Tauranga City Western Zone

Liquefaction Hazard Assessment

Tauranga City Council

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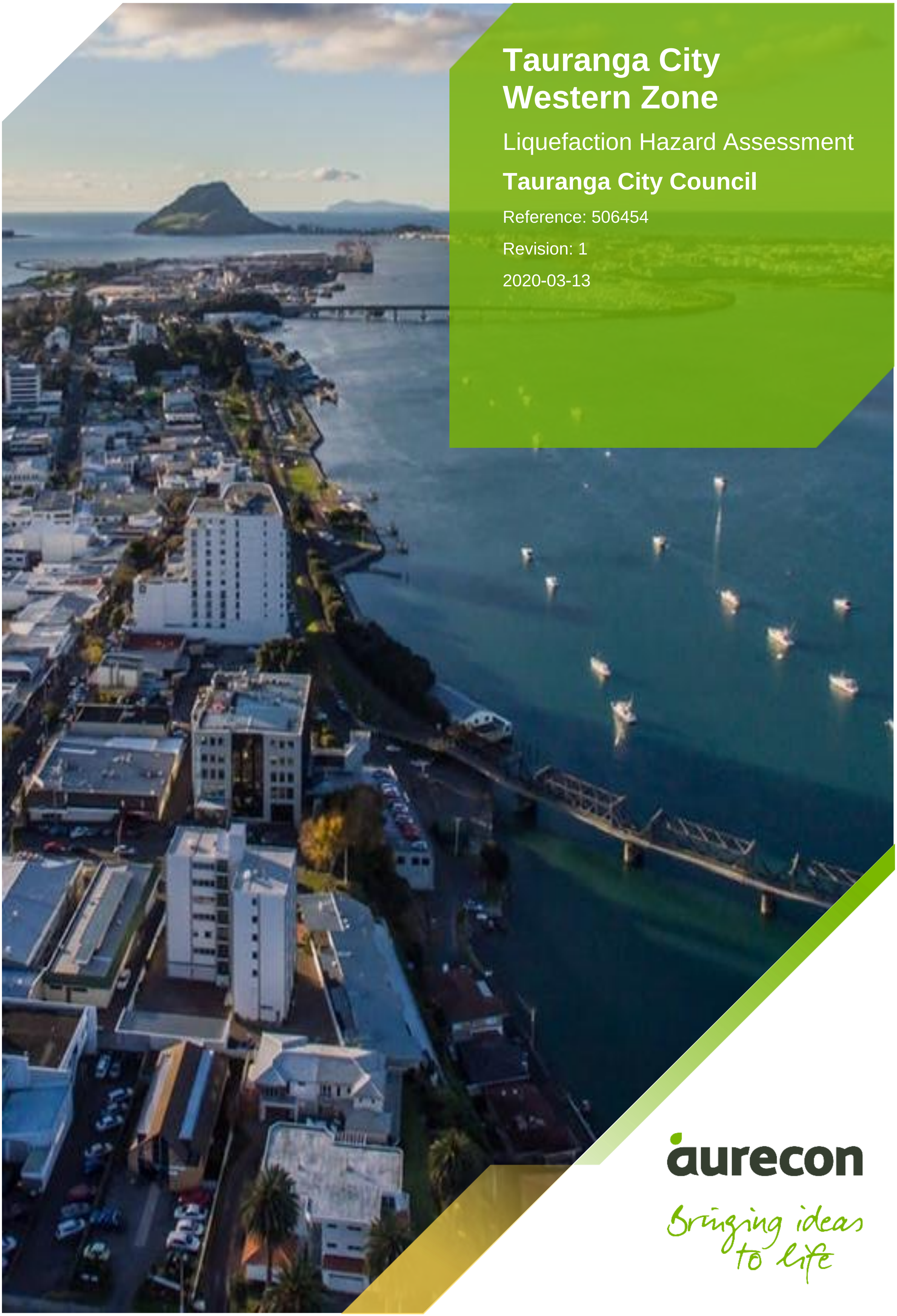

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Liquefaction Assessment Summary	
This liquefaction assessment has been undertaken in general accordance with the guidance document '*Assessment of Liquefaction-induced Ground Damage to Inform Planning Processes*' published by the Ministry of Business, Innovation and Employment in 2017. **https://www.building.govt.nz/building-code-compliance/geotechnical-education**	
Client	Tauranga City Council (TCC)
Assessment undertaken by	Aurecon New Zealand Ltd, Ground Floor, 247 Cameron Road, Tauranga 3110. PO Box 2292, Tauranga 3140
Extent of the study area	The Western Zone study area comprises the central, western and southern portions of Tauranga City and has an area of approximately 154 km^2. The extent of the Western Zone study area is shown in Plan A1 - Western Zone Study Area Boundary, Appendix A.
Intended RMA planning and consenting purposes	To provide Tauranga City Council with a district-wide liquefaction vulnerability assessment to help inform spatial planning and assessment of land use, subdivision and building consents. It is not intended to replace site-specific assessment required to inform landform or foundation design for consenting purposes.
Other intended purposes	This study has been completed as part of a wider programme of resilience work within Tauranga City. It will provide Tauranga City Council with an understanding of expected land damage performance for a range of potential future earthquake and groundwater scenarios. Predicted land damage and vulnerability classification will help to identify council-owned infrastructure and assets susceptible to liquefaction and lateral spread hazard. This assessment has been made at a broad scale across the entire 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 will be required for some purposes (e.g. for G1 Assessment of Subdivision Suitability, design of building foundations).
Level of detail	A Level B (Calibrated Desktop Assessment) has been performed for the entire Study Area.
Notes regarding base information	The geomorphic terrains mapped as part of this study are derived based on collation and interpretation of desktop information acquired from a range of sources. The precision and level of scale at which the terrain boundaries have been mapped provide a high level geographic overview and are not intended to provide specific interpretation of ground conditions and risk for individual property owners. This assessment has utilised Cone Penetration Test data from three primary data sources: ▪ New Zealand Geotechnical Database (accessed to 16 July 2019), ▪ Ground investigation data recovered from Aurecon's internal database (not available publicly), and ▪ Additional ground investigation works completed as part of the current engagement. Please refer to Section 3.2.3 and Plan A6, Appendix A for investigation details. The groundwater model provided by Tauranga City Council for use as part of this assessment does not cover the southernmost extent of the Western Zone Study Area. For this reason, the calculated results of liquefaction analyses used to predict land damage and liquefaction vulnerability from CPT data within this area has been excluded from use within our geostatistical analyses, and calculated results are not shown in Appendix B.

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Explanatory statement

This Level B liquefaction assessment has been completed at a broad scale across the western half of the city. It is intended to describe approximately the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. It is not suitable for any alternative process beyond that specifically outlined as part of the original study intent, as set out within the brief as provided (TCC Ref. TC51/19, 2 May 2019).

It is not intended to be used for land use or subdivision consent applications or detailed foundation design. The recommendations and opinions given in this report are based on limited, and often widely spaced, geotechnical test locations and the nature and continuity of ground conditions away from these locations are inferred. It must be appreciated that actual conditions could vary from the assumed model.

We have prepared this report following best practice as set out by MBIE Guidelines for Planning and engineering guidance for potentially liquefaction-prone land (2017) for a Level B – Calibrated Desktop Assessment, and in accordance with the brief. The contents of this report are for the sole use of Tauranga City Council and no responsibility or liability will be accepted to any third party. Data or opinions contained within the report may not be used in other contexts or for any other purposes without our prior review and agreement.

The recommendations in this report are based on data collected at specific locations and by using appropriate investigation methods with limited site coverage. Only a finite amount of information has been collected to meet the specific financial and technical requirements of the Client's brief and this report does not purport to completely describe all the site characteristics and properties. This report is not to be reproduced either wholly or in part without our prior written permission.

Glossary of acronyms

Term	
ARI	Annual Recurrence Interval
BOPRC	Bay of Plenty Regional Council
CES	Canterbury Earthquake Sequence
CPT	Cone Penetration Test
DEM	Digital Elevation Model
ENZ (IPENZ)	Engineering New Zealand (formerly Institute of Professional Engineers, New Zealand)
EQC	Earthquake Commission
GIS	Geographic Information System
GNS	Institute of Geological and Nuclear Sciences
km	Kilometres
LiDAR	Light Detection and Ranging
m	Metres
MBIE	Ministry of Business, Innovation and Employment
MfE	Ministry for Environment
mRL	Elevation in terms of metres relative level
NZGD	New Zealand Geotechnical Database
NZGS	New Zealand Geotechnical Society
NZ RCP 8.5	New Zealand Representative Concentration Pathway 8.5 (NIWA, 2017)
NZSEE	New Zealand Society for Earthquake Engineering
NZVD2016	New Zealand Vertical Datum 2016
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Assessment
TC1-3	Technical Category 1 – 3 (MBIE, 2012)
TCC	Tauranga City Council
TCC Cat 1	Tauranga City Council Category 1 Geo-professional
TVZ	Taupo Volcanic Zone
V_{s30}	Average shear wave velocity through upper 30 m of soil and/or rock profile

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1 Introduction

Tauranga City Council (TCC) requires up-to-date liquefaction risk information to inform future vulnerability assessments and resiliency projects. The overall objective of the resilience project is to inform future land-use planning and capital expenditure to minimise the disruption to municipal assets and the community, in the event of future large-scale natural disaster events including earthquakes, tsunami and heavy rainfall.

To achieve this outcome TCC engaged Aurecon New Zealand Ltd (Aurecon) to undertake geomorphological mapping, liquefaction hazard analyses and risk mapping for the Western Zone of Tauranga City under contract TC51/19. The extent of the Western Zone study area is shown in *Plan A1 - Western Zone Site Boundary*, Appendix A.

The primary objective of this assessment is to identify the presence and extent of liquefaction vulnerability in the Western Zone of Tauranga City. This liquefaction hazard study has been undertaken in general accordance with recently published Ministry of Business, Innovation and Employment (MBIE, 2017) Guidance Document *Planning and engineering guidance for potentially liquefication-prone land* to a *Level B - Calibrated Desktop Assessment* level of detail.

The report includes:

- The ground conditions within the study extent.
- The groundwater assumptions for the purpose of the liquefaction assessment.
- The seismic shaking hazard adopted for the assessment of liquefaction for the study extent.
- Information about lateral spreading.
- An assessment of the likelihood of liquefaction-induced land damage within the study extent.
- An assessment of the overall liquefaction vulnerability of the Western Zone of Tauranga City.

This Revision of the report incorporates and addresses peer review comments from Wentz Pacific Limited and Tonkin & Taylor (related specifically to the geomorphology).

2 Project Context

2.1 Liquefaction Hazard in the Western Zone

2.1.1 General

Under cyclic loading (i.e. during an earthquake) loose, non-cohesive materials such as gravels, sands, silty-sands, tend to decrease in volume resulting in settlement. This tendency within loose soils to decrease in volume is much greater than for more dense soils, where resistance to seismic loading is greater.

When loose non-cohesive soils are saturated and rapid loading occurs under undrained conditions, the densification of soil particles causes pore water pressure to increase. The increase in pore water pressure results in a loss of soil strength due to a decrease in effective stress and eventually liquefaction occurs when the effective stress drops to zero. Liquefaction can lead to large displacements of foundations and service infrastructure, flow failures of slopes, ground surface settlement, sand boils, and post-earthquake stability failures. Three primary factors contribute to liquefaction potential:

- Soil grading and density - loose non-plastic soil (typically sands and silts, or in rare cases gravel)
- The presence of groundwater – having a saturated soil (i.e. below the groundwater table)
- Earthquake intensity and level of ground shaking – i.e. creating a sufficient ground shaking (a combination of the duration and intensity of shaking)

2.1.2 Landforms commonly susceptible to liquefaction

As defined in MBIE (2017), natural soil types that are susceptible to liquefaction are typically:

> "*those that are geologically young (i.e. <11,000 years old) and deposited in low energy environments, forming loose and soft layers*".

Anthropogenic materials (e.g. man-made fills) can also be susceptible where they are not placed and compacted in a controlled manner. While granular sandy soils are the most likely to liquefy, silts that are of low plasticity or 'cohesiveness' can also liquefy. In addition to sandy and silty soils, some gravelly soils are potentially susceptible to liquefaction. Most gravelly soils drain relatively well (hence no increase in pore pressure can occur), however, they may be susceptible to liquefaction when:

- Their voids are filled with finer particles;
- They are surrounded by less pervious soils; or
- Drainage is impeded.

Some clay soils can also exhibit liquefaction-like behaviour (i.e. cyclic softening). The areas containing significant deposits of potentially liquefiable soils are often relatively flat and close to waterways, which have historically made for attractive places to develop buildings and infrastructure. Reclaimed land formed by placing uncompacted or poorly compacted fill within existing waterways is particularly susceptible to liquefaction as it is often relatively loose and saturated.

Figure 2.5 (reproduced as Figure 1 below) of the MBIE Guidelines highlights landforms typically more susceptible to liquefaction hazard; all of which can be found within the Tauranga City boundary, and more specifically the Western Zone study area, which straddles the margin of the Tauranga Harbour (an estuarine lagoon) and accommodates large surface water catchments such as the Kopurererua Stream and the Wairoa River. Reworking and reclamation is common, particularly around the Te Papa Peninsula and at Sulphur Point. Dredging has occurred within the Tauranga Harbour dating back to 1968 (de Lange *et al.* 2015) creating deep channels adjacent to Sulphur Point, The Central Business District and the area of Tauranga Port to the south of Mount Maunganui, exacerbating potential lateral spread risks in these areas.

Figure 1 Landforms identified by MBIE to be commonly susceptible to liquefaction (Taken from Figure 2.5 of the MBIE guidelines, 2017)

2.2 Consequences of liquefaction

While the immediate effects of liquefaction relate primarily to land damage, it can also cause a wide range of flow-on consequences. This is summarised in Table 2.1 and Figure 2.6 of MBIE (2017) and reproduced below as Table 1 and Figure 2.

Table 1 Potential Consequences of Liquefaction - after Table 2.1, MBIE (2017)

Heading	
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 or 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 weathertightness of the building. ▪ Loss of foundation-bearing capacity, resulting in settlement of the structure. In some cases, this can result in tilting or overturning of multi-level buildings. ▪ Stretch of the foundation due to lateral spreading, pulling the structure apart. In some cases, this can result in collapse or near-collapse of buildings. ▪ Damage to piles due to lateral ground movements, and settlement of piles due to down drag 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 deformation (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 stop banks, resulting in leakage and loss of freeboard. ▪ Disruption of storm water 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 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).

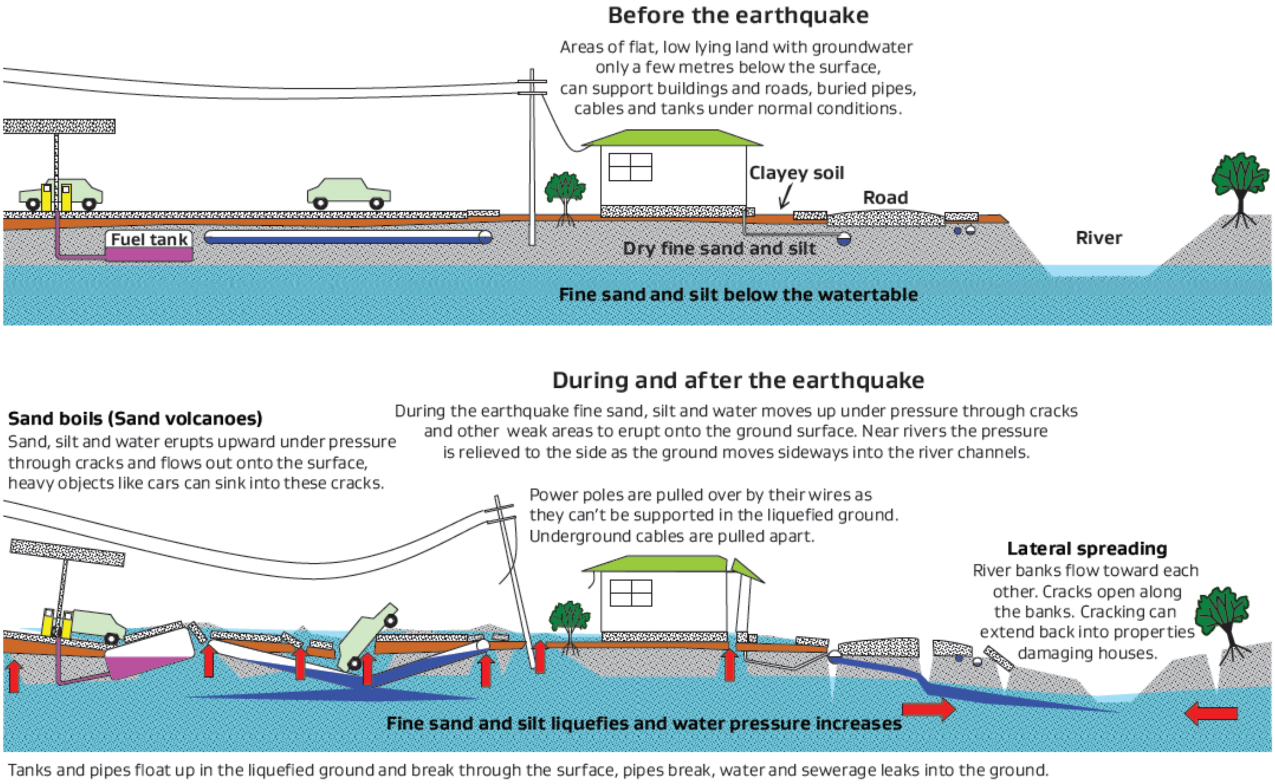

Figure 2 Liquefaction and its effects - after Figure 2.5 MBIE (2017) originally sourced from Engineering New Zealand (ENZ)

2.3 Intended purpose and scope of works

Previous liquefaction mapping for Tauranga and the Western Bay of Plenty Areas was completed in 2002 (Refer Section 2.4). TCC require up-to-date liquefaction risk information to inform future vulnerability assessments and resilience projects seeking to minimise disruption to municipal assets in the event of future large earthquake events. This information will also be used to help inform future land use planning, as the city continues to exceed predicted growth expectations in terms of population.

To help facilitate council decisions concerning investment in future infrastructure resilience projects an updated liquefaction hazard analyses and risk mapping exercise has been undertaken for the Western Zone of Tauranga City (the Western Zone study area). The scope of services underpinning this assessment and reporting can be summarised as follows:

- Provide a new geomorphological map of the Western Zone study area. This has been completed based on collation and review of data from, but not limited to, the following sources:
  - Topographic maps and LiDAR information provided by TCC
  - Regional and city-wide published geological mapping
  - Groundwater surface modelling
  - Historic Aerial Photography from TCC's GIS system and third-party sites such as 'Retrolens™'
  - Historic photography showing early development around Tauranga available from a range of local historical webpages, archaeological websites, library sources and social media pages
  - Technical reporting and ground investigation data (primarily from Aurecon's internal geotechnical database)
  - Previous liquefaction susceptibility assessment reporting

- Collation of historical ground investigation data (principally Cone Penetration Testing) for use in updated analyses from the New Zealand Geotechnical Database (NZGD) and Aurecon's internal geotechnical database.
- Specification of additional ground investigation works (Cone Penetration Testing) completed by TCC to infill potential data gaps from desktop sources.
- Review of the city-wide Probabilistic Seismic Hazard Assessment (PSHA) completed by Bradley Seismic Ltd (Bradley, 2019) and use of statistical analyses to develop predicted ground accelerations in a range of design earthquake events for each geomorphic terrain from modelled data provided.
- Completion of quantified liquefaction analyses to measure predicted liquefaction response behaviour, settlements and lateral displacements from over 1,200 data points across the Western Zone collated from desktop sources, the NZGD and additional ground investigation works collected by TCC. Analyses has been completed for 25, 100, 250, 500 and 1,000-year average recurrence intervals. These analyses have been completed for two modelled groundwater events; a current groundwater surface provided by TCC; and an anticipated elevation of the groundwater table as an effect of predicted climate change model.
- Interpretation of analyses and subsequent sensitivity checks to develop predicted land damage maps for each design earthquake event conforming to the requirements of the MBIE (2017) guidelines.
- Development of liquefaction vulnerability maps to the requirements of the MBIE (2017) guidelines accounting for both current and future sea level rise based on interpretation of predicted land damage.
- Provision of new GIS data layers of updated liquefaction hazard levels for publication on TCC's 'MAPI', GIS system.

2.4 Previous information about liquefaction in Tauranga

A district wide liquefaction hazard study *Western Bay of Plenty Lifelines Study Microzoning for Earthquake Hazard* carried out in 2002 and was reported in 2003 for the Western Bay of Plenty Lifelines Group (Opus, 2003). The area covered by the 2002 study includes the majority of the Western Zone. The mapped liquefaction hazard from this 2002 study is presented in *Plan A2 – 2002 Liquefaction Study* in Appendix A.

The key outcomes of this study identified the upper ridges and elevated terraces within the Western Zone as having limited liquefaction susceptibility. The lower Alluvial Channels, Alluvial Flood Plain and Harbour Margin terrains (Refer Section 3.2.2) were identified as having significantly higher liquefaction susceptibility.

The report inferred that significant lateral spreading-induced damage could be expected around the major waterways of the Wairoa River on the western boundary of the Western Zone study area and the Kopurererua, and Wairoa Rivers and Waimapu Stream flowing north through the southern and central parts of the Western Zone study area. Lateral spreading-induced damage could also be expected in many parts of the low-lying Harbour Margin areas.

3 Liquefaction Risk Identification

3.1 Level of detail required for intended purpose

This Liquefaction Hazard Assessment is intended to be carried out to a *Level B – Calibrated Desktop Assessment* level of detail as per the requirements of the recently published guidance document *Planning and engineering guidance for potentially liquefication-prone land* (MBIE, 2017). The level of assessment undertaken for the Western Zone is shown in *Plan A3 – Study Detail Level* in Appendix A.

3.2 Base information currently available

3.2.1 Ground Surface Levels

A Digital Elevation Model (DEM) in terms of the New Zealand Vertical Datum 2016 (NZVD 2016), exists of the Tauranga City region and has been provided for assessment by TCC. The DEM has been created from LiDAR surveys in 2019.

In the Western Zone, the main topographical features comprise north-south trending ridge lines and valleys dipping to the north, the Tauranga Harbour, and the sloping hillsides of Welcome Bay. There are several large waterways running parallel to the ridge lines in incised valleys draining northward into Tauranga Harbour. The main waterways are the Wairoa River on the western boundary of the Western Zone study area and the Kopurererua, and Wairoa Rivers and Waimapu Stream flowing north through the southern and central parts of the Western Zone study area. Numerous other small streams flow through the study area typically draining into these major waterways or directly into Tauranga Harbour.

The ridge lines are upwards of 70 mRL (metres Relative Level in terms of NZVD 2016), while the Welcome Bay area rises to an elevation over 100 mRL at the south-eastern edge of the study area. The valley floors comprise low lying areas in the order of less than 10 mRL. The ridges and valley floors fall towards the coastal margins on the northern boundary of the site formed by Tauranga Harbour. This coastal area comprises several incised inlets and bays forming several estuary areas. Harbour Margins are a combination of coastal cliffs (approximate 20m high) and low-lying (less than 5 mRL) flatland areas.

In review of the DEM, we have noted several areas of discrepancy regarding the interpretation of actual ground surface elevation which has been considered through our liquefaction assessment. Areas of discrepancy noted include:

- Inaccurate surface elevations noted in and around the Tauranga Crossing Shopping Mall development which was undergoing pre-load earthworks at the time the survey was undertaken.
- Inaccurate surface elevations noted in and around the Sulphur Point, where the top of temporary log stockpiles and shipping containers stacks has been recorded.
- Difficulty in differentiation of ground elevation where building structures are constructed on or near sloping ground (Fraser Cove shopping centre).

These minor discrepancies highlight that the results of this assessment, while suitable for a region-wide study, will not supersede any requirement for site-specific investigation and assessment of liquefaction. Care should be taken in correctly interpreting this information by others. The DEM of the study area is shown in *Plan A4 – Ground Surface* in Appendix A.

3.2.2 Geology and Geomorphology

Geological Setting

The regional geology of the Western Zone is described in the 1:250,000 scale geological map of the Rotorua Area (Leonard et, al., 2011) and the 50,000 scale geological map for the Tauranga area (Briggs et, al., 1996). Both geological maps indicate that ignimbrites comprise terraces at higher elevations (i.e. >20 mRL) trending in a southwest-northeast orientation through the study area. These ignimbrites have been mapped as Middle-Pleistocene Chimp Formation by Leonard et al. (2011) and called the Te Ranga Ignimbrite by Briggs et al. (1996). These are described as *non-welded, poorly-consolidated rhyolite ignimbrite, commonly with nearly aphyric pumice; minor fall deposits*.

In the upper reaches of the study area, near Tauriko, the ignimbrites are mapped as Middle-Pleistocene Pokai Formation (Leonard et al., 2011); *rhyolite ignimbrite with brown matrix, orange pumice clasts, non-welded, cream-coloured base to welded jointed; minor fall deposits* or the Waimakariri Ignimbrite (Briggs et al., 1996). In the east of the study area, within Welcome Bay, the ignimbrites are Neogene Waiteariki Formation ignimbrite; a *crystal-rich dacitic welded ignimbrite*, and Neogene Papamoa Formation ignimbrite; *Basaltic andesite to dacite ignimbrite*. The Neogene-aged Papamoa Ignimbrite has been mapped in the far east of the study area within Welcome Bay East – this ignimbrite is a *basaltic andesite to dacite ignimbrit*e.

Following their deposition, the ignimbrites covering the study area were progressively incised and the eroded material redeposited as alluvium within the Tauranga Basin – where Early to mid-Pleistocene Tauranga Group alluvium and younger Quaternary alluvium has been mapped infilling river valleys and basins. The Tauranga Group includes the Matua Subgroup, which comprises terrestrial and estuarine deposits formed after the deposition of the ignimbrite and covers a wide range of ages (2.18 – 0.35 Ma) (Briggs et al., 1996). The Matua Subgroup rapidly changes in lithology both laterally and vertically and includes fluvial pumiceous deposits, lignites and peats with intercalated airfall tephras, typically older and significantly weathered, containing high concentrations of allophane and halloysite minerals resulting in highly sensitive behaviour.

Overlying the Matua Subgroup and ignimbrites is up to 10 m of Late Quaternary Taupo Volcanic Zone tephras comprising (from youngest to oldest): the Younger Ash (including the Kawakawa tephra); Rotoehu Ash (~>50 ka in age); and Hamilton Ash (~0.35 Ma) (Briggs et al., 1996). The Younger Ash comprises inter-layered zones of silt ash, interspersed with layers of pumice rich sandy silts. The Rotoehu Ash usually consists of a thin loose pumiceous sand layer which overlies the Hamilton Ash. At the top of the Hamilton Ash there is often a distinctive paleosol layer (old topsoil horizon) locally known as the 'Chocolate Layer'. The Hamilton Ash grades into older more weathered ash deposits at depth. These vary in consistency and comprise beds of silt and clay rich deposits. These tephras are unmapped by both Leonard et al., (2011) and Briggs et al., (1996).

Unmapped non-engineered and engineered fill is likely to be present throughout the study area, particularly around the current shoreline, and within the base of gullies and across floodplains.

Geomorphic Setting

The Tauranga Basin is a semi-circular structure 40 km long and 15 km wide the extent of which can be roughly defined by the current shoreline of the Tauranga Harbour, which reflects the extent of the Tauranga structural depression. The Harbour is a typical shallow estuarine lagoon formed behind Matakana Island, a Pleistocene-aged coastal barrier island feature. The harbour is formed of a series of drowned river valleys; through a combination of alternating sea levels with high rates of erosion and sedimentation. Along with sporadic volcanic eruptions through the Pleistocene and Holocene, the basin has filled with thick sequences of sediments intercalated with tephras overlying basal ignimbrite flows.

These sediments have formed a range of terrace features bisected by current streams draining north towards the harbour, creating a series of north-south trending ridgelines, mantled by volcanic ashes derived from the Taupo Volcanic Zone (TVZ). Active erosion and sedimentation has resulted in steeply incised gullies with poorly consolidated Holocene-aged sediments being deposited within the base of gullies and around the margins of the harbour.

For the Western Zone, we have identified six key geomorphological terrains. These terrains are summarised in Table 2 and locations and extent of each geomorphological terrain is presented as *Plan A5 - Feature Mapping - Terrain* in Appendix A.

The mapping of the geomorphic terrains was completed through collation and interpretation of a number of data sources in GIS and include:

- LiDAR Digital Elevation Model (DEM, NZVD 2016) provided by TCC

- Contour and shaded relief maps derived from the DEM
- QMap Geological Map of Rotorua (Leonard et al., 2011)
- 1:25,000 Geological Map of Tauranga (Briggs et al., 1996)
- Bay of Plenty Regional Council Soils map (BOPRC webmap)
- Historical and current aerial photographs (TCC webmap)
- New Zealand Geotechnical Database
- Aurecon's internal Geotechnical Database
- Geotechnical investigations undertaken as part of this project (refer to Section 3.2.3)
- Groundwater model provided by TCC (Tonkin and Taylor, 2019)

The geomorphic terrain development and mapping, review and verification has been undertaken by experienced Chartered Geologists. In addition to being chartered, the reviewer and verifier are also TCC accredited Category 1 Geo-professionals.

Uncertainties and limitations exist due to the scale and complexity of the mapping exercise (approximately 1:25,000) and data sources used for input into the geomorphic mapping of the terrains. The geomorphic terrains are based upon the data sources, largely utilising the geological maps and DEM to identify discernible geomorphic features. Field mapping and local knowledge assisted with the predominantly desk-based mapping of the geomorphologic terrains, including their surface expression characteristics and distribution. It is not intended at the regional scale produced by this mapping exercise that these maps be used for site specific purposes however the terrains will provide useful guidance to anticipate ground conditions and inform future detailed studies.

The published geological maps are of a different scale (i.e. 1:50,000 and 1:250,000) to that mapped for the terrains (presented in Appendix A, Plan A5 but mapped to higher resolution). In addition, quaternary ash cover is not presented on the geological maps. The thickness and/or presence of ash has largely been informed by previous geotechnical investigations, local knowledge and ground truthing. Previous geotechnical investigations can be uncertain due to the variability of logging, particularly pre-2005 when the New Zealand Geotechnical Society logging standards were introduced.

Discrepancies in the DEM have been noted and discussed in Section 3.2.1. In addition, the modelled groundwater surface does not extend fully to the southern edge of the Western Zone study (Refer Section 3.2.4.)

Table 2 Key geomorphic terrains within the Western Zone

Terrain Code	Terrain Name	Landform	Predominant Geology (upper 10m)	Type localities within the Western Zone	Terrain Photos
LR	Land Reclamation	Variable landforms associated with coastal reclamation, infilled gullies and landfills.	Uncontrolled and engineered fill, reworked natural soils or construction waste > 3m. Could also include hydraulic fill/end-tipping of loose materials into water.	Sulphur Point, The Strand (CBD)	 Sulphur Point Marina
AF	Alluvial Flood Plain	Alluvial Flood Plain and stream valley floors, characterised by low-lying flat topography, and typically dominated by active alluvial processes.	Undifferentiated Holocene-aged alluvium comprising gravel, sand, silt, mud and clay with localised peat; includes modern river beds. Occasionally interbedded with estuarine deposits and peats.	Wairoa Valley, Kopurererua Valley	 Kopurererua Valley
AC	Alluvial Channels	Active fluvial systems eroding older volcanic terraces forming steep-sided, typically narrow, north-south channels or small gullies. Characterised by colluvial / alluvial deposition typically at the base of gullies or within the upper reaches of stream valleys. Also includes the deposits of side slope processes and fans. Maybe capped by surficial terrestrial or low energy fluvial sediments, organic deposits and older alluvial processes.	Thin deposits of Holocene to recent-aged alluvium, colluvium or peat cover overlying predominantly Matua Subgroup silts/sands with in-situ and reworked tephra. In upper reaches, overlying shallow ignimbrite. The geology is inferred to be significantly influenced by underlying geological units.	Nanako Stream catchment (site of TCC Stormwater Pond 25); Welcome Bay	 Nanako Stream catchment

Terrain Code	Terrain Name	Landform	Predominant Geology (upper 10m)	Type localities within the Western Zone	Terrain Photos
HM	Harbour Margin	Low-lying areas surrounding the present-day shoreline of the Tauranga Harbour inferred to be dominated by estuarine type processes, rather than by alluvial or deltaic processes.	Variable combination of Holocene-aged estuarine silts and clays, beach sand or loosely poorly consolidated littoral/fluvial sands.	Otumoetai and Matua Foreshore	 Matua
AT	Lower (Alluvial) Terrace	Generally steep-sided terraces and sea cliffs (up to 30 mRL). The terraces typically comprising Pleistocene-age or older alluvium, with various interbedded ash and tephra deposits.	Ash covering Matua Subgroup alluvium. The Ash cover is variable and is typically a thickness of maximum 5 - 6 m at the top of the terrace ridges and thins around the terrace perimeter.	Te Papa Peninsula, Maungatapu Peninsula	 CBD
IT	Upper (Ignimbrite) Terrace	Steep-sided upper terraces (up to 60+ m RL) which are generally flat to gently sloping to the north east. The terraces are inferred to include a thick layer of mantling ash covering ignimbrite deposits.	Ash overlying thin Matua Subgroup alluvium and ignimbrite. Ash cover is >5 m thick.	Pyes Pa, Welcome Bay, Cambridge Road	 Cambridge Road

3.2.3 Geotechnical Investigations

For this study we have undertaken a review of readily available geotechnical information from both the New Zealand Geotechnical Database (NZGD, 2019) and internal Aurecon records, and following review of these databases scoped additional targeted ground investigation to infill data gaps or increase density of testing in areas of interest. In general, the amount of investigation data collected is considered suitable for the purposes of a Level B Assessment.

The locations of these tests are presented in *Plan A6 – Western Zone Geotechnical Test Locations* in Appendix A. Due to the semi-automated nature of our Liquefaction Hazard Assessment process we have relied upon Cone Penetrometer Test (CPT) data only for the use in the liquefaction triggering assessment.

Other geotechnical information (boreholes and test pit logs, maps etc.) have been incorporated into geomorphic mapping process, although this is not detailed explicitly here. These data were reviewed whilst undertaking the mapping to check and constrain the terrain type and interpreted boundary. In addition, reports available on the NZGD website and within Aurecon's internal database were accessed to provide further QA during the mapping process.

In total this study has accessed 1,236 usable CPT records, summarised in Table 3 and discussed in the following subsections. Table 4 presents the number of usable CPT within each geomorphic terrain within the Western Zone study area.

Table 3 Number of CPT data points utilised

Data source	Number of useable CPTs
New Zealand Geotechnical Database	479
Aurecon's internal Geotechnical Database	677
Additional ground investigations commissioned by TCC in concurrence with this study	80

Table 4 Number of CPT data points by geomorphic terrain

Geomorphic Terrain	Number of useable CPTs
Upper (Ignimbrite) Terrace	340
Alluvial Channels	93
Alluvial Flood Plain[1]	177 (+7)
Lower (Alluvial) Terrace	284
Harbour Margin	265
Land Reclamation	70

1. An additional 7 CPTs were incorporated into the dataset from outside the Western Zone study area. The CPTs were completed for the Tauriko West future growth area, which extends across the Western Zone study area in the south-west corner. These CPTs, located on the Wairoa River flood plain are within an area corresponding to the Alluvial Floodplain terrain and are shown on Plan A6, Appendix A.

New Zealand Geotechnical Database

All readily available geotechnical testing records (CPT, boreholes, test pits etc.) have been uploaded from the New Zealand Geotechnical Database (NZGD) to 16 July 2019. From the NZGD we have 479 usable CPT records for our liquefaction hazard study.

A total of 66 CPT records for which .pdf information was available but could not be utilised due to missing raw data. A total of 55 of these records relate to historic investigations for Routes P, K and J within the Kopurererua Valley and the Tauranga Harbour Link (to the north of the CBD). The remaining 11 CPT records relate to small private residential investigations for which the original data owners could not be contacted to supply, or give approval to supply, raw data. Due to potential inaccuracies and misinterpretation, a manual conversion of data from pdf records was not undertaken for this assessment.

Internal Aurecon Records

We have reviewed internal Aurecon records for usable historical geotechnical data. Where third party approval was granted, these CPT logs have been incorporated into our liquefaction hazard study. From our internal reporting database we have 677 usable CPT records within the Western Zone.

2019 Liquefaction Study Testing

As part of the liquefaction hazard study TCC has undertaken a limited programme of ground investigation works to supplement existing data. In the Western Zone a total of 80 CPT soundings were carried out. Testing was undertaken to a nominal 15m depth at all locations unless early refusal of the CPT cone was encountered on dense soil layers. The test locations were selected to maximise site coverage, and where practicable fill in 'blank' areas with limited testing and to target key geomorphic terrains. Physical site constraints such as site access, in-ground services, and traffic management requirements limited testing to TCC-owned land.

3.2.4 Groundwater

The Tauranga Harbour forms the northern and eastern boundary of the Western Zone, and the Wairoa River flows along the western boundary. Numerous streams flow south to north through incised gullies and wider alluvial river channels and flood plains through the Western Zone discharging into the Tauranga Harbour. Thick, unconsolidated sediment holds much groundwater, and is fed from the ranges and deeper levels.

A long-term groundwater modelling project has been undertaken separately for TCC (Tonkin and Taylor, 2019). From this study a long-term groundwater surface has been modelled and provided for use in this liquefaction hazard study. For the purpose of the liquefaction hazard assessment we have adopted the median (50^{th} percentile) depth to groundwater model. This groundwater model generally follows the expected groundwater trend with higher water levels to the south, corresponding to the higher geographical elevation, and dropping to the north towards Tauranga Harbour and to the major waterways that bound and drain through the Western Zone.

To model the effects of long-term sea level rise and climate change we have also looked at the nominal groundwater level in 100 years' time (2120). This 100-year groundwater level has been modelled as the median depth to groundwater model provided by TCC with a nominal 1.25 m increase in groundwater level. The 1.25 m increase in groundwater level has been chosen to align with the predicted change in sea level by 2130 for an NZ RCP 8.5 (median) value derived by NIWA (2017) and adopted by the Bay of Plenty Regional Policy Statement for Natural Hazard Assessment.

The modelled groundwater surface and corresponding depth to groundwater level is presented as *Plan A7 - Depth to Groundwater Surface* in Appendix A. It is noted that this modelled groundwater surface does not extend fully to the southern boundary of the Western Zone study area. The majority of this non-modelled area is underlain by elevated Upper (Ignimbrite) Terrace geomorphic terrain features, so the groundwater is known to be at a significant depth in these areas. However, there are some lower-lying areas in the southwest edge of the study area adjacent to the Wairoa River, and the Kopurererua and Waimapu Streams, which are underlain by Alluvial Flood Plain geomorphic terrain. In these areas, the groundwater is expected to be shallow (less than 5 m depth).

3.2.5 Regional Seismicity

Tauranga is located within a zone of seismic hazard considered to be moderate relative to the rest of New Zealand. The city is situated between the Hauraki Rift (to the west) and the Taupo Volcanic Zone (TVZ, to the east and south).

The TVZ marks the zone of extension along a north-west to south-east orientation. The surficial extension rate is estimated to be approximately 2 mm per year, increasing to 4 to 10mm at depths of 6 to 10 km (Villamor and Berryman, 2001). Within the TVZ, a seismogenic zone 6 to 8 km deep is defined by widespread moderate to large earthquake activity (typical magnitudes of less than 6.5) (Bryan et. al., 1999).

A review of the Geological and Nuclear Science (GNS, 2019b) active fault database indicates no evidence of active faulting within the Western Zone of Tauranga City. The sediments underlying the Western Zone include a mantle of Holocene and Pleistocene-aged tephras and sediments, thus evidence of active faulting could be concealed.

The Western Zone is located approximately 50 km east of the Kerepihi Fault, which is a normal dipping fault with an average recurrence interval of 2000 to 3500 years (GNS active fault database). An area of persistent active normal faulting associated with the TVZ exists offshore, approximately 30 km north-east of Tauranga. Figure 1 shows the active faults in the Bay of Plenty region based on the 2010 National Seismic Hazard Model for New Zealand (Stirling et. al., 2012).

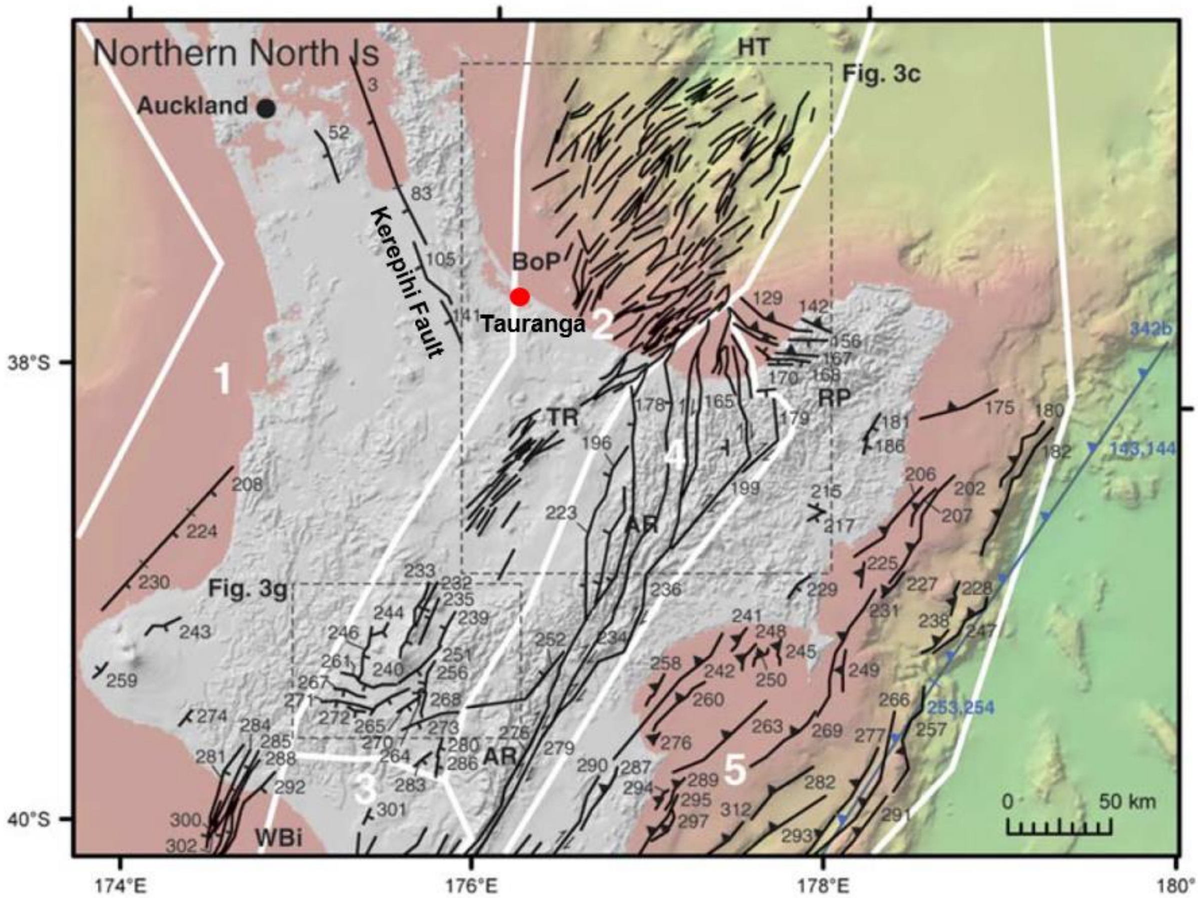

Figure 3   Active Faults in the Bay of Plenty Region

3.2.6 Historical observations of liquefaction

A review of historical evidence of liquefaction in Tauranga and the Wider Bay of Plenty Region has been undertaken. Fairless and Berrill (1984) in their review of recorded liquefaction across New Zealand did not identify any recorded liquefaction events in the region dating back to 1843.

Since Fairless and Berrill (1984) was published, the largest seismic event the Bay of Plenty Region has experienced was the 2 March 1987 M_w 6.5 Edgecumbe Earthquake. Tauranga City is located approximately 50 km northwest of the epicentre of the Edgecumbe Earthquake.

Dowrick (1988) reported ground shaking in the Bay of Plenty Region associated with the Edgecumbe Earthquake. At the Western Zone of Tauranga City, the experienced Modified Mercalli intensity ground shaking was modelled in the order of MM VI. A MM VI corresponds to "*Felt by all, many frightened and run outdoors; some heavy furniture moved; a few instances of fallen plaster or damaged chimneys; damage slight" (Kramer, 1996)*, i.e. no ground damage is expected at this level of ground shaking intensity.

Based on the peak ground acceleration attenuation model developed by Dowrick (1988 and 1989) at a 50 km distance from the epicentre, the PGA at the Western Zone study area was expected to be in the order of 0.06 g to 0.07 g. Although a high variability in attenuation with distance was noted by Dowrick. We note that under this level of ground shaking (0.06 g to 0.07 g) surface manifestation of liquefaction would not be expected.

The NZSEE Reconnaissance Report (NZSEE, 1987) and Christensen (1995) identified liquefaction related phenomena were observed across the Rangitāiki Plains up to 25 km from the epicentre, i.e. approximately half the distance of the Western Zone from the epicentre of the Edgecumbe Earthquake.

Based on this review there are currently no known recorded observations of liquefaction in the Tauranga Region since 1843. The 1987 Edgecumbe Earthquake was likely in the order of a 1-in-25 to 1-in-50-year event at the Western Zone (see Section 4.3 for further details).

3.3 Level of detail supported by current available base information

The study area is approximately 154 km^2 in area, with 105 km^2 of that covered by the modelled groundwater extent. For the assessment of the Western Zone study area, 932 CPT logs of the 1,236 usable CPT logs are located in the area where there is an accurate groundwater model; 304 CPT logs are located beyond the extent of the modelled groundwater surface. The study area is approximately 154 km^2 in area, with 105 km^2 of that covered by the modelled groundwater extent. This corresponds to an average spacing of 8.0 CPT per km^2; with 8.8 CPT per km^2 located within the extent of the modelled groundwater surface and 6.2 CPT per km^2 currently beyond its extent.

Table 3.3 (reproduced as Figure 4) of the MBIE (2017) guidelines identifies that a *Level B – Calibrated Desktop Assessment* should have an average investigation density of 0.5 to 20 per km^2. For the Western Zone, the distribution of CPT from historical sources is clustered across the study area reflecting useable data from previous investigations for site specific assessment of subdivisions, buildings and linear infrastructure. Where possible the additional CPT testing commissioned as part of this study was physically located to ‘fill in the blanks’ in key areas and terrain types between clusters of historic test information. Even with additional investigations to attempt to fill spatial gaps there is still a clustering of data points across the Western Zone potentially increasing residual uncertainty in our assessment associated with geological and geomorphic variation between test positions. Based on the currently available CPT information, we consider the density of available geotechnical information in Western Zone study area to be applicable for a Level B assessment. The locations and extent of the Level B assessment areas are presented in *Plan A3 – Study Detail Level* in Appendix A.

LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT [1,2]	AVERAGE INVESTIGATION DENSITY	AVERAGE SPACING BETWEEN	MINIMUM TOTAL NUMBER OF INVESTIGATIONS
Level A[3] **Basic desktop assessment**	0.01 to 1 per km^2	1 to 10 km	–
Level B **Calibrated desktop assessment**	0.5 to 20 per km^2	220 to 1400 m	3 for each geological sub-unit
Level C **Detailed area-wide assessment**	0.1 to 4 per Ha	50 to 320 m	5 if area > 1 Ha 3 if area 0.25 – 1 Ha 2 if area < 0.25 Ha
Level D[4] **Site-specific assessment**	2 to 40 per Ha	15 to 70 m	2 within or very close to the building footprint

Notes:

1 Investigation densities listed in this table are cumulative – suitable data from investigations undertaken in previous stages of work should be incorporated in subsequent stages.

2 The key feature defining each level of detail is the degree of residual uncertainty in the assessment (refer Table 3.1), not necessarily the spatial density of ground investigations. In some circumstances a significantly higher or lower investigation density might be appropriate to provide the required degree of certainty for a particular target level of detail or purpose. For example, the lower end of the recommended minimum range might be appropriate where investigations show ground conditions to be reasonably consistent (eg some marine or lake deposits), while the upper end of the range may be more appropriate if ground conditions prove to be highly variable (eg many river deposits).

3 There are no minimum investigation density requirements for a ***Level A*** liquefaction assessment. However, the geological maps that are normally used for a ***Level A*** assessment have often been 'ground-truthed' at approximately the density shown. New ground investigations are unlikely to be required, provided that existing information such as geology, geomorphology and groundwater maps is suitable (relative to the scale and purpose of the assessment), and categories are assigned with appropriate consideration of the uncertainties.

4 For a ***Level D*** assessment, the key requirement is to confidently characterise the ground conditions at the specific location of the proposed building. Therefore the particular arrangement and proximity of investigations within and surrounding the building footprint will often be of greater importance than the minimum investigation density criteria.

Figure 4 Indicative spatial density of deep ground investigation for adequate ground characterisation for liquefaction assessments to inform planning and consenting processes, after Table 3.3 of MBIE (2017)

4 Liquefaction Risk Analysis

4.1 Area Covered by Analysis

The study area comprises the western portion on Tauranga City and has an area of approximately 154 km^2. The extent of the Western Zone study area is shown in *Plan A1 - Western Zone Site Boundary* in Appendix A

4.2 Groundwater Levels for Analysis

For the liquefaction hazard assessment, two basic groundwater levels have been adopted:

1. Current groundwater level
2. Future groundwater level corresponding to anticipated conditions in 110 years' time

For the current groundwater scenarios the median ground water level, as provided by TCC as detailed in Section 3.3.4, has been adopted. For the future groundwater level, to account for future sea level rise the median groundwater surface has been increased by a nominal 1.25 mRL.

For liquefaction assessment for both the current and future groundwater levels, we have undertaken a separate sensitivity check with a nominal ±0.5 m variation on modelled ground water levels.

Noting that the modelled groundwater surface does not extend fully to the southern boundary of the Western Zone study area, extending the surface further to the south was not possible due to a lack of available information and resulting uncertainty that extrapolation would cause.

Of the total study area of 154 km^2 the groundwater model does not cover 49 km^2 of the southern extent, which is approximately 32% of the total study area. Furthermore, there are 1236 CPT positions analysed across the Western Zone, of which 304 fall outside the area covered by groundwater surface (approximately 25%).Therefore, approximately 25% of the CPT results are excluded from the liquefaction analysis due to no modelled groundwater surface being made available.

To discuss the implications of excluding data from the analyses, of the 49 km^2 with no groundwater model, 39 km^2 is mapped as either Lower (Alluvial) Terrace or Upper (Ignimbrite) Terrace. These terrains of which have been assessed to have 'low' and 'very low' liquefaction vulnerability respectively and thus the lack of modelled water surface for these areas does not significantly impact the outcome of our assessment for these areas. For other low-lying terrain types of the southern extent area, e.g. Alluvial Flood Plain, the lack of water table may have more significant influence in the outcomes of our assessment.

In the absence of a known water surface, a reduced dataset using only CPTs with a known depth to water has been used to develop common geostatistical liquefaction parameters for a given geomorphic terrain. Those common parameters have then been applied to areas of mapped terrain currently lacking groundwater information. The accuracy of the analyses for the Alluvial Flood Plain terrain is reduced as a consequence of excluding the CPT data set obtained for this area. Generating a new water surface would result in a new level of inconsistency with the original groundwater model and thereby creating another uncertainty factor in the analysis output. Additionally, the level of detail targeted (Level B) with this assessment still allows the application of the principals of extrapolation relatively comfortably across the affected area, given our extensive history, experience and knowledge of the geology working across the affected area, from Welcome Bay west towards Tauriko. The effects of this lack of a groundwater surface on the liquefaction damage and hazard mapping and the technical solution adopted are presented in detail in Section 4.6.

4.3 Earthquake Scenarios

4.3.1 General

The level of ground shaking is one of the key factors in determining whether liquefaction will or will not occur. As per TCC and project requirements we have looked at five levels of ground shaking:

i) 1-in-25-year ARI earthquake
ii) 1-in-100-year ARI earthquake
iii) 1-in-250-year ARI earthquake
iv) 1-in-500-year ARI earthquake
v) 1-in-1000-year ARI earthquake

To determine the design level of shaking TCC have separately commissioned Bradley Seismic Ltd to undertake Probabilistic Seismic Hazard Analysis (PSHA) assessment for Tauranga City. This PSHA assessment is presented in the report *Regional ground motion hazard for liquefaction and landslide assessment, Tauranga City* dated 21 July 2019 (Bradley, 2019). The design Peak Ground Acceleration (PGA) values from this PSHA study are being adopted for this city-wide liquefaction hazard study.

One of the key parameters in determining PGA from the PSHA study is the average shear wave velocity over the upper 30 m of the subsoil profile (V_{s30}). For the purpose of this liquefaction assessment, we have derived a methodology to spatially allocate PGA across the Western Zone through the adoption of an appropriate design V_{s30} value for each geomorphic terrain, from which a design PGA value can be calculated.

As per the recommendations in the PSHA study the methodology for determining the design PGA values varies for the study area. For the bulk of the Western Zone the V_{s30} model has been provided and PGA can directly be assessed. However, for the Sulphur Point reclamation area the PSHA recommends that a site specific V_{s30} is derived prior to calculating the PGA values. The following subsections detail our proposed methodology for spatially allocating design PGA values for each geomorphic terrain.

4.3.2 Main body of the Western Zone (excluding Sulphur Point Reclamation)

To determine the design PGA values for each mapped 'natural' geomorphic terrain type the following steps have been undertaken:

1. The PSHA V_{s30} model of Foster et al. (2019) as presented in Figure 1 of the Bradly Seismic PSHA report (Bradley, 2019), and comprise of approximately six million separate V_{s30} values for the entire Tauranga Region. The V_{s30} model presented in Figure 1 of PSHA report is reproduced below as Figure 4 below for clarity. This V_{s30} model was imported into our GIS system and overlain by our mapped geomorphic terrain polygons.
2. The individual V_{s30} values within each terrain polygon was allocated to one of the 5 mapped geomorphic terrains (noting 6 terrains are mapped within the Western Zone, but the Land Reclamation terrain requiring specifically derived PGA; refer Section 4.3.3).
3. For each geomorphic terrain type a statistical analysis of the spread of the modelled V_{s30} values was undertaken to obtain the minimum, maximum and 5th, 15th, 50th, 85th and 95th percentile V_{s30} values.
4. The design Peak Ground Acceleration (PGA) as a function of Annual Rate of Exceedance, λ, and V_{s30} has been provided by Bradley Seismic Limited. From these tabulated results, for a given site V_{s30} and λ, the calculation of PGA can be performed with linear interpolation between the PGA hazard curves for the specific λ. Thus, allowing direct calculation of PGA for any given V_{s30} and λ combination.
5. For each geomorphic terrain type we have calculated PGA using the minimum, maximum, and 5th, 15th, 50th, 85th and 95th percentile V_{s30} values for each of the five design earthquake events (1-in-25 year, 1-in-100 year, 1-in-250 year, 1-in-500 year and 1-in-1000 year events).

From this analysis it is apparent that for each terrain type, at each design earthquake event, the PGA is relatively insensitive to the modelled variations in V_{s30} (i.e. there is little variation in PGA, typically less than

10%, when calculated using V_{s30} ranging between the 15th to 85th percentile values). Therefore, for our liquefaction hazard assessment we have adopted the 15th percentile PGA value for each terrain and design earthquake event. The results of this assessment and our recommended design PGA values for each earthquake event and geomorphic terrain type are presented Section 4.3.4.

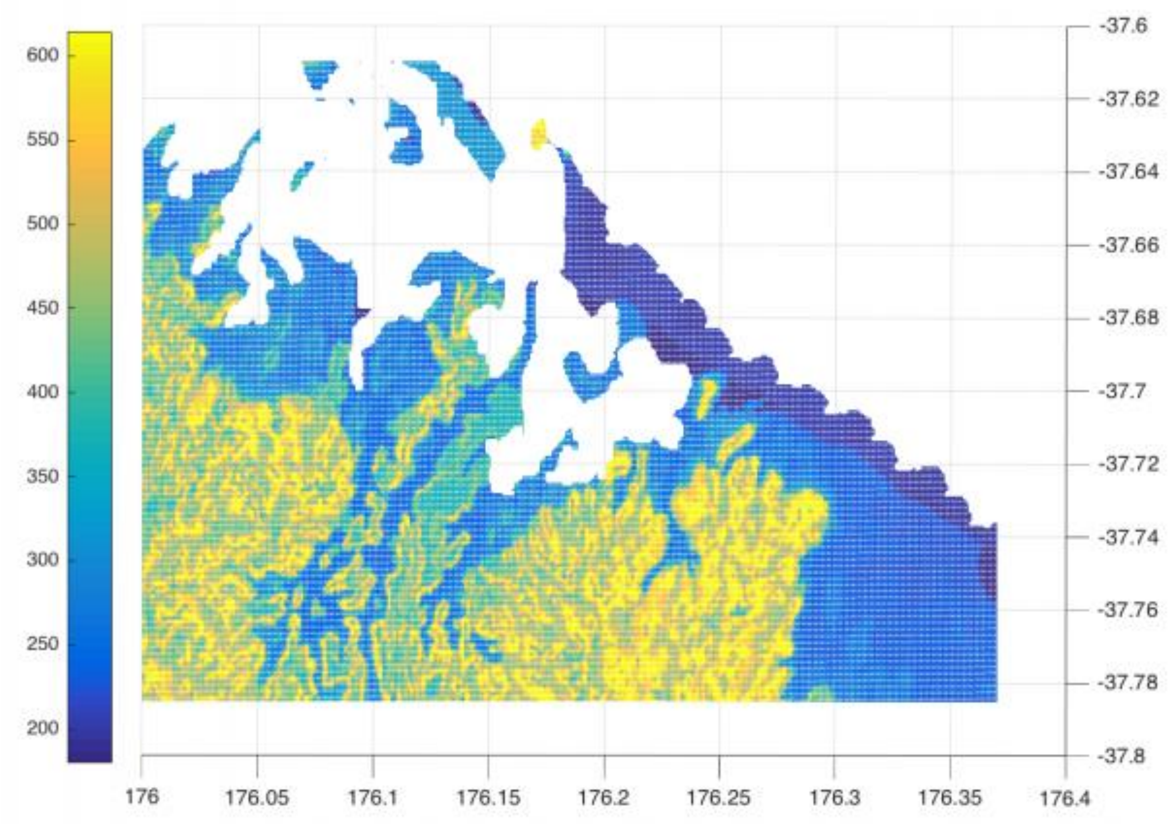

Figure 1: Variation in 30m shear wave velocity (Vs30) (colors in units of m/s) in the Tauranga city region. Latitude and Longitude in WGS84 units.

Figure 5 Reproduction of Figure 1 of PSHA Report (Bradley, 2019)

4.3.3 Sulphur Point Reclamation

As per recommendations in PSHA report, the regional V_{s30} model is not appropriate for use at the Sulphur Point Land Reclamation terrain. Following on from this, as per the PSHA report recommendations we have calculated design PGA values using the following methodology:

1. We have determined a design V_{s30} based on eight CPT traces located in the Sulphur Point reclamation area using the published correlation of McGann et al. (2015) to calculate V_s over the depth of the CPT test, V_{sz}. These V_{sz} values are then converted to a V_{s30} value using the method of Boore et al. (2011).
2. These modelled V_{s30} values are then used to calculate PGA(λ, V_{s30}) as per the methodology detailed above for eight CPT traces
3. The design PGA(λ, V_{s30}) is then calculated as the average of the eight calculated PGA(λ, V_{s30}) values.

The results of this assessment and our recommended design PGA values for each earthquake event of the Sulphur Point Land Reclamation terrain is presented in Section 4.3.4. We note that there are inherent uncertainties in our V_{s30} assessment for Sulphur Point Reclamation. As the V_{s30} value has been derived from only a limited number of CPT logs using published correlation and has not been derived from direct V_s measurements on site. Despite this, when running the analysis, the resulting design PGA values are all similar for a given design earthquake event indicating stability and limited variation in the overall PGA (λ, V_{s30}) system.

4.3.4 Design Earthquake Values

Based on the above methods the proposed PGA values for use in the liquefaction assessment for each terrain type are presented in Table 5.

Table 5 Design PGA Values by Geomorphic Terrain

Geomorphic Terrain	Design V_{s30} [m/s]	Design PGA [g]				
		1-in-25 Yr.	1-in-100 Yr.	1-in-250 Yr.	1-in-500 Yr.	1-in-1000 Yr.
Upper (Ignimbrite) Terrace	400	0.05	0.10	0.14	0.18	0.23
Alluvial Channels	300	0.06	0.10	0.15	0.19	0.24
Alluvial Flood Plain	250	0.06	0.11	0.15	0.19	0.24
Lower (Alluvial) Terrace	250	0.06	0.11	0.15	0.19	0.24
Harbour Margin	250	0.06	0.11	0.15	0.19	0.24
Land Reclamation	200	0.06	0.11	0.16	0.20	0.23

From the PSHA report and interpolating for the 1-in-250-year earthquake event, the adopted earthquake magnitudes are presented for each design earthquake event in Table 6.

Table 6 Earthquake Magnitude with Return Period

Return Period	1-in-25 Yr.	1-in-100 Yr.	1-in-250 Yr.	1-in-500 Yr.	1-in-1000 Yr.
Mean Magnitude	6.1	6.1	6.2	6.2	6.3

4.4 Determination of expected degree of liquefaction-induced ground damage

The ability for subsoils to resist the effect of ground shaking associated with the design level earthquakes has been assessed from the subsoil information obtained from the CPT data. Liquefaction can have a number of effects on buildings, land and linear infrastructure. In our assessment we have considered the following effects:

- Site geomorphology
- Extent (both vertically and horizontally) of the liquefiable layers
- Liquefaction-induced reconsolidation settlement
- Liquefaction-induced ground damage, including lateral spreading

The numerical components of the liquefaction assessment have been carried out using the references in Table 7.

Table 7 Liquefaction Assessment Methodology

Test Type	Liquefaction Triggering Methodology	Fines Content	Liquefaction Cut Off	Liquefaction Reconsolidation on Strain / Settlement Methodology	Liquefaction Ground Damage	Lateral Spreading
CPT	Boulanger and Idriss (2014) with a 15% probability of liquefaction (PL)	Based on I_c with C_{fc}=0.0	Based on a 2.6 I_c cut off	Zhang et al. (2002)	Surface manifestation based on Ishihara (1985), LSN based on T+T (2013) and Technical Category Classification System (MBIE, 2012)	Zhang et al. (2004) constrained with a subjective assessment based on channel size and set-back distance

4.5 Liquefaction vulnerability against performance criteria

The likelihood of ground damage has been assessed using three main methodologies:

1. Non-liquefied crust thickness approach based on Ishihara (1985).
2. Utilising the concept of a *Liquefaction Susceptibility Number* (LSN) approach.
3. Utilising *indexed* (within upper 10 m subsurface profile) reconsolidation settlement based on the Technical Category Classification adopted in Canterbury following the Canterbury Earthquake Sequence (CES).

These ground damage methodologies are detailed in Section 4.5.1 to 4.5.3. The effect of lateral spreading has been assessed separately; the methodology for this process set out within Section 4.5.4.

4.5.1 Crust thickness and surface expression

As a preliminary screening we have used the method of Ishihara (1985) to conservatively look at areas where liquefaction induced surface manifestation, and hence a proxy to ground damage, is not expected based on the thickness of the non-liquefied layer. This method looks at the thickness of both the non-liquefiable surface layer and the underlying liquefiable layer. For a given size of earthquake, in terms of PGA, it can be determined if surface manifestation of liquefaction, and hence ground damage, is likely. This relationship from Ishihara (1985) is shown in Figure 6.

As an initial screening we have taken the maximum 1 in 1000-year earthquake from this study, corresponding to a PGA of approximately 0.24 g. From the relationship in Figure 6, we can see that with a nominal crust thickness of 10 m then surface manifestation of liquefaction is not expected irrespective of the thickness of any underlying liquefiable layer. This process excludes any effects of lateral spreading, which is assessed separately and detailed in Section 4.5.4.

All areas which have a depth to groundwater exceeding 10 m, or 11 m corresponding to the 100-year sea level case, have been assessed as unlikely to have liquefaction induced ground damage at all levels of shaking for this study. Areas of the Western Zone with a depth to groundwater being equal to or greater than 10m depth are shown on *Plan A7 - Depth to Groundwater Surface* in Appendix A.

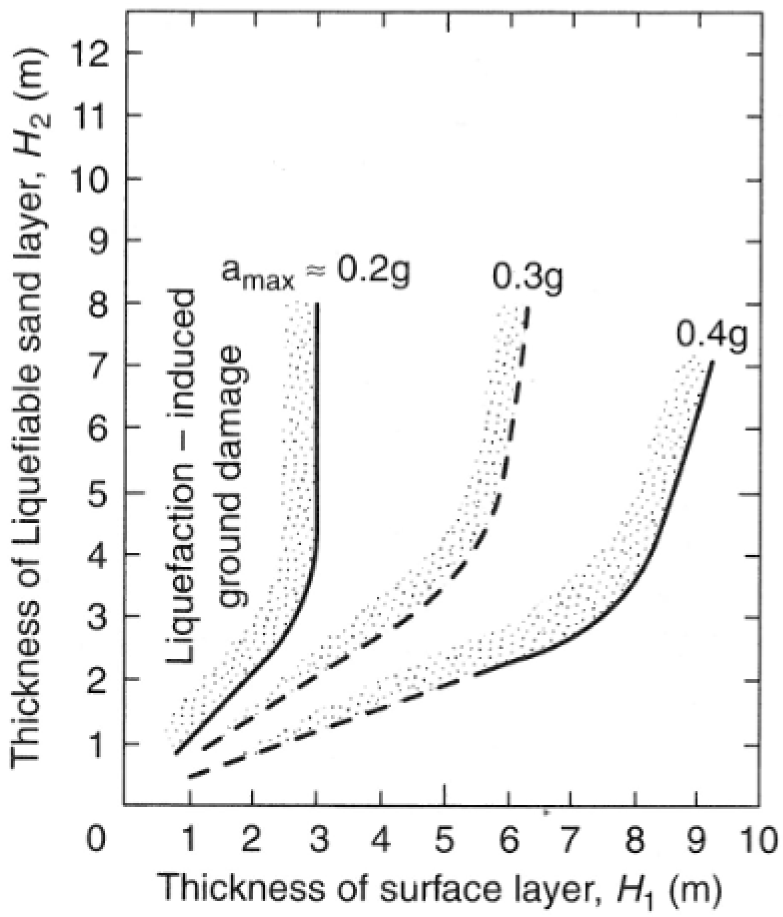

Figure 6 Relationship between thickness of liquefiable layer and thickness of overlying (Ishihara, 1985)

4.5.2 Liquefaction Severity Number

The LSN approach has been adopted as the primary land damage assessment methodology for this liquefaction hazard study. LSN has been assessed using the method detailed in Tonkin and Taylor (2013). How we consider the characteristic LSN values relates to the damage types defined in MBIE (2017) as represented in Table 8. Example photographs of different degrees of liquefaction induced ground surface damage are presented in Appendix A of MBIE (2017).

Table 8 Degree of liquefaction induced land damage and corresponding characteristic LSN value

Degree of liquefaction induce land damage	Characteristics of liquefaction and its consequences	Characteristic LSN value
None to Minor	None to minor signs of ejected liquefied material at the ground surface. None or minor differential settlement of the ground surface (e.g. undulations <25 mm in height). No apparent lateral spreading ground movement. Liquefaction causes no or only cosmetic damage to buildings and infrastructure.	<16
Minor to Moderate	Minor to moderate quantities of ejected material at the ground surface; and/or Moderate differential settlement of the ground surface (e.g. undulations 25 mm to 100 mm in height). No significant lateral spreading ground movement (e.g. ground cracks <50 mm and primarily caused by ground oscillation or settlement rather than lateral spreading). Liquefaction causes moderate but typically repairable damage to buildings and infrastructure.	16 to 25
Moderate to Severe	Large quantities of ejected material at the ground surface; and/or Moderate to severe differential settlement of the ground surface (e.g. undulations >100 mm in height); and/or Significant lateral spreading ground movement (e.g. ground cracks >50 mm and primarily caused movement downslope or towards a free-face). Liquefaction causes substantial damage and disruptions to buildings and infrastructure. Repair may be difficult or uneconomical.	>25

LSN and a sensitivity of change in LSN (∆LSN) with ±0.5m variation in groundwater level have been calculated for each CPT location for each of the five design earthquake events, for both the current ground water level and the nominal future groundwater level. This analysis outputs are used in the land damage assessment as details in Section 4.6.

Maps of the calculated LSN at each CPT location, for each of the five design earthquake events for the current groundwater level are presented as *Plan B1* to *Plan B5*, and for the future groundwater level as *Plan B6* to *Plan B10* in Appendix B.

The calculated LSN and ∆LSN results in a tabulated format presented in a box-and-whisker format grouped by geomorphic terrain type and design earthquake event are presented in Appendix C. This has been completed for both the current and future ground water levels.

4.5.3 Technical Category Classification

The indexed settlement approach has been adopted as a secondary land damage assessment methodology in this liquefaction hazard study. This alternative approach to LSN was undertaken following the general principles of the Technical Category Classification system (MBIE, 2012) adopted in Christchurch following the CES, noting this Technical Category classification system is intended for residential construction and is not directly applicable to other types of structures and/or linear infrastructure.

This approach looks to classify the liquefaction risk into three broad Technical Categories (TC1, TC2 and TC3), with TC1 having the lowest liquefaction potential through to TC3 with the highest. With the classification based on calculated *'indexed'* reconsolidation settlements in the upper 10m of the soil profile. In general terms the three Technical Categories relate to land damage as follows:

1. **Technical Category 1 (TC1)** – None to Minor land damage from liquefaction is possible in future large earthquakes.
2. **Technical Category 2 (TC2)** – Minor to Moderate land damage from liquefaction is possible in future large earthquakes.
3. **Technical Category 3 (TC3)** – Moderate to Severe land damage from liquefaction is possible in future large earthquakes.

MBIE (2012) has defined the following liquefaction and lateral spreading deformation limits as detailed in Table 9.

Table 9 Liquefaction deformation limits and corresponding land damage characteristics (MBIE, 2012)

Technical Category	Indexed Liquefaction Deformation Limits			
	Vertical		Horizontal	
	1-in-25 yr. EQ (SLS)	1-in-500 yr. EQ (ULS)	1-in-25 yr. EQ (SLS)	1-in-500 yr. EQ (ULS)
TC1	15 mm	25 mm	Nil	Nil
TC2	50 mm	100 mm	50 mm	100 mm
TC3	>50 mm	>100 mm	>50 mm	>100 mm

It is noted that this is a Christchurch specific approach that was not originally intended to be used as a land classification or ground performance system. However, it does provide a useful additional screening approach for site liquefaction hazard assessment and has been adopted for use in land development projects in Tauranga.

When relating the MBIE (2017) land damage criteria to the Technical Category classification approach we consider that:

- TC1 relates to Very Low Liquefaction Vulnerability or Low Liquefaction Vulnerability
- TC2 relates to Medium Liquefaction Vulnerability
- TC3 relates to High Liquefaction Vulnerability

Calculated settlements at each CPT location, for each of the five design earthquake events for both the current ground water level and the nominal future groundwater level. This analysis outputs are used in the land damage assessment as details in Section 4.6.

Maps of the calculated 'indexed' settlements at each CPT location, for each of the five design earthquake events for the current groundwater level are presented as *Plan B11* to *Plan B15*, and for the future groundwater level as *Plan B16* to *Plan B20* in Appendix B.

The calculated 'indexed' settlements results in a tabulated format presented in a box-and-whisker format grouped by Geomorphic Terrain type and design earthquake event are presented in Appendix C. This is for both the current and future ground water levels.

4.5.4 Lateral Spreading

General

Observations from previous earthquakes indicate that severe damage to ground, buildings, infrastructure and the environment can be caused by liquefaction-induced lateral spreading. Therefore, the potential for lateral spreading must be considered when assigning liquefaction induced land damage.

Lateral spreading occurs as surface soils move downslope or towards a free edge, such as a river or basin. Lateral spreading can occur during an earthquake under seismic loading and following the earthquake until the excess pore water pressure caused by ground shaking dissipate and the liquefied soil regains strength.

Lateral spreading can cause disproportional damage to urban infrastructure, over and above, that from the vertical settlement effects of liquefaction alone. However, lateral spreading is very difficult to accurate quantify and/or predict with any high degree of certainty, being a highly complex process dependent upon multiple variables including:

- The elevation difference between the base of the free-face (i.e., a road cutting, old terrace or a river bank) and the elevation of the land at the point of interest (referred to as the free-face height 'H' herein);
- The distance (L) from the base of the free-face to the point of interest;
- The earthquake ground motions including Peak Ground Accelerations (PGA) and earthquake magnitude (M_w);
- The thickness, relative density and location of liquefying layers within the soil profile; and
- Additional topographic and geological boundary conditions.

This complexity means that the development of lateral spreading assessment methods is particularly challenging and there are limitations associated with the methods that are currently available. There are several numerical methods are available to quantify the likely deformation, they all feature high degrees of uncertainty depending on site geometry, geomorphic conditions etc.

Threshold between 'Minor to Moderate' and 'Moderate to Severe' land damage

With specific regard to lateral spreading, from the Table 8, the three categories of land damage are defined as:

- None to Minor – no apparent lateral spreading ground movement
- Minor to Moderate - no significant lateral spreading ground movement (e.g. ground cracks <50 mm and primarily caused by ground oscillation or settlement rather than lateral spreading)
- Moderate to Severe - significant lateral spreading ground movement (e.g. ground cracks >50 mm and primarily caused movement downslope or towards a free-face)

While from the Technical Category land classification system approach, as detailed in Table 8 above, the three categories of land damage are defined as:

- TC1 – being equivalent to None to Minor land damage – with nil lateral spreading
- TC2 – being equivalent to Minor to Moderate land damage – Up to 100 mm of lateral spreading in 1-in-500-year earthquake
- TC3 – being equivalent to Moderate to Severe land damage – Over 100 mm of lateral spreading in 1-in-500-year earthquake

For this liquefaction hazard study, we have defined the lateral spreading demarcation threshold between Minor to Moderate and Moderate to Severe land damage as 50 mm of ground cracking/lateral stretch corresponding to 100 mm of total lateral displacement/lateral spreading.

Calculation of lateral spreading setback distance

The numerical methods currently recommended for use in engineering practice in New Zealand (NZTA, 2018; MBIE/NZGS, 2016) for the assessment of liquefaction related lateral spreading can be broadly categorised into the following two groups:

- Empirically based methods
- Newmark sliding block methods

For the Western Study zone, due to:

- The study being an area wide Level B – Calibrated Desktop Assessment only; and
- The inherent difficulties in applying a numerical method to an area-wide assessment

we have adopted the empirical based method of Zhang et al. (2004) due to it being able to be readily run directly from CPT logs and hence well suited to being applied to area wide assessment using the currently available geotechnical information. The method is known to have several key limitations, including:

- These empirical correlations are based on a limited case history database of lateral spreading observations. In particular, the CPT case history database is limited, and
- Back analysis of observations of lateral spreading from the 2010-2011 Canterbury Earthquake Sequence have demonstrated significant differences between the observed and the predicted horizontal movements using empirical methods.

Therefore, this simplified empirical based numerical method has been applied on an area wide basis but constrained by local mapped geomorphic terrains and geographical constraints. Additionally, we have further constrained the lateral spreading assessment with engineering judgement to determine a likely zone that lateral spreading could adversely affect the liquefaction hazard rating.

In particular we note the MBIE (2017) guidelines indicated 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."* Cubrinovski and Robertson (2015) observed lateral spreading of 100 mm displacement upwards of 200 m back from the free faces of the Avon River during the Canterbury Earthquake Sequence. We note that many of the free faces associated with streams and rivers in the Western Zone study area are of a similar size to the Avon River in Christchurch.

For our assessment we have looked at the free edges associated with larger waterways and surface water bodies only. These include:

- Low-lying Harbour Margin areas and reclaimed land around the shores of Tauranga Harbour
- Wairoa River on the western boundary of the study area
- Kopurererua and Waimapu Streams flowing north through the southern and central parts of the study area
- Permanent storm water basins, lakes and ponds

These exclude small drains within the Alluvial Flood Plain and Alluvial Channels terrain, where wetland has historically been drained to develop pastoral grazing land. In addition to drains, potential lateral movement associated with internal changes in topographical level, river terraces etc., or ponds and pits associated with temporary earthworks and construction activities have not been assessed. The free-faces we have considered in our analysis are presented in Appendix A as *Plan A8 – Mapped Free Faces*.

For each CPT record in the geomorphic terrains of Harbour Margin, Alluvial Flood Plain, and Land Reclamation, we have calculated the Lateral Displacement Index (LDI) using Zhang et al. (2004) for: free faces between 1 m and 10 m height (H), for each of the five design earthquake events, for both current and future ground water levels assuming level ground and restricting the depth of influence to twice the free-face height (2H). The calculated LDI values have been based on the earlier liquefaction triggering assessment using the method of Boulanger and Idriss (2014) with a PL of 15%.

The calculated LDI results have been grouped by geomorphic terrain, free-face height, earthquake event, and depth to groundwater combinations. We have then calculated the 85th percentile LDI value from each grouping. This 85th percentile LDI value has then been adopted for our land damage assessment and has been used to account for the inherent uncertainty in the lateral spreading assessment and represents the same level of statistical certainty used elsewhere in the liquefaction assessment, e.g. PL15% in the liquefaction triggering, LSN to ground damage correlations etc. These calculated LDI combinations are presented in Appendix C.

The free-face heights along each of the major waterways have been mapped. From these free face heights, the lateral setback for 100 mm of lateral spreading has been calculated for each of the five earthquake scenarios and two groundwater level scenarios. Due to the limitations of the adopted lateral spreading assessment methodology (Zhang et al., 2004), and supported by previously noted case history, we have limited the setback distance to 200m.

These calculated setback distances have then been set as the demarcation between the 'Minor to Moderate' and 'Moderate to Severe' land damage classifications. As required these setback distances and corresponding areas of 'Moderate to Severe' land damage have been added to the mapped ground damage in Plans D1 to D10 in Appendix D.

4.6 Land Damage Assessment

Our liquefaction damage mapping assessment has used a 'lines of evidence' geomorphic-driven qualitative approach combined with a 'geo-statistical' information derived from bulk analysis of the available CPT logs. Our mapping assessment has been undertaken as follows:

- Starting with the mapped geomorphic terrains (see Plan A5 – Geomorphic Terrains in Appendix A) and the groundwater model (see Plan A7 - Depth to Groundwater in Appendix A) an initial Western Zone screening has been undertaken using the crust thickness and surface manifestation approach after Ishihara (1985), as detailed in Section 4.5.1. Any areas which have a depth to groundwater mapped as greater than 10m depth for current ground water level, or greater than 11m depth to account for future ground water level, are considered as having a limited if any susceptibility to liquefaction induced ground damage. This is due to the crust thickness being sufficient to suppress surface manifestation of liquefaction and associated ground damage even during the largest 1-in-1000-year earthquake event. The areas screened as 'no damage' typically correspond to the 'Lower (Alluvial) Terrace' and 'Upper (Ignimbrite) Terrace' geomorphic terrains.
- A bulk liquefaction triggering analysis was then run on all CPT logs which are located in the extent of the groundwater model, see Plan A7 - Depth to Groundwater Surface in Appendix A for further details on the extent of the groundwater model. This resulted in 926 out of the 1236 available CPT logs, or 75% of CPT logs, being included with the analyses. The liquefaction analysis was run ten times, once for each of the ten design level earthquake-groundwater level combinations. For each earthquake-groundwater combination the vertical land damage assessment parameters of LSN (primarily land damage assessment method), indexed settlement and sensitivity of LSN (ΔLSN) to small changes in groundwater level (secondary land damage assessment method) were calculated.
- These results were then grouped by geomorphic terrain type and assessed statistically to get baseline land damage classifications for each geomorphic terrain type. The results of this statistical assessment are presented in Appendix C.
- Baseline damage ratings are then allocated by geomorphic terrain type for each of the ten earthquake-groundwater event combinations using the definitions of land damage detailed in Sections 4.5.2 and 4.5.3. For this baseline assessment we adopted the 85th percentile land damage values, as calculated and presented in Appendix C.
- For the areas located outside of the groundwater model, typically along the southern edge of the Western Zone study area, the land damage category was allocated based on mapped geomorphic terrain type. The land damage category was assigned to geomorphic terrains outside of the extent of the groundwater model using extrapolated data from the statistical analyses.
- The effect of lateral spreading is then accounted for by calculating a setback distances as per the methodology detailed in Section 4.5.4. Where appropriate the baseline liquefaction land damage rating is locally adjusted to reflect the effects of lateral spreading. This was initially restricted to locally increase a 'Minor to Moderate' land damage classification to a 'Moderate to Severe' land damage classification, as in

general terms areas classified as having ‘None to Minor’ land damage is not expected to have lateral spreading damage; the liquefaction is not functionally triggered so lateral spreading is less likely to occur.

- Each of the ten baseline land damage maps were then manually checked and where required the land damage categories were locally revised to account for local deviations in quantified results from the statistical analyses, and changes in thickness of the non-liquefiable crust. Key elements which were likely to effect, and increase, the mapped land damage classification include:
  - Where the crust thickness was very limited, typically 1 to 2 m and locally less than 1 m thick, as land damage is likely to be more severe that the baseline assumption.
  - For the elevated groundwater case in the 1-in-100 year earthquake event within the Alluvial Flood Plain and Harbour Margin terrains where the free-face is reasonably high, i.e. 3m of greater, in and around the Wairoa River, Kopurererua Valley and Waimapu Stream. A lateral spreading setback buffer has been added to areas where the initial land damage was mapped as ‘None to Minor’ to increase it to ‘Minor to Moderate’ due to the calculated potential for free-face movements, despite the initial ‘None to Minor’ free-field land damage classification.

4.7 Land Damage Maps

Our land damage maps for each of the five design earthquake events for both the current and future ground water levels detailing the above land damage mapping outcomes are presented in Appendix D and *Map D1* to *Map D10*.

4.8 Liquefaction Hazard Assessment

Our overall liquefaction hazard assessment for the Western Zone, for both groundwater level scenarios, has been undertaken using the approach detailed in MBIE (2017). Each part of the Western Zone study area has been allocated a liquefaction vulnerability based on the hierarchy presented in Table 4.4 of MBIE (2017), as reproduced as Figure 7.

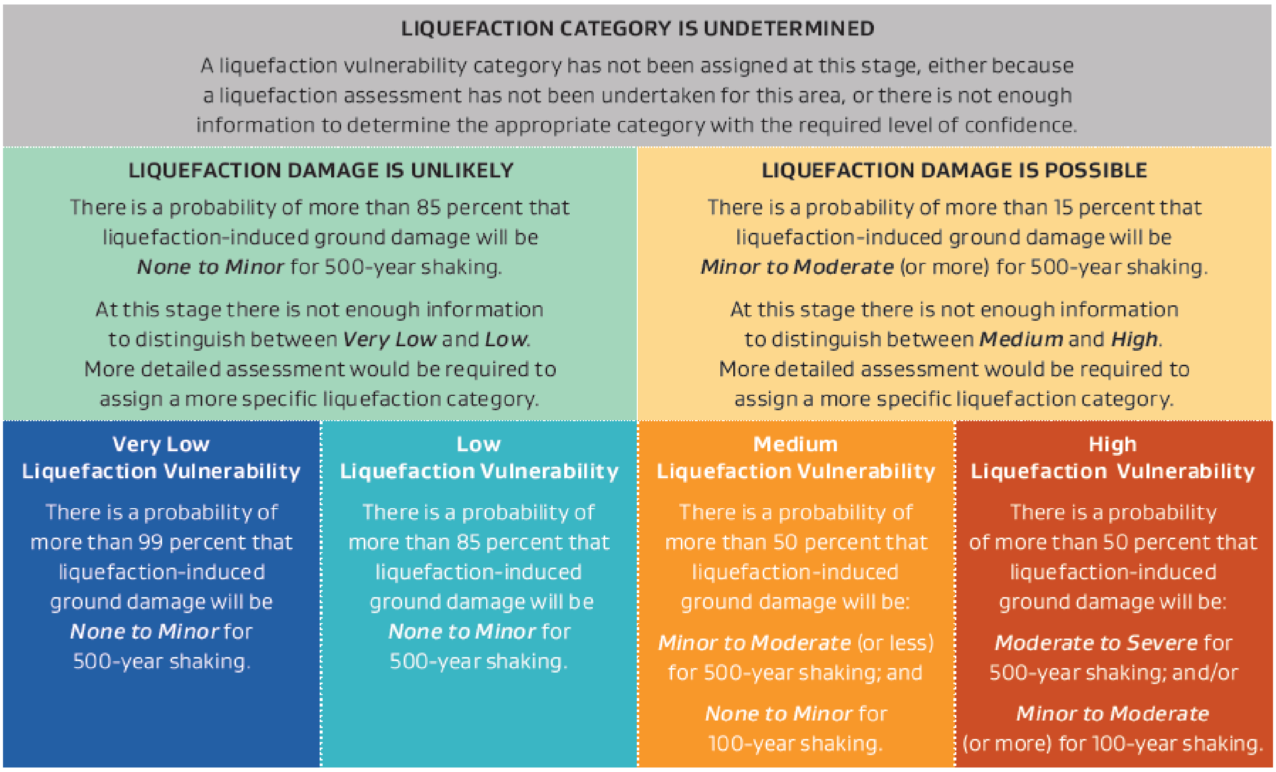

Figure 7 Performance criteria for determining liquefaction vulnerability category (after Table 4.4 of MBIE, 2017)

As per MBIE (2017) the allocation of liquefaction vulnerability criteria is dependent not only on the density of testing, the results of the land damage mapping but also on the level of detail and information available when carrying out these assessments.

Despite only being a *Level B – Calibrated Desktop Assessment*, when considering the geomorphic terrain constraints and the statistical analysis approach we have adopted when generating our land damage maps, we consider it applicable to classify all geomorphic terrain types, with the exception for Alluvial Channels and Alluvial Flood Plain (at the current groundwater level), with the highest accuracy of classification i.e. 'Very Low Liquefaction Vulnerability', 'Low Liquefaction Vulnerability', 'Medium Liquefaction Vulnerability' or' High Liquefaction Vulnerability'.

For Alluvial Channels geomorphic terrain, we only have 31 CPT logs with useable groundwater model information out of a total of only 83 CPT, i.e. only 37% the CPT logs can provide meaningful liquefaction assessment outputs. Combined with the geographically widespread and discontinuous spacing of this terrain type and known localised variability in groundwater levels we considered there to be insufficient level of detail to provide the highest accuracy of classification. As such the lower level of classification has been adopted i.e. 'Liquefaction Damage is Unlikely' or 'Liquefaction Damage is Possible'.

For the Alluvial Flood Plain geomorphic terrain there are only have 111 CPT logs in the terrain with usable groundwater model information out of a total of 177 CPT. Therefore, only approximately 63% of CPT logs can provide meaningful liquefaction assessment outputs for this terrain.

The Alluvial Flood Plain ground is generally more stratified with peat, gravel, sand and fine grained (silt and/or clay) layers. Consequently, this stratification is expected to result in interbedded liquefiable and non-liquefiable layers, which is considered less vulnerable to liquefaction than a continuous column of liquefiable soil. The liquefaction vulnerability throughout this terrain type is expected to vary significantly over very short distances. Performance will be highly variable with 'None to Minor' land damage through to 'Moderate to Severe' being expected throughout the terrain type. This terrain type is considered vulnerable to lateral spreading although the extent and magnitude of the lateral spreading risk is difficult to accurately quantify. Due to the highly variable and stratified nature of this terrain type combined with the limited density of testing data and the lack of a groundwater model for large parts of the terrain a more refined assessment of the liquefaction vulnerability is currently not practicable following the MBIE (2017) framework. However, in the elevated groundwater scenario, due to the significant thinning of the non-liquefied crust and the disproportional damage this causes, despite the limited and variable analysis results we considered that the more refined ‘High Liquefaction Vulnerability’ classification is appropriate for the +1.25m ground water level scenario.

4.9 Liquefaction Hazard Maps

Our overall liquefaction vulnerability rating for the Western Zone are attached as *Map D11 - Liquefaction Vulnerability Map (current GWL)* and *Map D12 - Liquefaction Vulnerability Map (future GWL)* in Appendix D.

5 Conclusion

5.1 Summary of Vulnerability

Based on the results of the liquefaction damage and vulnerability assessment detailed above, the mapped liquefaction vulnerability by geomorphic terrain type is summarised in Table 10.

Table 10 Summary of liquefaction vulnerability assessment

Terrain Type	Current Ground Water Level	Future Groundwater Level	General Comments
Land Reclamation	*High Liquefaction Vulnerability* On the basis of predicted land damage response a high liquefaction vulnerability category has been assigned to all areas mapped as part of the Land Reclamation geomorphic terrain. This terrain type is considered vulnerable to lateral spreading although the extent and magnitude of the lateral spreading risk is difficult to accurately quantify. The composition of Land Reclamation ground conditions and edge support systems are not well understood and may be variable. For example, there may be areas of ground improvement which may be relatively less vulnerable to liquefaction. Therefore, there is uncertainty with the expected seismic performance, particularly the lateral spreading performance.	*High Liquefaction Vulnerability* On the basis of predicted land damage response a high liquefaction vulnerability category has been assigned to all areas mapped as part of the Land Reclamation geomorphic terrain. This terrain type is considered vulnerable to lateral spreading although the extent and magnitude of the lateral spreading risk is difficult to accurately quantify. The composition of Land Reclamation ground conditions and edge support systems are not well understood and may be variable. For example, there may be areas of ground improvement which may be relatively less vulnerable to liquefaction. Therefore, there is uncertainty with the expected seismic performance, particularly the lateral spreading performance.	The liquefaction assessment is based on statistical analysis of 70 CPTs within all mapped areas of Land Reclamation with usable groundwater level information. The CPTs were sourced from the NZGD, testing specifically undertaken for this liquefaction study, and other data available from historical projects. Depth to groundwater was based on the median groundwater depth from the TCC regional groundwater model and is generally less than 5m deep. This model considered monitoring data at 29 piezometer locations across the western zone, recorded up to March 2019. The potential beneficial effects of unknown ground improvement works have not been accounted for in the liquefaction damage and vulnerability assessment works.

Terrain Type	Current Ground Water Level	Future Groundwater Level	General Comments
Alluvial Flood Plain	*Possible / High Liquefaction Vulnerability* A 'Possible' vulnerability category has been assigned to all areas mapped as part of the Alluvial Flood Plain geomorphic terrain, with the exception of areas located in Bethlehem East and Brookfield. Performance will be highly variable with 'None to Minor' land damage through to 'Moderate to Severe' being expected throughout the terrain type. On average a 'Minor to Moderate' land damage classification has been given. This terrain type is considered vulnerable to lateral spreading although the extent and magnitude of the lateral spreading risk is difficult to accurately quantify. High vulnerability areas in Bethlehem East and Brookfield are mapped on the basis of a shallower groundwater table of <2m; the reduced non-liquefiable crust reducing resilience to predicted land damage. The ground may be generally more stratified with peat, gravel sand and fine grained (silt/clay) layers, than Harbour Margin areas. Consequently, this stratification may imply interbedded liquefiable and non-liquefiable layers, which is considered less vulnerable to liquefaction than a continuous column of liquefiable soil. Due to the highly variable and stratified nature of this terrain type combined with the limited density of testing data and the lack of a groundwater model for large parts of the terrain a more refined assessment of the liquefaction vulnerability is currently not practicable following the MBIE (2017) framework.	*High Liquefaction Vulnerability* A 'High' vulnerability category has been assigned to all areas mapped as part of the Alluvial Flood Plain geomorphic terrain. Due to the significant thinning of the non-liquefied crust as a result of anticipated rise in water table, and the disproportionate damage this causes we considered a that the more refined 'High Liquefaction Vulnerability' classification is appropriate for the +1.25m ground water level scenario. This terrain type is considered vulnerable to lateral spreading although the extent and magnitude of the lateral spreading risk is difficult to accurately quantify. However, as this terrain is mapped as having a High liquefaction vulnerability there is no specific setback buffer. The ground may be generally more stratified with peat, gravel sand and fine grained (silt/clay) layers, than Harbour Margin areas. Consequently, this stratification may imply interbedded liquefiable and non-liquefiable layers, which is considered less vulnerable to liquefaction than a continuous column of liquefiable soil. Due to the significant thinning of the non-liquefied crust and the disproportion damage this causes, despite the limited and variable analysis results we considered a that the more refined 'High Liquefaction Vulnerability' classification is appropriate for the +1.25m ground water level scenario.	The liquefaction assessment was based on statistical analysis of 112 CPTs within all Alluvial Flood Plain areas, with usable groundwater level information, sourced from NZGD, tests specifically undertaken for this liquefaction study, and other data available from historical projects. Depth to groundwater was based on the median groundwater depth from the TCC regional groundwater model and is generally 2m to 5m deep. This model considered monitoring data at 29 piezometer locations across the western zone, up to March 2019. The TCC regional groundwater model extent only partially covers this terrain type area. Liquefaction analysis of CPTs within the southern portion of this area therefore could not be undertaken. The vulnerability category has been assigned based on the analysis of the same and geomorphic terrain type with usable ground water information. The Tauriko Business Estate and Lakes Subdivision have undergone significant landform alteration from its natural state, which has not been accounted for land damage classifications or vulnerability rating.

Terrain Type	Current Ground Water Level	Future Groundwater Level	General Comments
Alluvial Channels	*Liquefaction Damage is Possible* A ‘Possible’ vulnerability category has been assigned to all areas mapped as part of the Alluvial Flood Plain geomorphic terrain. There are limited number of CPTs within the Alluvial Channels terrain. There is also limited groundwater monitoring data within this area. Groundwater may be variable, generally shallowest near low points of gullies close to streams and ponding water. Therefore, due to the limited geotechnical information the lower accuracy vulnerability assessment of ‘Liquefaction Damage is Possible’ has been allocated to this terrain type. Liquefaction induced ground damage may be variable where occurring. It’s likely that ground damage is relatively worse closer to streams and ponded water, in the low areas (middle of gullies) of the Alluvial Channels.	*Liquefaction Damage is Possible* A ‘Possible’ vulnerability category has been assigned to all areas mapped as part of the Alluvial Flood Plain geomorphic terrain. There are limited number of CPTs within the Alluvial Channels terrain. There is also limited groundwater monitoring data within this area. Groundwater may be variable, generally shallowest near low points of gullies close to streams and ponding water. Therefore, due to the limited geotechnical information the lower accuracy vulnerability assessment of ‘Liquefaction Damage is Possible’ has been allocated to this terrain type. Liquefaction induced ground damage may be variable where occurring. It’s likely that ground damage is relatively worse closer to streams and ponded water, in the low areas (middle of gullies) of the Alluvial Channels.	It is anticipated that this terrain is perhaps the most variable in terms of response to liquefaction hazard, noting that thinner and more incised channels have increased erosion and shallower depth to non-liquefiable base geology material in comparison to wider channels, such as the Nanako Stream (Pyes Pa) where potential for increased deposition of loose or soft alluvial material may have occurred. The liquefaction assessment was based on statistical analysis of 31 CPTs within all 'Alluvial Channels' terrain polygons, with usable groundwater information, sourced from NZGD, tests specifically undertaken for the liquefaction assessment, and other data available from historical projects. Depth to groundwater was based on the median groundwater depth from the TCC regional groundwater model, and generally ranges between 3 and 10m deep. This model considered monitoring data at 29 piezometer locations across the Western Zone, up to March 2019. The TCC regional groundwater model extent only partially covers this terrain type area. Liquefaction analysis of CPTs within the southern portion of this area therefore could not be undertaken. The vulnerability category has been assigned based on the analysis of the same and geomorphic terrain type with usable ground water information.

Terrain Type	Current Ground Water Level	Future Groundwater Level	General Comments
Harbour Margin	*High Liquefaction Vulnerability* A ‘High’ vulnerability category has been assigned to all areas mapped as part of the Harbour Margin geomorphic terrain. The groundwater model shows some areas to have particularly shallow groundwater (i.e. 1m deep or shallower). At such shallow groundwater levels, the CPT based liquefaction assessment outputs can be spurious. The liquefaction vulnerability of this terrain is affected by lateral spreading. The accurate local assessment of lateral spreading potential is difficult, and a terrain wide geo-statistical approach has been adopted. Therefore, there remains significant uncertainty of the extent and magnitude of lateral spreading damage in this terrain. However, setback buffers have been developed to demarcate between ‘Minor to Moderate’ and ‘Moderate to Severe’ land damage areas.	*High Liquefaction Vulnerability* A ‘High’ vulnerability category has been assigned to all areas mapped as part of the Harbour Margin geomorphic terrain. The groundwater model shows some areas to have particularly shallow groundwater (i.e. 1m deep or shallower). At such shallow groundwater levels, the CPT based liquefaction assessment outputs can be spurious. The liquefaction vulnerability of this terrain is affected by lateral spreading. The accurate local assessment of lateral spreading potential is difficult, and a terrain wide geo-statistical approach has been adopted. Therefore, there remains significant uncertainty of the extent and magnitude of lateral spreading damage in this terrain. However, setback buffers have been developed to demarcate between ‘Minor to Moderate’ and ‘Moderate to Severe’ land damage areas	The liquefaction assessment was based on statistical analysis of 267 CPTs within all 'Harbour Margin' areas, with usable groundwater level information, sourced from NZGD, tests specifically undertaken for this liquefaction study, and other data available from historical projects. Depth to groundwater was based on the median groundwater depth from the TCC regional groundwater model and is generally less than 2-3m deep. This model considered monitoring data at 29 piezometer locations across the western zone, up to March 2019. Areas with thicker crust (groundwater >2-3m deep) are expected to experience relatively less liquefaction induced ground damage than areas with shallow groundwater (<1-2m deep).

Terrain Type	Current Ground Water Level	Future Groundwater Level	General Comments
Lower (Alluvial) Terrace	*Low Liquefaction Vulnerability* A 'Low' vulnerability category has been assigned to all areas mapped as part of the Lower (Alluvial) Terrace geomorphic terrain. There may be localised areas with shallow groundwater and loose sandy soils, that may be of Medium Liquefaction Vulnerability, though this assessment did not have sufficient information, or testing density, to define those areas. The exact boundaries with 'Upper (Ignimbrite) Terrace', the lower lying Harbour Margin and Alluvial Flood Plain terrains are uncertain. Terrain boundaries have been allocated based published geology, aerial photography, topography and vegetation cover. The DEM shows the Lower (Alluvial) Terrace is typically >5mRL or greater.	*Low Liquefaction Vulnerability* A 'Low' vulnerability category has been assigned to all areas mapped as part of the Lower (Alluvial) Terrace geomorphic terrain. There may be localised areas with shallow groundwater and loose sandy soils, that may be of Medium Liquefaction Vulnerability, though this assessment did not have sufficient information, or testing density, to define those areas. The exact boundaries with Upper (Ignimbrite) Terrace, the lower lying Harbour Margin and Alluvial Flood Plain terrains are uncertain. Terrain boundaries have been allocated based published geology, aerial photography, topography and vegetation cover. Lower (Alluvial) Terrace is typically >5mRL.	The liquefaction assessment was based on statistical analysis of 270 CPTs within all Lower (Alluvial) Terrace areas, with usable groundwater level information, sourced from NZGD, tests specifically undertaken for this liquefaction study, and other data available from historical projects. Depth to groundwater was based on the median groundwater depth from the TCC regional groundwater model, and is generally 5 to 10m deep, or deeper. This model considered monitoring data at 29 piezometer locations across the western zone, up to March 2019. The TCC regional groundwater model extent only partially covers this terrain type area. Liquefaction analysis of CPTs within the southern portion of this area therefore could not be undertaken. The vulnerability category has been assigned based on the analysis of the same and geomorphic terrain type with usable ground water information.

Terrain Type	Current Ground Water Level	Future Groundwater Level	General Comments
Upper (Ignimbrite) Terrace	*Very Low Liquefaction Vulnerability* A 'Very Low' vulnerability category has been assigned to all areas mapped as part of the Upper (Ignimbrite) Terrace geomorphic terrain. The vulnerability rating is based on the thickness of non-liquefiable crust given groundwater is generally deeper than 10m and the landform is elevated.	*Very Low Liquefaction Vulnerability* A 'Very Low' vulnerability category has been assigned to all areas mapped as part of the Upper (Ignimbrite) Terrace geomorphic terrain. The vulnerability rating is based on the thickness of non-liquefiable crust given groundwater is generally deeper than 11m (accounting for future water table) and the landform is elevated.	The liquefaction assessment is based on statistical analysis of 176 CPTs within all Upper (Ignimbrite) Terrace areas, with usable groundwater level information, from NZGD, tests specifically undertaken for this liquefaction study, and other data available from historical projects. Depth to groundwater was based on the median groundwater depth from the TCC regional groundwater model and is generally deeper than 10m. This model considered monitoring data at 29 piezometer locations across the western zone, up to March 2019. The TCC regional groundwater model extent only partially covers this terrain type area. Liquefaction analysis of CPTs within the southern portion of this area therefore could not be undertaken. The vulnerability category has been assigned based on the analysis of the same and geomorphic terrain type with usable ground water information.

5.2 Key uncertainties in the study

The following key uncertainties may have influenced, to some degree, the veracity of our assessment and resulting findings:

5.2.1 Tauranga's unique geological characteristics

Tauranga's geology, particularly in the Western Zone, is a story of late Quaternary erosion and deposition that has resulted in a complex arrangement of sediments interbedded with volcanic debris and tephra layers from multiple sources. While key geological units are identified as part of routine geotechnical assessments, it is recognised that these units are groups of materials from a range of sources. This is particularly so for the Matua Subgroup / Tauranga Group alluvial sediments which underlie much of the Harbour Margin, Alluvial Channels and Alluvial Flood Plain terrains; as well as older sediments forming the Lower Terrace terrain.

As a consequence, the geological units are variable in age as well as physical and chemical characteristics and can be laterally discontinuous even over short distances. It is noted that the Harbour Margin terrain is potentially underlain by soft, highly plastic sediments that are less prone to liquefication; or conversely underlain by thick sequences of loose sand where the liquefaction response can be significant. The presence of weathered rhyolitic tephras and lithologies with increased pumice content can influence collection and interpretation of CPT logs resulting in an underprediction of soil strength and a corresponding increase in theoretical liquefaction vulnerability.

The region-wide assessment groups the predicted liquefaction response by terrain over an area of 175 km^2. Thus, it is recognised that, while we have attempted to modify mapped land damage and vulnerability based on local conditions, constraints in data density make this a considerable uncertainty that can only be resolved through site-specific analyses.

Challenges in mapping boundaries between terrains, in particular the transition from Harbour Margin to Alluvial Flood Plain, and also the lower and upper terraces, are also noted. However, the assessment of predicted liquefaction response across these transitions are limited as the underlying sub-surface geological profiles have similar characteristics.

5.2.2 Mapping of natural geomorphic terrains

Areas of uncertainty exists along the terrain boundaries, particularly in the transition between Harbour Margin and Alluvial Flood Plain terrains. In general, the Harbour Margin Terrain has been mapped in areas adjacent to the shoreline of the harbour, and where the ground surface elevation is <5mRL. Where the elevation increases to the south within low lying areas and valley floor away from the harbour, this has been mapped as Alluvial Flood Plain. This transition is also marked by a change in vegetation and land use between the terrains, as shown in aerial photos; with mangrove (a coastal shrub or small tree growing in brackish or partially saline environments) growing within the Harbour Margin transitioning into pastoral grazing land with irrigation and drainage ditches typical of flood plain environment which has been drained in the 20^{th} century for pastoral grazing.

It has been recognised that there will be overlap between the Harbour Margin and Alluvial Flood Plain deposits due to the changeable environment in which they were formed (i.e. sea level rise/fall, periods of deposition and erosion) and colluvial deposition from terraces adjacent to the edge of the harbour. There is also some degree of uncertainty in lateral extent of low-lying terrains (Harbour Margin, Alluvial Channels, Alluvial Flood Plain), and their transition into terrace terrains. Our mapping philosophy determines the extent of lower lying terrains to coincide with the base of sloping ground, marking the transition from deposition of younger sediments to erosion of older sediments and basal ignimbrites.

5.2.3 Influence of anthropogenic activities on geomorphic terrains

It was recognised early in the assessment that a number of the geomorphic terrains, in particular the 'Harbour Margin' and 'Alluvial Floodplain', have been modified at the surface by residential and commercial development in the 20^{th} century. Typical landform alterations include filling (Fraser Cove; Maleme Street, Greerton) or drainage for pastoral land (Kopurererua Valley). It is noted also that extensive engineered filling has taken place at the southern end of the Kopurererua Valley for construction of the Tauriko Business Estate and Lakes Developments.

Historic aerial photographs, previous reporting and anecdotal information provide evidence that the Alluvial Floodplain Terrain landform at the southern end of Kopurererua Valley has been extensively modified. The floodplains have been infilled with up to 5 m of engineered pumice fill to construct the Tauriko Business Estate and the Lakes Residential Subdivision. The adjacent mapped Ignimbrite Terraces have also been extensively cut down and used as a source of fill material to infill low-lying areas. The extent of modification in these specific areas is more than likely to influence the predicted seismic response, but this area has not been mapped as a unique terrain due to a lack of certainty in data sources (i.e. all the CPTs were pushed pre-development), exacerbated by a lack of modelled groundwater surface over the entire area. In such circumstances the pre-development landform and associated geomorphological terrains have been used in the assessment.

Much of the ground investigation information used to inform the analyses is typically collected prior to developments occurring. Assessing the extent to which these activities have influenced the predicted response to seismic behaviour cannot be determined by this region-wide study. While it is possible that such site-specific development may have increased resilience to liquefaction hazard, it is not considered appropriate to draw such conclusions on a regional scale, as these developments are site specific and likely to vary in level of resilience considerably over the study area. For this reason the study has selected to disregard the potential site specific effects of filling and ground improvement and instead assume the natural underlying geomorphological terrain mapped across such areas will govern the predicted ground behaviour. By disregarding localised development this allows the study to more clearly delineate areas of reclamation, such as Sulphur Point and The Strand. See Section 5.2.3 for further details.

5.2.4 Groundwater model

The current Tonkin and Taylor (2019) groundwater model provided by TCC for this study excludes approximately 32% of the Western Zone study area, at the southern end. It is understood from TCC that new piezometers were installed towards the end of 2019 and useable data to expand the current model will be available towards the end of 2020. By applying a consistent water surface model to CPTs across the study area a greater data set would be available to refine the results of our geo-statistical approach and achieve a greater level of accuracy. It is also recognised that current the study has adopted a simplistic approach to anticipating groundwater rise across the city due to climate change effects in 100 years' time; with an assumed 1.25 m increase in ground water elevation across the Western Zone. Further detailed hydrogeological studies are required to refine predicted groundwater effects due to climate change and sea level rise.

There are also other local discrepancies with the regional ground water model and local field observations. Bulk earthworks on sites can have a significant effect on the hydrogeological regime, and hence the depth to groundwater. In places in the Tauriko area, at the southern extent of the regional groundwater model, the groundwater is likely to be ~1-2 m shallower than the current model hypothesises based on recent work completed by Aurecon in support of the Tauranga Crossing retail development at the intersection of SH29 and SH36. Large scale earthworks include cutting down of natural ridgelines resulting in the interception of aquifers and perched groundwater tables which are now locally influencing the groundwater model. Such localised groundwater influences are difficult to model on a regional scale and require site specific investigation and assessment.

5.2.5 Probabilistic Seismic Hazard Assessment

The methodology for deriving city-wide seismic response as used by Bradley (2019) based on a national model that assigns measured response to common geological units derived from QMap. The mapped geological units in Tauranga relate to Tauranga Group soils, which are derived from measurements of shear wave velocity obtained away from Tauranga. The practice of measuring of shear wave velocity is becoming more common in geotechnical ground investigations and assessments, but the data pool across the Tauranga City region is still relatively limited, with testing across the city dispersed and commonly not being measured to a depth of 30 m, and a variety of techniques being employed to a range in accuracy (geophysical, seismic dilatometer, seismic CPT etc). While there is considerable uncertainty in the PSHA, we note that for limited data set of shear wave velocity we have measured or extrapolated in Tauranga (as part of other investigations) does correlate with the national model used by Bradley. Regardless, the assessment incorporates five shaking events to evaluate response to a range of accelerations, acting as a sensitivity check in its own right on the end liquefaction vulnerability. Direct measurement of shear wave velocity as part of site-specific assessments is recommended to better refine predicted response behaviour.

5.2.6 Data density

The density and spatial distribution of CPT locations is variable across the Western Zone, and typically reflecting more recent developments and infrastructure projects. While we have confidence in the seismic response of the lower and upper terrace terrains, future region wide assessments will benefit from having more information to improve understanding and refine models, especially in the Alluvial Flood Plain geomorphic terrain. This study emphasises the ongoing benefit and importance of tools such as the NZGD for natural hazard assessments and supporting resiliency and growth projects across New Zealand.

5.2.7 Quantitative analyses

For consistency and ability to bulk process quantitative analyses across the Western Zone a simplified numerical assessment procedure, albeit an industry standard assessment methodology, has been applied. Due to the level of detail of this study (Level B assessment) generic settings that may not fully reflect actual site conditions have been adopted. Given the variability in Tauranga's soil profile (Refer Section 5.2.1.) site specific assessment would be required to better refine predicted seismic response and liquefaction behaviour for detailed site assessments.

Industry standard liquefaction assessment methodologies have been utilised, however the adopted numerical assessment methodology has inherent simplifications in it, that is semi-empirical methodology is potentially conservative, and in particular at lower levels of ground shaking. In the absence of Tauranga specific soil parameters default settings have been adopted (e.g. fines correction factor, C_{fc} of 0; probability of liquefaction PL of15%, presence of pumice soils etc.).

The adopted land damage parameters (LSN and indexed settlements) have not been calibrated for Tauranga specific soils. The design has adopted the 85^{th} percentile damage values for assessment, albeit constrained with engineering judgement. Therefore, the analysis is considered to have greater uncertainty during mid-sized earthquake events i.e. 1-in-100 year and 1-in-250 year events when there is a greater calculated spread in expected ground damage. As a result, there is a limited risk that the assessment does locally under predicted liquefaction damage.

5.2.8 Lateral spreading

As discussed in Section 4.5.4, region-wide assessment of lateral spread using the chosen method is recognised to have significant numerical uncertainty, but well suited to the use of CPT information and able to me constrained with case history observations and engineering judgement. Based on the current density of testing there is little opportunity to refine the predicted lateral spread behaviour, and thus it is important to recognise that this assessment shall not be used as an alternative to site-specific analyses at the point of land development, building development or linear infrastructure design. The numerical analysis of CPT logs within a given terrain type results in a significant variation in calculated lateral spreading displacement for the given earthquake and free face conditions. Due to the disproportional damage lateral spreading can induced in urban infrastructure our nominal buffer distances of 'Moderate to Severe' land damage has been calculated using the 85^{th} percentile setback distances. Therefore, the risk does exist that lateral spreading induced ground damage could be worse than anticipated.

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A

Input Information

Appendix A
Input Information

Table A1 Summary of Input Information

Input Information	Comment
Plan A1 - Western Zone Site Boundary	Identifies the Western Zone location and boundary as assessed in this study by Aurecon
Plan A2 – 2002 Liquefaction Study	Extent of, and outcomes from, 2002/03 liquefaction hazard study
Plan A3 – Study Detail Level	Identifies the extent of *Level B – Calibrated Desktop Assessment*
Plan A4 – Ground Surface Elevations	EDM of the 2019 ground surface in terms of NZVD16
Plan A5 - Geomorphic Terrains	Geomorphic terrains mapped at the Western Zone site. Terrains include: ▪ Harbour Margin ▪ Alluvial Channels ▪ Alluvial Flood Plain ▪ Lower (Alluvial) Terrace ▪ Upper (Ignimbrite) Terrace ▪ Land Reclamation
Plan A6 – Western Zone CPT Test Locations	Locations of the CPT tests used in numerical component of the liquefaction vulnerability hazard assessment
Plan A7 - Depth to Groundwater Surface	Median GWL model as provided by TCC in terms of depth below ground level – DEM Surface
Plan A8 – Mapped Free Faces	Identified free faces which have undertaken lateral spreading assessment on.

B

Liquefaction Analysis Outputs - Maps

Appendix B
Liquefaction Analysis Output Maps

Table B1 Summary of Liquefaction Damage and Hazard Maps

Map Title	Comment
Plan B1 – LSN 1-in-25 Year EQ (Current GWL)	Calculated LSN values at each CPT location for the 1-in-25 year earthquake events using the current modelled groundwater level
Plan B2 – LSN 1-in-100 Year EQ (Current GWL)	Calculated LSN values at each CPT location for the 1-in-100 year earthquake events using the current modelled groundwater level
Plan B4 – LSN 1-in-250 Year EQ (Current GWL)	Calculated LSN values at each CPT location for the 1-in-250 year earthquake events using the current modelled groundwater level
Plan B4 – LSN 1-in-500 Year EQ (Current GWL)	Calculated LSN values at each CPT location for the 1-in-500 year earthquake events using the current modelled groundwater level
Plan B5 – LSN 1-in-1000 Year EQ (Current GWL)	Calculated LSN values at each CPT location for the 1-in-1000 year earthquake events using the current modelled groundwater level
Plan B6 – LSN 1-in-25 Year EQ (Future GWL)	Calculated LSN values at each CPT location for the 1-in-25 year earthquake events using the current modelled groundwater level
Plan B7 – LSN 1-in-100 Year EQ (Future GWL)	Calculated LSN values at each CPT location for the 1-in-100 year earthquake events using the future modelled groundwater level
Plan B8 – LSN 1-in-250 Year EQ (Future GWL)	Calculated LSN values at each CPT location for the 1-in-250 year earthquake events using the future modelled groundwater level
Plan B9 – LSN 1-in-500 Year EQ (Future GWL)	Calculated LSN values at each CPT location for the 1-in-500 year earthquake events using the future modelled groundwater level
Plan B10 – LSN 1-in-1000 Year EQ (Future GWL)	Calculated LSN values at each CPT location for the 1-in-1000 year earthquake events using the future modelled groundwater level
Plan B11 – Indexed Settlement 1-in-25 Year EQ (Current GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-25 year earthquake events using the current modelled groundwater level
Plan B12 – Indexed Settlement 1-in-100 Year EQ (Current GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-100 year earthquake events using the current modelled groundwater level
Plan B13 – Indexed Settlement 1-in-250 Year EQ (Current GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-250 year earthquake events using the current modelled groundwater level
Plan B14 – Indexed Settlement 1-in-500 Year EQ (Current GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-500 year earthquake events using the current modelled groundwater level
Plan B15 – Indexed Settlement 1-in-1000 Year EQ (Current GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-1000 year earthquake events using the current modelled groundwater level
Plan B16 – Indexed Settlement 1-in-25 Year EQ (Future GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-25 year earthquake events using the current modelled groundwater level
Plan B17 – Indexed Settlement 1-in-100 Year EQ (Future GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-100 year earthquake events using the future modelled groundwater level
Plan B18 – Indexed Settlement 1-in-250 Year EQ (Future GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-250 year earthquake events using the future modelled groundwater level
Plan B19 – Indexed Settlement 1-in-500 Year EQ (Future GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-500 year earthquake events using the future modelled groundwater level
Plan B20 – Indexed Settlement 1-in-1000 Year EQ (Future GWL)	Calculated Reconsolidation Settlement values at each CPT location for the 1-in-1000 year earthquake events using the future modelled groundwater level

C

Liquefaction Analysis Outputs – Tabulated Data

Appendix C
Liquefaction Analysis Output – Tabulated Data

Table C1 Geo-statistical analysis of land damage and lateral spreading analysis

Map Title	Comment
Plots C1 – C12 – Vertical Land Damage	Box and whisker plots of calculated land damage parameters of: ■ Indexed LSN ■ Change in LSN ■ Indexed Settlement At each of the five design earthquake scenarios, at both current and future groundwater levels.
Plots C13 – C18 – Lateral Spreading	Box and whisker plots of setback distance for 100mm of lateral spreading by free face height, for geomorphic terrains of: ■ Alluvial Flood Plain ■ Land Reclamation ■ Harbour Margin At both current and future groundwater levels.

D

Liquefaction Damage and Hazard Maps

Appendix D
Liquefaction Damage and Hazard Maps

Table D1 Summary of Liquefaction Land Damage and Vulnerability Assessment Maps

Map Title	Comment
Map D1 – Land Damage – 1-in- 25 Year EQ (Current GWL)	Liquefaction land damage maps for 1-in-25 year earthquake with current GWL
Map D2 – Land Damage – 1-in-100 Year EQ (Current GWL)	Liquefaction land damage maps for 1-in-100 year earthquake with current GWL
Map D3 – Land Damage – 1-in-250 Year EQ (Current GWL)	Liquefaction land damage maps for 1-in-250 year earthquake with current GWL
Map D4 – Land Damage – 1-in-500 Year EQ (Current GWL)	Liquefaction land damage maps for 1-in-500 year earthquake with current GWL
Map D5 – Land Damage – 1-in-1000 Year EQ (Current GWL)	Liquefaction land damage maps for 1-in-1000 year earthquake with current GWL
Map D6 – Land Damage – 1-in- 25 Year EQ (Future GWL)	Liquefaction land damage maps for 1-in-25 year earthquake with future GWL
Map D7 – Land Damage – 1-in-100 Year EQ (Future GWL)	Liquefaction land damage maps for 1-in-100 year earthquake with future GWL
Map D8 – Land Damage – 1-in-250 Year EQ (Future GWL)	Liquefaction land damage maps for 1-in-250 year earthquake with future GWL
Map D9 – Land Damage – 1-in-500 Year EQ (Future GWL)	Liquefaction land damage maps for 1-in-500 year earthquake with future GWL
Map D10 – Land Damage – 1-in-1000 Year EQ (Future GWL)	Liquefaction land damage maps for 1-in-1000 year earthquake with future GWL
Map D11 - Liquefaction Vulnerability Map (Current GWL)	Liquefaction Vulnerability rating for Western Zone at current GWL
Map D12 - Liquefaction Vulnerability Map (Future GWL)	Liquefaction Vulnerability rating for Western Zone at future GWL

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