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Tauranga's Western Zone: A regional-scale liquefaction case study

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ABSTRACT

Tauranga is one of New Zealand's fastest growing cities and port economies. The city is susceptible to many natural hazards therefore resilience planning is imperative to its future. As part of Tauranga City Council's Resilience Programme, a city-wide liquefaction study has been completed, comprising geomorphic, land damage, and vulnerability mapping.

The Western Zone study, performed to meet MBIE's 2017 guidelines, explores liquefaction potential within an area of complex geology and geomorphology. Key terrains deemed susceptible to liquefaction include Alluvial Flood Plain, the Harbour Margin and areas of Land Reclamation. These terrains are separated by terraces of Pleistocene-aged alluvial deposits and ignimbrites. A standardised liquefaction assessment was derived with the Client's project team and incorporated data sourced from the New Zealand Geotechnical Database, internal consultancy reports database and new ground investigations, resulting in 1236 test positions in a 77km^2 area. Due to the low density and clustered nature of test positions, a qualitative risk assessment was completed following a lines of evidence approach; derived from liquefaction analyses with sensitivity checks, thickness of non-liquefiable crust, anticipated lateral spread hazard, and local geological knowledge.

Key challenges to the study included: assessing the likely effects of landform moderation as part of late 20th century urban development in low lying marginal areas, pumice and clay content within sensitive volcaniclastic material, and inherent uncertainties in groundwater and seismic parameters used for the assessment. This study provides a template for achieving higher levels of detail whilst overcoming these technical challenges.

1 INTRODUCTION

Territorial authorities across New Zealand require up-to-date liquefaction risk analyses to inform future vulnerability assessments and resiliency projects. The overall objective of identifying liquefaction risk is to inform future land-use planning and capital expenditure to minimise the disruption to municipal assets and the community, in the event of large-scale seismic events.

Tauranga City Council (TCC) engaged Aurecon New Zealand Limited (Aurecon) to undertake geomorphological mapping, liquefaction hazard analyses and risk mapping for the Western Zone (Refer Figure 1). Tonkin and Taylor Limited (T+T) were engaged concurrently to evaluate the eastern area of the city, herein referred as the 'Eastern Zone' part of a joint study to assess Tauranga's liquefaction vulnerability.

Figure 1: Tauranga City Council Liquefaction Assessment Zone noting the Western Zone (green), Eastern Zone (blue), and Calibration Zone (white) (Basemap: TCC 2019).

This liquefaction hazard study for the Western Zone was undertaken in accordance with the most recently published Ministry of Business, Innovation and Employment Guidance with the aim of achieving a *Level B - Calibrated Desktop Assessment* level of detail. (MBIE 2017).

Similar liquefaction studies (T+T 2019a; Barrell 2019; Golder Associates (NZ) Limited 2019) have been undertaken across New Zealand using the same MBIE, 2017 framework. A previous Tauranga regional liquefaction hazard study, which included a significant portion of the Western Zone, was carried out in 2002 and was reported in 2003 for the Western Bay of Plenty Lifelines Group (Opus 2002).

2 GEOMORPHIC SETTING OF THE WESTERN ZONE

The geomorphic terranes established as part of the Western Zone were derived following the desktop review of published geological mapping, topographic mapping, academic and technical reporting, current and historical aerial imagery, groundwater levels, and relevant geotechnical testing data. All of this information was collated within a GIS-database. Within this database, the geomorphic terrains were mapped and land damage and vulnerability classification were later assigned following correlation of geomorphology with quantitative assessment.

2.1 Geological Setting

The Tauranga urban area is positioned at the south eastern edge of the Tauranga Basin, a semi-circular feature, 40 km long and 15 km wide, the eastern 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.

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.

The geology of the Western Zone is described by the 1:250,000 scale Geological Map of the Rotorua Area (Leonard *et al.* 2010) and the 50,000 scale Geological Map for the Tauranga area (Briggs *et. al.* 1996). Both geological maps indicate that terraces at higher elevations (i.e. >20 mRL) are comprised of ignimbrite (identified as the oldest basin material). The most widespread ignimbrite is the Middle-Pleistocene (0.78 to 0.1 Ma) Chimp Formation as mapped by Leonard et al. (2010), also known as the Te Ranga Ignimbrite as mapped by Briggs et al. (1996).

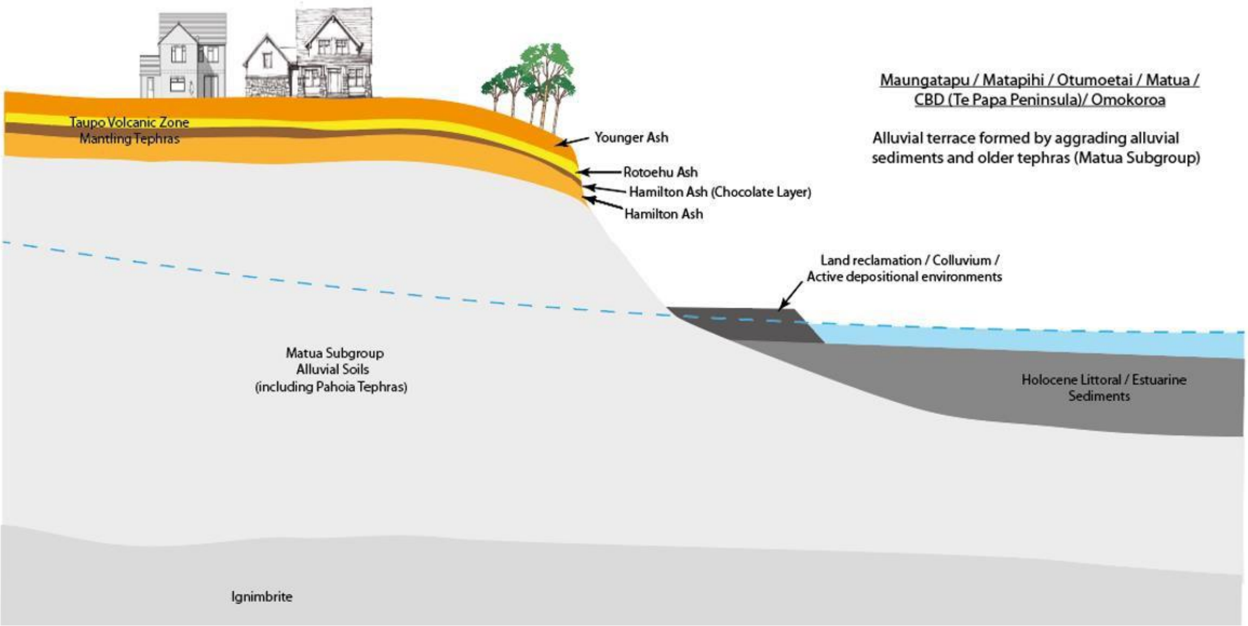

Figure 2: A schematic diagram illustrating a typical cross-section of an alluvial terrace bounded by the harbour (Te Papa Peninsula/Maungatapu).

Following placement, the ignimbrites covering the study area were progressively incised and the eroded material redeposited as alluvium within the Tauranga Basin. This is where Early to mid-Pleistocene (2 Ma to 50 ka) 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 and includes fluvial pumice deposits, lignites and peats with intercalated tephras. Figure 2 demonstrates a cross-section through a Pleistocene alluvial terrace. These geological units are mantled by unmapped Taupo Volcanic Zone Tephra layers broadly categorised into three distinct units: Younger (50 ka to present), Rotoehu (60 ka), and Hamilton (100 – 350 ka) ashes.

2.2 Geotechnical Investigations

For this study, we undertook a review of readily available geotechnical information from both the New Zealand Geotechnical Database (NZGD 2019) and relevant reports held within Aurecon's database from previous studies completed within the Western Zone. Areas with limited information were prioritised for additional CPT tests completed as part of the study.

In total this study has accessed 1,236 usable CPT records, Table 1 presents the number of usable CPT within each geomorphic terrain within the Western Zone study area.

Table 1: Number of CPT data points by geomorphic terrain

Geomorphic Terrain	Number of useable CPTs
Upper (Ignimbrite) Terrace	340
Lower (Alluvial) Terrace	284
Alluvial Channels	93
Alluvial Flood Plain	184
Harbour Margin	265
Land Reclamation	70

2.3 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. Generally Tauranga City has two hydrogeological regimes: Elevated terraces with groundwater surfaces >10 metres depth and low lying areas in close proximity to surface water bodies with groundwater typical <5 metres depth.

A long-term groundwater modelling project has been undertaken separately for TCC (T+T 2019b). 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 adopted the median (50^{th} percentile) depth to groundwater model. Figure 3 shows the groundwater model extents and depths across the Western Zone study area.

To model the effects of long-term sea level rise, we accounted for the groundwater level in 100 years' time. This 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.

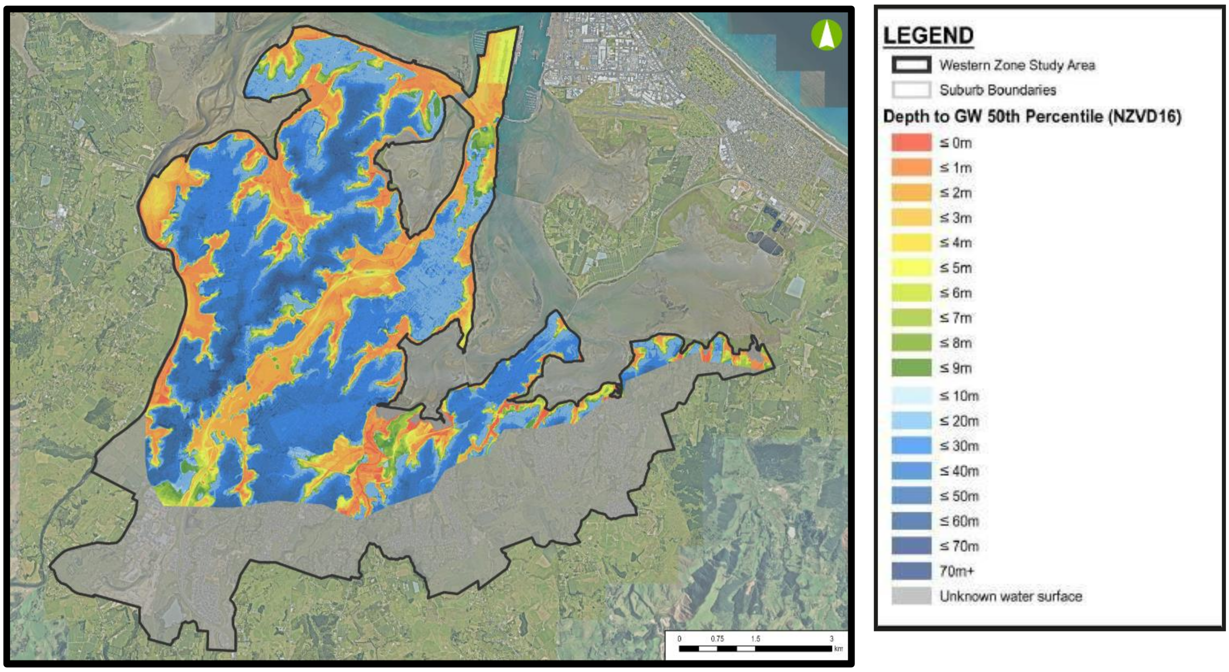

Figure 3: Groundwater modelling extents used within the liquefaction assessment. (Aurecon 2020a)

2.4 Tauranga Liquefaction Case History

The key outcomes of the Western Bay of Plenty study (Opus 2002) identified the elevated terraces within the Western Zone as having "*None*" to "*Minor*" liquefaction susceptibility. Areas of lower elevation with a shallower groundwater table were identified as having "*Moderate*" to "*Major*" susceptibility with "*Extensive*" damage associated with lateral spreading, around major waterways.

In addition to the previous liquefaction study, we undertook a literature review of historic cases of liquefaction within the Bay of Plenty Region. The largest seismic event the Bay of Plenty Region has experienced since 1843 was the 2 March 1987 M_w 6.5 Edgecumbe Earthquake (Fairless and Berrill 1984; Dowrick 1988), with Tauranga City being located approximately 50 km northwest of the epicentre of the Edgecumbe Earthquake.

Figure 4: The Edgecumbe fault surficial expression following the 1987 M_w 6.5 Edgecumbe earthquake. (Leonard et al 2010)

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. 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 1987 Edgecumbe Earthquake was likely in the order of a 1-in-25 to 1-in-50-year event at the Western Zone.

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.

2.5 Geomorphic Terrain Derivation

On the basis of the aforementioned desktop review we identified six key geomorphological terrains within the western zone (Aurecon, 2020b). These terrains are summarised in Table 2.

Table 1: A summary of the geomorphic terrains

Terrain Name	Landform	Predominant Geology (upper 10m)
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.
Alluvial Flood Plain	Alluvial Flood Plains 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.
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.	Thin deposits of Holocene to recent-aged alluvium, colluvium or peat cover overlying predominantly Matua Subgroup silts/sands with in-situ and reworked tephra. The geology is inferred to be significantly influenced by underlying geological units.
Harbour Margin	Low-lying areas surrounding the present-day shoreline of the Tauranga Harbour inferred to be dominated by estuarine type processes.	Variable combination of Holocene-aged estuarine silts and clays, beach sand or loosely poorly consolidated littoral/fluvial sands.
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 (maximum 5 – 6 m thick) covering Matua Subgroup alluvium.
Upper (Ignimbrite) Terrace	Steep-sided upper terraces (up to 60+ m RL). 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.

3 LIQUEFACTION ASSESSMENT METHODOLOGY

In the early stages of the project, a Calibration Zone assessment was undertaken by both the Eastern Zone and Western Zone project teams in collaboration with the project peer reviewer to ensure consistency in the assessment process. A workshop was held prior to undertaking the full analyses of the respective Zones and comparisons were made of the methodologies that were established.

In developing our analyses methodology, it was very apparent that liquefaction response behaviour was significantly governed by underlying geomorphic setting. For this reason, the study has selected to disregard the potential site-specific effects of filling and ground improvement. This is with the exception of the Land Reclamation Terrain where several metres of loose sand was placed to extend the natural shoreline.

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 were computed using the references in Table 2.

Table 2: Liquefaction Assessment Methodology

Test Type	Liquefaction Triggering Methodology	Fines Content	Liquefaction Cut Off	Liquefaction Settlement Methodology	Liquefaction Ground Damage	Lateral Spreading
CPT	Boulanger and Idriss (2014) with a 15% probability of liquefaction (P_L)	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

3.1 Design Earthquake Values

To determine the design level of shaking TCC separately commissioned a Probabilistic Seismic Hazard Analysis (PSHA) assessment for Tauranga City (Bradley 2019). The design Peak Ground Acceleration (PGA) values from this PSHA study were adopted for this city-wide liquefaction hazard study and are derived from V_{s30}. Figure 5 shows the V_{s30} model generated by Foster et al. (2019) and presented in Figure 1 of Bradley (2019).

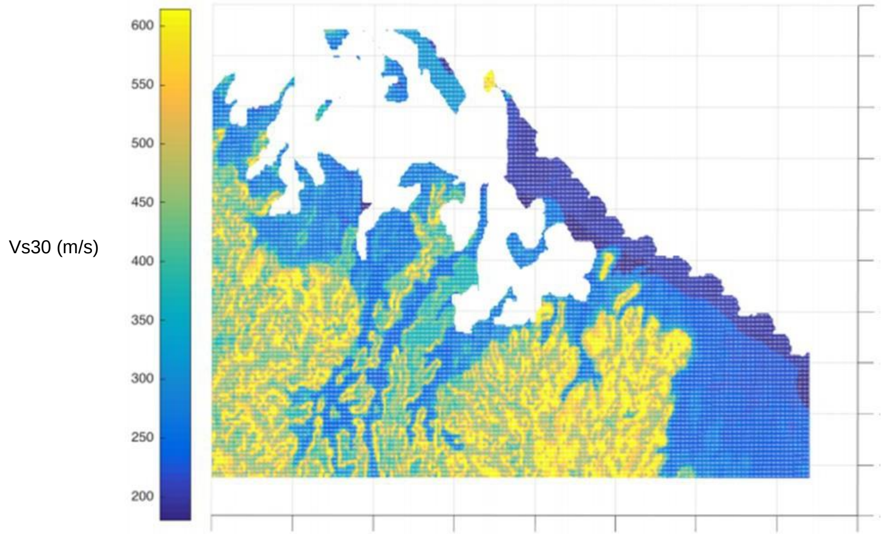

Figure 5: Reproduction of Figure 1 of PSHA Report (Bradley 2019)

The level of ground shaking is one of the key factors in determining whether liquefaction will or will not occur. We analysed five levels of ground shaking associated with the following annual recurrence intervals: 1-in-25-year, 1-in-100-year, 1-in-250-year, 1-in-500-year, and 1-in-1000-year earthquake. The adopted PGA values used in the Western Zone assessment, by geomorphic terrain type are presented in Table 3.

Table 3: 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
Lower (Alluvial) Terrace	250	0.06	0.11	0.15	0.19	0.24
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
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 study and interpolating for the 1-in-250-year earthquake event, the adopted earthquake magnitudes are presented for each design earthquake event in Table 4.

Table 4: 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

3.2 Surface Expression of Liquefaction damage

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.

3.3 Liquefaction Severity Number

The LSN approach has been adopted as the primary land damage assessment methodology for this liquefaction hazard study. With expected ground damage ranges and how they relate to characteristic LSN values being defined in MBIE (2017). Example photographs of different degrees of liquefaction induced ground surface damage are presented in Appendix A of MBIE (2017).

3.4 Lateral Spread Calculations

For the Western Study zone, we 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 CPT correlations are based on a limited case history database of lateral spreading observations, 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.

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%.

3.5 Land Damage Assessment Methodology

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. The land damage mapping was assessed as follows:

- An initial screening was undertaken to identified areas unlikely to be susceptible to liquefaction induced ground damage. Any areas which have a depth to groundwater mapped as greater than 10m depth for current and/or future ground water level are considered as having a limited, if any, susceptibility to liquefaction induced ground damage in accordance with Ishihara (1985).
- A bulk liquefaction triggering analysis was then run on all CPT logs which are located within 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 numerical analyses.
- These numerical results were then grouped by geomorphic terrain type and assessed statistically to derive baseline land damage classifications for each geomorphic terrain type. Baseline damage ratings were then allocated by geomorphic terrain type for each of the ten earthquake-groundwater event combinations, i.e. five design earthquake events multiplied by the two ground water levels. From this, preliminary land damage mapping was undertaken on a geomorphic terrain specific basis and damage categories allocated based on MBIE (2017).
- 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 extrapolated based on the mapped geomorphic terrain type.
- The effect of lateral spreading was then accounted for by calculating setback distances as per Zhang et al. (2004). Where appropriate, the baseline liquefaction land damage rating was locally adjusted to account for the effects of lateral spreading.
- 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.

- With all this completed finalised liquefaction vulnerability categories were assigned based on the categories in MBIE (2017).

Full details of the land damage assessment methodology can be found in Aurecon's full report (Aurecon 2020a).

4 THE QUIET FALCON I

Applying the methodology above across 1236 Cone Penetration Tests under five different earthquake events, two groundwater conditions, and several lateral spread calculations with terrain specific peak ground accelerations required extensive automation. In order to undertake these calculations, Aurecon designed an automated liquefaction assessment tool, *Quiet Falcon I*, to bulk analyse all the CPT data for each of the design events concurrently. This resulted in significant time savings and ensured quality and repeatability of outputs by minimising any human error in the analysis process. The result was the development of a software, which allows a bulk import of an unlimited number of CPTs from a geodatabase. Once the CPTs are uploaded, the earthquake event and groundwater table are assigned for each CPT. The output resulted in a CPT, their location, an indexed ground settlement, Liquefaction Severity Number (LSN), and a sensitivity check on the LSN based on minor groundwater changes.

The results were then assessed using statistical comparisons (median, 15th and 85th percentiles) by terrain type to assess the variability of each terrain and how each terrain would respond to various earthquakes under two groundwater conditions. An example of the generated output plots for a given geomorphic terrain type can be seen in Figure 6.

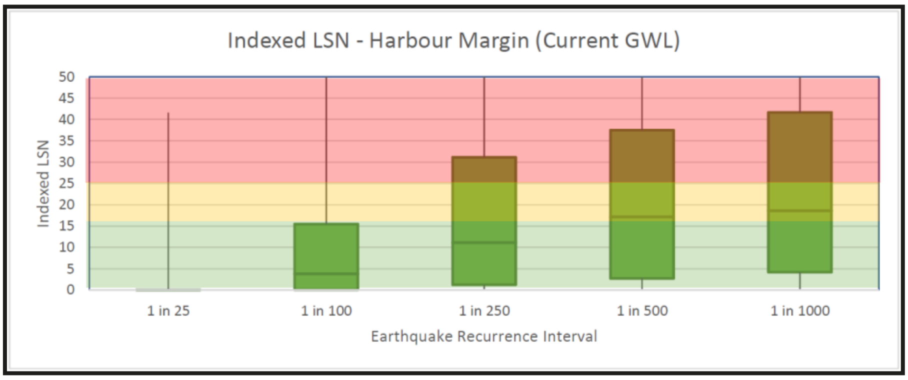

Figure 6: An example of the statistical assessment output undertaken for each terrain. (Aurecon 2020a)

5 RESULTS

The outcome of the liquefaction study resulted in the production of 10 land damage maps representing the five earthquake cases under the two different groundwater cases, and two liquefaction vulnerability maps in accordance with MBIE (2017), Table 1.1. These maps are intended to inform the general public and Territorial Authorities understanding of the predicted ground response under several earthquake scenarios and the anticipated effects of climate change on liquefaction vulnerability. TCC has since incorporated this into their publicly accessible online GIS tool with the supplementary technical report. The assessment also provides improved confidence in the validity of the outputs based on adopting the updated MBIE guidelines.

Whilst the results of the liquefaction study largely aligned with the 2003 study, a higher resolution map was established due to detailed geomorphic mapping and increased data density. The refinement of the liquefaction model resulted in a 9% reduction of vulnerable land within the Western Zone. A key factor for these changes is the more refined geomorphological mapping exercise, which better constrained liquefiable terrains.

6 KEY RESIDUAL UNCERTAINTIES

The scale of the TCC Liquefaction study means that many uncertainties needed to be accounted for within the assessment. A number of key uncertainties associated with the study were identified and include:

- Variable geology across terrains including the presence of rhyolite-derived pumiceous soils, which have the potential to result in underestimation of soil strength upon testing, and the corresponding influences of these factors on our predictions of seismic response.
- Influence of anthropogenic activities on geomorphic terrains which influence the assumed extents of the predicted liquefaction response and associated land damage
- The spatial density and distribution of CPT locations is variable across the Western Zone and typically focuses on areas of recent development and linear infrastructure.
- The regional scale groundwater model excluded approximately 32% of the Western Zone study area. Data from the unmodeled area was excluded from numerical calculations, requiring the extrapolation of predicted liquefaction damage based on correlation of geomorphological terrain
- Inherent uncertainty in the application of the national PSHA model to a complex stratigraphy of rhyolitic tephras interbedded within a mix of heterogeneous alluvial and estuarine soils, often with a large pumiceous component, even with some calibration against local shear wave velocity measurements.
- Finally, the 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 was able to be constrained with case history observations and engineering judgement.

7 CONCLUDING REMARKS

The Western Zone liquefaction study refines the previous work completed in 2003, utilising a higher resolution geomorphic map, and updated analytical methods using a larger data set. This has resulted in a more accurate interpretation of liquefaction hazard within the Western Zone from which TCC can make better informed decisions as part of their ongoing resilience programme.

The analysis undertaken follows the latest recommendations and guidelines specified within MBIE (2017) and the most practical industry accepted methods for assessing liquefaction and lateral spread risk in New Zealand. The 2020 TCC liquefaction study was the first liquefaction risk study in New Zealand, which applies the updated liquefaction guidance from MBIE (2017), while further reducing uncertainty through geomorphological mapping, applying a city-specific probabilistic seismic hazard assessment, and a long-term monitored groundwater table.

This study highlighted that local geological knowledge and understanding of landform is critical to land damage and vulnerability assessment; it removes unnecessary conservatism introduced through quantitative analysis in isolation and provides more realistic expectations of the ground response. In short, the geological input provided the very necessary 'ground truthing' of our numerical liquefaction analysis. By adopting this approach and despite not having the target data density as defined in MBIE (2017) for a Level C assessment, we have been able to arrive at a higher level of detail for our vulnerability mapping. A holistic 'lines of evidence' approach, combining geological understanding with numerical analyses, is recommended for future regional liquefaction studies where investigation data density is unlikely to be available.

Given the high level of computation required, Aurecon's *Quiet Falcon I* tool produced a data-rigorous output while saving the much-needed time required to evaluate all required scenarios for our interpretation.

More details on the specific assessments and the maps can be found in the 2020 Aurecon Report (Aurecon 2020b) on Tauranga City Council's webpage at:

https://www.tauranga.govt.nz/living/natural-hazards/understanding-our-hazards-studies-maps-and-data/earthquakes-and-liquefaction/liquefaction

8 RECOMMENDATIONS FOR FUTURE STUDIES

While this study was one of the first to apply the MBIE (2017) guidelines to a city-wide liquefaction study in a dense urban area with reasonable level of investigation points, we note several improvements could be made for future major natural hazard studies:

- A regional scale long-term groundwater model may not be necessary. However, a generic model could be established through using the hydrogeological relationship with surface-water bodies, in addition to well-bore consent information retained by local governmental authorities.
- To further reduce seismic uncertainty, more detailed Probabilistic Seismic Hazard Assessment will be useful to refine peak ground acceleration models when compared to using the national level seismic assessment e.g. NZS1170, NZTA Bridge Manual Section 6.2.
- A vulnerability assessment based on geomorphic terrains requires the terrain polygons to be finalised prior to commencing quantitative analyses. This will avoid significant geospatial and data management rework where boundaries are at risk of revision later in the project. As detailed by the MBIE (2017) guidance within a Level A assessment, it is crucial to incorporate geomorphology to further reduce any uncertainty established by detailed statistical engineering assessments.
- Within every district or region-wide liquefaction assessment, local experience in the working area should be applied or heavily involved to ensure result validation and provide 'ground truthing' of numerical outputs.
- An external peer review is crucial to ensure a robust methodology is in place prior to beginning the assessment.

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