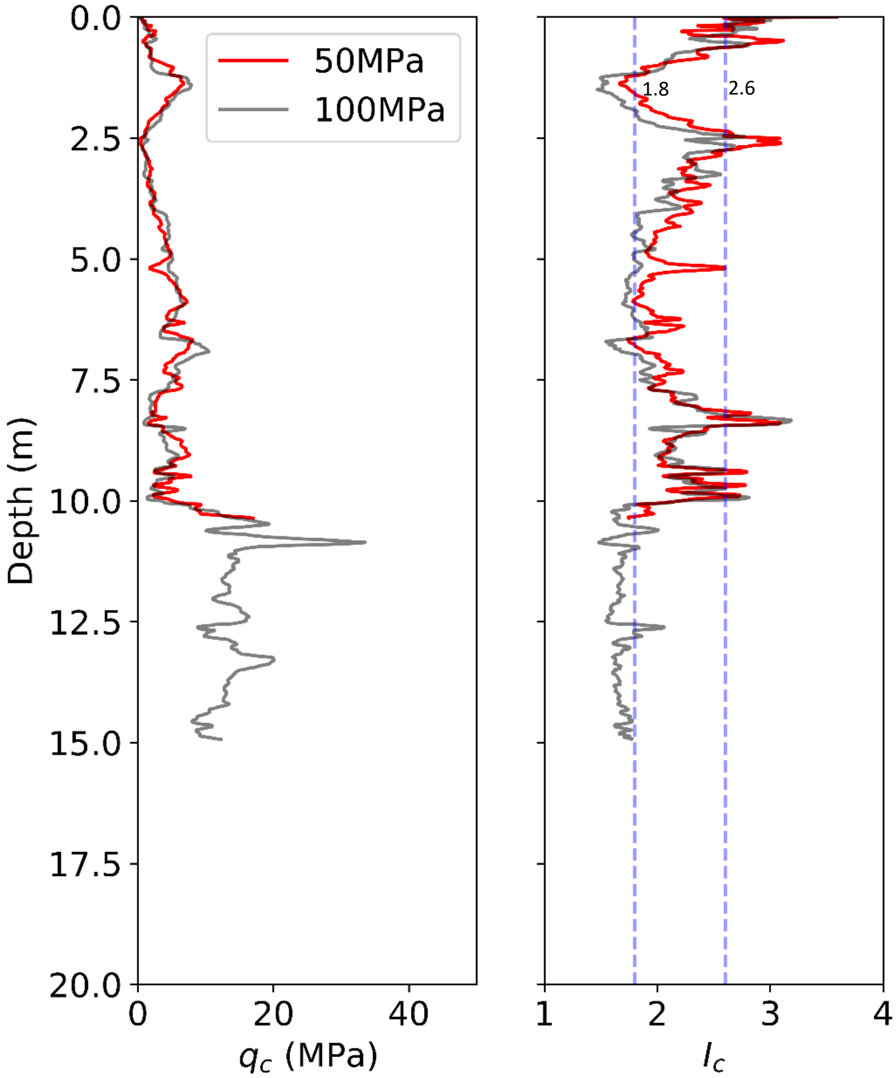


Figure 4.4: CPT cone tip density (q_c) vs. depth and soil behaviour type (I_c) vs. depth from adjacent 50 MPa and 100 MPa tip resistance cones (location one) in the Matapihi Harbour Margin geomorphic terrain

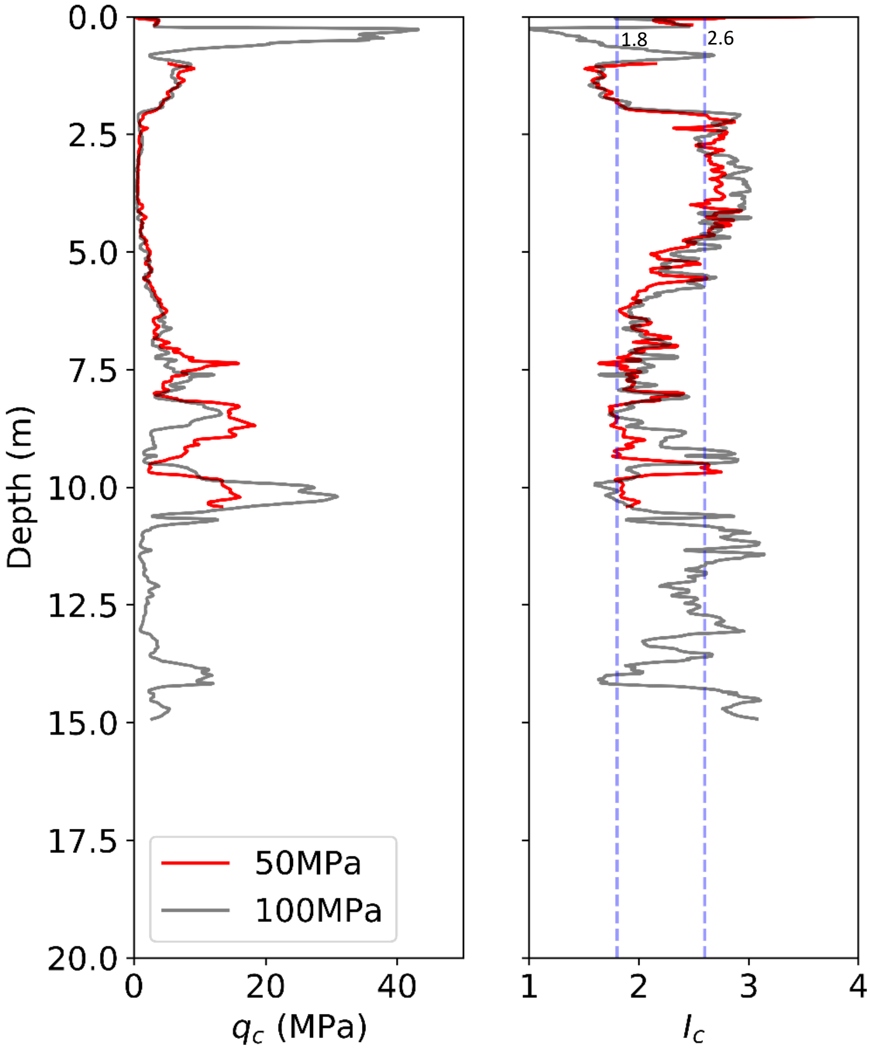


Figure 4.5: CPT cone tip density (q_c) vs. depth and soil behaviour type (I_c) vs. depth from adjacent 50 MPa and 100 MPa tip resistance cones (location two) in the Matapihi Harbour Margin geomorphic terrain

The result of most interest is the I_C plot where the value of I_C is close to 2.6. This is a critical value because it is used as a screening threshold in CPT-based liquefaction analyses to differentiate between soils that are susceptible to liquefaction and soils that are not. That is a soil that has an I_C value of greater than 2.6 is assumed to be not susceptible and conversely a soil with an I_C value of less than 2.6 is assumed to be susceptible. In both location one and location two, the 50 MPa and 100 MPa CPT plot sit on opposite sides of this threshold I_C value for relatively small portions of the curve. While these differences are relatively minor it does illustrate the point that the choice of cone used can impact the liquefaction analyses undertaken.

Figure 4.6 and Figure 4.7 show PGA vs. Liquefaction Severity Number (LSN) plots of the 50 MPa and 100 MPa CPT cones undertaken at location one and location two respectively for an assumed groundwater depth of 1 m. Inspection of Figure 4.6 indicates that for location one there are relatively large differences (e.g. more than 20 LSN points at 0.15 g) between the calculated LSN values for each cone type. Whereas inspection of Figure 4.7 indicates there are relatively small differences between the calculated LSN values for each cone type with the plots being effectively equivalent up to 0.2 g.

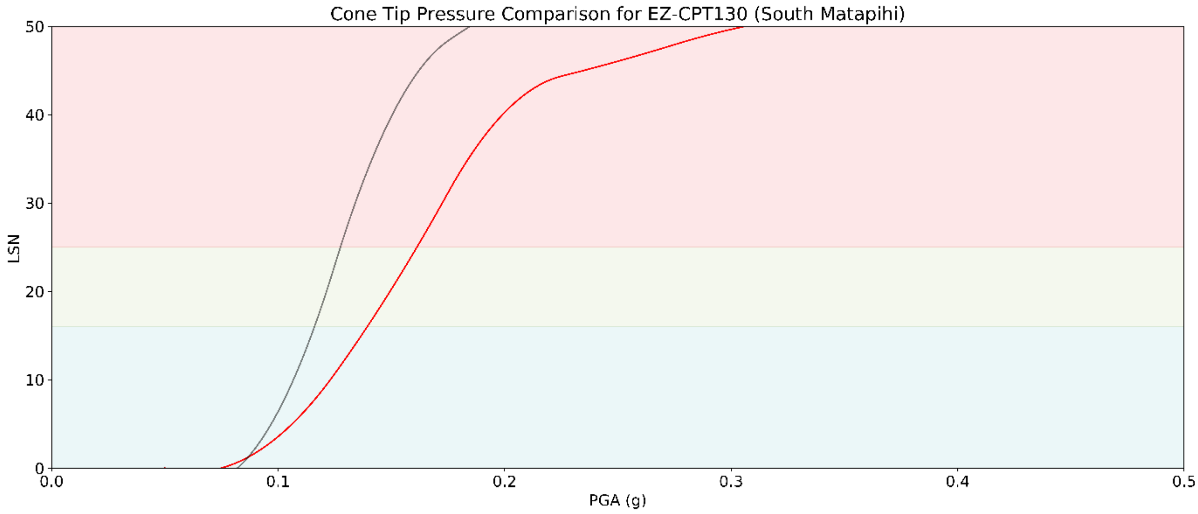


Figure 4.6: PGA vs. LSN plots from adjacent 50 MPa (red) and 100 MPa (grey) tip resistance cones (location one) in the Matapihi Harbour Margin geomorphic terrain for an assumed groundwater depth of 1 m

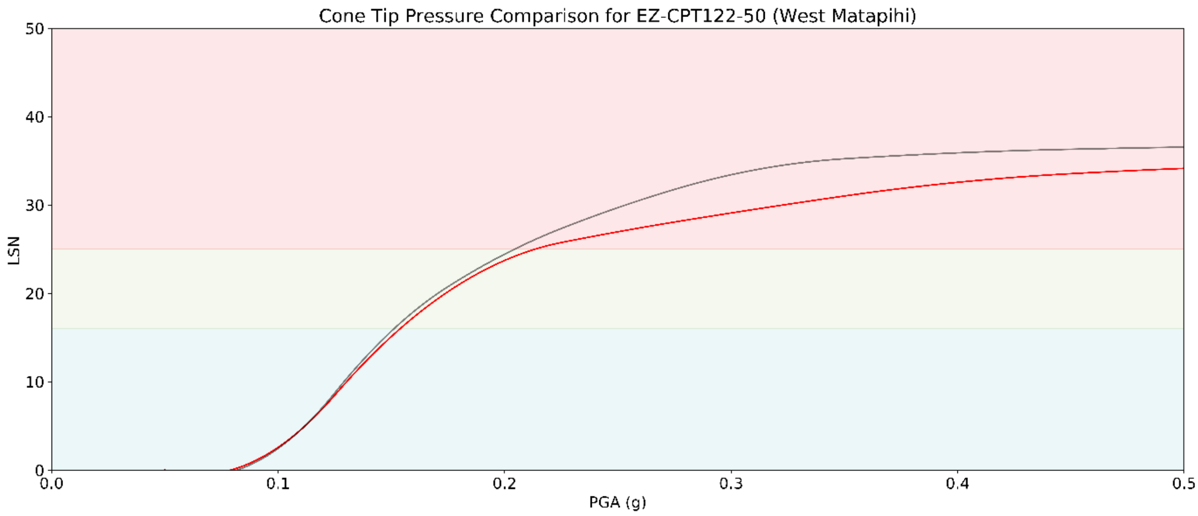


Figure 4.7: PGA vs. LSN plots from adjacent 50 MPa (red) and 100 MPa (grey) tip resistance cones (location two) in the Matapihi Harbour Margin geomorphic terrain for an assumed groundwater depth of 1 m

It is important to recognise that once the LSN values calculated by both cones become large (e.g. 30 – 40 LSN) the exact value for each curve is less relevant because above these values moderate to severe land damage is indicated. For these test locations the more critical range lies between 0.12 and 0.2 g, i.e. approximately 100 – 500 year return period levels of earthquake shaking. Furthermore the differences that are observed between the two plots may be attributed to several factors such as: differences between the q_C, sleeve friction (F_S) and calculated I_C values by the two different cones (and resulting differences in fines correction factors applied to silty sand material); and/or minor differences in ground conditions between the two locations as discussed above.

In practice, the material impact of these differences on the analytical model will be a function of a number of factors including soil conditions of the geomorphic terrain under consideration, the modelled depth to groundwater and the level of earthquake shaking that is being assessed. This source of uncertainty is best managed by identifying geomorphic terrains where this may be significant (e.g. the Harbour Margin) and applying engineering judgement as required.

Uncertainty due to the spatial distribution and density of geotechnical investigations

Geotechnical investigations have been undertaken across Tauranga for a variety of different purposes. Each purpose has its own specific requirements for geotechnical investigations and the spatial distribution and density of the geotechnical investigation data is reflected by this. For example, a significant number of geotechnical investigations in the Eastern Zone are associated with transportation projects and location of the geotechnical investigations reflects the linear nature of transportation infrastructure.

To understand the spatial distribution and density of CPT investigations, a map of the Eastern Zone was prepared showing the distance from any point to the nearest CPT within the same geomorphic terrain. This map is shown in Figure 4.8 with a larger version included as Figure B2 in Appendix B.

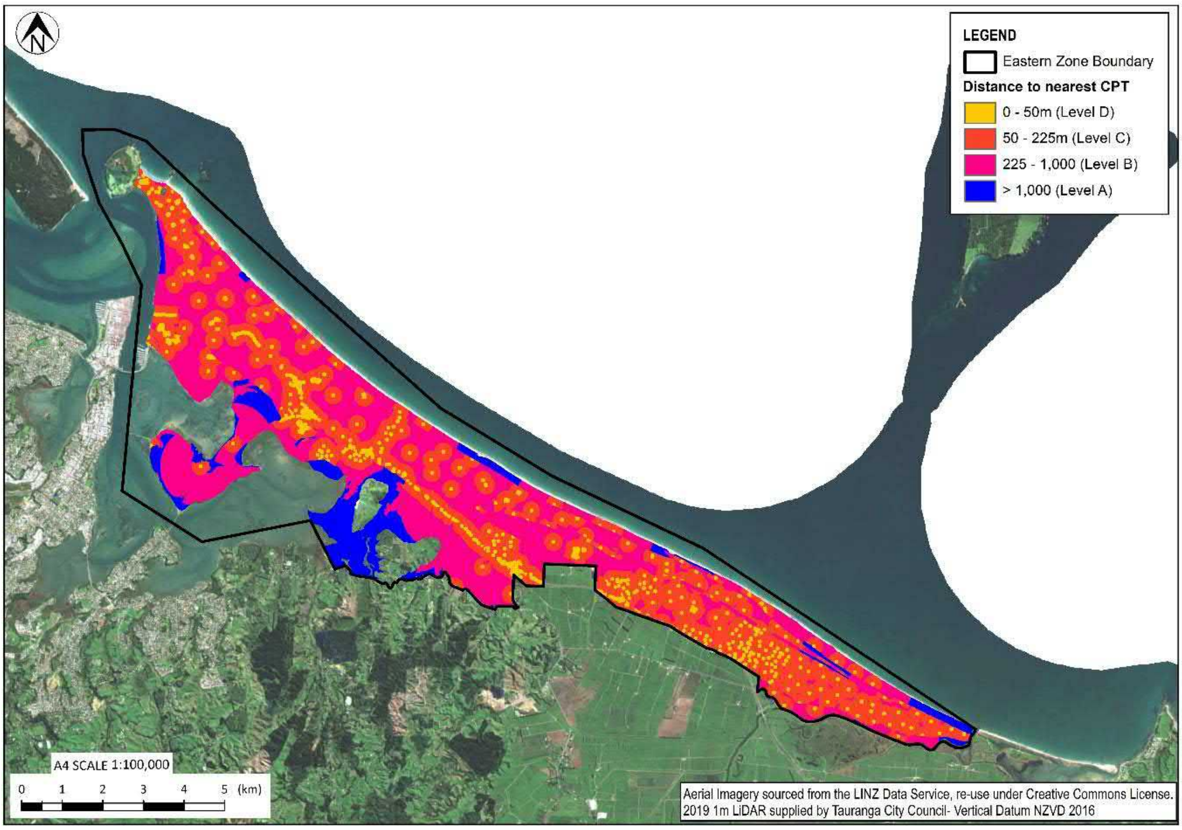


Figure 4.8: Distance to nearest CPT within the same geomorphic terrain

The distance from a cell to the nearest CPT has been categorised according to the CPT density guidelines presented in Table 3.3 of the MBIE/MfE Guidance (2017). This provides an indication of the level of detail supported by the available data although it is important to note that CPT density is not the only factor that influences the level of detail. As discussed in Section 3.1, the degree of residual uncertainty in the assessment is the key variable in the determination of the level of detail categories.

4.1.4 Groundwater

As discussed in Section 3.2.4, TCC engaged T+T to develop groundwater models in order to understand the effects of sea level rise on the groundwater table in Tauranga. The median groundwater model is used in the liquefaction assessment as a key input into the quantitative assessment of liquefaction vulnerability from CPT-based indicators. The key uncertainties associated with the groundwater data are discussed below.

Uncertainty due to spatial distribution of piezometers

Because the groundwater model is based primarily on measurements made at the monitoring wells (supplemented with information about water levels in major waterways), there is uncertainty regarding spatial variations in groundwater level between these measurement point locations. So while the model is expected to characterise the average large-scale pattern of groundwater level across the city reasonably well, it may not capture localised small-scale variations. These localised variations could exist for various reasons, such as:

- Groundwater levels can be drawn down locally by short-term active dewatering (e.g. during excavation to install a pipeline or basement) or by long-term passive drainage (e.g. field drains or deep stormwater pipe trenches with granular backfill)
- Groundwater levels might be higher locally due to water inflow (e.g. from a stream or leaking pipe).

Uncertainty due to the duration of groundwater monitoring

While the groundwater models developed for Tauranga provide a valuable source of information that is useful for a variety of different applications, the piezometers from which the groundwater model was developed were first installed in August 2015 and the piezometers installed in phases at different times. Therefore there is a relatively short record of groundwater monitoring available for the area and the length of monitoring record for each piezometer installation phase is varied.

Uncertainty due to the effects of climate change

Climate change introduces further uncertainty regarding the groundwater conditions that could exist at some time in the future when an earthquake occurs. The key effects of climate change on the future groundwater conditions may include:

- Changes in the intensity and distribution of rainfall influencing the recharge rate of the groundwater surface
- Reduction in the depth to groundwater due to the effects of sea level rise.

The approach used to model the groundwater conditions following 1.25 m of sea level rise is described in Section 3.2.4. It is important to recognise that this is a simplified approach because:

- It assumes a constant increase when in fact the likely effect of sea level rise on groundwater conditions are likely to be much more complex
- It doesn't account for the changes in the intensity and distribution of rainfall described above.

Uncertainty due to complex groundwater regime

For the current study, it has been assumed that all soil beneath the groundwater table is fully saturated (which is standard practice for most routine liquefaction analysis). However, the groundwater regime and hydraulic connectivity between soil strata can be vastly more complicated than simple hydrostatic assumptions. The majority of the Eastern Zone consists of permeable sandy soils and in these areas this is a reasonable assumption. However in areas where the ground conditions are such that there is the potential for complex groundwater regimes (e.g. lower alluvial terrace and the volcanic hills and ranges). This source of uncertainty has been allowed for in the determination of the liquefaction vulnerability category.

Groundwater confidence index map

To understand the uncertainty associated with the spatial distribution of the piezometers and the duration of groundwater monitoring undertaken, a groundwater confidence index was developed based on the methodology presented in GNS (2014). This method applies a maximum confidence index value of 10 to locations where groundwater monitoring has been undertaken or the groundwater level is able to be estimated with a reasonable degree of confidence due to other means (e.g. it is at a piezometer location or it intersects with a water body). The confidence index value then reduces with distance from the point at a constant rate of decay of 1 confidence index value per 25 m. The overall confidence index is calculated by summing the confidence index from each data source.

Figure 4.9 below show the groundwater confidence index value map for the Eastern Zone and Figure B3 in Appendix B shows a larger version of this map.

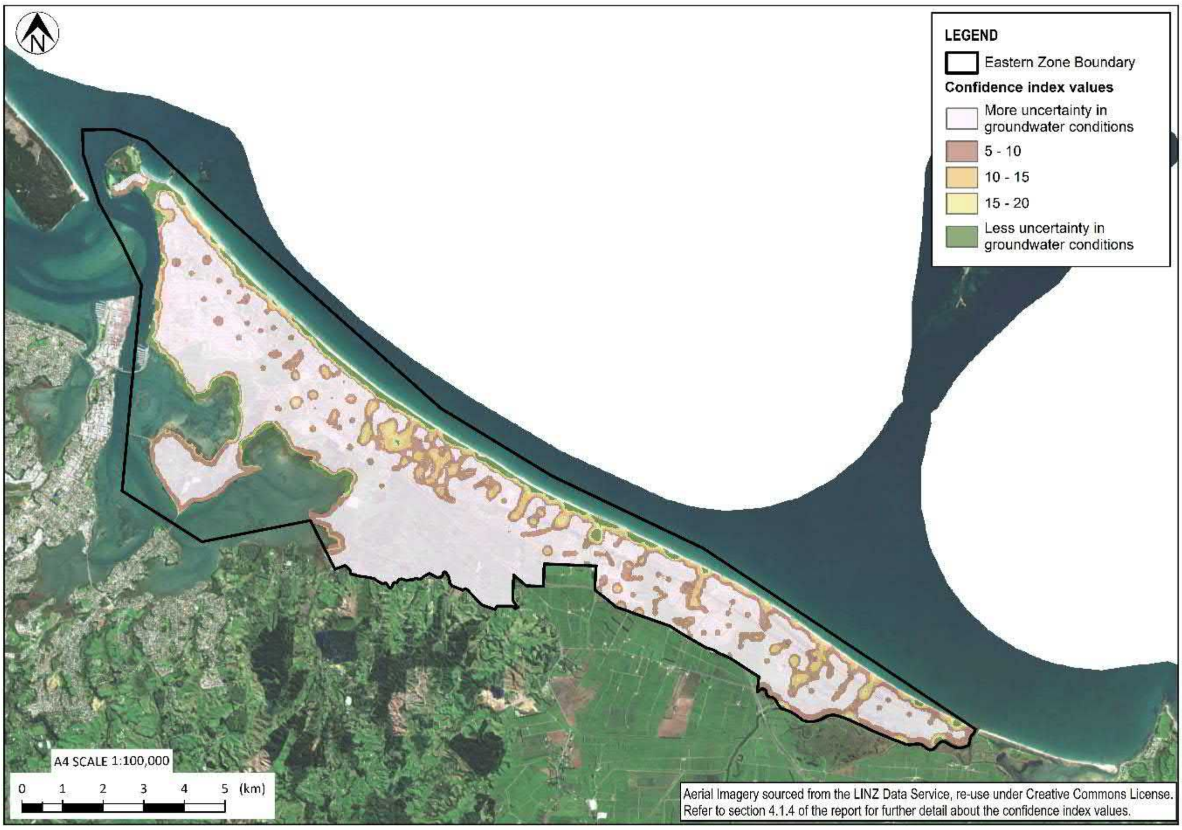


Figure 4.9: Confidence index value map for Tauranga. A higher index value represents higher confidence in the groundwater model, a lower confidence index value represents lower confidence in the groundwater model

4.1.5 Seismic hazard

As discussed in Section 3.2.5, TCC commissioned BSL to undertake a high-level regional seismic hazard assessment (BSL, 2019). The BSL report calculates a lower PGA (significantly lower at longer return period intervals) and slightly higher magnitude than the commonly adopted NZTA Bridge Manual (2018). Further analysis is provided below to assess variability of Vs30 within the eastern study area, its effect on the calculated PGA and the contribution this makes to the uncertainty in the liquefaction assessment undertaken.

While the Foster (2019) model includes information from field measurements, none of the Vs30 measurements used in its development are from within the TCC study area. Therefore, we have reviewed T+T's local database and the NZGD to collate available Vs30 measurements for comparison with the Foster model.

T+T identified sixteen locations that had measured shear wave velocity information that could be used to develop an estimate of Vs30. Ten of these locations are within the Eastern Zone. This data was mainly from seismic CPTs, with one from a downhole borehole measurement and three locations with preliminary results based on the seismic surface wave method (MASW) obtained from Dr Liam Wotherspoon from the University of Auckland (L. Wotherspoon, personal communication, 28 August 2019).

Where the depth of test was less than 30 m, a Vs30 value was estimated by linear extrapolation assuming that the soil profile remained consistent with depth. It is acknowledged that this may underestimate the Vs30 value if stiffer material is present below the depth of testing. It is important to note that the purpose of the testing was for geotechnical design and because tests are not typically completed on denser or competent deposits, the available test locations may not be representative of the full range of ground conditions across the wider area. This has potential to create bias such that the test locations could underestimate the modelled Vs30 for areas where testing has not been undertaken.

Comparison of measured Vs30 data and Foster model

Figure B4 in Appendix B shows the Vs30 estimate based on measured data and the value from the Foster model (2019) at each location in the Eastern Zone. For reference the geomorphic map for the Eastern Zone is also overlaid on this data. The data from all sixteen locations is plotted in Figure 4.10. Key observations from both of these figures include:

a The Foster model predicts relatively uniform Vs30 values of approximately 200m/s across the fixed foredunes geomorphic terrain. This uniformity in modelled values is to be expected, given the similarity of the geology and terrain across this area. However, the Vs30 values estimated from field measurements in this terrain are more variable and generally higher (although it is acknowledged that six of the eight field tests are from a single localised area at the edge of the geomorphic terrain). This geomorphic terrain is the largest in the eastern TCC study area, and perhaps most significant in terms of potential liquefaction consequences. This comparison highlights the importance of considering potential variability in site response, rather than simply adopting the modelled uniform Vs30 values.

b There are several locations in the western TCC study area where the Foster model provides estimated Vs values that are substantially higher than (almost double) those estimated from field measurements. It is acknowledged that the field test data does not extend to 30m depth at these locations, so the simple linear extrapolation we have used could have underestimated the shear wave velocity at depth. However, even if the material at depth was a very dense ignimbrite, it appears that the average shear wave velocity to 30m depth would still be over-predicted by the Foster model at these locations. This suggests some limitations in the terrain-based modelling in transitional areas between lower/flatter land and higher/steeper land. While this does not appear to be a significant issue for the Eastern Zone (except for the volcanic hills and ranges, where liquefaction vulnerability is inferred to be low regardless of shaking intensity), it could be significant for the Western Zone.

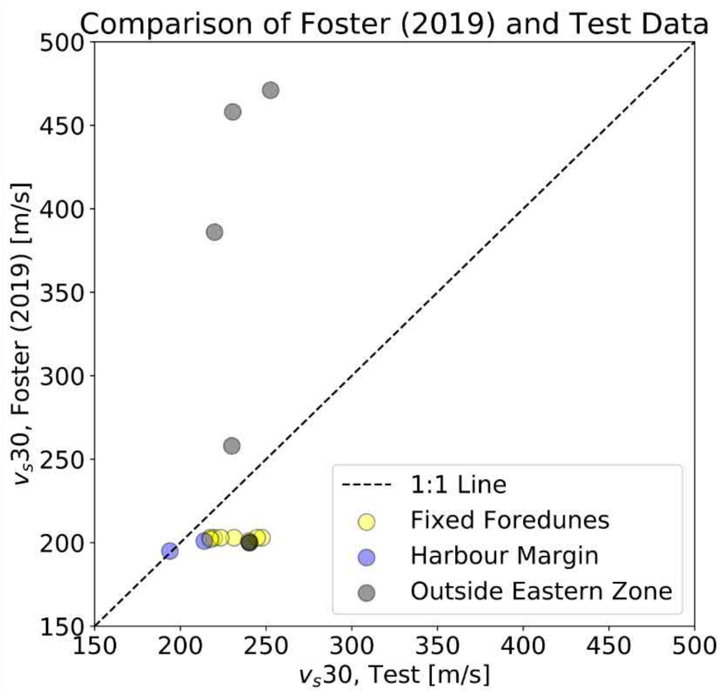


Figure 4.10: Comparison of Vs30 values from Foster et al. (2019) model and estimated from field measurements

Variability of Foster model by geomorphic terrain

Table 4.1 and Figure 4.11 show the variability of modelled Vs30 by geomorphic terrain. These figures show that the modelled interquartile range for the various geomorphic terrains typically lies within 180 to 300 m/s. The measured data is also shown to typically sit within this range. The exception is volcanic hills and ranges, for which the inferred liquefaction vulnerability is considered to be low because of the likely depth to groundwater in the hills and the composition of material in this geomorphic zone (weak rock, dense to firm soils).

Table 4.1: Variability of Foster model (2019) by geomorphic terrain (warmer colours indicate lower values of Vs30 cooler colours indicate higher values of Vs30)

	Vs30 (m/s)					Inferred Liquefaction Vulnerability
Geomorphic terrain	**Minimum**	**Lower Quartile**	**Median**	**Upper Quartile**	**Maximum**	
Active Foredunes	194	199	200	201	210	High
Alluvial Channels	258	262	269	269	279	High
Alluvial Flood Plains	180	195	231	248	597	High
Dune Troughs	193	200	201	201	204	High
Fixed Foredunes	180	197	201	203	456	High
Harbour Margin	180	181	201	204	416	High
Kaituna Flood Plain	181	183	219	230	283	High
Land Reclamation	199	202	202	208	212	Low to High
Lower Alluvial Terrace	180	258	260	288	597	Medium
Volcanic Hills and Ranges	254	375	528	590	615	Low

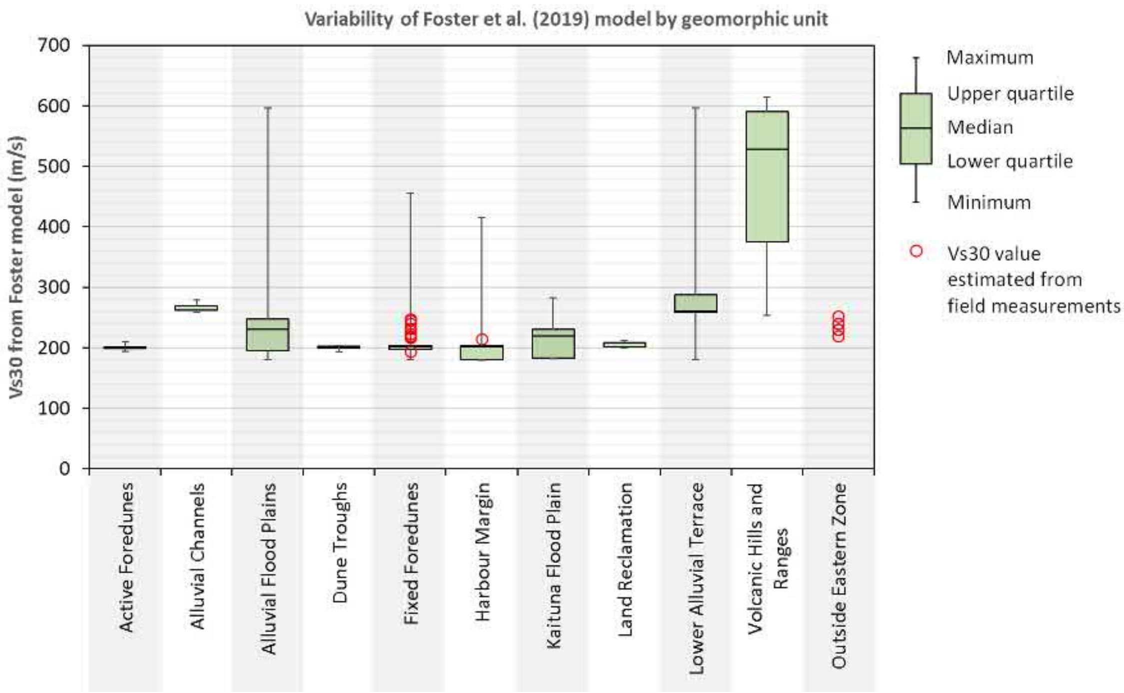


Figure 4.11: Variability of Foster et al. (2019) model Vs30 values by geomorphic terrain

Effect of variation in Vs30 on modelled Peak Ground Acceleration

As shown in Figure 3.11 of Section 3.2.5 The BSL report (2019) provides a seismic hazard curve for peak ground acceleration (PGA) based on the variability in Vs30. PGA values have been tabulated based on this curve for different return period earthquakes and Vs30 values, as shown in Table 4.2.

Table 4.2: Modelled PGA values based on Vs30 and return period

		Modelled PGA value (g)				
		Vs30 = 180 m/s	Vs30 = 250 m/s	Vs30 = 300 m/s	Vs30 = 450 m/s	Vs30 = 600 m/s
Return period (years)	25	0.07	0.06	0.06	0.05	0.04
	100	0.12	0.11	0.10	0.09	0.08
	250	0.17	0.15	0.15	0.13	0.12
	500	0.20	0.19	0.19	0.17	0.15
	1000	0.25	0.24	0.24	0.21	0.19

For the ground conditions of most interest for the liquefaction triggering analysis the typical range in Vs30 values is between 180 m/s and 300 m/s. Table 4.3 shows an indicative range of corresponding PGA values can be adopted for this typical range in Vs30 values. This shows that there is a relatively minor variation (0.02g) in modelled PGA values across the range of Vs30 values typically of interest for liquefaction assessment in the TCC Eastern Zone.

Table 4.3: Indicative range in PGA values adopted for assessing the impact of variability in ground motion intensity on the liquefaction analysis

		Modelled PGA value (g)	
		Vs30 ≈ 300 m/s	Vs30 ≈ 180 m/s
Return period (years)	25	0.05	0.07
	100	0.10	0.12
	250	0.15	0.17
	500	0.18	0.20
	1000	0.23	0.25

Effect of variation in PGA on predicted liquefaction consequences

The intensity of ground shaking required to trigger liquefaction, and the severity of the resulting consequences, varies depending on the ground conditions. MBIE/MfE Guidance (2017) (refer Figure 4.3) provides examples of ground damage response curves corresponding to "Low", "Medium" or "High" Liquefaction Vulnerability. Figure 4.12 shows similar response curves from four representative CPTs within the Eastern Zone. The steeper the response curve is at any given PGA value, the more sensitive the predicted ground damage is to variations in the assumed PGA value.

Figure 4.12 also presents an example sensitivity analysis, showing that for a 500 year design event the predicted ground damage is most sensitive to PGA variation for the *Medium* and *Gradual High* response curves (because this PGA range lies in the steeply rising part of the curves). There is less sensitivity for the *Low* curve (because the ground damage is lower overall) and very little sensitivity for the *Steep High* curve (because most of the liquefaction triggering has already occurred at lower PGA values).

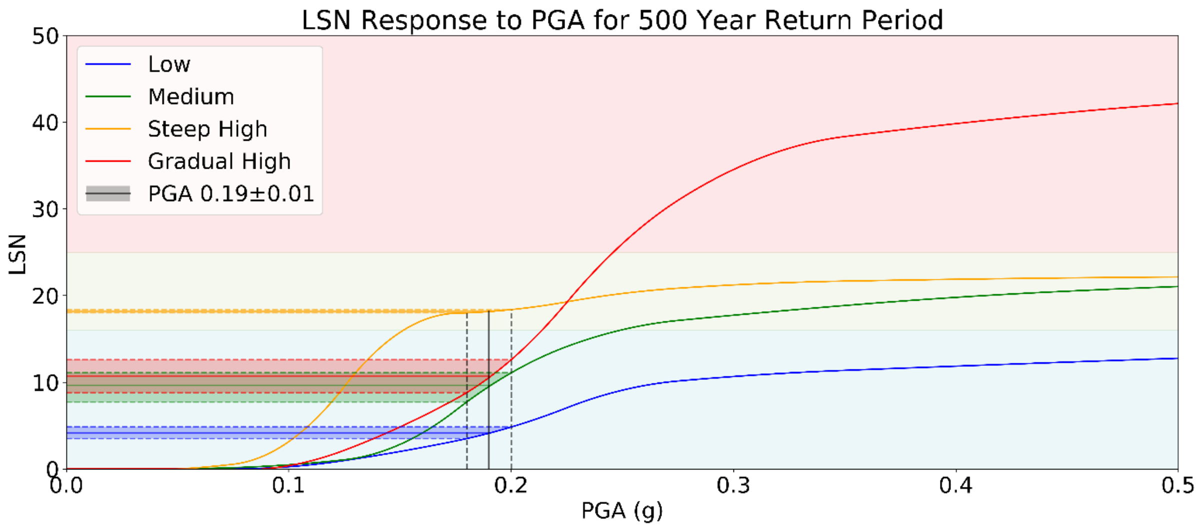


Figure 4.12: Effect of variation in PGA on liquefaction consequences for four different ground damage response curves (assuming a magnitude 6.2 earthquake and probability of liquefaction of (P_L = 15%). The vertical lines show the indicative range in PGA values of 0.18 to 0.20 g for the 500 year design event (from Table 4.3). The horizontal lines show the corresponding LSN values for each of the four ground damage response curves. Higher LSN values indicate a higher likelihood of more severe liquefaction consequences. The distance between horizontal lines of the same colour provides an indication of how sensitive the predicted ground damage is to variations in the PGA value for that particular response curve.

Similar analysis to that shown in Figure 4.12 has been undertaken for all return periods to be assessed in this study and the sensitivity in terms of numerical LSN values is summarised in Table 4.4, with a range in LSN of up to 5 in some situations.

Table 4.4: Effect of variation in PGA on predicted liquefaction consequences for four example CPTs

		Low	Medium	Steep High	Gradual High
Return Period (Years)	**25**	0.0	0.1	0.4	0.0
	100	0.5	0.4	4.8	1.3
	250	1.0	3.0	2.1	2.5
	500	1.3	3.4	0.4	3.8
	1000	1.6	1.5	0.7	5.3

Figure 4.13 presents an example sensitivity analysis for the 6.1 to 6.3 range of magnitude estimated in the BSL Report (2019). This shows that predicted ground damage is most sensitive to the earthquake magnitude across the PGA range of 0.15 – 0.30 g, and the *Gradual High* and *Medium* response curves are most sensitive to magnitude for a 500 year design event of 0.20 g.

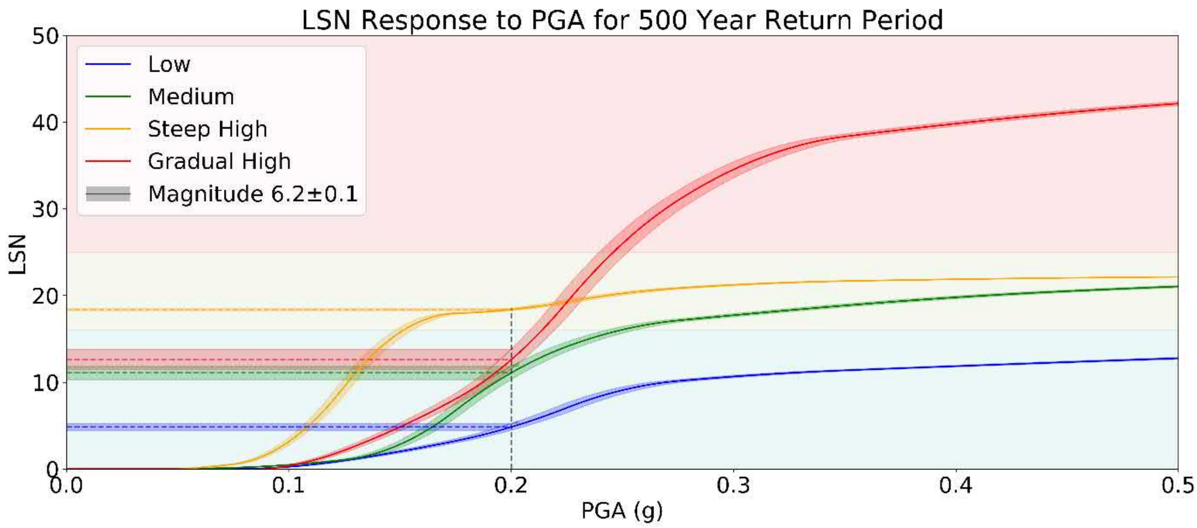


Figure 4.13: Effect of variation in magnitude on liquefaction consequences for four different ground damage response curves (assuming a magnitude 6.2 earthquake and probability of liquefaction of (P_L = 15%). The buffered area shows the variation in LSN for magnitude 6.2 ± 0.1 (i.e. magnitude 6.1 to 6.3). The vertical line shows the PGA value of 0.20 g for the 500 year design event. The horizontal lines show the corresponding LSN values for each of the four ground damage response curves. Higher LSN values indicate a higher likelihood of more severe liquefaction consequences. The width of the buffered area provides an indication of how sensitive the predicted ground damage is to variations in the magnitude for that particular response curve (also refer to Table 4.5).

Similar analysis to that shown in Figure 4.13 has been undertaken for all return periods to be assessed in this study and the sensitivity in terms of numerical LSN values is summarised in Table 4.5, with a range in LSN of up to 3 in some situations. Comparison of Table 4.4 with Table 4.5 indicates that the predicted damage is moderately sensitive across the expected range of uncertainty for both PGA and magnitude, and that the materiality of that sensitivity will vary depending on the specific circumstances (so we make allowance as needed using judgement).

Table 4.5: Effect of variation in magnitude on predicted liquefaction consequences for four example CPTs

		Low	Medium	Steep High	Gradual High
Return Period (Years)	25	0.0	0.0	0.1	0.0
	100	0.2	0.2	1.9	0.5
	250	0.5	1.6	0.4	1.2
	500	0.8	1.5	0.3	2.3
	1000	0.8	0.8	0.4	3.1

4.1.6 Estimate liquefaction-induced ground damage

The CPT-based methods that have been used in this study are a practical means of estimating liquefaction-induced ground damage that is considered appropriate for this application and is the industry standard approach. The key steps in the application of this methodology are as follows:

1 Evaluate whether or not the soil is **susceptible** to liquefaction
2 Estimate the earthquake shaking level required to **trigger** liquefaction for soils that are susceptible to liquefaction
3 Estimate the likely **consequences** of liquefaction triggering within the soil profile.

There are inherent limitations associated with this approach and the key uncertainties are discussed below. These methods are predominantly based on empirical evidence and therefore they are biased toward the case study evidence that has been collated to date.

Uncertainty in the assessment of liquefaction susceptibility

As discussed in Section 4.1.3 for CPT-based liquefaction analyses the I_C value of 2.6 is used as a screening threshold to predict whether or not a soil is susceptible to liquefaction. Typically, soils with I_C values greater than 2.6 are assumed to be too plastic to liquefy. While in the majority of cases this value provides a suitable means of differentiating between soils that are susceptible to liquefaction and soils that are not, there is some inherent uncertainty in the ability of the CPT to characterise soil type.

There are more advanced methods available to characterise liquefaction susceptibility (e.g. laboratory testing of soil samples). However, this comes at a considerable additional cost because soil sampling, lab testing and additional analytical time is required. Furthermore, based on inspection of the CPT data for each geomorphic terrain, the majority of the Eastern Zone is underlain by clean sandy soils such as those encountered in the Active Foredune where this additional analysis is not typically warranted as it would likely confirm the current assumption that they are susceptible.

Uncertainty in the assessment of liquefaction triggering

The simplified liquefaction triggering methodology utilised in CPT-based liquefaction analyses reduces the complex and irregular loading of an earthquake down to two measures of earthquake intensity; namely magnitude and PGA. While this simplified approach to characterising seismic demand reduces the complexity of the analysis, it should be recognised that the simplification introduces additional uncertainty. Similarly, there is inherent uncertainty in ability of the CPT to accurately characterise cyclic resistance of a particular soil, this is particularly true for soils outside the case history database.

Uncertainty in the assessment of liquefaction consequence

There are a range of factors that influence whether or not liquefaction below the ground surface will result in consequential land damage such as: depth to groundwater; soil density; and soil type. The LSN parameter reduces all of these factors into a single value in an attempt to quantify the potential consequences of liquefaction at the ground surface. While van Ballegooy et al. (2014) demonstrated the advantages of the LSN parameter over other CPT-based liquefaction severity index parameters, there is still a significant degree of uncertainty associated with the estimation of the consequences of liquefaction.

The LSN parameter was developed primarily from observations in Christchurch which has a different geology to Tauranga and even when the LSN parameter is applied in Christchurch there is significant overlap in observed damage in any given LSN value. The level of uncertainty associated with LSN (even when used in Christchurch) is not trivial and hence the uncertainty associated with using this as the primary basis for developing land damage models should be recognised.

It is important to note that LSN is one of a range of liquefaction severity index parameters that can be used to estimate the degree of liquefaction-induced ground damage depending on the specific circumstances of each assessment. The source of uncertainty discussed above is not unique to LSN and there is significant overlap in observed land damage when these parameters are applied to the Christchurch data set (van Ballegooy, et al., 2014).

To manage this source of uncertainty, T+T has presented the information using two different land damage models that provide a different interpretation on the same data source (refer Section 4.2.4) and provided commentary (such as the above) through the report such as the above to articulate this uncertainty to users.

Furthermore, because LSN is a depth weighted parameter, there is the potential for over-estimation of liquefaction induced ground damage in areas where shallow groundwater is encountered (typically at depths less than 1 m) and soils that are susceptible to liquefaction are present. This is because relatively thin layers of liquefiable soil contribute significantly to the calculated LSN value, when in practice they may only result in relatively minor liquefaction consequences at the ground surface. It is important to recognise that while the LSN parameter does become large in areas where the depth to groundwater is shallow and soils that are susceptible to liquefaction are present, it is not necessarily over-predicting liquefaction in all of these areas. We are recognising that there is the potential for this to occur in some (but not all) areas.

This potential source of uncertainty is managed by inspecting the soil profile when this issue has the potential to make a material difference to the assessment and applying engineering judgement as appropriate.

Uncertainty in the assessment of lateral spreading

As discussed in Section 4.1.1, one of the key sources of uncertainty is the estimation of the height of free faces using LiDAR derived DEM in the presence of water bodies. To manage this source of uncertainty engineering judgement has been used to make allowance for the additional free face height that may lie below the water level.

In addition to this lateral spreading is a complex phenomenon that is influenced by a number of factors and there is considerable uncertainty in the estimation of the extent and severity of lateral spreading using the currently available methodologies. To manage this uncertainty the lateral spreading assessment has been mapped with a conservative approach that is considered reasonable given the limitations of the methods available for assessment.

4.1.7 Assess ground damage response against the performance criteria

The MBIE/MfE Guidance (2017) provides the performance criteria shown in Figure 4.14 to determine the liquefaction vulnerability category for a particular area of land.

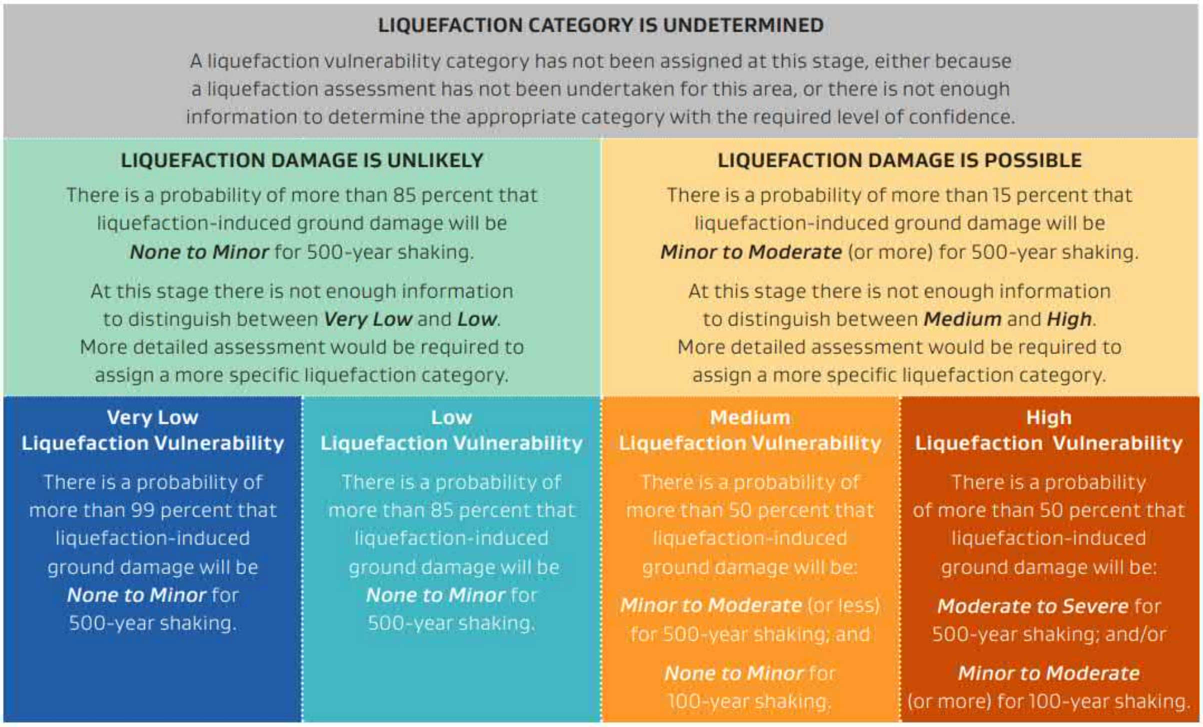


Figure 4.14: Performance criteria for determining the liquefaction vulnerability category – reproduced from MBIE/MfE Guidance (2017)

As discussed in Section 4.5.2 of the MBIE/MfE Guidance (2017), the performance criteria make reference to particular probabilities of a certain degree of damage occurring. These probabilities are intended to provide an indication of the level of confidence required to assign a particular category, rather than specific numerical thresholds to be calculated for each category. It is also important to recognise that these probabilities relate to the total effect of all uncertainties in the assessment, a characteristic that makes probabilistic calculation particularly challenging.

For this liquefaction hazard assessment the level of confidence has been evaluated qualitatively with these indicative probabilities used as guidance. As with any qualitative assessment, it was necessary to apply a degree of judgement to determine the liquefaction vulnerability category for each area of land within the Eastern Zone and there is inherent uncertainty associated with this subjective process.

For typical buildings and infrastructure, the consequences (or costs) of over-prediction are incurred upfront in the form of unnecessary capital expenditure on overly robust solutions. Conversely the costs of under-prediction are incurred at some time in the future when sufficiently strong earthquake shaking occurs and the buildings and infrastructure must be rebuilt or repaired. The potential consequences of incorrectly characterising the liquefaction vulnerability are discussed further in Appendix J of the MBIE/MfE Guidance (2017).

This source of uncertainty has been managed by the following means:

- Describing the logic behind the determination of the liquefaction vulnerability category with reference to the relevant sources of uncertainty described above. Care was taken not to assign vulnerability categories which are more precise than justifiable given the level of residual uncertainty (e.g. if it's not clear whether ***Medium*** or ***High*** should be assigned then don't assign ***High*** "just to be safe", instead assign ***Liquefaction Damage is Possible***). This is recorded in the metadata associated with each area of land that has been categorised; and
- Conveying to the end user the range of possible liquefaction induced land damage performance within a given area of similar expected performance.

4.1.8 Level of detail supported by the currently available base information

A liquefaction assessment draws on various sources of information to make a judgement as to the likely liquefaction vulnerability. For this study, the two key classes of information utilised relate to the ground conditions and the groundwater level. The types of available information are summarised in Table 4.6, along with the associated level of detail and residual uncertainty.

Table 4.6: Types of information considered in the liquefaction assessment

Type of information	**High detail** ***Less uncertainty***	**Moderate detail**	**Low detail** ***More uncertainty***
Information about the near-surface ground conditions.	Quantitative subsurface information such as CPT data from closely spaced investigations.	Qualitative subsurface information such test pit and borehole logs, often widely spaced.	Inferences about the ground conditions based on the surface geomorphology.
Information about groundwater levels.	Groundwater monitoring from wells that are closely spaced or have a long monitoring history.	Groundwater monitoring from wells that are widely spaced or have a short monitoring history.	Inferences about groundwater depth based on general location and ground elevation.

For each of these types of information, a qualitative assessment was made of how the uncertainty varied spatially across the study area. This qualitative assessment has been informed by the quantitative assessments developed. The pattern of uncertainty associated with the ground conditions is shown in Figure 4.15 with a more detailed map provided as Figure B5 in Appendix B. The pattern of uncertainty associated with the groundwater is shown in Figure 4.16 with a more detailed map shown in Figure B6 in Appendix B.

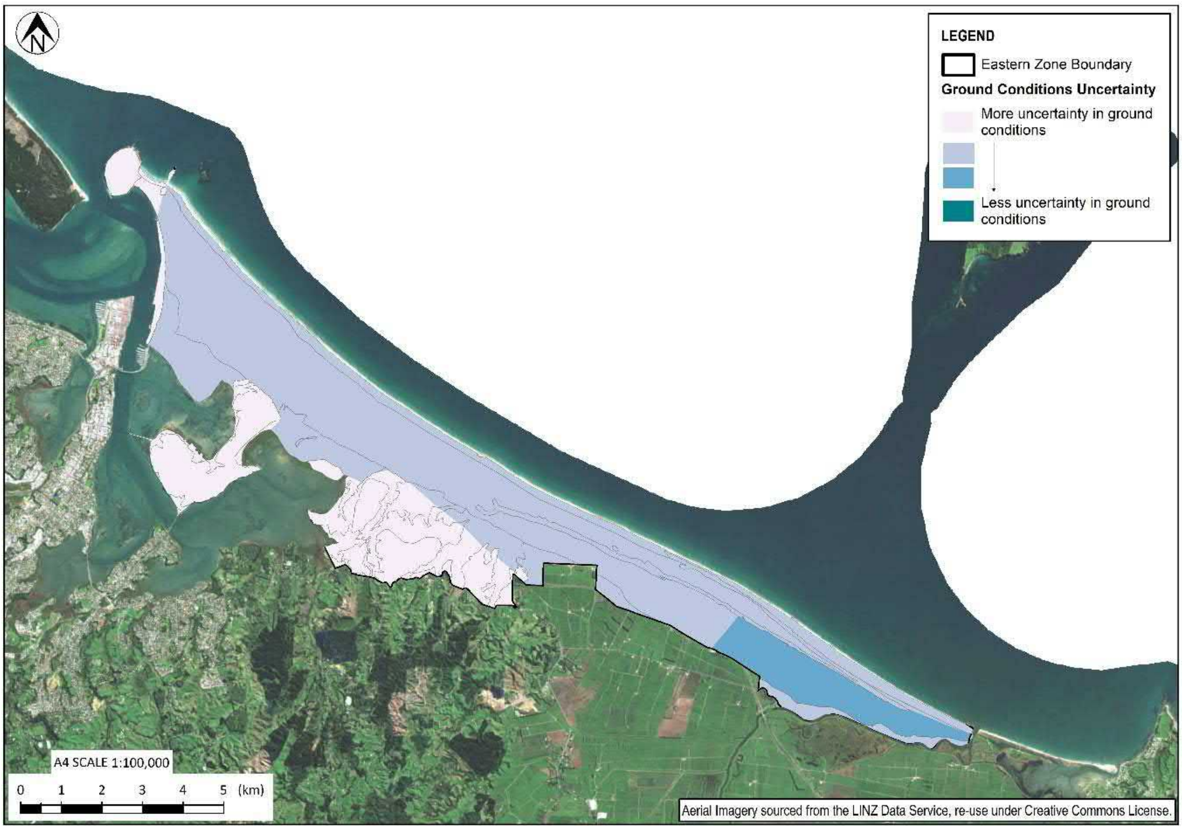


Figure 4.15: Ground conditions uncertainty

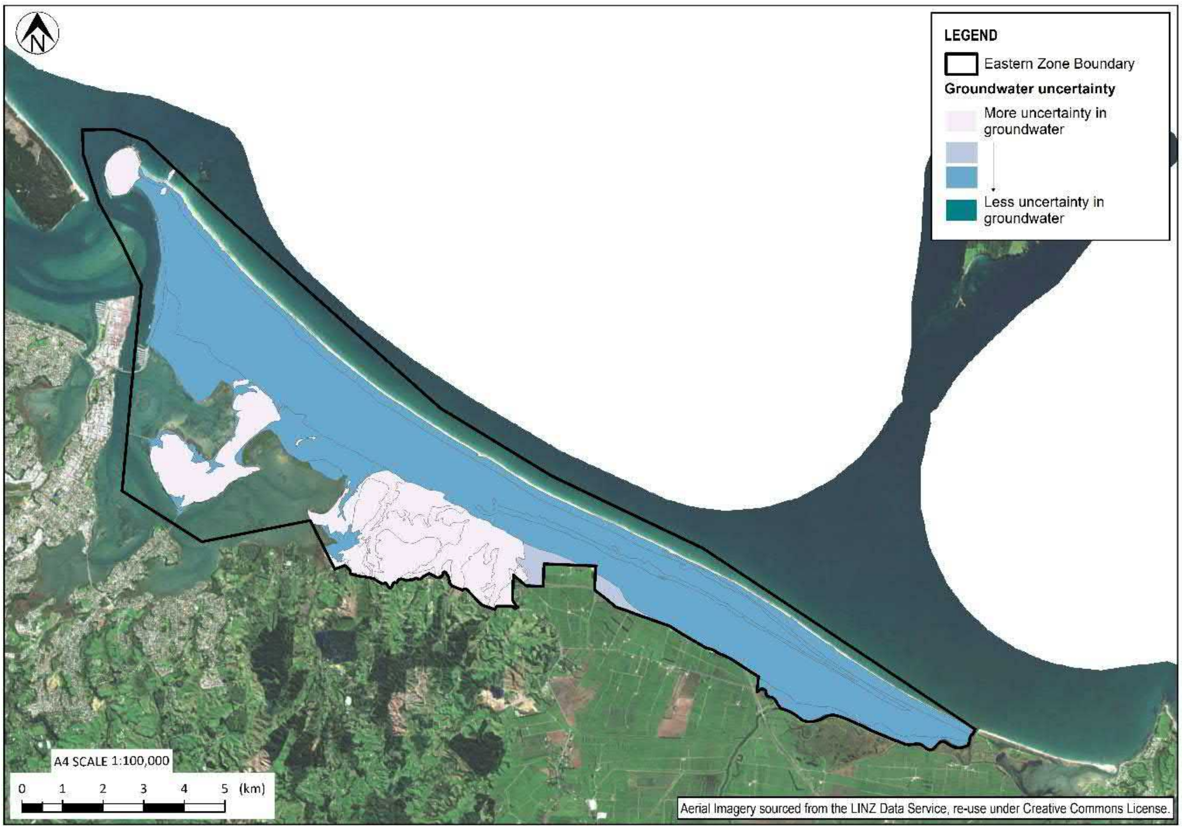


Figure 4.16: Groundwater uncertainty

Figure 4.15 and Figure 4.16 relate to the absolute level of uncertainty in the base information itself, not the resulting impact of that uncertainty on the final liquefaction assessment. There are some locations across the study area where there is substantial uncertainty in the base information, but for one reason or another this uncertainty does not have a material impact on the liquefaction assessment.

For example, Mauao to the North and the high point associated with Mangatawa near the southern boundary of the Eastern Zone have more uncertainty associated with both the ground conditions (because there are no geotechnical investigations available) and the groundwater (because there are no groundwater records in either area). However, based on the regional geology it is known that the depth to rock is typically less than 2 m and this is supported by visible rock exposures in both locations. Furthermore, even though there is more uncertainty associated with the groundwater level, due to the steeply sloping ground and relatively high elevation it is likely that the groundwater table is relatively deep. Therefore, it is possible to conclude with reasonable certainty that *Liquefaction Damage is Unlikely.*

The information described above has been used to inform the level of detail in the assessment supported by the currently available base information shown in Figure 4.17 with a more detailed map provided as Figure B7 in Appendix B. Where the residual uncertainty is evaluated as less a higher level detail in the assessment is supported. Conversely, where the residual uncertainty is more, a lower level of detail in the assessment is supported.

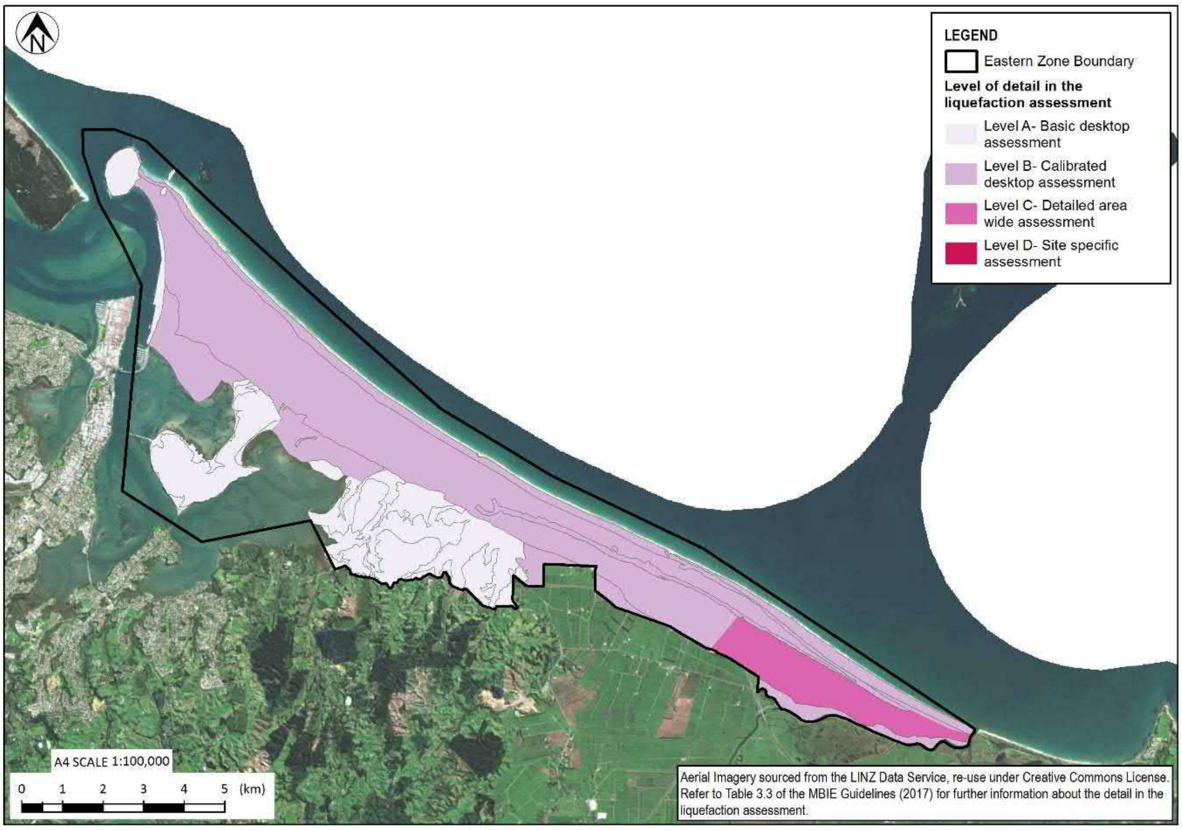


Figure 4.17: Level of detail supported by the currently available base information

4.2 Liquefaction analysis

The liquefaction analysis was undertaken in a series of stages as summarised below. These stages happened more or less sequentially with iteration as required.

1. Definition of groundwater levels for analysis (refer to Section 4.2.1)
2. Definition of earthquake scenarios for analysis (refer to Section 4.2.2)
3. Definition of sub areas of similar expected performance (refer to Section 4.2.3)
4. Determination of expected degree of liquefaction induced ground damage (refer to Section 4.2.3)
5. Assessment against performance criteria to determine the liquefaction vulnerability category (refer to Section 4.2.5).

4.2.1 Groundwater levels for analysis

As described in Section 2.3, the scope of works specified analysis assuming both current day groundwater conditions and the groundwater conditions following 1.25 m of sea level rise.

The current day median groundwater depth model shown in Figure 3.7 was used for the purpose of undertaking the current day liquefaction analysis. The use of the median model is considered appropriate because using an alternate groundwater surface level (i.e. higher or lower) will alter the return period of the liquefaction assessment (T+T, 2015) and sensitivity to groundwater was considered to inform engineering judgement.

The model of the groundwater 1.25 m shallower than the current day median shown in Figure 3.8 was used to consider the groundwater conditions following 1.25 m of sea level rise. As described in Section 3.2.4, there is considerable uncertainty associated with the effects of climate change on the future groundwater conditions.

Sensitivity testing of the liquefaction analysis to ±0.5 m of the assumed depth to groundwater was undertaken to inform engineering judgement.

4.2.2 Earthquake scenarios for analysis

In consideration of the uncertainty assessment provided in Section 4.1.5, for the liquefaction analysis it is considered appropriate to use a single fixed PGA value across the Eastern Zone for each return period earthquake. This is to be based on a representative Vs30 value of approximately 180 m/s across the expected areas where the land is likely to be categorised as “Liquefaction Damage is Possible”, as shown in Table 4.7. Similarly a single fixed magnitude of 6.2 has also been used for the liquefaction analysis across the Eastern Zone for each return period earthquake.

Table 4.7: Earthquake scenarios assumed for analysis

	Values adopted for liquefaction analysis	
ARI (years)	**PGA (g)**	**Magnitude (M)**
25	0.07	6.2
100	0.12	6.2
250	0.17	6.2
500	0.20	6.2
1,000	0.25	6.2

4.2.3 Sub areas of similar expected performance

The sub areas of similar expected performance have been derived by combining three key sources of information: the geomorphic terrain boundaries, the modelled depth to groundwater and buffer zones indicating areas where lateral spreading related damage is possible. Section 3.2.2 and Section 3.2.4 describe the information available to define the geomorphic terrains and groundwater model respectively.

The methodologies used to develop the buffers indicating areas where lateral spreading related damage is considered possible and derive the sub areas of similar expected performance are described in this section.

Buffer zones indicating where lateral spreading is considered possible

Lateral spreading is one of the most damaging consequences of liquefaction (refer Section 2.2). It most commonly occurs near rivers and watercourses where there is a free-face formed by the bank of the channel. Review of the case history database of lateral spreading from the 2010-2011 Canterbury Earthquake Sequence indicated that areas in Canterbury with similar ground conditions to those within the Eastern Zone typically sustained “distributed” type lateral spreading failures as described by Robinson (2016). These distributed failure modes are typically characterised by the following features:

- Exponential decay of displacement with distance from the crest
- Largest cracks closer to the crest, becoming smaller with distance
- Ground cracking typically most significant within 100-150 m of the free-face and up to 220m in some cases.

As a simple screening approach the MBIE/MfE Guidance (2017) recommends that particular attention should be given to liquefaction-susceptible land that is within 200 m of a free-face greater than 2 m high; or within 100 m of a free-face less than 2 m high.

Areas where lateral spreading is considered possible were identified by mapping land with free-faces (associated with waterbodies and other features) and sloping land. Free-faces were mapped using an automated approach that analysed the DEM from the 2019 LiDAR. While this automated process was manually reviewed by inspection of the DEM and the available aerial imagery, the inherent limitations of both the approach and the DEM mean that some free-faces may not have been mapped and the depth of free-faces associated with water-bodies may have been over or under estimated.

Buffer distances were then applied from the crest of the free-face or sloping land. The buffer distance was dependent on the assumed geometry of the free-face or slope and CPT-based analysis using the semi-empirical method developed by Zhang et al. (2004) as a high level screening tool. Based on review of the case history database from the 2010-2011 Canterbury Earthquake Sequence and the recommendations of the MBIE/MfE Guidance (2017) a maximum buffer distance of 200 m was applied. This buffered area was then manually “smoothed” to remove small areas between buffer zones. The results of the lateral spreading land damage mapping are shown in Figure 4.18 with a larger version shown in Figure B8 in Appendix B.

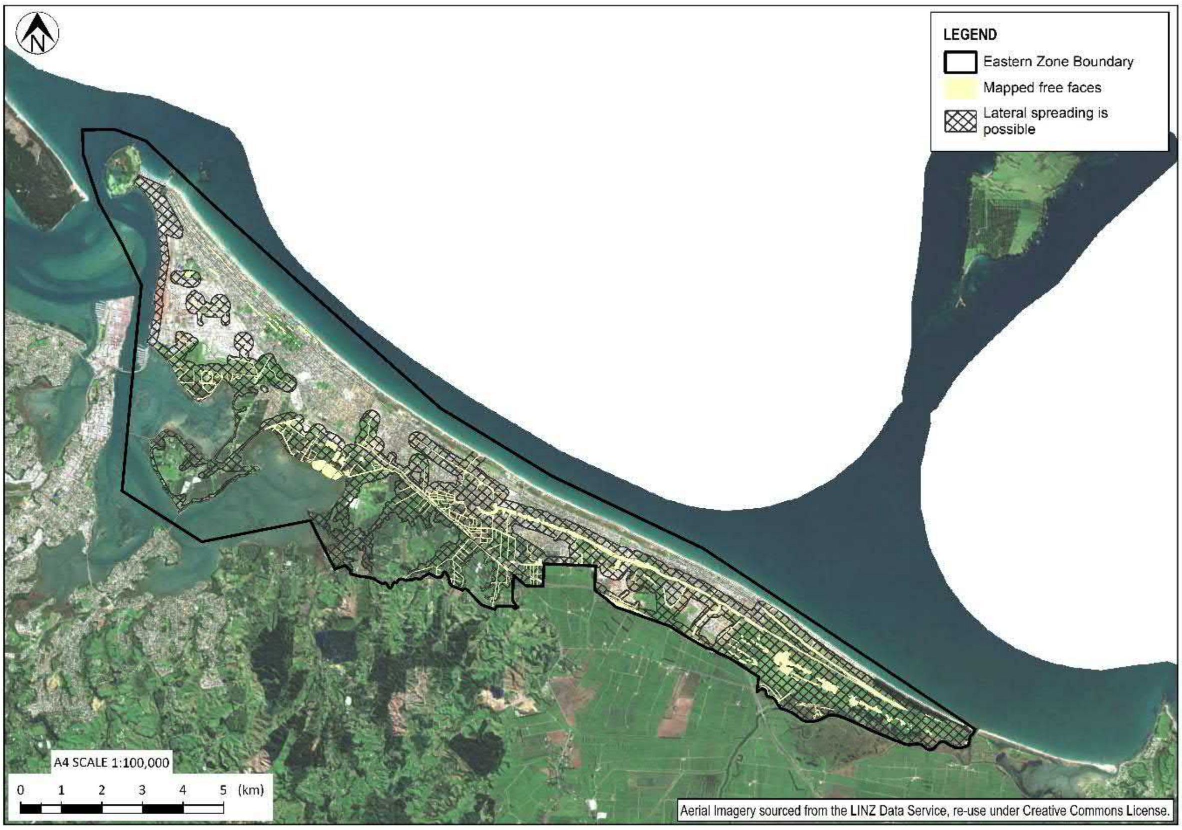


Figure 4.18: Mapped free-faces and areas where lateral spreading is possible at levels of earthquake shaking higher than the 100 year return period

The mapping of these areas is not an indication that lateral spreading is likely to occur to all land within these buffer zones. Further detailed assessment would be required to confirm both the potential occurrence and severity of lateral spreading in these areas.

Sub areas of similar expected performance

In order to develop the analytical model the Eastern Zone was delineated into sub areas of similar expected ground performance during shaking. The following method was used to define these sub areas:

1. Intersect the geomorphic terrain and lateral spread is possible boundaries and match these boundaries to the 25m x 25m raster grid from the groundwater model
2. Define typical groundwater depth classes with the following ranges: 0-1 m, 1-2 m, 2-3 m, 3-4 m, 4-6 m, 6-8 m
3. Delineate sub areas of similar expected performance, with break lines for each geomorphic terrain boundary, lateral spreading possible boundary and groundwater depth class, by aggregating the cell into each groundwater class described above
4. Post-process the groundwater polygons to produce “smoothed” polygons of similar groundwater conditions
5. Manually review and adjust the output of steps 1 - 4 relative to the original depth to groundwater model
6. Calculate groundwater statistics for each polygon including the mean, median and upper and lower quartiles from the original depth to groundwater models (i.e. both the current day median and groundwater 1.25 m shallower than current day median).

The manual review and adjustment described in step 5 involved the following main tasks:

- Ensure that all areas of the geomorphic terrain are appropriately categorised – in some small areas where the groundwater model did not extend manual classification of the groundwater polygon was required
- Divide elongated or large polygons of the same groundwater class into smaller polygons.

Figure 4.19 shows a portion of the Eastern Zone with the a) geomorphic terrains; b) lateral spreading is possible buffer zones; c) median depth to ground water model; and d) sub-areas of similar expected performance. This figure illustrates how the layers in a), b) and c) are combined to produce d).

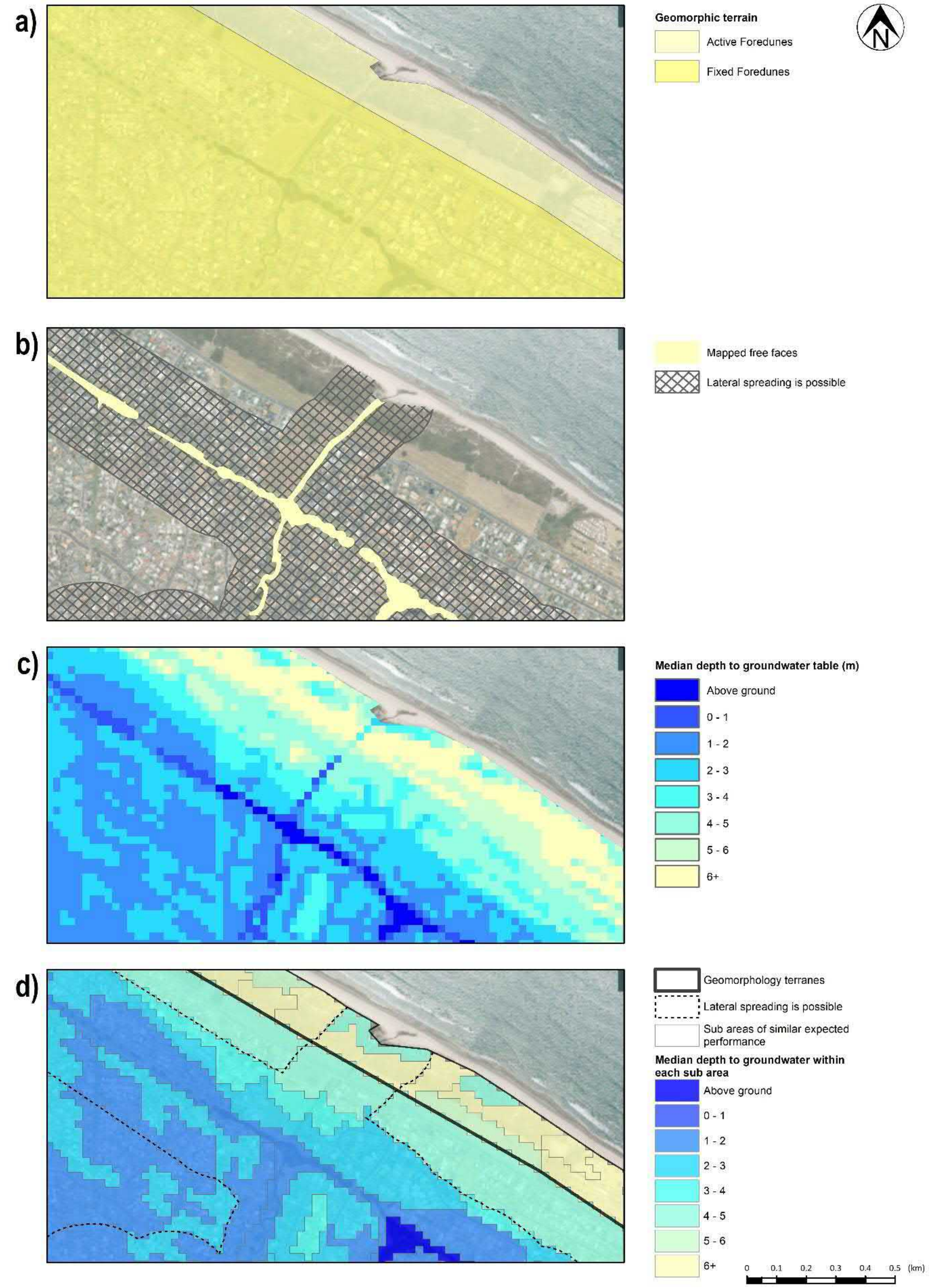


Figure 4.19: Portion of the Eastern Zone showing: a) geomorphic terrain boundaries; b) lateral spreading is possible buffer zone; c) median depth to groundwater model; and d) sub areas of similar expected performance derived from a), b) and c).

4.2.4 Expected degree of liquefaction induced ground damage

Degrees of liquefaction-induced land damage

The MBIE/MfE Guidance (2017) describes three degrees of liquefaction induced ground damage as follows:

- ***None to Minor:*** no observed liquefaction-related land damage through to minor observed ground cracking but with no observed ejected liquefied material at the ground surface.
- ***Minor to Moderate:*** observed ground surface undulation and minor-to-moderate quantities of observed ejected liquefied material at the ground surface but with no observed lateral spreading.
- ***Moderate to Severe:*** large quantities of observed ejected liquefied material at the ground surface and severe ground surface undulation and/or moderate to severe lateral spreading.

Detailed descriptions of each of the three land damage categories, including photographic examples from the Canterbury earthquakes, are provided in Section 2.5 and Appendix A of the MBIE/MfE Guidance (2017). This classification of ground damage was developed based on observations from the 2010-2011 Canterbury Earthquake Sequence and is provided to establish consistent classification terminology to describe various degrees of land damage.

As described in Section 2.3, the scope of works for this project specified the assessment of the likely liquefaction related land damage and the production of associated maps for Scenarios 1-10 listed in Table 2.2. For the Eastern Zone these maps have been produced in the following two ways:

1. **Median land damage model -** Classify the outputs of the analytical model using the degrees of liquefaction-induced damage described above. The challenge with this approach is that assigning a single land damage category to a sub area doesn't convey the uncertainty associated with the prediction of liquefaction-induced ground damage. As there will be natural variability in the ground conditions across a given sub area, there will also be variability in the ground damage that occurs. This mapping approach presents the average (50^{th} percentile) liquefaction-induced land damage predicted by the analytical model. At any particular location or in any particular event the actual damage could be more or less than the average value mapped (with approximately equal likelihood of under or over prediction).
2. **Extent and severity model -** Classify the outputs of the analytical model using the graduated scale shown in Figure 4.20. The relative proportions of the three different degrees of damage is represented by a 7-step gradient colour scale. The benefit of this approach is that it conveys to the end user the possible distribution of land damage (both in terms of extent and severity) for a given sub-area.

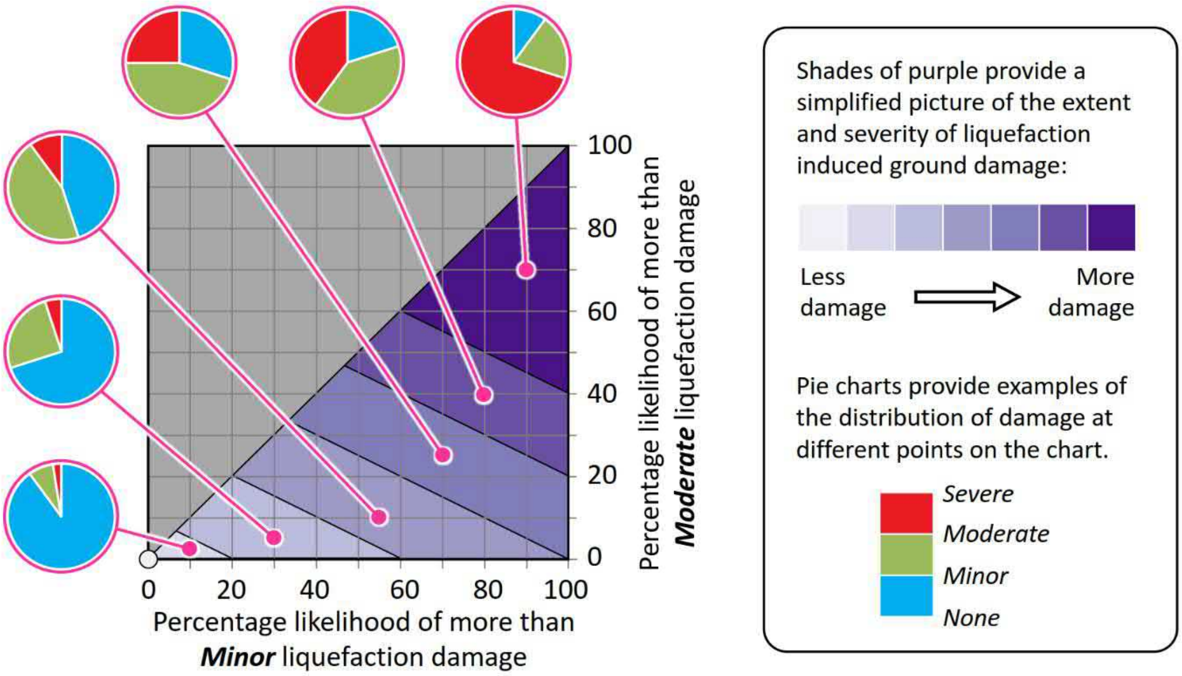
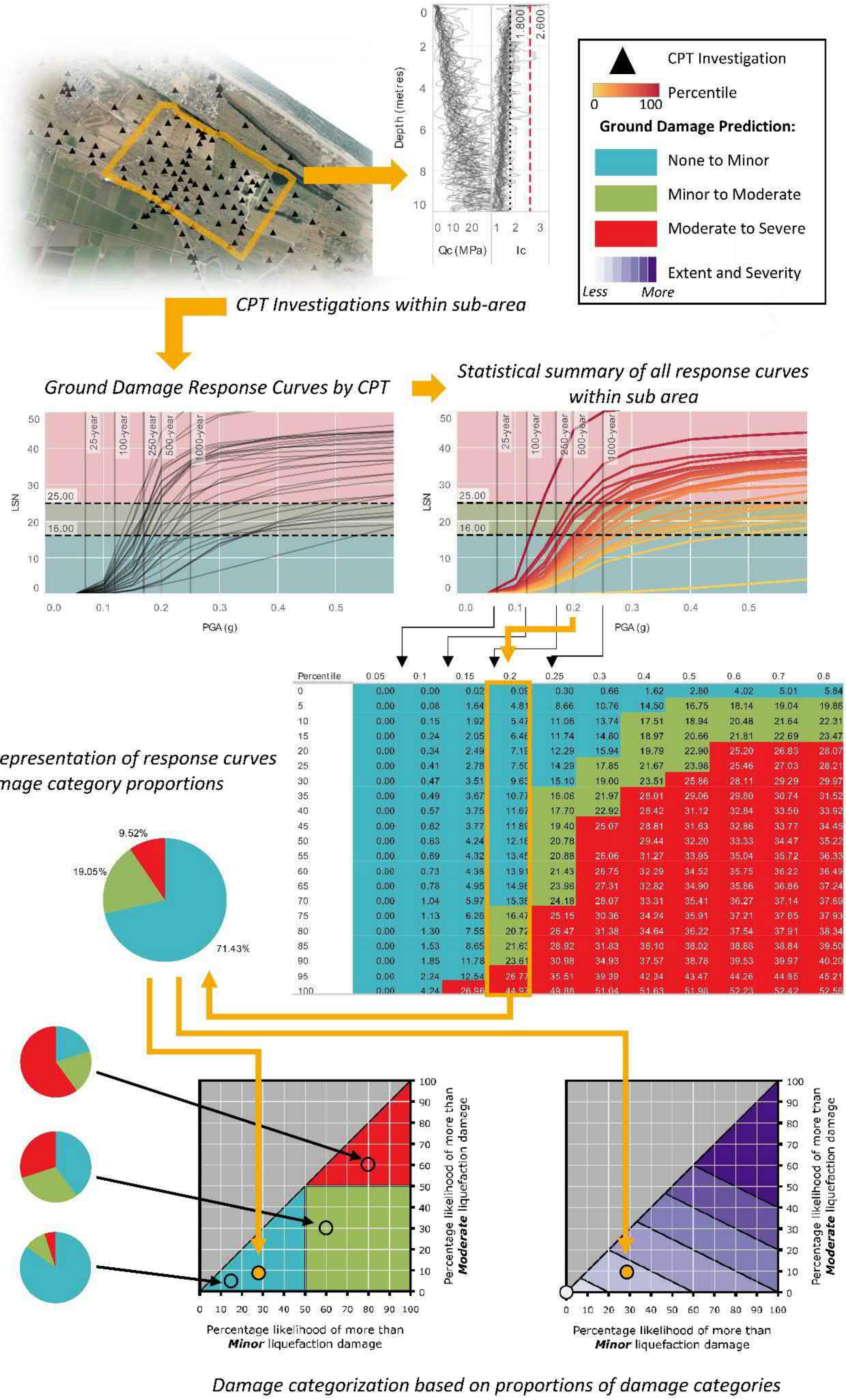


Figure 4.20: Colouring of sub areas for the various distributions of predicted liquefaction-induced ground damage

The methodology used to represent the analytical model for the Eastern Zone in the two ways described above is shown in Figure 4.21 and discussed further below.



Percentile	0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.5	0.6	0.7	0.8
0	0.00	0.00	0.02	0.09	0.30	0.66	1.62	2.80	4.02	5.01	5.84
5	0.00	0.08	1.64	4.81	8.66	10.76	14.50	16.75	18.14	19.04	19.86
10	0.00	0.15	1.92	5.47	11.06	13.74	17.51	18.94	20.48	21.64	22.31
15	0.00	0.24	2.05	6.46	11.74	14.80	18.97	20.66	21.81	22.69	23.47
20	0.00	0.34	2.49	7.19	12.29	15.94	19.79	22.90	25.20	26.83	28.07
25	0.00	0.41	2.78	7.50	14.29	17.85	21.67	23.98	25.46	27.03	28.21
30	0.00	0.47	3.51	9.63	15.10	19.00	23.51	25.86	28.11	29.29	29.97
35	0.00	0.49	3.67	10.77	16.06	21.97	28.01	29.06	29.80	30.74	31.52
40	0.00	0.57	3.75	11.67	17.70	22.92	28.42	31.12	32.84	33.50	33.92
45	0.00	0.62	3.77	11.89	19.40	25.07	28.81	31.63	32.86	33.77	34.45
50	0.00	0.63	4.24	12.18	20.78		29.44	32.20	33.33	34.47	35.22
55	0.00	0.69	4.32	13.45	20.88	26.06	31.27	33.95	35.04	35.72	36.33
60	0.00	0.73	4.38	13.91	21.43	26.75	32.29	34.52	35.75	36.22	36.49
65	0.00	0.78	4.95	14.98	23.96	27.31	32.82	34.90	35.86	36.86	37.24
70	0.00	1.04	5.97	15.38	24.18	28.07	33.31	35.41	36.27	37.14	37.69
75	0.00	1.13	6.26	16.47	25.15	30.36	34.24	35.91	37.21	37.65	37.93
80	0.00	1.30	7.55	20.72	26.47	31.38	34.64	36.22	37.54	37.91	38.34
85	0.00	1.53	8.65	21.63	28.92	31.83	36.10	38.02	38.68	38.84	39.50
90	0.00	1.85	11.78	23.61	30.98	34.93	37.57	38.78	39.53	39.97	40.20
95	0.00	2.24	12.54	26.77	35.51	39.39	42.34	43.47	44.26	44.85	45.21
100	0.00	4.24	26.96	44.97	49.88	51.04	51.63	51.98	52.23	52.42	52.56

Figure 4.21: Methodology used to represent land damage using the analytical model for the Eastern Zone

LSN thresholds for estimating the degree of liquefaction-induced ground damage

As discussed in Section 0 and outlined in the MBIE/MfE Guidance (2017), when assigning liquefaction vulnerability categories for an area-wide hazard assessment it is important to account for the uncertainties within the assessment, and the potential consequences of over-estimating or under-estimating the liquefaction vulnerability. Accordingly, Table 4.4and Appendix J of MBIE/MfE (2017) sets out a philosophy for evaluating performance based on the level of certainty in the estimated liquefaction-induced ground damage. Taking this philosophy into account, for the purposes of this study, we have adopted approximate characteristic LSN ranges for each degree of liquefaction-induced damage as shown in Table 4.8.

Table 4.8: Characteristic LSN adopted for the determination of "free-field" liquefaction-induced ground damage

Degree of liquefaction-induced ground damage	Approximate characteristic LSN ranges used for this high-level hazard study
None to Minor	0 - 16
Minor to Moderate	16 - 25
Moderate to Severe	> 25

NOTES:

1) There is considerable uncertainty involved in estimating liquefaction-induced ground damage using severity index parameters such as LSN. These ranges are intended to provide a general indication of the damage that might typically be expected. However there can be a wide variation in land performance, even where ground conditions appear to be similar, with damage in some cases being much greater or less than inferred from the LSN index.
2) These index values are intended only for use in this Tauranga area-wide hazard assessment using the MBIE/MfE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design) where more detailed information is available, there is less uncertainty, and there are different consequences for under-predicting or over-predicting liquefaction vulnerability.
3) These characteristic LSN values utilise P_L = 15%. Alternate index values would need to be considered if other P_L values are utilised.

LSN vs PGA ground damage response curves

Once the initial sub areas had been defined, liquefaction-induced ground damage response curves were computed for each CPT for a range of groundwater and PGA values. This was performed using all the collated CPT investigations subject to the filtering presented in Section 4.1.3 and computed using the simplified deterministic liquefaction assessment procedure with the Liquefaction Severity Number (LSN) employed for the estimation of ground damage. The default liquefaction triggering parameters shown in Table 4.9 were used.

Table 4.9: Input parameters for Boulanger and Idriss (2014)

Input parameter	Default value adopted
Soil density	18 kN/m^3
FC - I_c correlation	C_{FC} = 0.0
I_c - cut off	I_c cut off = 2.6
Probability of Liquefaction, P_L (%)	P_L = 15%

For each CPT, the ground damage response curve is simply the series of LSN values computed for a set of PGAs at a constant groundwater depth. The response curves were then collated for each area, producing a distribution of curves. There is dispersion in these curves, which can be substantial in some cases, because of the spatial variability in ground conditions and therefore calculated vulnerability across a sub area.

As shown in Figure 4.21, at each PGA increment, a cross-section of the response curves gives rise to a distribution of LSNs. It is possible to characterise this distribution using statistical methods. For this study, the collection of response curves has been characterised in cumulative frequency distribution (CFD) space. That is, LSN values are calculated corresponding to 5% increments from 0 to 100% at each PGA increment. The result is a matrix representation of the liquefaction vulnerability with PGA on the horizontal axis and CFD percentile on the vertical axis. Figure 4.21 also shows how the CFD data can be represented using each of the two land damage mapping methods applied for the Eastern Zone described above.

Grouping of CPT for the development of LSN vs PGA ground damage response curves

In some areas where a Level A (basic desktop) assessment was undertaken there were no or insufficient CPT to develop LSN vs. PGA ground damage response curves (e.g. land reclamation and volcanic hills and ranges). In these areas the analytical model was not developed and they are indicated as “unmodelled areas”.

For the assessment of areas where a Level A (basic desktop) or a Level B (calibrated desktop) assessment was undertaken and there was sufficient CPT to develop LSN vs. PGA ground damage response curves, the CPT were grouped according to the geomorphic terrain across the entire Eastern Zone. The CPT in these Level B areas were frequently densely clustered around project specific locations interspersed with significant areas of no CPT data. Therefore, to avoid over-representation due to areas of higher density, the median LSN value from a 100 m x 100 m grid was used to derive the LSN vs. PGA ground damage response curves.

For the assessment of areas where a Level C (detailed area wide) assessment was undertaken, the LSN vs. PGA ground damage response curves were grouped according to the boundary of the Level C area. Note, as shown in Figure 4.17 there were only two areas where the ground conditions were sufficiently well characterised to undertake a Level C assessment both of which are located at the eastern most extent of the Eastern Zone in the Fixed Foredunes.

Allowance for lateral spreading

Based on CPT-based analysis using the Zhang et al. (2004), extensive lateral spreading is not anticipated at levels of earthquake shaking that are less than or equal to the 100 year return period (M_W 6.2, 0.12g).

As discussed in Section 4.2.3, areas where liquefaction-induced lateral spreading is possible at levels of earthquake shaking higher than the 100 year return period have been identified by creating buffer zones around features where free-faces or sloping ground have been mapped. Allowance for lateral spreading has been made in the Median Land Damage and Extent and Severity models by factoring up the LSN values within these areas.

The lateral spreading factor applied increases LSN with increasing PGA to allow for the more severe lateral spreading related damage that is anticipated at higher levels of earthquake shaking. This ramping up of LSN is illustrated in Figure 4.22 and Figure 4.23 by applying it to the reference CPT introduced in Section 4.1.5.

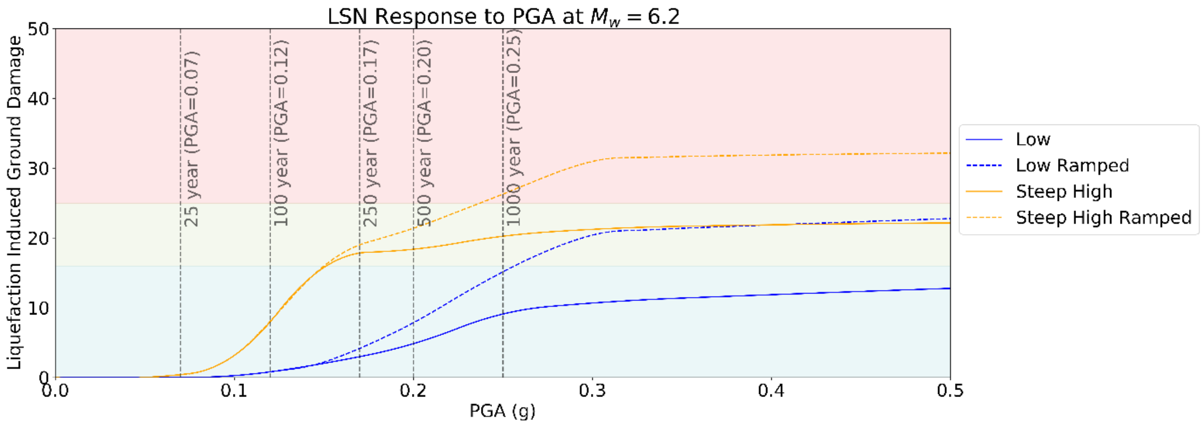


Figure 4.22: Effect of variation in PGA on liquefaction consequences for two different ground damage response curves (assuming a magnitude 6.2 earthquake and probability of liquefaction of (P_L = 15%). The ground damage response curves are shown both with and without the lateral spread ramp applied as represented by the smoothed and dashed lines respectively.

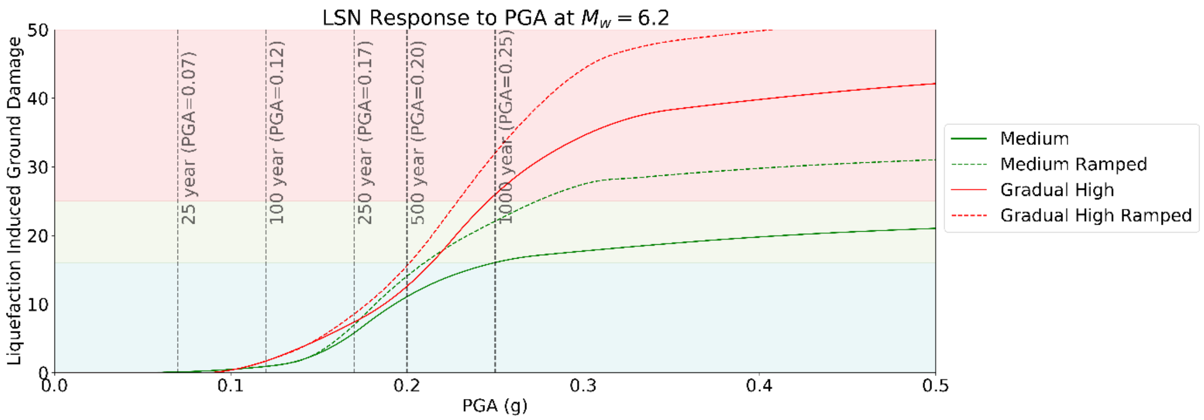


Figure 4.23: Effect of variation in PGA on liquefaction consequences for two different ground damage response curves (assuming a magnitude 6.2 earthquake and probability of liquefaction of (P_L = 15%). The ground damage response curves are shown both with and without the lateral spread ramp applied as represented by the smoothed and dashed lines respectively.

Liquefaction-induced land damage mapping

The results of the modelled liquefaction-induced land damage classification for Scenarios 2 - 5 and 7 - 10 in are shown in Figures B9 – B15 of Appendix B. Scenarios 1 and 6 have not been included in these figures because liquefaction related land damage is not anticipated at the low levels of earthquake shaking that are assumed for the 25 year return period earthquake (M_W = 6.2, PGA = 0.07g).

Table 4.10 provides a brief description of content shown on each of the Figures B9 – B15 in Appendix B.

Table 4.10: Description of content for Figures B9 – B15 in Appendix B

Figure No.	Scenario(s) shown	Description
Figure B9	2 – 5	Comparison of median land damage model with extent and severity model.
Figure B10	7 – 10	Comparison of median land damage model with extent and severity model.
Figure B11	2 – 5 & 6 – 10	Comparison of current day and potential future groundwater conditions.
Figure B12	2	Detailed view of current day groundwater conditions with 100 year return period earthquake shaking.
Figure B13	4	Detailed view of current day groundwater conditions with 500 year return period earthquake shaking.
Figure B14	7	Detailed view of potential future groundwater conditions with 100 year return period earthquake shaking.
Figure B15	9	Detailed view of potential future groundwater conditions with 500 year return period earthquake shaking.

4.2.5 Liquefaction vulnerability assessed against performance criteria

Vulnerability assessment process

For each sub area a liquefaction vulnerability category has been assigned according to the framework recommended in the MBIE/MfE Guidance (2017) as shown in Figure 4.24 to Figure 4.26.

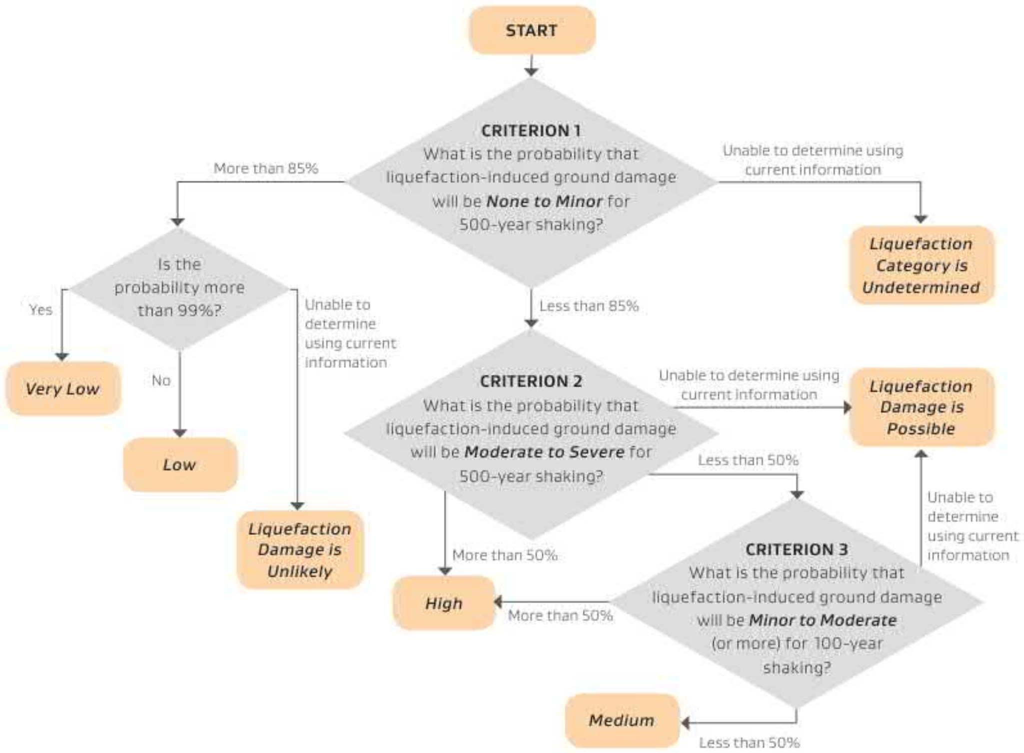


Figure 4.24: Flow chart for determining the liquefaction vulnerability category - from MBIE/MfE Guidance (2017)

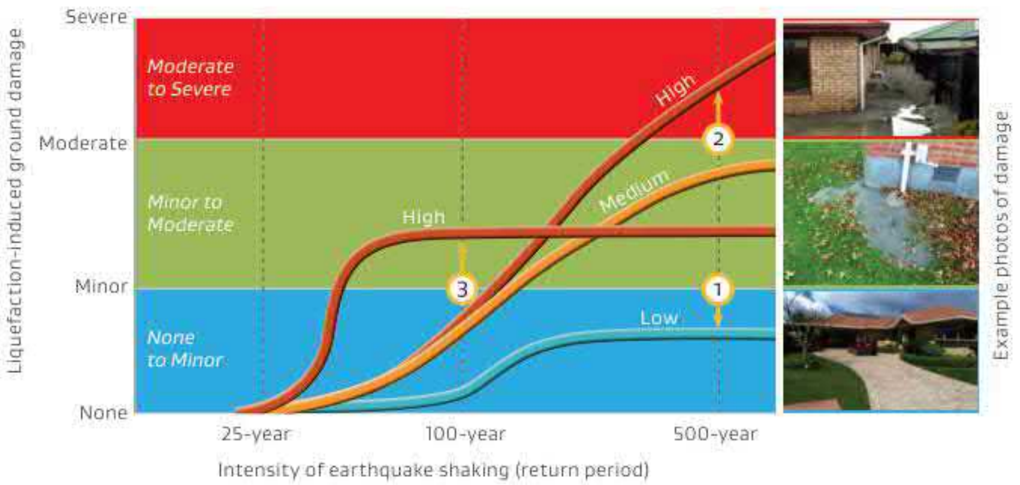


Figure 4.25: Example ground damage response curves for low, medium, and high liquefaction vulnerability categories, and performance criteria used for liquefaction categorisation - from MBIE/MfE Guidance (2017)

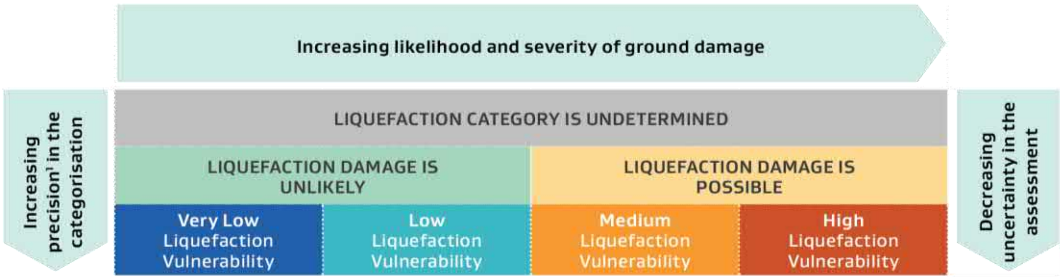


Figure 4.26: Liquefaction vulnerability categories – from MBIE/MfE Guidance (2017)

Results

The end result of the assessment against the performance criteria is the assigned liquefaction vulnerability categories shown in Figure 4.27. A larger version of this map is shown in Figure B16 in Appendix B. Taking into account the residual uncertainty for the categorisation of each sub area, achieved levels of detail have been designated as described in Section 4.1.8.

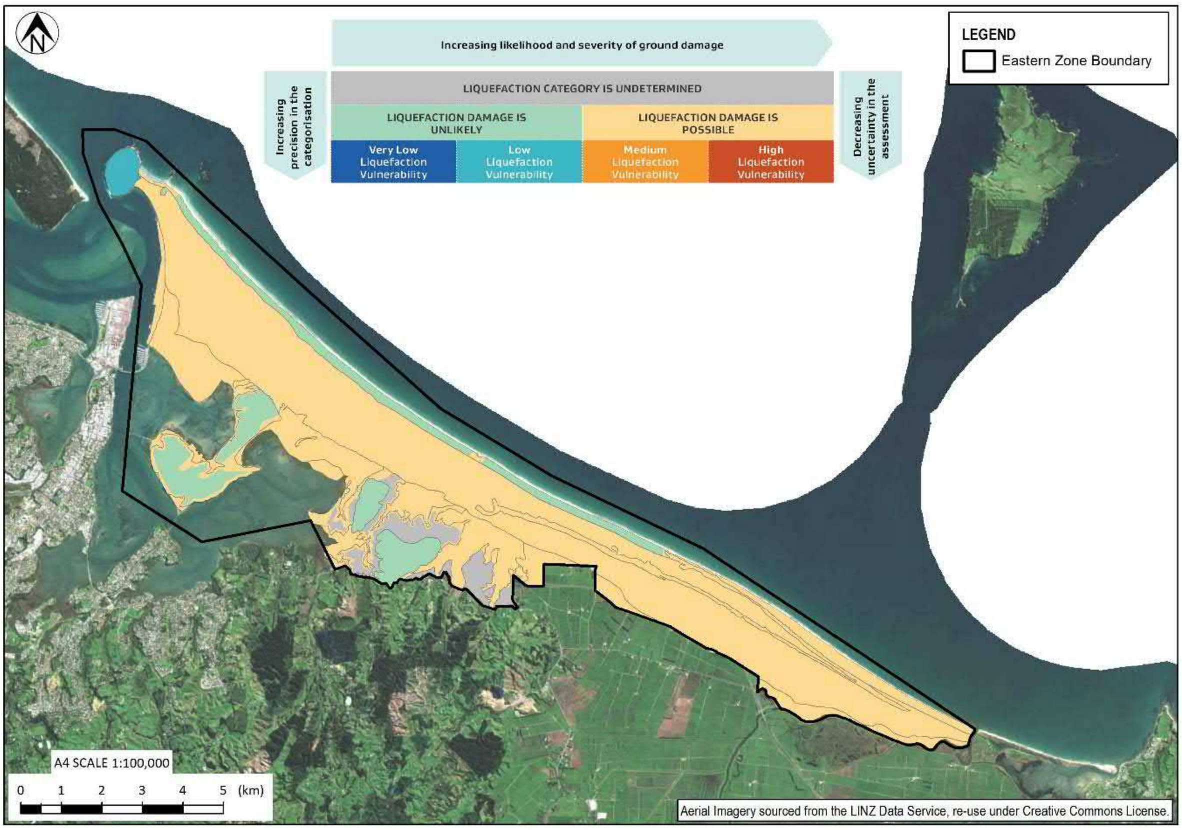


Figure 4.27: Liquefaction vulnerability categories for Tauranga City assigned in this study. Refer to Figure 4.26 for map legend

5 Discussion and conclusions

This section presents discussion about key aspects of this study and its conclusions. Section 5.1 presents the discussion and is structured as follows:

- The residual uncertainty that remains at the conclusion of this study in particular as it relates to the base information that is currently available (refer to Section 5.1.1)
- The expected degree of liquefaction induced ground damage in each of the 10 scenarios based on the land models developed (refer to Section 5.1.2)
- The liquefaction vulnerability categorisation for particular areas that warrant further discussion (refer to Section 5.1.4).

Section 5.2 presents the key conclusions and recommendations from this study.

5.1 Discussion

5.1.1 Residual uncertainty

Ground surface levels

One of the key limitations of the DEM available within the context of this study is the inability of LiDAR to penetrate water bodies. This limits the usefulness of LiDAR data for mapping free faces in water features. If this limitation is not recognised and managed this can in turn can result in the under prediction of the extent and severity of lateral spreading. As discussed in Section 4.1.6, the current approach T+T has adopted to manage this source of uncertainty is to make a relatively conservative assessment of the height of any free faces associated with water bodies and therefore a relatively conservative assessment of potential extent of lateral spreading.

To address this source of uncertainty TCC could commission bathymetric surveys of waterbodies within the Eastern Zone such as the Wairakei Stream. This survey data could be used to develop a bathymetric model that could then be meshed with the LiDAR derived DEM. This would enable a more accurate estimation of the height of free-faces and a refinement in the assessment of the potential extent and severity of lateral spreading.

Another key limitation associated with any DEM (regardless of the survey source) is the potential for temporal changes in the ground surface elevation due to landform modification from both natural (e.g. erosion) and anthropogenic (e.g. land development) processes. This is because relatively small changes in ground surface elevation may have a significant impact on liquefaction vulnerability. This is particularly relevant in areas where the depth to groundwater is relatively shallow (e.g. less than 5m). To address this potential source of uncertainty in the DEM T+T recommends that TCC continue the existing program of undertaking regular LiDAR survey of the land area. As well as providing an understanding of relatively gradual changes to landform, this information may be critical for post-earthquake response and recovery. This was demonstrated in the use of this information to understand large scale ground surface elevation changes as a result of the 2010 – 2011 Canterbury Earthquake Sequence.

T+T recommends that TCC require liquefaction assessments accompanying resource and building consent applications consider the proposed finished ground surface elevation.

Geology and geomorphology

In areas some areas the boundaries between geologic terrains and geomorphic terrains can be difficult to define for a regional study such as this and incorrect definition of these boundaries may result in incorrect assessment of the liquefaction vulnerability for a given area (both over and under-estimation of liquefaction vulnerability). As described in Section 4.1.2 to identify where this is a potential issue T+T has identified boundaries between geomorphic terrains where there is more uncertainty have been mapped in Figure B5 in Appendix B. The red line indicates areas where there is more uncertainty associated with the boundary between geomorphic terrains because it is not clearly defined by a feature such as a clear change in elevation.

In some instances the effect of this uncertainty is less significant on the overall liquefaction study due to the similarity of the ground conditions in each geomorphic terrain and their associated liquefaction response under earthquake load (e.g. boundary between active and fixed foredunes). In other areas where the soils from different geomorphic terrains are likely to respond differently under earthquake loads (e.g. the alluvial terraces and harbour margin on the Matapihi Peninsula) this can contribute significantly to the residual uncertainty that remains.

To address these sources of uncertainty T+T recommends that TCC continue to support the collection and uploading of geotechnical investigation data onto the NZGD[10]. As further investigations are gathered this information can be used to review and refine the location of the mapped boundaries between geologic terrains and geomorphic terrains.

Geotechnical investigations

As discussed in Section 4.1.3 there are a number of different sources of uncertainty that relate to geotechnical investigations such as the variably density of geotechnical investigations across the TCC study area, the variability of ground conditions within each geomorphic terrain and the variability in the quality of the data collected by the various contractors that undertake investigations in Tauranga.

To address this source of uncertainty T+T recommends that TCC continue to support the collection and uploading of geotechnical investigation data onto the NZGD and facilitate the education and upskilling of contractors undertaking investigations throughout the Tauranga area to ensure that appropriate data quality standards are maintained[11].

Groundwater

TCC's existing program of groundwater monitoring and modelling within the Eastern Zone is amongst the highest quality data of its kind in New Zealand and provided a valuable data source for this study. However, as discussed in Section 0, these groundwater models were developed in order to understand the effects of sea level rise on the groundwater table in Tauranga and as such the piezometers are predominantly located in lower lying areas where sea level rise is more likely to influence the groundwater table. As a result, as shown on Figure B6 in Appendix B, there is more uncertainty associated with the depth to groundwater in some areas.

[10] TCC may wish to consider making this a condition of granting resource and building consents.

[11] Refer to Module 2 of the NZGS Earthquake Geotechnical Engineering Practice Guidelines (NZGS/MBIE, 2017) for technical information about undertaking geotechnical investigations for the assessment of liquefaction vulnerability.

To address this source of uncertainty, T+T recommends that TCC continue to fund this program for the existing piezometer locations because a longer length of record will help to understand the response of the groundwater table to both sea level rise and other factors that influence the elevation of the groundwater table (e.g. drought and rainfall). TCC may also wish to consider expanding the number of piezometer locations into areas at higher elevation where the groundwater is less likely to be influenced by sea level rise (e.g. the lower alluvial terrace in the Kairua area).

Seismic hazard

TCC's commissioning of the BSL Ltd. to undertake a seismic hazard study for the TCC land area has provided a significant refinement to the understanding of seismic hazard in the Tauranga area. This has reduced the residual uncertainty associated with this key input to the liquefaction vulnerability assessment. The most significant impact of this is the reduction in the estimate of PGA for lower probability (longer return period) earthquake events when compared to the estimates derived using the NZTA Bridge Manual method (refer Section 4.1.5).

To further reduce the uncertainty of Seismic Hazard for liquefaction assessment TCC may consider supporting refinement of the Vs30 model for Tauranga. As discussed in Section 4.1.5 this is a key source of uncertainty in the model.

The BSL report states that the results are intended for use in regional liquefaction and slope instability hazard triaging (e.g. for housing and horizontal infrastructure development), and are not appropriate for site-specific assessment of commercial or industrial structures in lieu of conventional prescriptive design standards and guidelines. It is envisioned that these national standards will eventually be updated with more up-to-date seismic hazard estimates, but in the meantime there is some uncertainty regarding what parameters should be adopted for design in various situations. TCC may wish to provide clarification for resource and building consent applicants as to the situations and extent it might be reasonable for them to rely on the BSL results in preference to current standards (e.g. NZTA Bridge Manual). This is important because if engineers are not able to rely on the lower PGA values from the BSL report then they may calculate higher liquefaction vulnerability than indicated in the TCC liquefaction vulnerability study, resulting in inconsistencies and confusion. TCC may also wish to encourage that site-specific seismic hazards be undertaken for high-importance projects.

Estimate liquefaction-induced ground damage

Understanding of liquefaction science has evolved considerably in recent years, in particular as a result of learnings from the 2010-2011 Canterbury Earthquake Sequence. However, as discussed in Section 4.1.6, there are limitations associated with the currently available methods used to estimate liquefaction-induced ground damage and in turn these limitations contribute to the residual uncertainty in this assessment. Of particular relevance to this study are the limitations of the currently available methods to estimate both the extent and severity of lateral spreading. While related, this is a separate issue from the mapping of free-faces as it is dependent on progression in understanding of the mechanisms behind lateral spreading rather than a deficiency in any particular base information.

To address this source of uncertainty, T+T recommends TCC continue to support the development of understanding in liquefaction hazard in the Tauranga area. This may take the form of continued support of educational material and activities for geo-professionals working in the Tauranga area and the support research and development for academic activities. In both cases in-kind support, such as the provision of meeting rooms for professional gatherings and facilitating access to public lands for research purposes, are relatively low cost activities which could provide significant benefit.

5.1.2 Level of detail in the assessment

As discussed in Section 3.1.2, the target level of detail in the assessment (in accordance with MBIE Guidelines (2017)) that is required for TCC's intended purposes was developed in a workshop held on 26 February 2019 (T+T, 2019) (refer Figure 5.1). Following the completion of the uncertainty assessment described in Section 4.1, T+T evaluated the level of detail supported by the currently available base information (refer Figure 5.2).

Comparison of Figure 5.1 and Figure 5.2 shows that while the general patterns in the target level of detail and the level of detail supported by the base information are similar, there are some relatively minor differences between the two maps. The two primary reasons for these differences are as follows:

- The level of detail required for TCC's intended purposes was primarily derived using Area Unit polygons from Statistics New Zealand. These were useful reference points for the workshop however they do not relate to the expected liquefaction vulnerability of the land. Whereas the level of detail supported by the available base information was primarily derived from geomorphic terrain boundaries which do relate to the expected liquefaction vulnerability of the land. The geomorphic terrain boundaries were developed during the course of this study and therefore they were not available when the target level of detail was established; and
- The level of detail supported by the base information is primarily a function of the degree of residual uncertainty in the available information. As this had not been evaluated at the time the target level of detail was established, some differences between this and the level of detail supported by the base information would be expected.

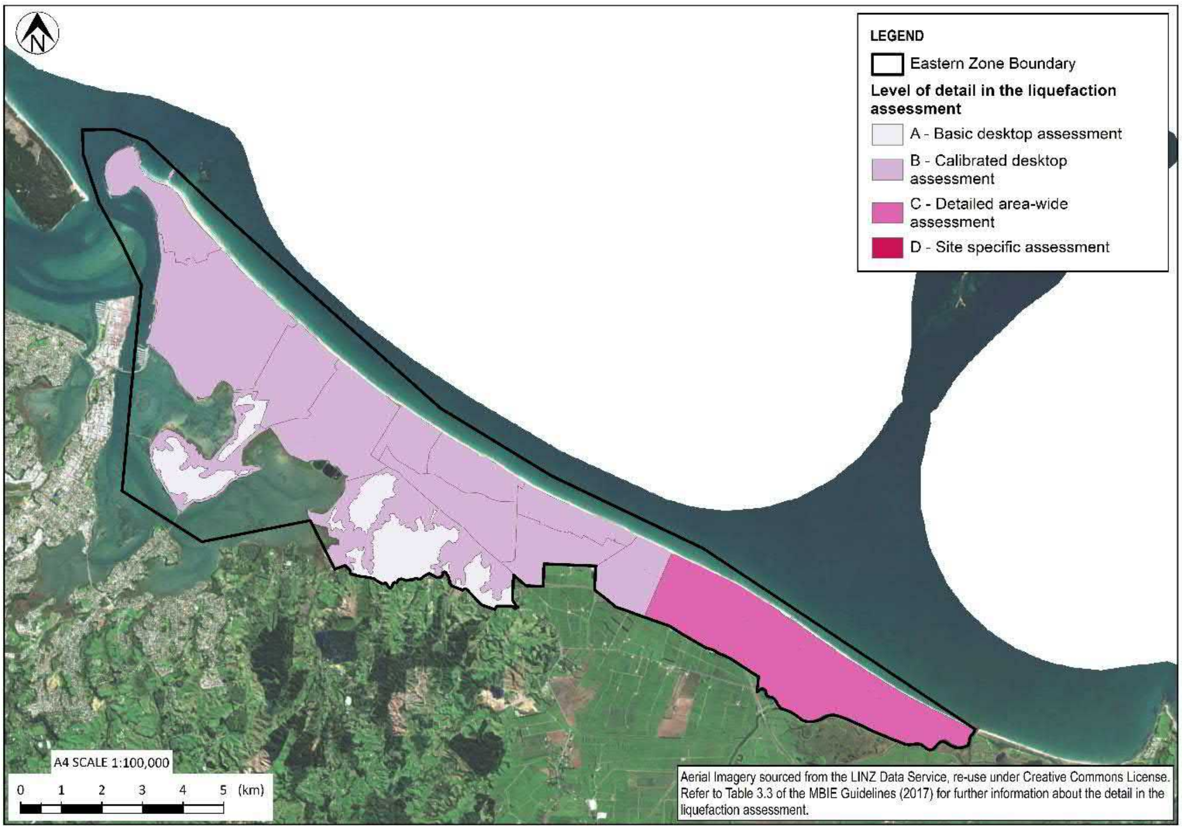


Figure 5.1: Target level of detail in the liquefaction assessment for the Eastern Zone

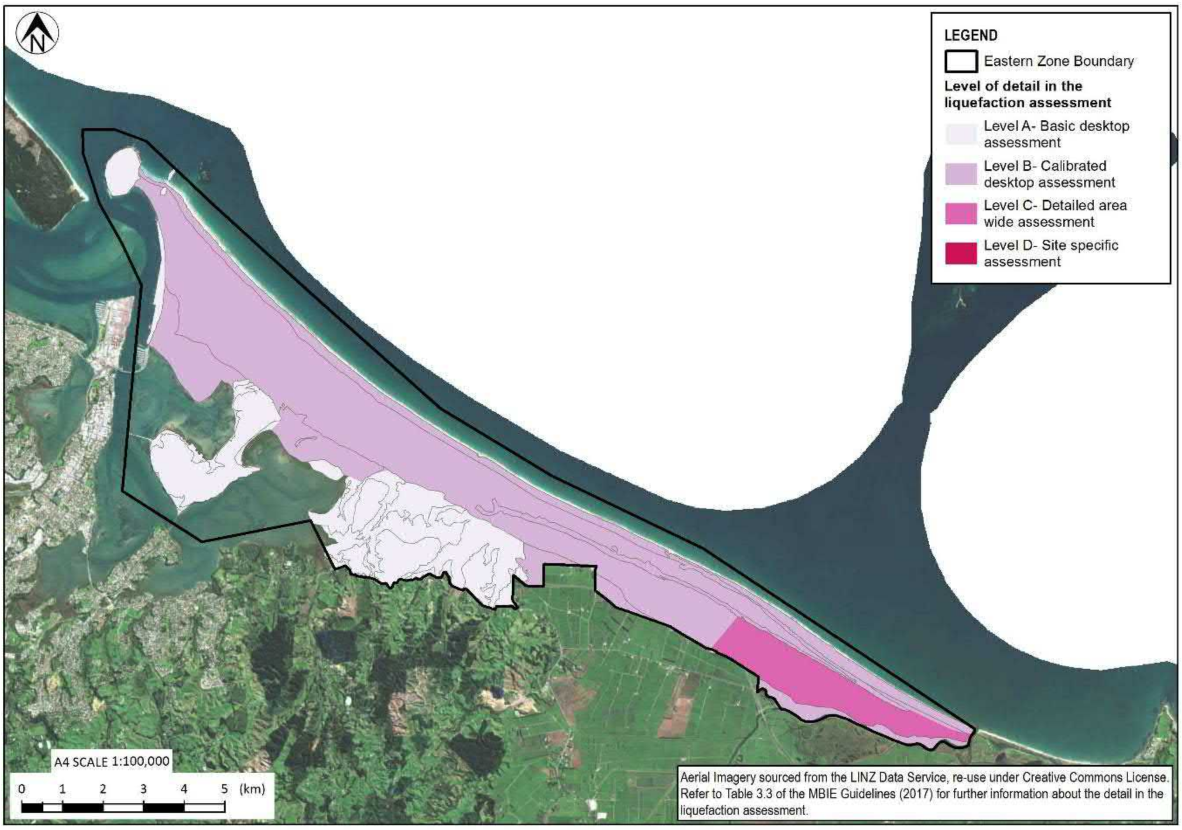


Figure 5.2: Level of detail supported by the currently available base information

5.1.3 Expected degree of liquefaction-induced ground damage

Median land damage model vs. extent and severity land damage model

As presented in Section 4.2.4, we have used two different models to represent the same information. It is important to recognise that both of these models are sourced from the same base information and represent the same calculated LSN vs. PGA distributions. The key difference is the way in which the information is presented.

The median land damage model presents the estimate of land damage in a manner that is consistent with the three degrees of liquefaction induced ground damage described in the MBIE/MfE Guidelines (2017). This three degree model presents a relatively simple picture in particular when read in conjunction with the example photographs presented in Appendix A of the MBIE/MfE Guidelines (2017). However as these maps are based on the calculated median LSN value only, the actual damage at any particular location or in any particular event could be more or less than the average value mapped (with approximately equal likelihood of under or over prediction). This means that it does not capture potential distribution of both the extent and severity of land damage that could occur within a given area as a result of the potential sources of uncertainty that have been discussed in this report (refer Section 4.1).

While at face value the graduated scale presented on the extent and severity model requires more interrogation of the information in order to interpret, it also provides a more effective representation of the potential distribution of land damage that could occur within a given area. This provides a useful tool to convey this information to any end users (including the general public) and provides an alternate parameter that can be utilised for quantitative analysis such as infrastructure damage modelling. Furthermore, the increased number of gradations in the extent and severity model (7 as opposed to 3) enables greater resolution of the potential for liquefaction-induced land damage while still representing the analysis in a manner that is consistent with the limitations of the model.

Comparison of the two models representation of Scenario 2 on Figure B9 in Appendix B demonstrates the benefit of this increased resolution. The median land damage model represents the entire Eastern Zone as none-to-minor land damage which would imply that similar performance can be expected across the entire area. Conversely, for Scenario 2 the extent and severity model differentiates between low-lying areas with elevated groundwater where there is a greater likelihood of land damage (even at this relatively low level of earthquake shaking) and elevated areas where there is a lower likelihood of land damage. A similar pattern can be seen for Scenario 7 (which represents the same level of shaking) on Figure B10 in Appendix B.

These differences aside, it is important to recognise the inherent uncertainty associated with the use of the LSN parameter from which both of these models are developed when utilising both of these models. Refer to Section 4.1.6 for further discussion about the uncertainty associated with the LSN parameter and the prediction of the consequences of liquefaction.

Seismic hazard

Interrogation of Figure B9 in Appendix B demonstrates the sensitivity of the analysis to seismic shaking at the current-day median depth to groundwater. The extent and severity of liquefaction-induced ground damage increases with increasing seismic shaking with the following key trends:

- As described in Section 4.2.4 liquefaction-induced land damage is not anticipated at the relatively low levels of earthquake shaking that are assumed for Scenario 1 (M_W = 6.2, PGA = 0.07 g).
- In Scenario 2 (M_W = 6.2, PGA = 0.12 g) some liquefaction-induced land damage is predicted in areas where the groundwater elevation is modelled as being shallower (e.g. the Harbour Margins around the airport and Te Maunga) when compared to areas where the groundwater table is modelled as being deeper (e.g. the Active Foredunes). This pattern is only apparent in the extent and severity model.
- In Scenario 3 (M_W = 6.2, PGA = 0.17 g) these low-lying areas are starting to be clearly differentiated from the elevated areas with more liquefaction-induced ground damage being predicted for both models. In the extent and severity model, areas within the "lateral spreading is possible" buffer are predicting more liquefaction-induced ground damage than those outside that buffer.
- In Scenario 4 (M_w = 6.2, PGA = 0.20 g) and Scenario 5 (M_w = 6.2, PGA = 0.25 g) the extent of the area where liquefaction-induced land damage is predicted gets progressively larger with increasing levels of earthquake shaking. However, there is a relatively modest increase in the extent of areas mapped in the highest category of liquefaction-induced ground damage (red on the Median model and the darkest shade of purple on the Extent and Severity model). This indicates while the damage may be widespread in Scenario 5 the most severe damage will likely be isolated to areas where the depth to groundwater is shallow (between 0-3 m) and there is the potential for lateral spreading (e.g. the Harbour Margins, Kaituna Flood Plain and parts of the Fixed Foredunes).

Groundwater

Interrogation of Figures B9 to B15 in Appendix B provides an indication of the change in liquefaction-induced land damage as a result of sea level rise in the order of 1.25 m and demonstrates the sensitivity of the analysis to groundwater. .

The key observation from interrogation of these figures is for earthquakes with return periods of 250 years and greater, sea level rise of 1.25 m is predicted to result in a significant increase in the extent and severity of liquefaction induced land damage. This observation applies in areas where the soils are susceptible to liquefaction and the groundwater is relatively shallow (typically less than 10 m deep). While there is uncertainty associated with the degree and timeframe over which sea level rise will occur and how groundwater will respond, T+T recommends that TCC recognise this potential increase in liquefaction vulnerability and allow for it in their planning processes.

Furthermore, comparison between Scenario 2 and 7 shows that at this relatively low level of shaking the analysis is relatively insensitive to groundwater rise with only a relatively small land area indicating a difference in ground response. Comparison between Scenarios 3 and 8 indicate more sensitivity to groundwater rise with increasing levels of ground shaking with a significant area of land shown as the highest category of sensitivity and more extensive areas of sensitivity. A similar picture emerges with comparison between Scenarios 4 and 9 with a larger area shown as the highest category of sensitivity and even more extensive areas of sensitivity. Comparison between Scenario 5 and 10 shows a slightly different picture emerging, while there are more extensive areas of sensitivity the area shown as most sensitive to groundwater has reduced.

As would be expected, areas where "less damage" is predicted across all ranges of seismic shaking (e.g. the Matapihi Peninsula) exhibit less sensitivity to groundwater rise. In areas where "more damage" is predicted at higher levels of shaking (e.g. the land around Te Maunga) also exhibit less sensitivity to groundwater rise. This is attributable to these areas having already sustained "more damage" at the current day median groundwater conditions and therefore the reduction in groundwater depth is expected to have less net effect.

5.1.4 Liquefaction vulnerability assessed against performance criteria

While for the most part the liquefaction vulnerability map in Figure 5.3 is self-explanatory, there are several locations across the city where further discussion may be useful to explain the rationale for the assigned categories. These locations are identified with labels A to E in Figure 5.3 and discussed below.

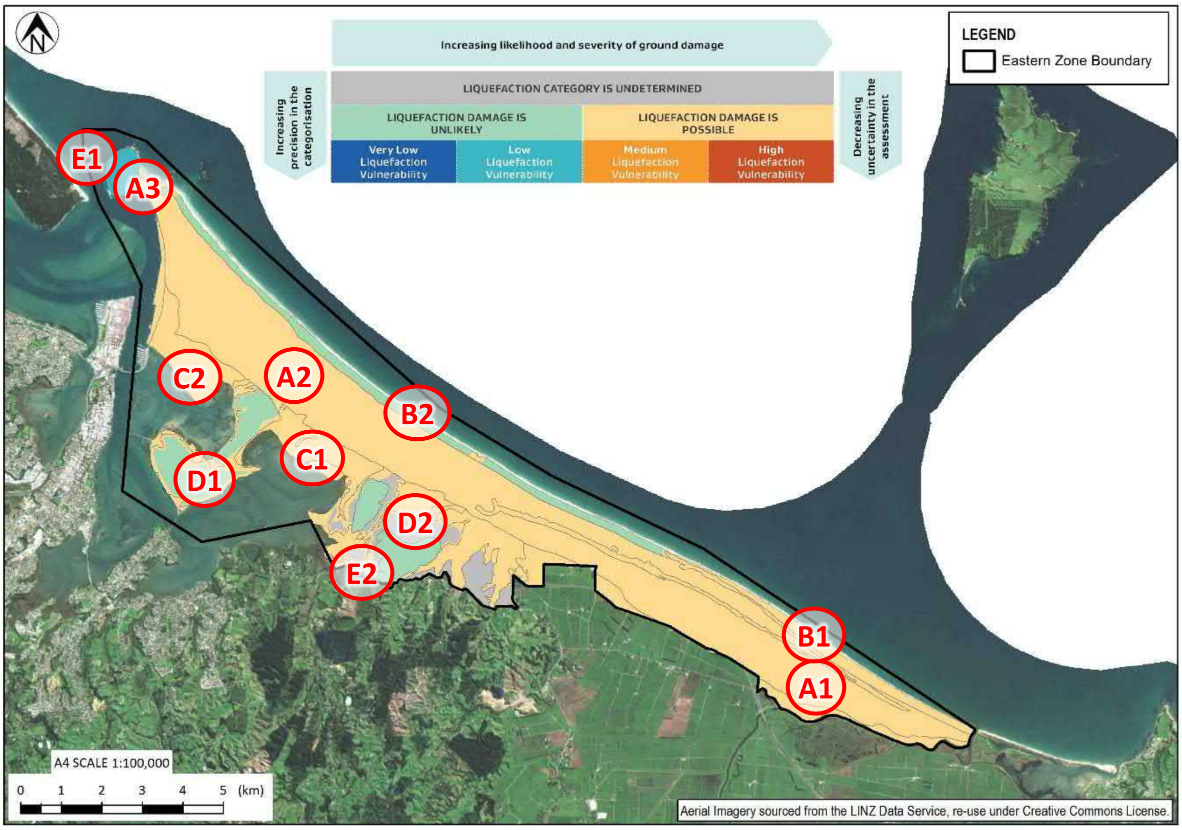


Figure 5.3: Liquefaction vulnerability categories for Tauranga City assigned in this study. Refer to Figure 4.26 for map legend

Area A – Fixed Foredunes

While the entire Fixed Foredune terrain is mapped as "Liquefaction Damage is Possible" the rationale behind that vulnerability categorisation varies as follows:

- **Area A1** comprises the Level C areas in Papamoa and Te Tumu. In this location there is less uncertainty associated with the ground conditions (refer Figure 4.15) which is a function of the relatively high density of deep investigations available and the consistent ground conditions in this terrain. There is also less uncertainty associated with the depth to groundwater (refer to Figure 4.16) which is a function of the number of piezometers and the relatively long length of monitoring record in this area. These factors have enabled a Level C level of detail to be assigned.

  The key source of residual uncertainty that prevents a higher precision of liquefaction vulnerability categorisation is the potential extent and severity of lateral spreading. This uncertainty is a function of the inability of LiDAR to penetrate water bodies and therefore accurately estimate the height of free faces (refer Section 4.1.1) and the limitations of the currently available methodologies for estimating lateral spreading related ground damage (refer Section 4.1.6).
- **Area A2** comprises the level B areas in Mount Maunganui to the South East of Mount Drury. Similar to Area A1 there is less uncertainty associated with the depth to groundwater (refer to Figure 4.16). However there is more uncertainty associated with the ground conditions (refer Figure 4.15) which is a function of the relatively large distances between individual deep investigations and groups of deep investigations in this area.

  This uncertainty in ground conditions is the key source of residual uncertainty that prevents a higher precision in the categorisation of liquefaction vulnerability. Note that similar to Area A1 there are some sub areas in this location where lateral spreading is considered possible which also contributes to the degree of uncertainty.
- **Area A3** comprises the Level B areas in Mount Maunganui to the North West of Mount Drury. While there is a relatively large number of deep investigations available these are typically clustered around specific projects and inspection of those investigations indicates that the ground conditions are highly variable. For this reason there is more uncertainty associated with the ground conditions in this area (refer Figure 4.15). Furthermore, for the majority of the land in this area lateral spreading is considered possible.

Due to the residual uncertainty outlined above T+T considers it would not be appropriate at the current time to attempt to delineate areas of "Medium" and "High" liquefaction vulnerability, therefore the entire area has been assigned a less precise category of "Liquefaction Damage is Possible."

Area B – Active Foredune

The Active Foredune terrain is classified as a combination of "Liquefaction Damage is Possible" and "Liquefaction Damage is Unlikely". In both Area B1 and B2 there is less uncertainty associated with the depth to groundwater (refer to Figure 4.16) and there is more uncertainty associated with the ground conditions (refer Figure 4.15). The key differentiating features between the two areas are as follows:

- **Area B1** comprises land in the Active Foredune where the depth to groundwater is typically modelled as less than 8m and/or the land is within an area where lateral spreading is considered possible. For this/these reason(s) the land is categorised as "Liquefaction Damage is Possible."
- **Area B2** comprises land in the Active Foredune where the depth to groundwater is typically modelled as more than 8m and the land is not within an area where lateral spreading is considered possible. While uncertainty remains with the ground conditions, the uncertainty is not considered material to the vulnerability classification because the groundwater is considered too deep for the damaging consequences of liquefaction to manifest at the ground surface.

  Furthermore, inspection of the CPT available within the Active Foredune terrain indicates that the below a typical depth of 6m the sands in this area become too dense for liquefaction to be triggered at 500 year levels of earthquake shaking (M_w=6.2, PGA=0.2g). For these reasons the land is categorised as "Liquefaction Damage is Unlikely."

Area C – Harbour Margin

The Harbour Margin terrain is classified as "Liquefaction Damage is Possible." In both Area C1 and C2 there is less uncertainty associated with the depth to groundwater (refer to Figure 4.16) and there is more uncertainty associated with the ground conditions (refer Figure 4.15). In both areas the modelled depth to groundwater is typically less than 2 m and there are multiple free-faces associated with drainage channels. The key differentiating features between the two areas are as follows:

- **Area C1** comprises the Level B areas around the Te Maunga wastewater treatment plant. While there are a significant number of deep investigations in these areas these investigations are typically clustered around project specific locations leaving large areas without any investigations. Inspection of these investigations indicates that the ground conditions are highly variable which adds uncertainty to the interpretation of the likely performance of the land where there are no investigations. This landform has also undergone significant anthropogenic change associated with the construction of the Te Maunga wastewater treatment plant and other facilities including significant areas of land reclamation.
- **Area C2 –** comprises the Level B areas around the Tauranga Airport. In this area there are very few investigations available to characterise the land. Understanding the highly variable nature of the ground conditions (as indicated by the other available investigations in the other parts of the Harbour Margin terrain) means there is considerable residual uncertainty associated with the ground conditions in between the available investigations.

Due to the residual uncertainty outlined above T+T considers it would not be appropriate at the current time to attempt to delineate areas of "Medium" and "High" liquefaction vulnerability, so the entire area has been assigned a less precise category of "Liquefaction Damage is Possible"

Area D – Lower Alluvial Terrace

The Lower Alluvial Terrace terrain is classified as a combination of "Liquefaction Damage is Possible", "Liquefaction Damage is Unlikely" and "Liquefaction Category is Undetermined." In both Area D1 and D2 there is more uncertainty associated with both the depth to groundwater (refer to Figure 4.16) and the ground conditions (refer Figure 4.15). The key differentiating features between these classifications are as follows:

- **Area D1** comprises the Level A areas on the Matapihi peninsula within the Lower Alluvial Terrace terrain. While there are very few deep investigations (Boreholes and CPT) in this area, there are a number of test pit locations that run along Matapihi Road. These test pit locations indicate that the geology in this area is consistent with a typical soil profile comprising of a thin layer of top soil (typically 0.2 to 0.5 m thick) underlain by the Younger Ashes (typically 2.0 to 3.0 m thick) underlain by Rotoehu Ash (typically 1.0 to 2.0 m thick) with the test pit terminating at a target depth of 4.0 m.

  The Rotoehu Ash is dated at more than 50,000 years old and its presence at relatively shallow depths across this area (typically 2-3 m below ground level) is important because empirical observations indicate that liquefaction occurs more commonly in Holocene age (<12,000 year old) soil deposits than older deposits such as Pleistocene age (12,000 to 2.5 million years old) soil deposits.

  To account for this issue of soil age Table 4.3 of the MBIE/MfE Guidelines (2017) provide semi-quantitative screening criteria for identifying land where liquefaction-induced ground surface damage is unlikely. This table recommends that a category of "Liquefaction Damage is Unlikely" be assigned for soils of Pleistocene age or older if design PGA for 500-year intensity of earthquake shaking is less than 0.3 g **and/or** the depth to groundwater is greater than 4 m.

  While there is more uncertainty associated with the depth to groundwater along the Matapihi Peninsula (refer to Figure 4.16) it is likely that the depth to groundwater for ground at higher elevation is significantly deeper than 4 m and therefore that uncertainty is not considered material to the assessment of liquefaction vulnerability. Therefore, given that both criteria in Table 4.3 of the MBIE/MfE Guidelines (2017) are likely to be met the category of "Liquefaction Damage is Unlikely" is assigned to most of the Lower Alluvial Terrace of the Matapihi Peninsula. The exception to this is the land within the lower lying areas of the Lower Alluvial Terrace in closer proximity to coastal margin where there is the potential for shallower groundwater for thicker deposits of Holocene age soils to be present.

- **Area D2** comprises the Level A areas in the Kairua area within the Lower Alluvial Terrain. While it is likely that the ground conditions within this area will be similar to those encountered in Area D1 there is a higher degree of uncertainty associated with the depth to the Rotoehu Ash, the location of the boundary between this terrain and others in the area and the depth to groundwater where a more complex groundwater regime is likely to exist. For these reasons considerable residual uncertainty exists and the category of "Liquefaction Category is Undetermined" has been assigned.

Area E – Volcanic Hills and Ranges

The volcanic Hills and Ranges terrain is classified as a combination of "Liquefaction Damage is Unlikely" and "Low". In both Area E1 and E2 there is more uncertainty associated with both the depth to groundwater (refer to Figure 4.16) and the ground conditions (refer Figure 4.15). The key differentiating features between these classifications are as follows:

- **Area E1** comprises the Level A area around Mauao. While there is more uncertainty associated with the precise ground conditions (due to a lack of geotechnical investigations) exposed rock is visible in the aerial photography and site walkover indicates that any residual soil layers are typically less than 1.0 m thick across the site. Furthermore, while there is more uncertainty associated with the depth to groundwater in this area the steepness of the terrain and the high elevation indicate that it is likely that the groundwater is very deep across the majority of the site. For these reasons the uncertainty that remains is not considered material to the assessment and a liquefaction vulnerability category of "Low" has been assigned.
- **Area E2** comprises the Level A around the Kairua area that is within the Volcanic Hills and Ranges terrain. While it is likely that the ground conditions are similar to those found around Mount Mauo, there isn't as much exposed rock visible in the aerial photography, the thickness of residual soil deposits is not as well established and there is more uncertainty associated with the location of the boundary between this terrain and the adjacent terrains. For these reasons there is a higher degree of residual uncertainty than Area E1 and the land has been categorised as "Liquefaction Damage is Unlikely."

5.2 Conclusions

T+T has undertaken a liquefaction vulnerability study in accordance with the MBIE/MfE Guidelines (2017) for the area defined as the Eastern Zone in this study. The following are the key conclusions and recommendations from this study:

- The current LiDAR derived DEM that is available for the TCC area provides a valuable tool both for assessing liquefaction vulnerability and other applications. One of the key limitations associated with any DEM (regardless of the survey source) is the potential for temporal changes in the ground surface elevation due to landform modification from both natural (e.g. erosion) and anthropogenic (e.g. land development) processes.

  To address this potential source of uncertainty T+T recommends that TCC continue the existing program of undertaking regular LiDAR survey of the land area. As well as providing an understanding of relatively gradual changes to landform, this information may be critical for post-earthquake response and recovery.

  T+T recommends that TCC require liquefaction assessments accompanying resource and building consent applications consider the proposed finished ground surface elevation.
- The published geomorphic map provides a valuable tool and a significant refinement of the available information in its own right. While it has been developed for the purposes of liquefaction assessment it is likely to provide benefit to other applications throughout Tauranga. For this reason a separate report has been prepared to support the geomorphic mapping and T+T understands that this information will be made available through TCC GIS Portal.

- The geotechnical investigation data collected through the course of this program provides significant benefit to the community. This is not only with respect to liquefaction but also for consideration of other applications.

  T+T recommends that TCC continue to support the collection and uploading of geotechnical investigation data onto the NZGD. One mechanism by which this may be achieved is making the granting of resource and building consents conditional on uploading supporting geotechnical investigations onto the NZGD. TCC may also wish to facilitate the education and upskilling of contractors undertaking investigations throughout the Tauranga area to ensure that appropriate data quality standards are achieved.
- The available groundwater information is comprehensive and provides a valuable resource both for this application and others. This information has been critical for the development of the liquefaction-induced land damage models developed for this study of the Eastern Zone and has been a significant tool for reducing the degree of residual uncertainty associated with the mapping of liquefaction vulnerability.

  T+T recommends that TCC continue to fund this program for the existing piezometer locations because a longer length of record will help to understand the response of the groundwater table to both sea level rise and other factors that influence the elevation of the groundwater table (e.g. drought and rainfall). TCC may also wish to consider expanding the number of piezometer locations into areas at higher elevation where the groundwater is less likely to be influenced by sea level rise (e.g. the lower alluvial terrace in the Kairua area).
- The seismic hazard information collected for this study represents a significant refinement and update to the existing information. Critically the BSL study has provided a significant reduction in uncertainty with respect to the seismic hazard in the Tauranga region. While the magnitude value is slightly higher there is a significant reduction in the estimated PGA when compared to previous estimates. The net effect is an overall reduction in the expected liquefaction related land damage when compared to previous assessments of liquefaction vulnerability.

  To further reduce the uncertainty of Seismic Hazard for liquefaction assessment TCC may consider supporting refinement of the Vs30 model for Tauranga as this is a key source of uncertainty in the model.

  The BSL report states that the results are intended for use in regional liquefaction and slope instability hazard triaging (e.g. for housing and horizontal infrastructure development), and are not appropriate for site-specific assessment of commercial or industrial structures in lieu of conventional prescriptive design standards and guidelines. It is envisioned that these national standards will eventually be updated with more up-to-date seismic hazard estimates, but in the meantime there is some uncertainty regarding what parameters should be adopted for design in various situations.

  TCC may wish to provide clarification for resource and building consent applicants as to the situations and extent it might be reasonable for them to rely on the BSL results in preference to current standards (e.g. NZTA Bridge Manual). This is important because if engineers are not able to rely on the lower PGA values from the BSL report then they may calculate higher liquefaction vulnerability than indicated in the TCC liquefaction vulnerability study, resulting in inconsistencies and confusion. TCC may also wish to encourage that site-specific seismic hazards be undertaken for high-importance projects.

- The two land damage models developed based on the available information represent a significant refinement of the existing information. These models provide a valuable tool to enable assessment of the consequences of liquefaction related land damage to roads, bridges, pipelines and other city owned infrastructure. They also provide a valuable tool for TCC to use in public education programmes.

  However, given the uncertainties associated with these models, they should not be relied upon for informing RMA and Building Consenting processes. These processes should rely on the liquefaction vulnerability map provided in Figure B16 and the associated meta-data.
- One of the key sources of uncertainty in the land damage models is the extent and severity of lateral spreading that can be expected under earthquake loading. The uncertainty associated with lateral spreading primarily comes from the following two sources:
  - The limitations of the usefulness of LiDAR derived DEM for the mapping of free faces associated with water features. To address this limitation TCC could commission bathymetric surveys of waterbodies within the Eastern Zone such as the Wairakei Stream. This would enable a more accurate estimation of the height of free-faces and consequently a refinement in the assessment of the potential extent and severity of lateral spreading; and
  - The limitations of existing methods (even using highly complex models) to reliably predict lateral spreading related land damage. Over time it is likely that the suite of analytical tools available will improve to a point where further refinement of the available information is warranted.
- The key observation from interrogation of these figures is for earthquakes with return periods of 250 years and greater, sea level rise of 1.25 m is predicted to result in a significant increase in the extent and severity of liquefaction induced land damage. This observation applies in areas where the soils are susceptible to liquefaction and the groundwater is relatively shallow (typically less than 10 m deep). While there is uncertainty associated with the degree and timeframe over which sea level rise will occur and how groundwater will respond, T+T recommends that TCC recognise this potential increase in liquefaction vulnerability and allow for it in their planning for the future.
- The majority of the study zone has been assigned as either a Level A or a Level B level of detail with some smaller areas assigned Level C. This is consistent with the regional scale assessment that has been undertaken. The key output from this study is the categorisation of the majority of land in the Eastern Zone into one of the three following liquefaction vulnerability categories “Liquefaction Damage Category is Undetermined” or “Liquefaction Damage is Unlikely” or “Liquefaction Damage is Possible” with some smaller areas mapped as “Low.”

  This degree of precision in the categorisation of liquefaction vulnerability is generally consistent with a regional scale study such as this undertaken to the level of detail described above, particularly in areas where the majority of surficial soils are considered susceptible to liquefaction. This map output provides a valuable tool for TCC intended purpose of informing policy, planning and consenting processes.

  T+T recommends that TCC incorporate this information into their current business processes to inform policy, planning and consenting processes. This is particularly relevant with respect to the processing of building consent applications as changes to the definition of “good ground” in the Building Code are due to take effect by 28 November 2021.

6 Applicability

This report has been prepared for the exclusive use of our client Tauranga City Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Recommendations and opinions in this report are based on data from individual CPT and borehole locations. The nature and continuity of subsoil away from these locations are inferred and it must be appreciated that actual conditions could vary from the assumed model.

The susceptibility analyses carried out represent probabilistic analyses of empirical liquefaction databases under various earthquakes. Earthquakes are unique and impose different levels of shaking in different directions on different sites. The results of the liquefaction susceptibility analyses and the estimates of consequences presented within this document are based on regional seismic demand and published analysis methods, but it is important to understand that the actual performance may vary from that calculated.

This assessment has been made at a broad scale across the Eastern Zone of Tauranga City, and is intended to approximately describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g. for design of building foundations).

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