REPORT

Tonkin+Taylor

Christchurch Liquefaction Vulnerability Study

Prepared for
Christchurch City Council
Prepared by
Tonkin & Taylor Ltd
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Document control

Title: Christchurch Liquefaction Vulnerability Study					
Date	**Version**	**Description**	**Prepared by:**	**Reviewed by:**	**Authorised by:**
Sep-19	1.0	Initial issue	MLO/MEJ	MEJ	PRC
Nov-19	1.1	Minor updates responding to peer review comments	MLO/MEJ	MEJ	PRC
Jul-20	1.2	Updated Section 6 to clarify that new Liquefaction Vulnerability Categories do not supersede existing hazard management maps and processes.	MLO/MEJ	MEJ	PRC

Distribution:

Christchurch City Council	1 PDF copy
Tonkin & Taylor Ltd (FILE)	1 PDF copy

Liquefaction assessment summary

<table>
<tr><td colspan="2">This liquefaction assessment has been undertaken in general accordance with the guidance document ‘Planning and engineering guidance for potentially liquefaction-prone land’ published by the Ministry of Business, Innovation and Employment in 2017.
https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land</td></tr>
<tr><td>Client</td><td>Christchurch City Council (CCC)</td></tr>
<tr><td>Assessment undertaken by</td><td>Tonkin & Taylor Ltd</td></tr>
<tr><td>Report date</td><td>27 July 2020</td></tr>
<tr><td>Extent of the study area</td><td>To the Christchurch City territorial boundary in the east / north / west, and to the top of the Port Hills in the south. Refer to Figure 1.1 in Section 1.</td></tr>
<tr><td>Intended RMA planning and consenting purposes</td><td>• To provide Council with a district-wide liquefaction vulnerability assessment to help inform spatial planning and assessment of land use, subdivision and building consents. Refer to Table 3.2 in Section 3.2.</td></tr>
<tr><td>Other intended purposes</td><td>• To provide Council with an understanding of expected land performance for a range of potential future earthquake and groundwater scenarios.
• Inputs to a public awareness liquefaction hazard web viewer.</td></tr>
<tr><td>Level of detail</td><td>Varies between Level B (calibrated desktop assessment) and Level C (detailed area-wide assessment) depending on available information and uncertainties in the assessment. Refer to Figure 4.15 in Section 4.8.</td></tr>
<tr><td>Notes regarding base information</td><td>The assessment leverages previous high-level work conducted over the study area which includes:
• Geomorphic mapping undertaken by GNS Science.
• Area-wide groundwater models developed by GNS Science and EQC.
• Post-earthquake liquefaction and lateral spreading observations made by EQC.
• Post-earthquake residential building damage observations made by EQC and private insurers.
• Model of shaking intensities during the Canterbury earthquakes developed by the University of Canterbury.
• Geotechnical investigation data available on the NZ Geotechnical Database and Environment Canterbury well records as at July 2019.</td></tr>
<tr><td>Other notes</td><td>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 may be required for some purposes (e.g. for design of building foundations).</td></tr>
</table>

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REPORT BODY

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REFER TO SEPARATE PDF FILE FOR REPORT APPENDICES

1 Introduction

Tonkin & Taylor Ltd (T+T) has been engaged by Christchurch City Council (CCC) to provide a technical review of information relevant to the liquefaction hazard in Christchurch, and from this information develop a broad-scale liquefaction vulnerability model to help inform various future activities.

The liquefaction vulnerability model has been calibrated against observations from the Canterbury earthquakes and has been developed in general accordance with the guidance document ‘Planning and engineering guidance for potentially liquefaction-prone land’ published by the Ministry of Business, Innovation and Employment (MBIE/MfE 2017).

The model provides a risk-based estimate of how the liquefaction vulnerability varies across the study area, which is defined by the territorial authority boundary that encompasses Christchurch City to the east / north / west and to the top of the Port Hills in the south. The area covers approximately 46,000 hectares of land and consists of residential, commercial, industrial, recreational, and rural areas. The extent of the study area is illustrated in Figure 1.1.

While excluded from the current study area, there are some locations around Lyttelton Harbour and across Banks Peninsula where the land is potentially liquefaction-prone (e.g. valley floors around the heads of the bays). For information about liquefaction vulnerability in parts of eastern Canterbury outside the current study area refer to Brackley (2012).

This report includes:

- The context in which the model has been developed and the intended purposes for which it should be used.
- A summary of previously-collated information about the liquefaction hazard across the study area.
- Previously-collated information about the geological, groundwater, and seismic conditions for the study area.
- The delineation of the study area into zones of similar expected ground performance.
- The groundwater levels and earthquake scenarios assessed in order to develop the model.
- The determination of the expected degree of liquefaction-induced ground damage for the chosen groundwater levels and earthquake scenarios.
- Liquefaction vulnerability measured against the performance criteria in MBIE/MfE (2017).

The liquefaction vulnerability assessment and the layout of this report follows the risk management process recommended in ISO 31000:2018, as shown in Figure 1.2.

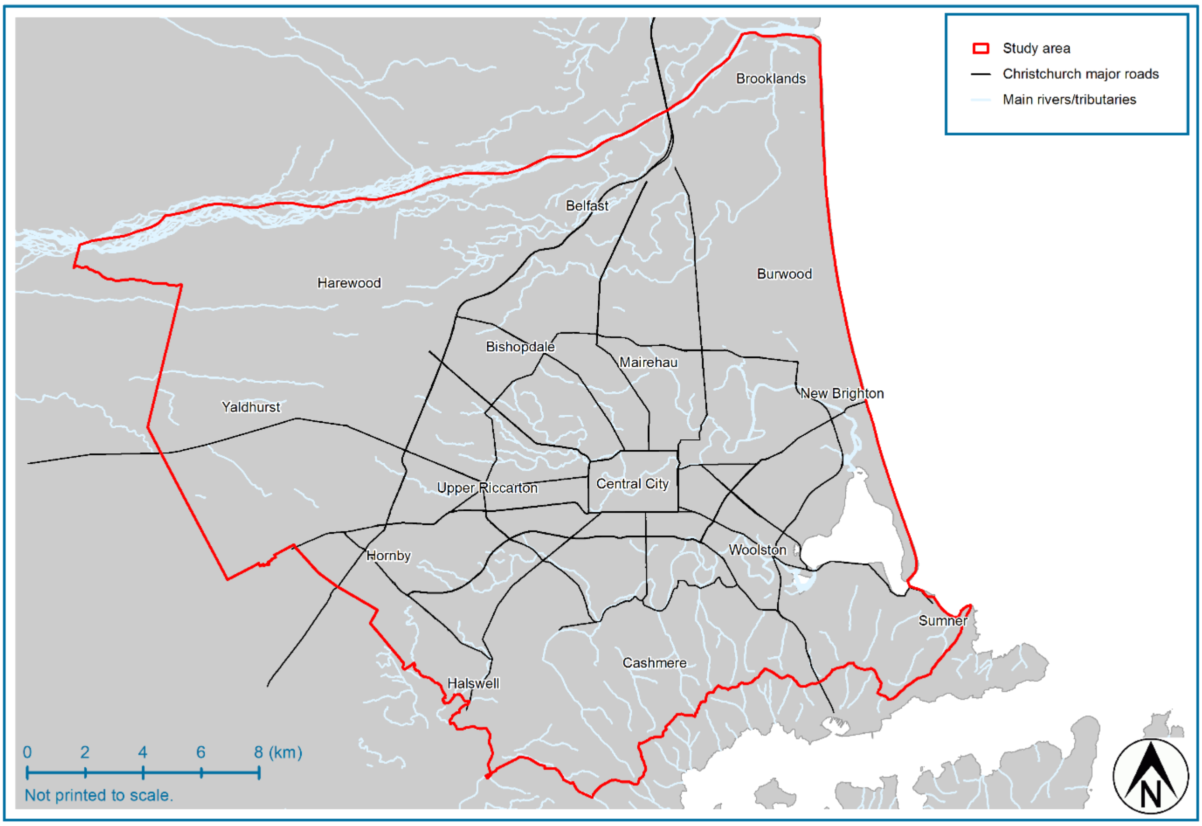


Figure 1.1: Extent of the study area for the liquefaction vulnerability assessment.

Figure 1.2: Risk management process defined in ISO 31000:2018, which has been used to guide the liquefaction vulnerability assessment and the layout of this report.

2 Context

2.1 Background

The objective of this study is to identify potentially liquefaction-prone land across Christchurch City, and to quantify the severity of liquefaction-induced ground damage that could occur across a range of shaking intensities and groundwater levels in future earthquake events. The outcomes of the study are primarily intended to support public awareness, land use planning and development decision-making, however this information may also be of use in other contexts (if the limitations of using the results beyond the intended purpose are understood).

There is already a substantial amount of previous information regarding the liquefaction hazard in Christchurch, and at a broad scale, the results of this current study generally align with what was previously known. This study seeks to make incremental improvements to the previous understanding of liquefaction vulnerability by:

- Analysing the extensive collection of ground investigation data now available on the New Zealand Geotechnical Database.
- Using observations of land damage caused by the Canterbury earthquakes to help calibrate analytical predictions of land damage.
- Drawing on improved scientific understanding for analysis of liquefaction triggering and the resulting consequences.
- Utilising the improved geomorphic map and groundwater model now available for Christchurch to better delineate areas of similar expected land performance.
- Providing spatial coverage of the entire flat-land extent of the Christchurch City territorial land area.
- Using the consistent national framework of MBIE/MfE (2017) to standardise the assessment methodology and how results and uncertainties are communicated.

This updated liquefaction assessment responds to two important changes in how liquefaction hazard is managed across all New Zealand:

- In 2017 the government released “Planning and engineering guidance for potentially liquefaction-prone land” (MBIE/MfE, 2017). The guidance established a nationwide framework for how liquefaction is assessed, so that efficient consenting and building solutions could be developed.
- This will be followed in November 2021 with changes to the Building Code which mean that councils will need to understand the liquefaction hazard for every site before a building consent can be issued.

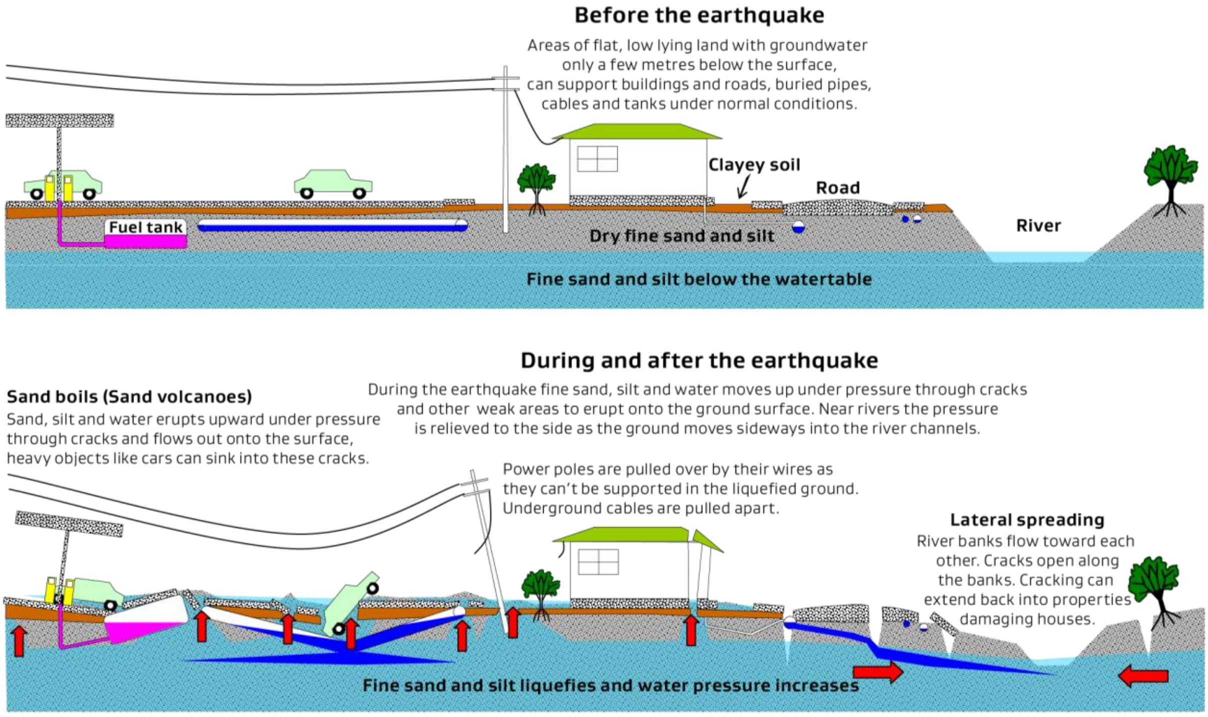
The underlying objective of both these changes is that buildings and infrastructure are located and built with appropriate consideration of the land conditions.

2.2 Liquefaction hazard

Liquefaction is a natural process where earthquake shaking increases the water pressure in the ground in some types of saturated soil, resulting in temporary loss of soil strength. Liquefaction can cause significant damage to land, buildings and infrastructure (e.g. through the ejection of sediment to the ground surface, ground settlement, and lateral spreading). For a more detailed explanation of the liquefaction process and the resulting consequences, refer to MBIE/MfE (2017).

When liquefaction is triggered, a wide range of potential consequences can result, as summarised in Figure 2.1 and Table 2.1. The analysis undertaken for this study took into account a range of factors which can influence the severity of these consequences at any particular location, such as:

- **Strength of earthquake shaking.** Stronger shaking can mean that a greater thickness of the soil profile liquefies, resulting in more severe consequences.
- **Depth to groundwater.** Soil can only liquefy if it is saturated (below the groundwater table). So deeper groundwater can mean there is a thicker surface “crust” of unsaturated, non-liquefied soil at the ground surface that helps to reduce the consequences from liquefaction below.
- **Strength of surface “crust”.** If the surface “crust” of non-liquefiable soil is formed of strong material (e.g. gravel) then this can also help to reduce the consequences from liquefaction below.
- **Layering of the soil profile.** The way in which a soil was deposited (e.g. by a river, an estuary, or the sea) can influence how the soil profile is layered. If there are thick continuous layers of liquefied soil then this can have more severe consequences than if there are thinner isolated layers of liquefied soil interbedded between layers of non-liquefied soil.



Areas of flat, low lying land with groundwater only a few metres below the surface, can support buildings and roads, buried pipes, cables and tanks under normal conditions.

Sand, silt and water erupts upward under pressure through cracks and flows out onto the surface, heavy objects like cars can sink into these cracks.

During the earthquake fine sand, silt and water moves up under pressure through cracks and other weak areas to erupt onto the ground surface. Near rivers the pressure is relieved to the side as the ground moves sideways into the river channels.

Power poles are pulled over by their wires as they can’t be supported in the liquefied ground. Underground cables are pulled apart.

River banks flow toward each other. Cracks open along the banks. Cracking can extend back into properties damaging houses.

Tanks and pipes float up in the liquefied ground and break through the surface, pipes break, water and sewerage leaks into the ground.

Figure 2.1: Typical consequences of liquefaction (reproduced from MBIE/MfE (2017) / IPENZ).

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

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

2.3 Purposes for which liquefaction information is used

Information about liquefaction-related risk is used in a wide variety of ways, including a range of policy, planning and consenting processes. The relevant context for these purposes is summarised below, with Section 3.2 providing further detail regarding the degree to which the liquefaction assessment presented in this report is intended to inform specific activities.

2.3.1 Regional strategy

The Greater Christchurch Urban Development Strategy includes a strategic goal regarding integrated and managed urban development. A desired outcome is that we understand and plan for risk from natural and other hazards, including flooding, seismic activity, sea level rise and climate change.

2.3.2 Regional policy

Chapter 6 of the Canterbury Regional Policy Statement addresses land use and development for the recovery of Greater Christchurch following the Canterbury Earthquakes. District plans need to give effect to this policy statement, and there is also a requirement to have regard to it when considering resource consents.

The policy statement includes a map showing priority areas for development for Greater Christchurch out to 2028, including greenfield priority areas for business and residential development and infrastructure servicing. This emphasises the intention to consolidate and intensify urban areas. Within Christchurch City, greenfield land identified for future housing and business is mainly in the northern and southwest areas, and minimum development densities are stipulated.

Chapter 11 promotes a risk-based approach for natural hazard management, whereby zones of liquefaction and lateral spreading hazard are identified where site-specific investigations are required. Environment Canterbury seeks to assist territorial authorities to delineate these zones. Development is then to be managed according to the likelihood of liquefaction or lateral spreading, as well as the type of development proposed for the site and possible mitigation options.

The regional policy statement requires that territorial authorities:

- Manage new subdivision, use and development of land in areas known to be potentially susceptible to liquefaction and lateral spreading.
- Ensure that the risk of liquefaction and lateral spreading hazards are assessed before any new areas are zoned or identified (in a district plan) in ways that enable intensification of use, or where development is likely to be damaged and/or cause adverse effects on the environment.
- Supply information to the Regional Council captured at time of subdivision in relation to areas susceptible to liquefaction and lateral spreading.

2.3.3 Regional plan

The Canterbury Land and Water Regional Plan notes that natural hazards arise where natural processes or events impact the use of an area. The plan acknowledges that these uses are important but when people locate themselves, their property, infrastructure, and their activities in these areas they can be subject to loss or damage from natural events.

The plan warns that sometimes our activities increase the likelihood of natural processes being triggered (e.g. excavation of a stormwater basin could allow lateral spreading to occur in an earthquake), and that some areas of land are more prone to the effects of seismic activity. It concludes that promoting the sustainable management of natural and physical resources requires managing the natural hazard risk to an acceptable level.

The plan notes that with regard to natural hazards, councils have a role in:

- Managing natural hazards by controlling activities that may exacerbate the risk.
- Emergency response following a natural hazard event.
- Aiding recovery following a natural hazard event by enabling required activities to occur.

The plan observes that the Canterbury earthquakes had significant social, economic, infrastructural, environmental and cultural impacts. Damage to natural and physical resources included substantial destruction of buildings, damage to infrastructure and services, and widespread land damage. The effects of the seismic activity on land and water has included the re-emergence of springs, sedimentation from liquefaction processes, land subsidence and changes to bed levels and banks of water bodies.

2.3.4 District plan

Chapter 3 (Strategic Directions) of the Christchurch District Plan outlines three objectives where liquefaction could be a relevant factor, as summarised below.

- Housing capacity and choice:
  - A target of at least 55,950 additional dwellings by 2048.
  - A combination of residential intensification, brownfield and greenfield development.
  - A range of housing types, densities and locations.
- Natural hazards:
  - New subdivision, use and development ensures the risks of natural hazards to people, property and infrastructure are appropriately mitigated.
  - New critical/strategic infrastructure may be located in hazard areas if there is no reasonable alternative, and it is designed to maintain its integrity and mitigate risks.
  - There is increased public awareness of the range and scale of natural hazard events that can affect Christchurch District.
- Urban growth, form and design:
  - Provide for urban activities only within the existing urban areas and identified greenfield priority areas.
  - Increased housing development in the urban area to meet intensification targets for the Central City, activity centres, larger neighbourhood centres, core transport nodes, greenfield priority areas and suitable brownfield areas.
  - Support redevelopment of brownfield sites.
  - Promote the safe, efficient and effective provision and use of infrastructure.

Chapter 5 (Natural Hazards) takes a risk-based approach, taking into account the scale, likelihood and consequences of a natural hazard event. For assessment of liquefaction, no specific measure of risk is applied, instead areas are mapped where liquefaction is more likely to occur than not. Within that area, liquefaction-related risk and appropriate mitigation is to be assessed on a site-specific basis using best practice geotechnical and engineering methods to determine the performance of infrastructure and buildings.

The level of control over activities in the district plan is related to the consequence of the natural hazards and whether the risks are considered acceptable or not. Where risk is able to be managed to reduce it to acceptable levels, Council may require assessment and mitigation in relation to potential effects.

The plan outlines several policies where liquefaction is relevant:

- Manage activities in all areas subject to natural hazards in a manner that is commensurate with the likelihood and consequences of a natural hazard event on life and property.
- Avoid locating new critical infrastructure where it is at risk of being significantly affected by a natural hazard unless there is no reasonable alternative. Enable critical infrastructure to be designed, maintained and managed to function to the extent practicable during and after natural hazard events.
- Ensure people are informed about the natural hazards relating to their properties and surrounding area, including through provision of relevant information on Land Information Memoranda and hazard mapping on the Council's website.
- Ensure that the level of assessment undertaken for plan changes, subdivision or development reflects the potential scale and significance of the hazard; and the nature and scale of the rezoning, subdivision or development and its susceptibility to those hazards.
- Map the Liquefaction Management Area based on a district-wide assessment of where damaging liquefaction is more likely to occur. Provide for rezoning, subdivision, use and development on flat land where liquefaction risk has been appropriately identified and assessed, and can be adequately remedied or mitigated.

The plan rules apply controlled activity status to subdivision, or restricted activity status for any activities on larger sites where other development controls apply. Similar assessment matters apply for both:

- Whether proposed remediation/mitigation techniques are appropriate, including ground strengthening, foundation design, resilient services and setbacks from free faces (or alternative solutions to address lateral spread).
- The layout of the subdivision in relation to the liquefaction hazard, including location of earthworks, roads, access, servicing and building platforms.
- The effect of remediation/mitigation on the reasonable use of the site.

The natural hazards provisions of the plan were updated following the Canterbury earthquakes, with review by the independent hearings panel between 2015 and 2017. Whilst this update is relatively recent, it was undertaken with some urgency to provide for post-earthquake recovery so took a pragmatic approach to natural hazard management based on the technical information readily available at the time. With improvements in the technical information now available, CCC has identified an opportunity to refine the liquefaction-related provisions as a priority in future plan review.

2.3.5 Plan change

Strategic spatial planning undertaken as part of the Greater Christchurch Urban Development Strategy and Greater Christchurch Settlement Pattern Update (Our Space 2018-2048) has now been implemented via the regional policy statement and district plan land use zonings for priority areas. This means that large-scale changes in land use zonings for spatial planning are unlikely to be needed in the immediate future to accommodate growth, but smaller-scale plan changes might still be proposed.

To meet the objectives of the regional policy and district plan, any significant changes to land use zoning would need to consider whether liquefaction is likely to occur, and if so then how this could be managed. In some cases existing hazard information (such as the mapped Liquefaction Management Area) may be sufficient to assess proposed plan changes, but in some cases (particularly where *Liquefaction Damage is Possible*) more detailed assessment of liquefaction-related risk may be required.

2.3.6 Land use consent and subdivision consent

As outlined in Section 2.3.4, the district plan applies controlled/restricted status to various land use and subdivision activities, with assessment matters that allow liquefaction-related risk and proposed remediation/mitigation options to be taken into account when deciding whether to approve consent or what conditions apply.

At the present time, substantial reliance is placed on Part D of the MBIE Canterbury guidance MBIE (2015) when assessing liquefaction-related risk for proposed subdivision of land. This provides recommendations for ground investigation and liquefaction assessment to broadly categorise the liquefaction characteristics of the land. It notes that information from deep subsurface investigations (e.g. to 15m depth) will be required to adequately characterise the ground conditions, unless it can be shown that the ground is of acceptable quality from shallower depths. This could be the case in areas known to be underlain by competent gravels and deep groundwater profiles, or in hillside areas. A useful reference here is the mapping of liquefaction observations and vulnerability assessment in Brackley (2012).

Part D of the MBIE guidance strongly recommended that residential lots in new subdivisions meet the performance criteria specified for TC1 or TC2. This appears to have become a de-facto minimum standard across much of the local residential land development market, with concerns regarding consenting, construction cost and market appeal if new residential lots were to be provided at TC3-equivalent performance levels.

2.3.7 Building consent

The extensive damage caused to buildings as a result of liquefaction during the Canterbury earthquakes highlighted the importance of providing foundations which are appropriate for the land conditions at a site. Following the Canterbury earthquakes, the Building Code was updated to exclude liquefaction-prone land (in the Canterbury earthquake region only) from the definition of “good ground” in acceptable solution B1/AS1.

To avoid a situation where a geotechnical report might be required to support every building consent for repair/rebuilding of damaged homes regardless of the actual liquefaction vulnerability, MBIE (2015) provided guidance for assessment/repair of existing foundations and construction of new foundations. This included a map delineating three “Technical Categories” which corresponded to the level of geotechnical assessment recommended as part of post-earthquake repair and rebuilding. These categories only applied to residential land (as at 2010) in the main urban areas – rural and non-residential land was not assigned a category.

The MBIE (2015) guidance also included potential options for repaired and new foundations for each of the Technical Categories (TC’s). For TC1 and TC2 these foundations were intended for use “off the shelf” without any specialist geotechnical input or deep ground investigations. For TC3, foundation requirements are strongly dependant on the particular ground conditions, so specialist geotechnical engineering input and subsurface ground investigation information was required to select and design the appropriate foundation solution for the specific site and building characteristics.

At the present time, assessment of building consents relating to residential foundation work in existing urban areas relies heavily on the MBIE Technical Category map to assess whether the ground is liquefaction-prone, and to confirm that proposed foundation details are appropriate. Where the land was not assigned a TC by MBIE (e.g. commercial/industrial or newly-developed residential land) geotechnical engineering input is typically required to assess the ground conditions and design appropriate foundations – although in many cases the engineer might recommend adopting one of the standard MBIE foundation options.

2.4 Previous information about the liquefaction hazard in Christchurch

Over the past three decades, a number of liquefaction hazard maps have been produced for Christchurch city. Whilst the information used to compile these maps was less detailed than what is available today, these maps still provide a useful summary of the knowledge about Christchurch ground conditions that has been collated over time. Key maps from these previous studies are presented below, along with a brief summary of the key features.

1991: The earthquake hazard in Christchurch

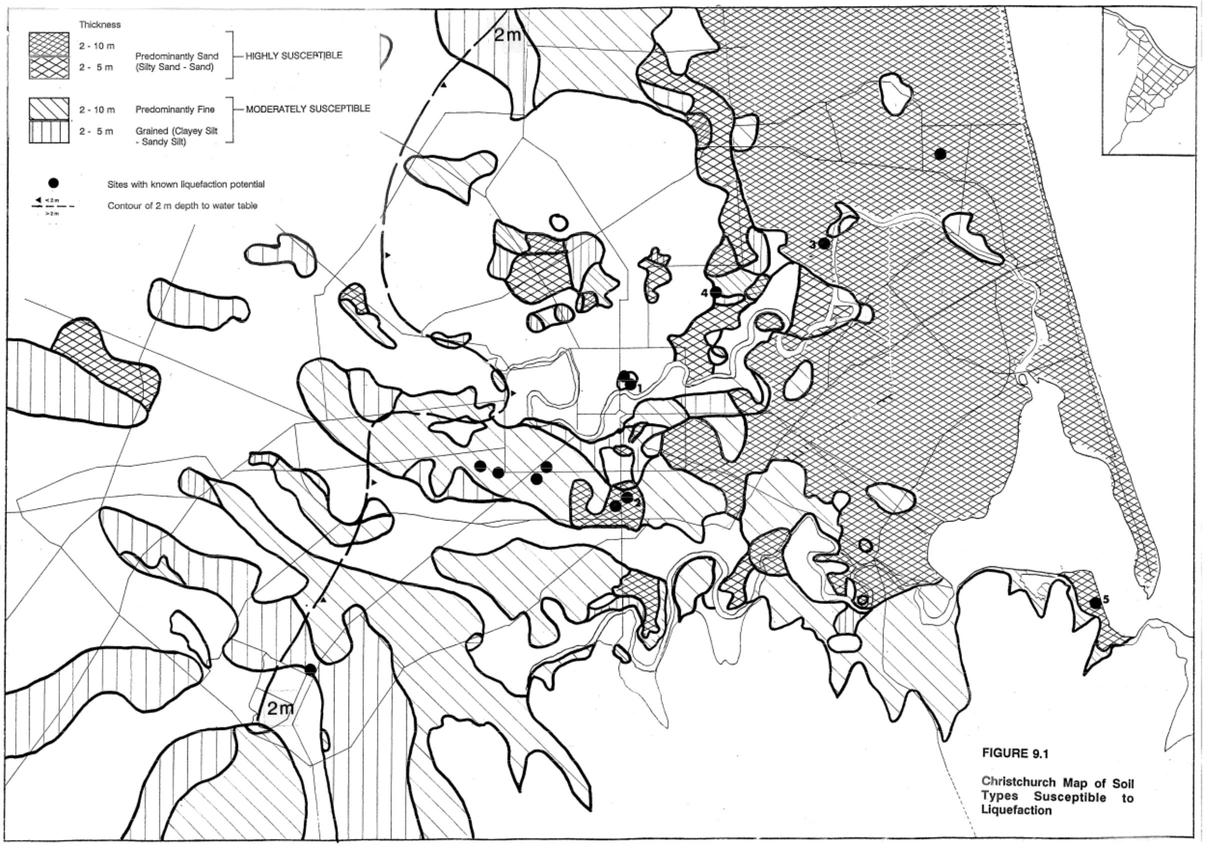


Figure 2.2: This map from 1991 identified locations of soils susceptible to liquefaction, characterised by the soil type and thickness of liquefiable soils, and included information about groundwater depth (Elder et al., 1991).

1992: Geology of the Christchurch urban area

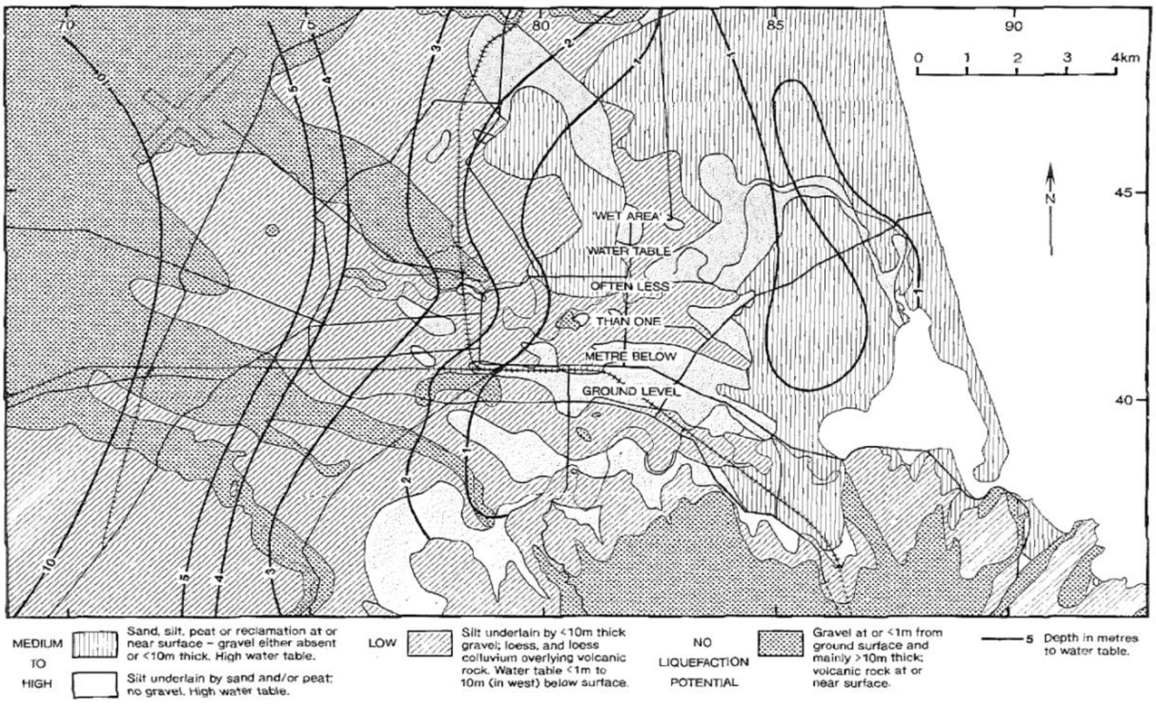


Figure 2.3: This map from 1992 identifies soil types susceptible to liquefaction and groundwater depth (Brown & Weeber, 1992).

1997: Risks & Realities

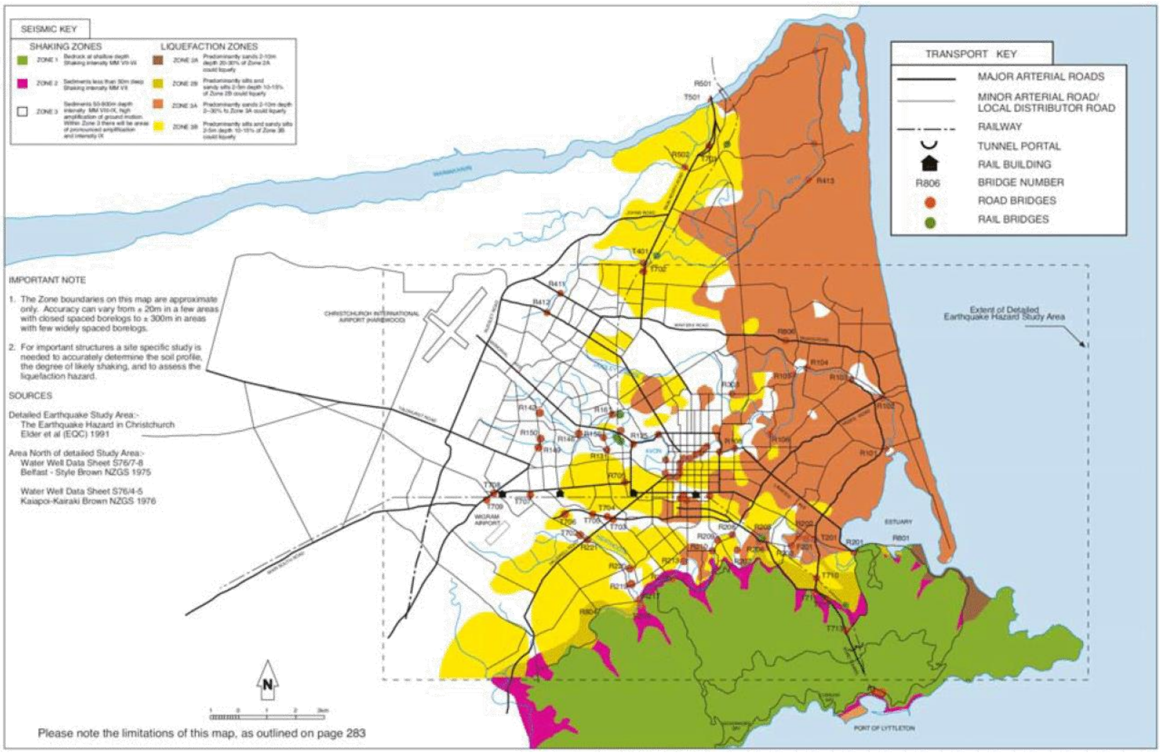


Figure 2.4: This map from 1997 assessed the vulnerability of lifelines to liquefaction-induced damage. It identified soil types susceptible to liquefaction, the general soil profile, and groundwater depth. Spatial variability in damage across an area was communicated by expressing damage severity as the proportion of an area affected (Lamb, 1997).

2005: Environment Canterbury - The solid facts on liquefaction

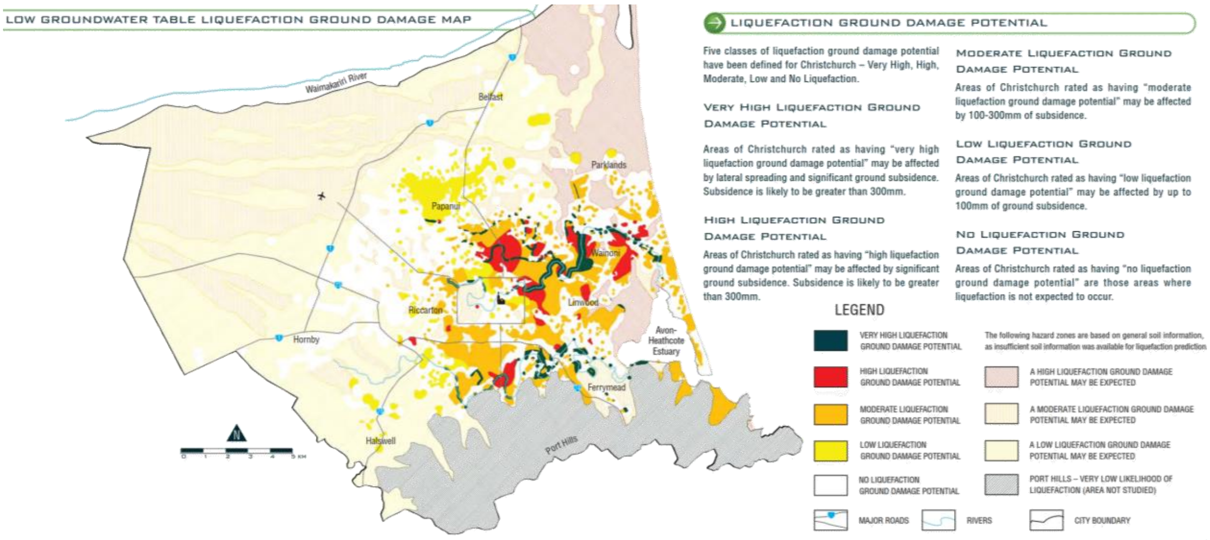


Figure 2.5: This map from 2005 is part of series of maps that explored liquefaction susceptibility and ground damage for a range of earthquake and groundwater scenarios, including impacts from lateral spreading Beca (2005).

2011: MBIE guidance for repairing and rebuilding houses affected by the Canterbury earthquakes

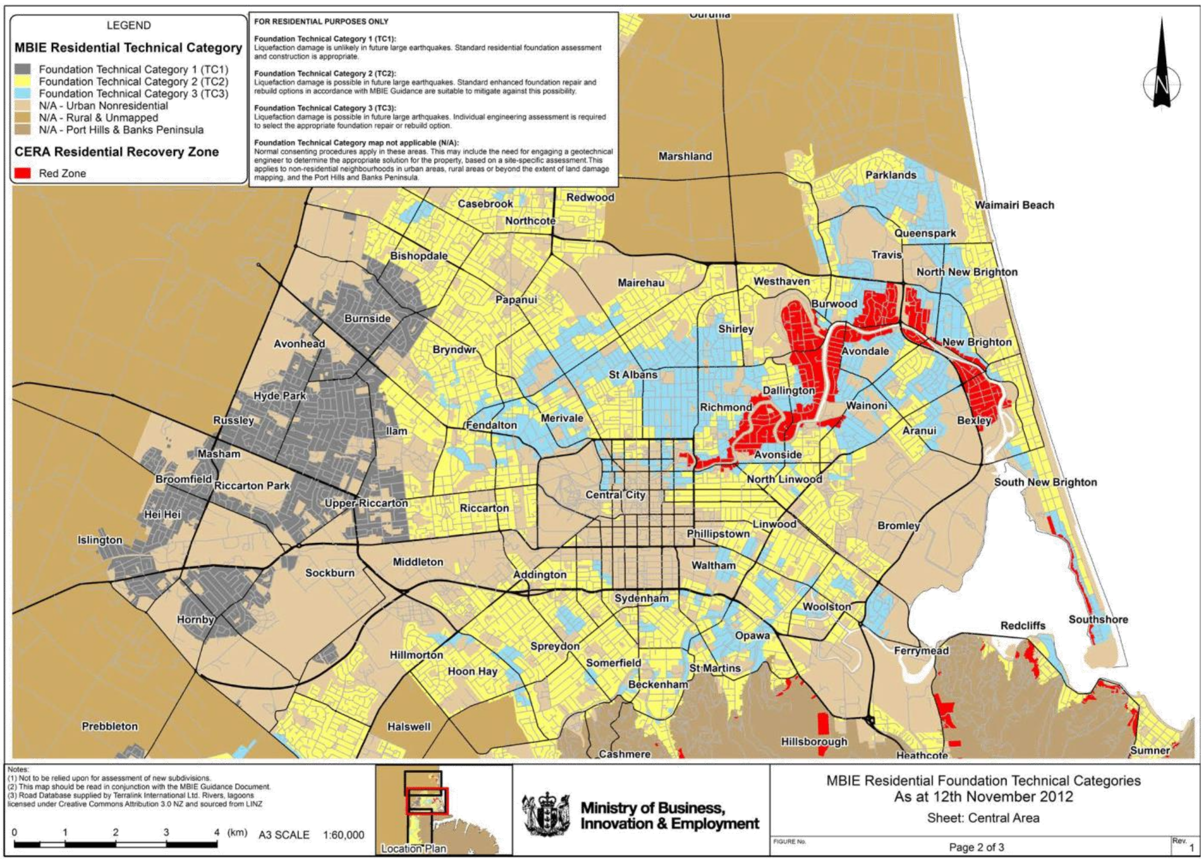


Figure 2.6: This map from 2011 (updated in 2012) shows Foundation Technical Categories assigned by MBIE, based on liquefaction observed during the Canterbury earthquakes and future performance expectations. This provided an indication of what geotechnical assessments were recommended as part of post-earthquake repair and rebuilding, and was not intended to be a comprehensive liquefaction hazard map. Source: MBIE (2015).

2012: Environment Canterbury - Review of liquefaction hazard information in eastern Canterbury

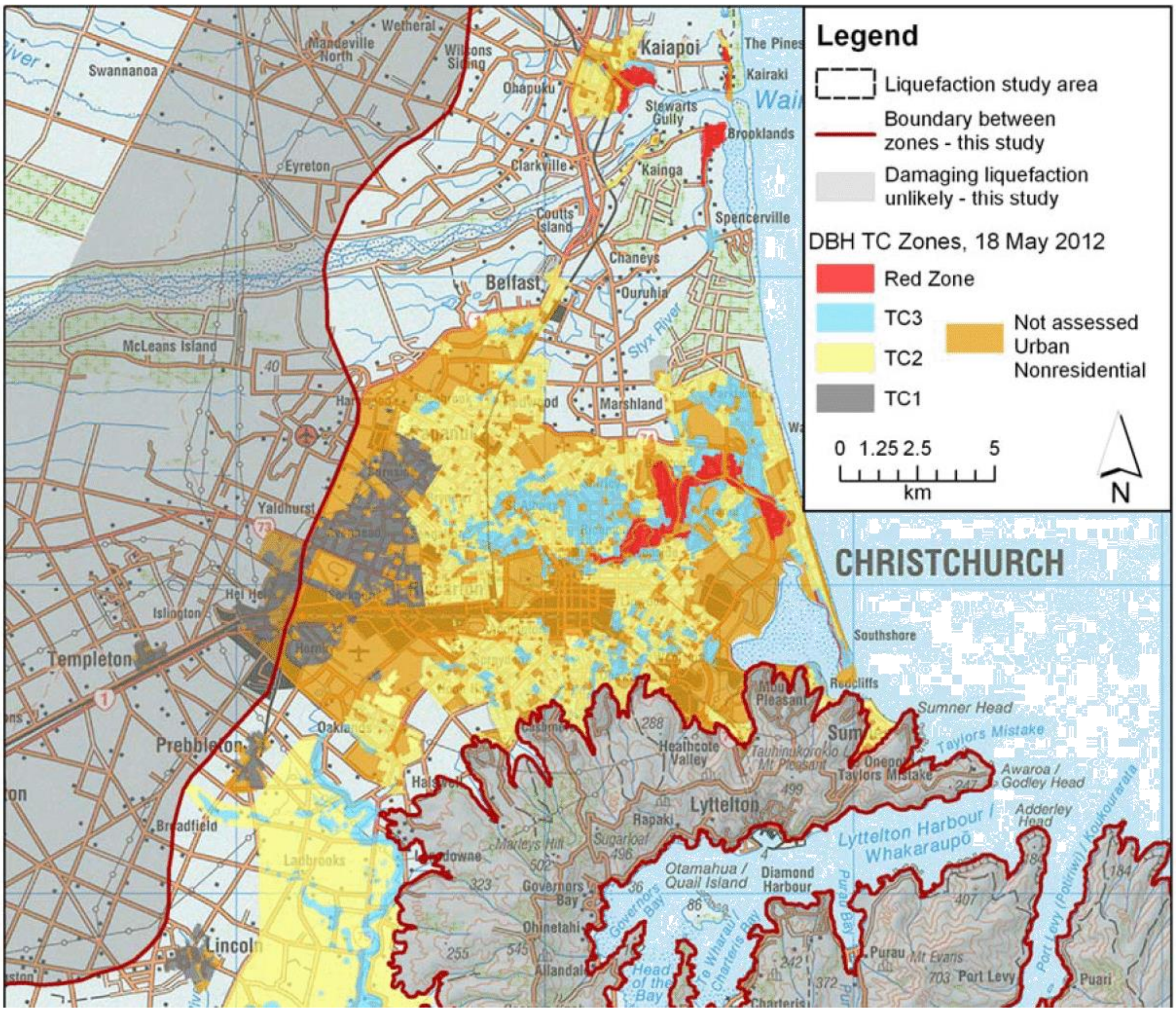


Figure 2.7: This map focused on identifying the area to the west of the city and across Banks Peninsula where damaging liquefaction is unlikely (Brackley, 2012).

3 Risk identification

3.1 The level of detail hierarchy

The MBIE/MfE (2017) guidance establishes a hierarchy for benchmarking the level of detail that a liquefaction assessment is undertaken at, from the least detailed assessment (Level A) to the most detailed (Level D). As summarised in Figure 3.1, more detailed information and assessment typically reduces the residual uncertainty(1) regarding the level of liquefaction-related risk and the delineation of boundaries between different areas.

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

Increasing level of detail and decreasing degree of uncertainty

Figure 3.1: Levels of detail for liquefaction assessment studies (reproduced from MBIE/MfE, 2017).

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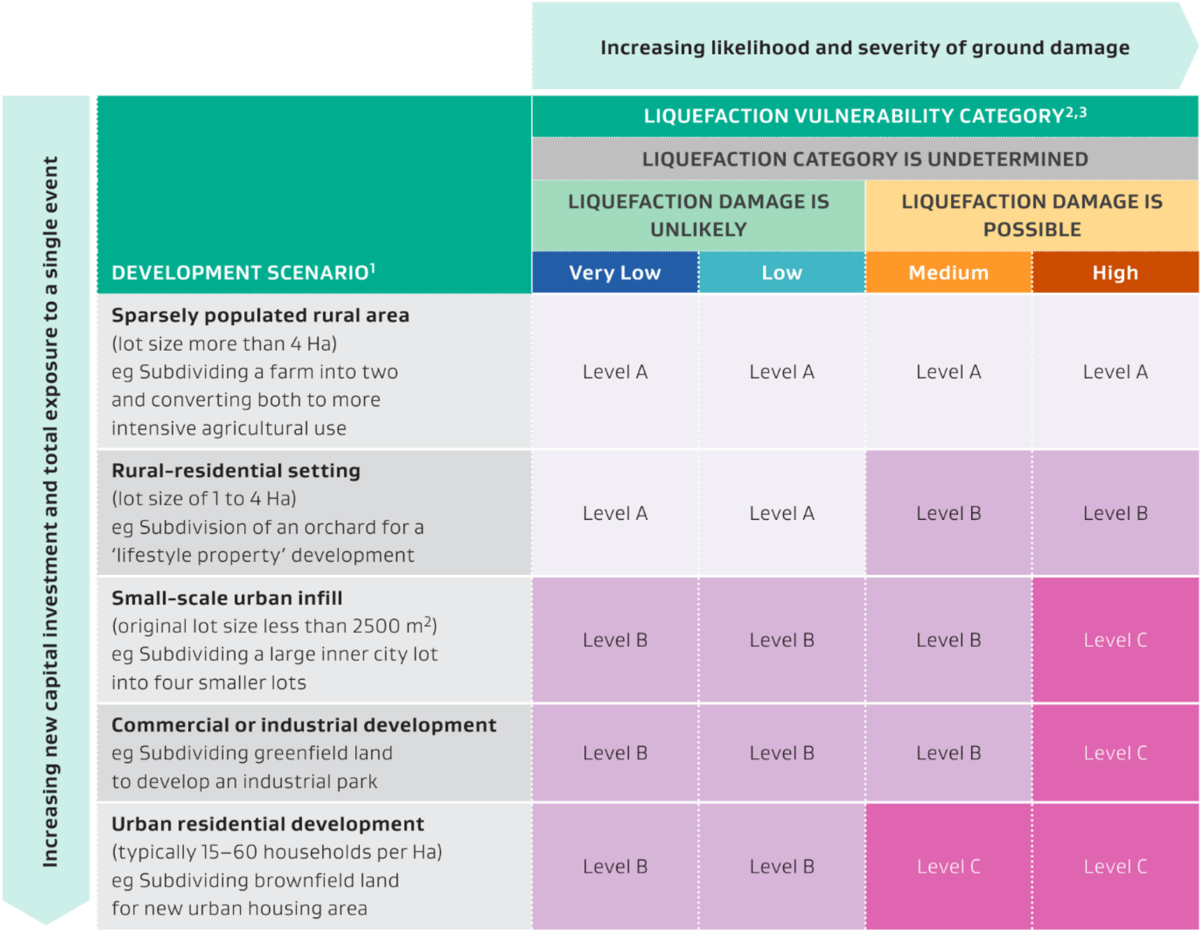
(1) The uncertainty which remains after the available information has been analysed.

3.2 Level of detail required for intended purposes

The first step in the risk identification process is to determine the level of detail that is required to satisfy the intended purposes of the liquefaction assessment information. The level of detail required can vary spatially across an area and change over time, and is related to the context (as outlined in Section 2) and the purposes for which the information will be used. Situations where greater certainty and higher resolution is required (e.g. for consenting of individual properties) require a greater level of detail in the liquefaction assessment than purposes where uncertainty can be more readily accommodated (e.g. setting broad objectives for managing natural hazards across a region).

MBIE/MfE (2017) provides guidance on the minimum level of detail likely to be appropriate for a liquefaction assessment, depending on the intended purpose, likelihood/severity of ground damage and the development intensity. Figure 3.2 shows an example of how the guidance focusses assessment effort where it can be of most use – similar tables are provided for various purposes ranging from regional policy down to building consent.



DEVELOPMENT SCENARIO[1]	LIQUEFACTION VULNERABILITY CATEGORY[2,3]			
	LIQUEFACTION CATEGORY IS UNDETERMINED			
	LIQUEFACTION DAMAGE IS UNLIKELY		LIQUEFACTION DAMAGE IS POSSIBLE	
	Very Low	Low	Medium	High
Sparsely populated rural area (lot size more than 4 Ha) eg Subdividing a farm into two and converting both to more intensive agricultural use	Level A	Level A	Level A	Level A
Rural-residential setting (lot size of 1 to 4 Ha) eg Subdivision of an orchard for a 'lifestyle property' development	Level A	Level A	Level B	Level B
Small-scale urban infill (original lot size less than 2500 m^2) eg Subdividing a large inner city lot into four smaller lots	Level B	Level B	Level B	Level C
Commercial or industrial development eg Subdividing greenfield land to develop an industrial park	Level B	Level B	Level B	Level C
Urban residential development (typically 15–60 households per Ha) eg Subdividing brownfield land for new urban housing area	Level B	Level B	Level C	Level C

Figure 3.2: Example matrix for determining minimum level of detail in the liquefaction assessment required for land use or subdivision consent (reproduced from MBIE/MfE, 2017).

The liquefaction assessment presented in this report is intended to help inform a range of policy, planning and consenting processes, as well as to provide general information for public awareness. These purposes are summarised in Table 3.1 below, along with the corresponding minimum level of detail recommended in MBIE/MfE (2017). It is emphasised the current study is not intended to necessarily provide the full detail required for these purposes (e.g. it would be unrealistic for this study to aim to provide Level D information for building consent purposes for every site in Christchurch). Rather, this table shows the minimum level of detail likely to be needed eventually (e.g. by resource or building consent applicants) to support particular activities.

Table 3.2 identifies the level of detail that this liquefaction assessment study would ideally achieve to usefully inform various activities at a broad scale across Christchurch city. Figures 3.3 and 3.4 summarise how this ideal level of detail varies spatially across the city, depending on the context (inferred from district plan zoning) and the likely ground conditions (inferred from Brackley 2012).

Table 3.1: Minimum level of detail required for various purposes across Christchurch city.

Purpose	**Minimum level of detail likely to be required eventually** *(e.g. by consent applicants, not necessarily in the current study)*
Regional policy Regional plan Strategy & policy development	Level A, however Level B may offer significant reduction in uncertainty, and thus better-informed decision-making, with only minor additional effort.
District plan Plan change Strategy & policy development	Level B in urban flatland areas. Level A in hill or rural areas.
Land use resource consent Subdivision resource consent	Level C in urban flatland areas. Level B in hill or rural areas.
Building consent	Level varies depending on vulnerability and development scenario. Refer to Table 3.7 of MBIE/MfE (2017). Typically Level C or D for flatland urban areas.
Public awareness Emergency preparedness and emergency management	Level A, however Level B may offer significant reduction in uncertainty, and thus better-informed decision-making, with only minor additional effort.

Table 3.2: **Level of detail this study would ideally achieve to usefully inform selected activities.**

Christchurch district plan zone	**Activities that this study aims to inform**	**Level of detail for this study to usefully inform these activities** *(More detail may be required eventually - e.g. by consent applicants)*	
		Where liquefaction damage is unlikely	***Where liquefaction damage is possible***
Residential new neighbourhood	Subdivision consent for new urban residential development.	Level B	Level C
Residential medium density and central city	Subdivision consent for small-scale urban infill.	Level B	Level C (or Level B if medium vulnerability confirmed).
All other residential	No specific activities, provide general information.	Level B	Level C (or Level B if medium vulnerability confirmed).
Rural urban fringe	Strategic regional and district spatial planning. Plan change for future development.	Level B	Level B
All other rural	Land use consent.	Level A	Level B
Commercial and industrial	Land use consent, subdivision consent.	Level B	Level C (or Level B if medium vulnerability confirmed).
Open space	Land use consent for maintenance and low intensity development.	Level A	Level B
All other zones	No specific activities, provide general information.	Level A	Level B

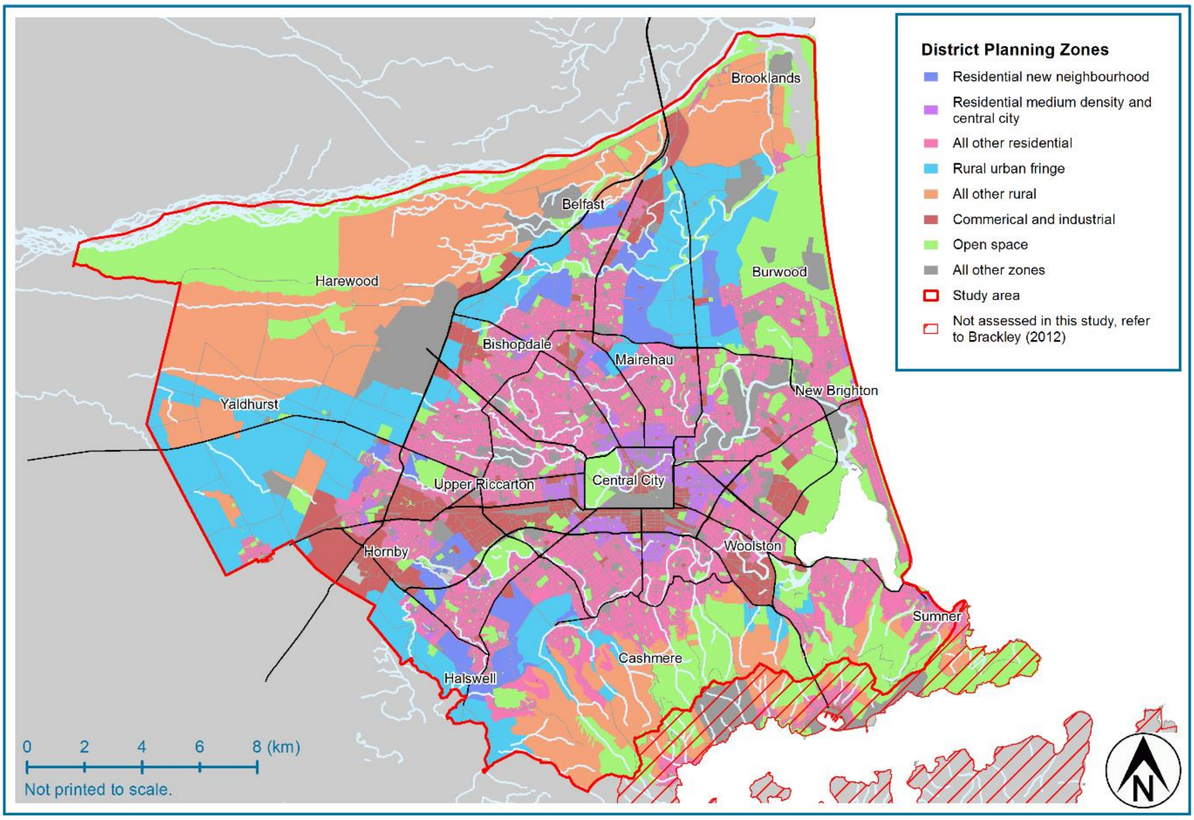


Figure 3.3: Spatial summary of land use planning zones defined in the Christchurch district plan. Refer to Appendix A for larger map.

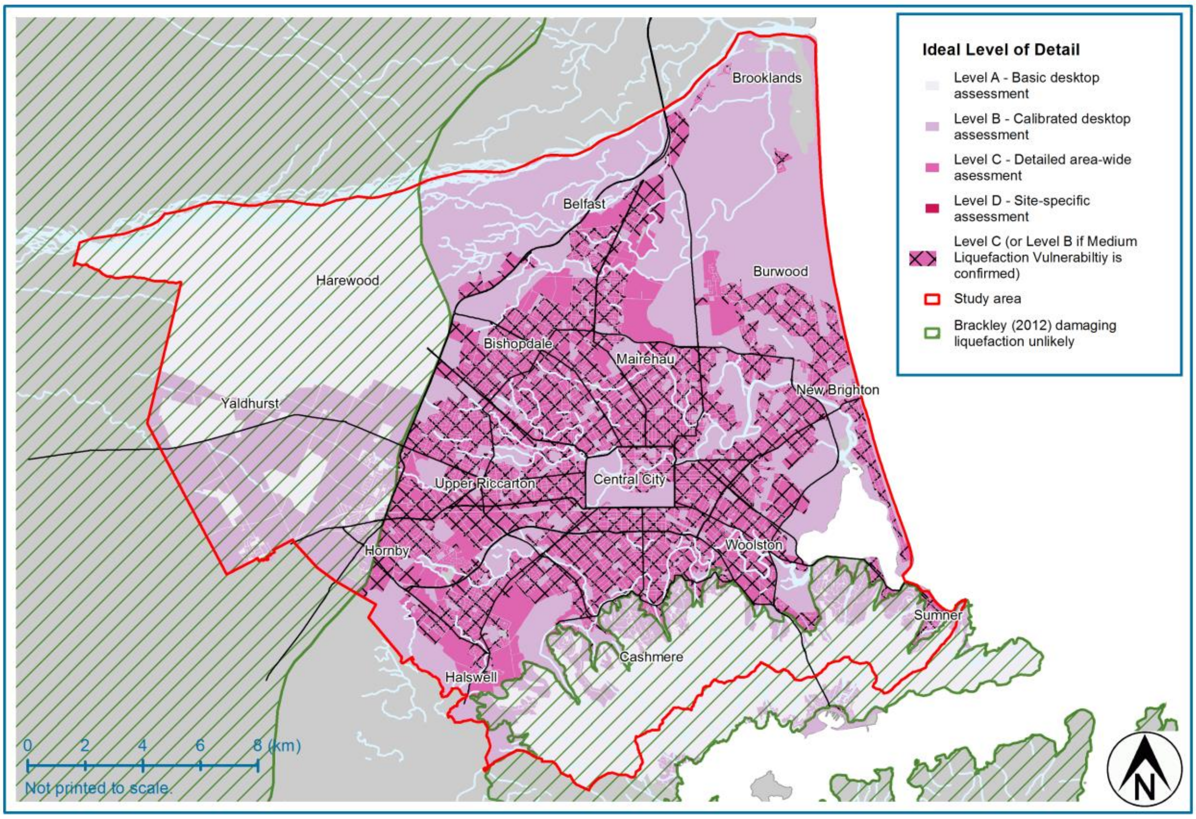


Figure 3.4: Level of detail that this study would ideally achieve to inform selected activities. Refer to Appendix A for larger map.

3.3 Base information currently available

This study is a regional-scale desktop assessment based on the available pre-existing information. A liquefaction assessment of this scale would typically only be able to achieve a low level of detail (e.g. Level A or B) due to limited information and substantial uncertainty in seismic land performance. However, the detailed observations of land performance in the Canterbury earthquakes and the extensive ground investigations subsequently undertaken mean that a more detailed assessment (e.g. Level C) can be achieved across much of Christchurch city.

The following sections summarise the base information that has been considered as part of this liquefaction hazard study.

3.3.1 Geology and geomorphology

The *Geology of Christchurch Urban Area* by Brown & Weeber (1992) provides a comprehensive description of the geological history and formation of the Christchurch area. The interacting geological processes that have influenced deposition of soils across the Canterbury plains include:

- Continuous changes in the direction and size of the braided river systems in the area, primarily the Waimakariri River, as illustrated in Figure 3.5.
- Progressive sea level raising and lowering.
- Tectonic uplift of the Southern Alps.
- Climatic changes and influences.

The interaction of these processes over time has resulted in the formation of complex geological deposits where the characteristics of the ground can vary significantly over short distances. The depositional processes that have influenced the near-surface soils across the study area can be broadly grouped into three main geomorphic categories as shown in Figure 3.6.

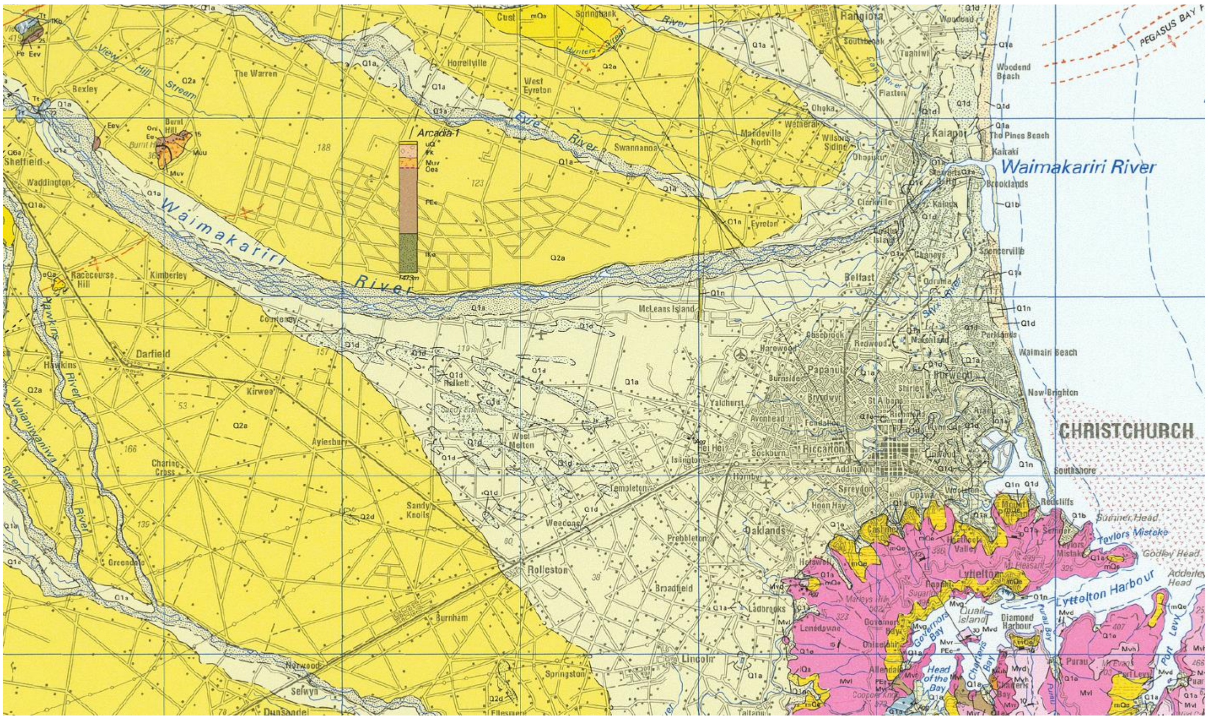


Figure 3.5: Geological map of the Canterbury area (reproduced from Forsyth, Barrell, & Jongens (2008). The light yellow shading across the eastern plains represents Holocene (less than 11,000 years old) river, fan, dune, swamp and coastal deposits. The darker yellow shading to the west represents Late Pleistocene (11,000 to 24,000 years old) river deposits. The pink shading represents the volcanic rock of Banks Peninsula.

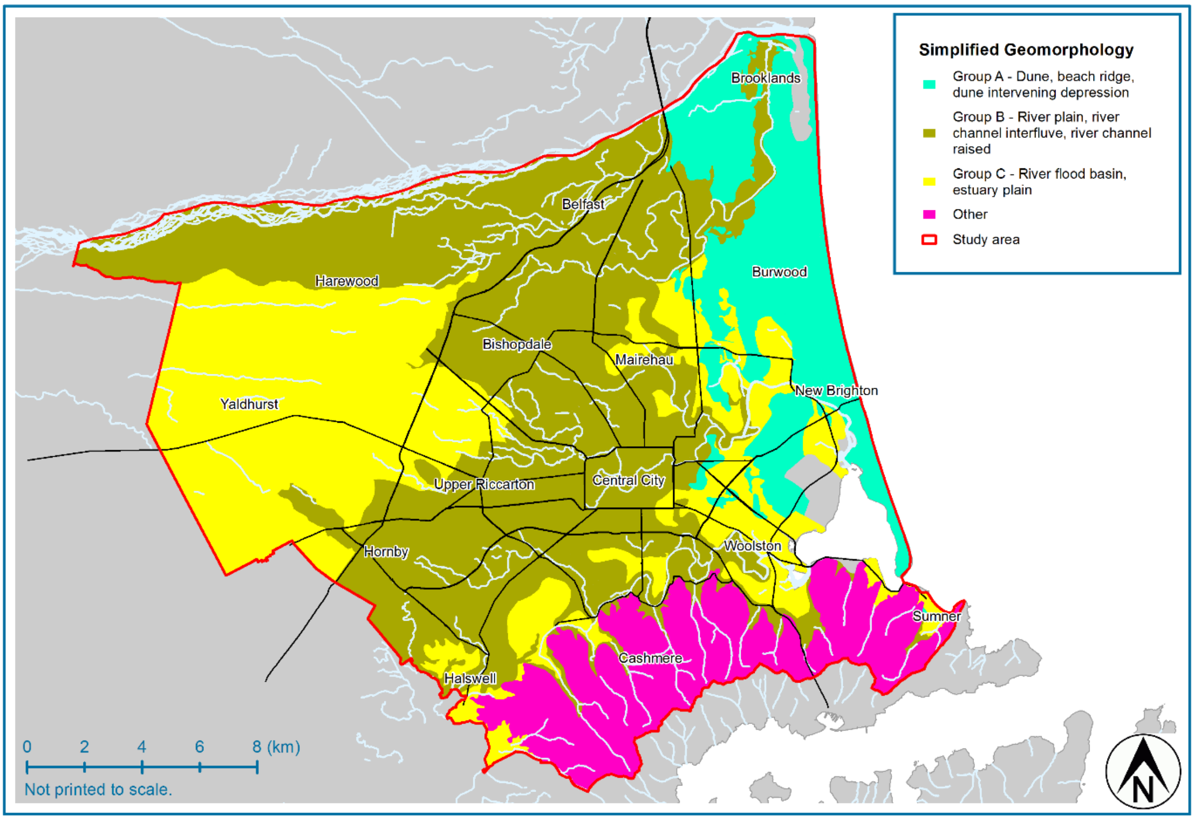


Figure 3.6: Broad geomorphological groupings, based on the mapping of Begg et al. (2015). Refer to Appendix A for more detailed map.

3.3.2 Geotechnical investigations

Following the Canterbury earthquakes thousands of geotechnical investigations were conducted across Christchurch to inform insurance assessment, repair/rebuilding and new development.

Much of this investigation data has been pooled into the New Zealand Geotechnical Database (NZGD), which now provides an internationally unique dataset for detailed analysis of liquefaction vulnerability. The current liquefaction assessment study has drawn from the approximately 22,000 cone penetration tests (CPTs) that are available on the NZGD within the extents of the study area as of Mid-2019, as shown in Figure 3.7.

To provide a consistent basis for quantitative analysis, an initial filtering process was applied to the CPT dataset used for calculation of liquefaction vulnerability index parameters. This involved only selecting CPTs for analysis that have a depth of investigation greater than 5 m, depth of pre drill less than 2 m, and no known data issues or prior ground improvement works. However, the full unfiltered dataset was utilised for more qualitative assessment purposes, such as examining soil profiles and depth to refusal on gravel layers (particularly relevant for the western part of the city).

In a number of the liquefaction assessment sub areas, new CPTs have been uploaded to the NZGD since early 2017 when the initial bulk analysis of investigation data was undertaken. These more recent investigations were added to recalculate an updated bulk analysis for these sub area if it was deemed to materially improve the statistical basis for ground characterisation (e.g. if the previous data was sparse or clustered).

As part of the liquefaction assessment for certain sub areas, ground conditions were confirmed through inspection of boreholes available on the NZGD. Similarly, groundwater measurements made during the investigation were compared against the median groundwater model to verify the representative groundwater depth calculated for the sub area.

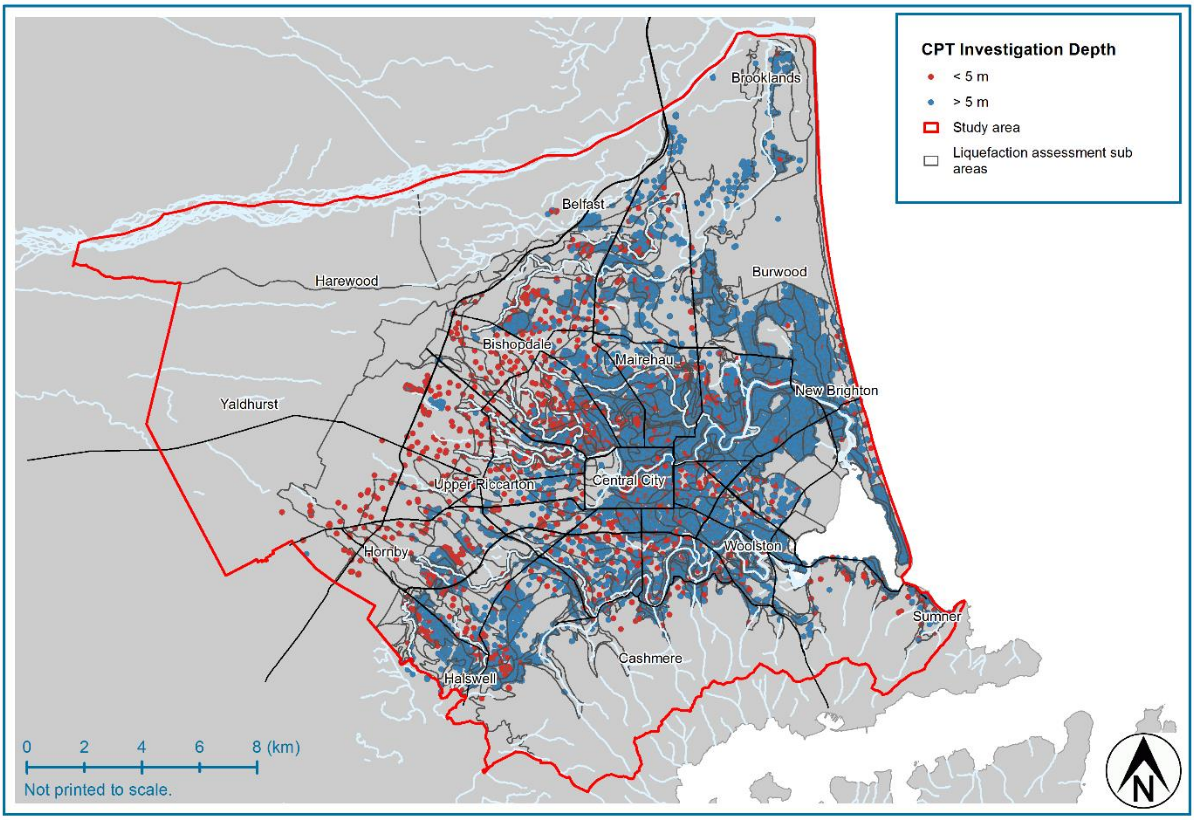


Figure 3.7: Locations of CPT investigations from the NZ Geotechnical Database that were utilised in this study. Refer to Appendix A for larger map.

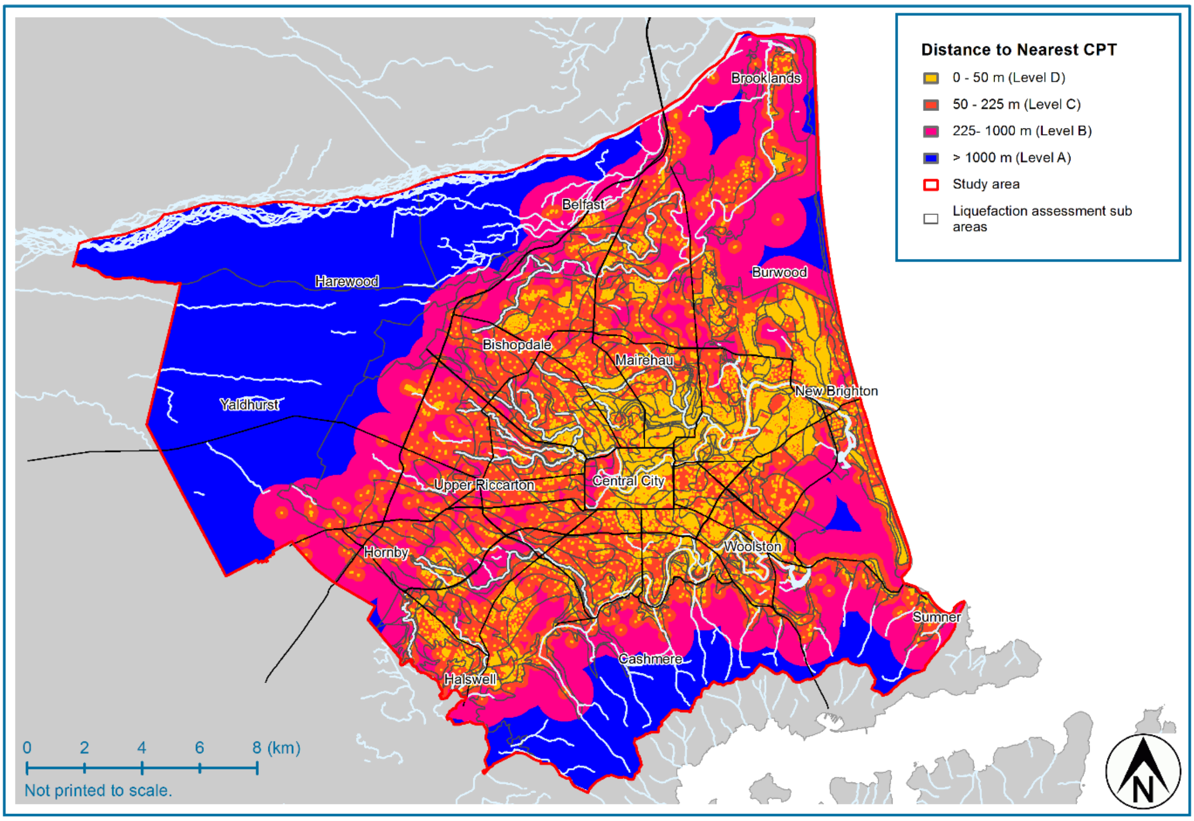


Figure 3.8: Spatial density of CPT investigations. Refer to Appendix A for larger map.

3.3.3 Groundwater

Current-day median groundwater level (2014 model)

A detailed study of the near-surface groundwater regime within the study area was carried out by van Ballegooy et al. (2014) following the recognition of a greater need to understand the elevation, spatial distribution, and temporal variability of the water table and the influence groundwater has on liquefaction-induced ground damage. The van Ballegooy et al. (2014) median depth to groundwater model presented in Figure 3.9 has been adopted as the primary current-day groundwater scenario for the assessment of liquefaction vulnerability across the study area.

While the 2014 model is now five years old, it is still considered to be reasonably representative of current-day conditions in 2019, particularly given the various other uncertainties involved (see following page). Improved groundwater models will likely become available over the coming years with the benefit of additional monitoring data collected since 2014, so the liquefaction model developed in this study includes flexibility to accommodate updated groundwater models in future.

Liquefaction vulnerability can be highly sensitive to groundwater conditions, as deeper groundwater can result in a thicker non-liquefied surface "crust". The van Ballegooy et al. (2014) groundwater model was based on data from 967 shallow monitoring wells across Christchurch. Whilst this is amongst the most detailed groundwater monitoring networks for a city anywhere in the world, almost all of these wells were installed by EQC after the Canterbury earthquakes. Therefore the groundwater model primarily reflects measurements made over a limited period between 2010 and 2013, but with some calibration using long term groundwater monitoring available for a small number of sites between 1990 and 2010. This relatively short duration of monitoring (relative to natural climatic cycles) means that there remains a moderate degree of uncertainty regarding longer-term variations in groundwater level across the study area.

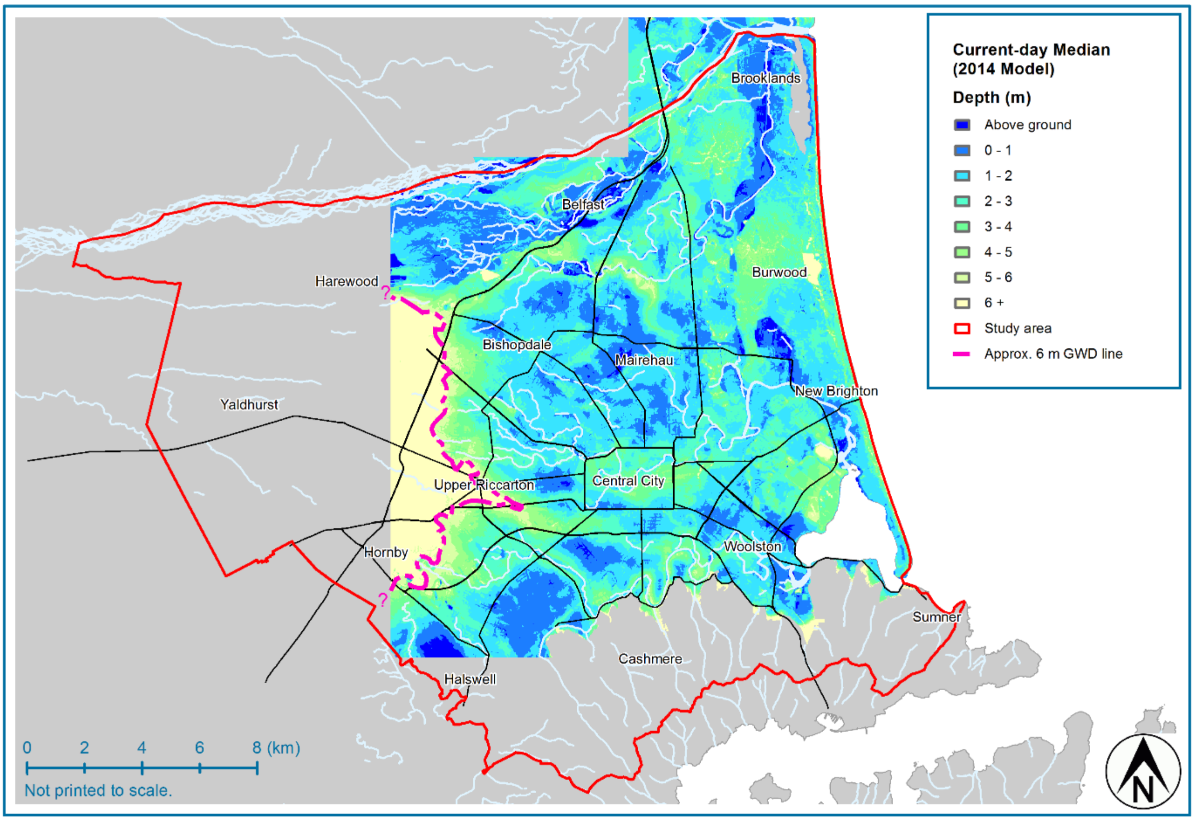


Figure 3.9: Groundwater model for current-day median (2014 model) depth to the groundwater table from van Ballegooy et al. (2014). Refer to Appendix A for larger map.

Models of groundwater level at the time of each main earthquake

Tonkin & Taylor (2013) presents models that were prepared to estimate the groundwater levels across the city at the time of each of the four main Canterbury earthquakes. These models were developed using monitoring wells and river level monitoring stations where measurements were available immediately prior to each earthquake. More data was available for the later earthquakes, as additional monitoring wells were installed over the course of 2010 / 2011. The difference between the measured water levels and the median groundwater model was calculated for each monitoring location and interpolated across the city to provide a model of the offset of groundwater levels at the time of the earthquake relative to the median model.

Uncertainty due to localised small-scale variations in groundwater level

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

- Groundwater heat exchange systems have been installed for various commercial developments across the city, particularly within the CBD over the past decade. These systems typically extract water from deep aquifers and re-inject it back into the near-surface aquifer, which can cause groundwater levels to rise locally in the area (e.g. up to 0.5m higher or potentially more).
- Groundwater levels can be drawn down locally by short-term active dewatering (e.g. during excavation to install a pipeline or basement) or by long-term passive drainage (e.g. field drains or deep stormwater pipe trenches with granular backfill).
- Groundwater levels might be higher locally due to water inflow (e.g. from a stream or leaking pipe).

Uncertainty due to complex groundwater regime

For the current study, it has been assumed that all soil beneath the groundwater table is fully saturated (which is standard practice for most routine liquefaction analysis). However, the groundwater regime and hydraulic connectivity between soil strata can be vastly more complicated than simple hydrostatic assumptions, which provides another source of uncertainty to be considered.

An example of this complexity is the artesian Riccarton Gravel aquifer which underlies the near-surface liquefaction-prone sand/silt soils across much of Christchurch. Upwards flow of water escaping from this aquifer has been postulated as a potential contributing factor to the observed liquefaction-induced ground damage in the Canterbury earthquakes. This could cause higher groundwater pressures than assumed for stress calculations in the simplified liquefaction analysis, and disrupt the natural aging process that helps to develop a stronger soil “fabric” over time.

Uncertainty due to climate change

Climate change introduces further uncertainty regarding the groundwater conditions that could exist at some time in the future when an earthquake occurs:

- The eastern part of the study area is predominantly low-lying gently sloping land close to the coast. This mean groundwater levels could be strongly influenced by sea level rise, with shallower groundwater levels in future than the current-day. A simplified model of potential changes in groundwater level as a result of 0.5m and 1.0m of sea level rise is presented in Quilter et al. (2014).
- The western part of the study area is higher and more steeply sloping land further from the coast. This means the influence of sea level rise will be less, but groundwater levels could be influenced by other climate-related factors such as changes in rainfall patterns, temperature/evaporation, vegetation, water extraction etc. It is uncertain whether the combined influence of these changes will be to make the groundwater shallower or deeper on average and/or increase the range of variability (spatially and over time).

3.3.4 Regional seismicity

Background

Ground shaking and the seismic hazard in the context of liquefaction is often simplified into two metrics – the duration of shaking and the intensity of shaking. Moment magnitude (M_W) is used as a proxy for the duration of shaking, or number of loading cycles, with a higher magnitude corresponding to a longer duration. Similarly, Peak Ground Acceleration (PGA) is used as an indicator for the intensity of shaking, with a higher PGA corresponding to more intense shaking. In reality, ground motions generated by earthquakes are significantly more complex with factors such as directionality, frequency, and variation within the soil profile that are not captured by the M_W and PGA metrics.

"Design" seismicity values used for consenting purposes

Following the Canterbury earthquakes, the Ministry of Business, Innovation & Employment (MBIE) made interim updates to the seismic loading standards for building design and liquefaction assessment, to take account of the newly-mapped faults and the temporarily heightened seismicity rates associated with the aftershock sequence. These updated seismic hazard parameters, were intended to provide a pragmatic basis for design. The recommended design values for liquefaction assessment are summarised in Table 3.3. Given the substantial uncertainties in the pattern of ongoing seismic activity and the amount of building work underway there was a preference for these interim values to be conservative rather than non-conservative.

The MBIE design PGA values correspond to a design earthquake magnitude of $M_W = 7.5$, however it has been identified that the seismic hazard in the Christchurch urban region is better represented by lower magnitude events (Bradley, 2014). The specific M_w and PGA combination used can be important for liquefaction analysis, so for the current study equivalent PGA values have been estimated for a design magnitude of $M_W = 6.0$ using the Idriss & Boulanger (2008) magnitude scaling factor.

Table 3.3: PGA values recommended by MBIE (2015) for liquefaction assessment for Site Class D in Christchurch, and equivalent values for a design earthquake magnitude of M_w = 6.

Return period (years)	MBIE design PGA (g) for M_w = 7.5	Equivalent PGA (g) for M_w = 6.0
25	0.13	**0.19**
100	0.20	**0.30**
500	0.35	**0.52**

"Best estimate" seismicity values used for public awareness purposes

A more rigorous first-principles seismic hazard analysis for Christchurch was undertaken by Bradley (2014). The key results from this analysis are presented in Table 3.4 and Figure 3.10. This analysis indicates lower seismic hazard parameters than the interim MBIE design PGA values, as shown in Figure 3.11. This difference creates additional uncertainty regarding the seismic hazard parameters use for liquefaction assessment. The MBIE-recommended values in Table 3.3 have been adopted as the primary seismic hazard scenario for the liquefaction vulnerability categorisation presented in this report. Whilst these MBIE values may over-represent the intensity of earthquake shaking, they are currently widely used across the industry – so it was considered preferable that the analysis undertaken for this study remain consistent with local engineering practice for consenting purposes. However, the best-estimate Bradley (2014) values have been used for conveying information about earthquake likelihood on the public-awareness website.

Intensity of ground shaking experienced during the Canterbury earthquakes

Every earthquake is unique, and factors such as the type of fault and the length of the fault rupture can influence the amount energy released. Also, the intensity of shaking from an earthquake is not uniform over a region. Shaking is usually stronger at locations that are closer to the fault or where local ground conditions cause an amplification effect. The depth of the fault can influence the intensity of shaking at the ground surface, and the direction of the fault and how it ruptures can focus energy in a particular direction.

This means that when we use observations from the Canterbury earthquakes to help calibrate our liquefaction assessment, we need to take into account the intensity of shaking that was experienced in each area in each event. For example, areas which are further from the fault might have had less liquefaction damage in a particular earthquake than areas that are closer, even if the soil conditions are the same. But in a future earthquake located somewhere else the pattern of damage across the city could be different.

Bradley & Hughes (2012a and 2012b) developed a model of how the intensity of shaking varied across the city for each of the main Canterbury earthquake events. This was estimated from an approximate model of how shaking from a given fault varies over a region, combined with actual measurements at the 20 seismograph stations across the city. This means that away from the seismograph locations there is substantial uncertainty in the modelled values. For the current study we have adopted the median estimate of ground shaking, as shown in Figure 3.12. Across most of urban Christchurch there is a confidence of at least 80% that the actual shaking intensity was within ±50% of the median estimate adopted.

Table 3.4: Summary of results from Bradley (2014) probabilistic seismic hazard analysis

	Return Period (years)			
	25	100	500	2500
Peak ground acceleration, PGA (g)	0.085	0.19	0.34	0.54
Mean magnitude, (M_w)	5.92	5.80	5.81	5.82

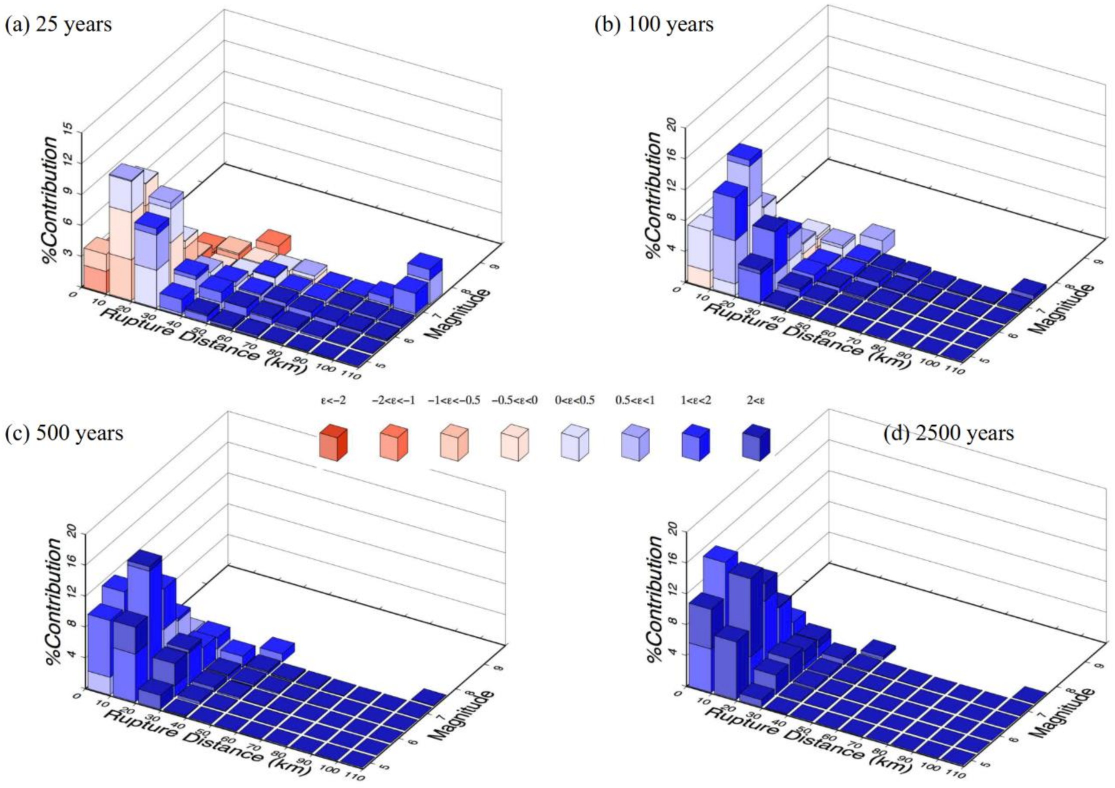


Figure 3.10: Deaggregation plots from probabilistic seismic hazard analysis (reproduced from Bradley, 2014).

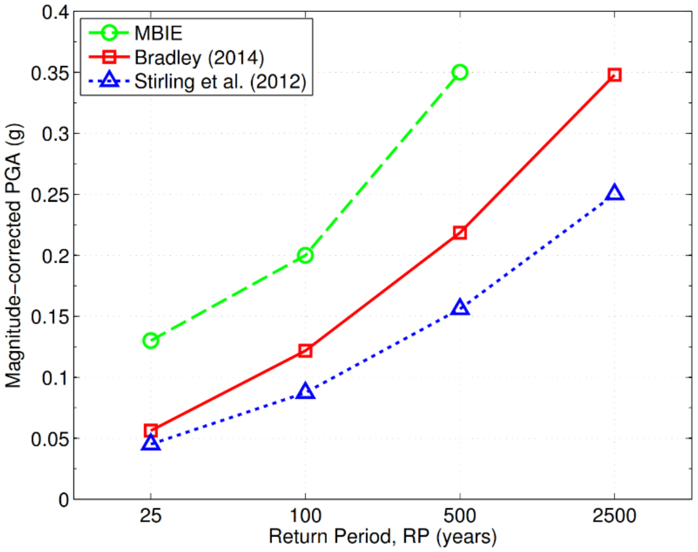


Figure 3.11: Comparison of MBIE interim design PGA values to probabilistic seismic hazard analysis results (adjusted to magnitude M_w = 7.5 equivalent), reproduced from Bradley (2014).

3.3.5 Historical observations of liquefaction occurrence or non-occurrence

3.3.5.1 Prior to the 2010/2011 Canterbury earthquakes

Historic records indicate that prior to the Canterbury earthquakes, Christchurch experienced at least five earthquakes which caused isolated building damage and significant contents damage (Downes & Yetton, 2012). There are no reports of liquefaction during these events in Christchurch, however liquefaction was reported in Kaiapoi and Belfast following the 1901 M_W6.8 Cheviot earthquake (Berrill et al., 1994; Ogden, 2018). The earlier 1869 Christchurch earthquake caused widespread building and chimney damage within the Central Business District and surrounding suburbs including Avonside. No liquefaction or ground deformation was reported in these events. However, based on observations from the Canterbury earthquakes it has been inferred that liquefaction was likely triggered in the most vulnerable areas during this earthquake (Quigley et al., 2013).

3.3.5.2 During the 2010/2011 Canterbury earthquakes

The 2010/2011 Canterbury earthquakes was a period of significant seismicity in the history of Christchurch with more than 50 earthquakes with magnitude M_W5 or greater following the initial M_W7.1 Darfield earthquake on 4 September 2010.

Four main earthquakes caused the majority of the liquefaction-induced ground damage:

- 4 September 2010 (M_W7.1).
- 22 February 2011 (M_W6.2).
- 13 June 2011 (M_W5.6 foreshock followed 80 minutes later by a M_W6.0 aftershock).
- 23 December 2011 (M_W5.8 foreshock followed 80 minutes later by a M_W5.9 aftershock).

Figure 3.12 summarises the observed liquefaction-induced ground damage mapped by EQC after each of the main earthquakes. The mapping was collated from extensive ground and aerial observations as discussed in Tonkin & Taylor (2013). The severity of observed liquefaction-induced ground was categorised as follows:

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

Detailed descriptions of each of the three land damage categories, including photographic examples from the Canterbury earthquakes, are provided in Appendix A of the MBIE/MfE (2017) guidance document.

Figure 3.12 also shows contours of the estimated PGA for each event illustrating how land performance varied depending on the intensity of shaking. However, it should be appreciated that these PGA contours have been estimated based on a small number of seismographs across the city, so there is substantial uncertainty in the intensity of shaking estimated between seismograph locations.

Observations of liquefaction having occurred or not occurred at a particular location can be more or less useful for calibrating the liquefaction assessment depending on the PGA experienced at the site. For example, if no liquefaction was observed but the PGA was relatively low then this observation does not necessarily demonstrate that the ground is not vulnerable to liquefaction, as it was not "well tested". Aggregation of the PGA estimated across the city in each of the four main earthquakes, and the associated uncertainties, indicates that it is highly likely (95% confidence) that shaking of at least 0.13g (M_w7.5 equivalent) was experienced across much of the study area as far north as Redwood.

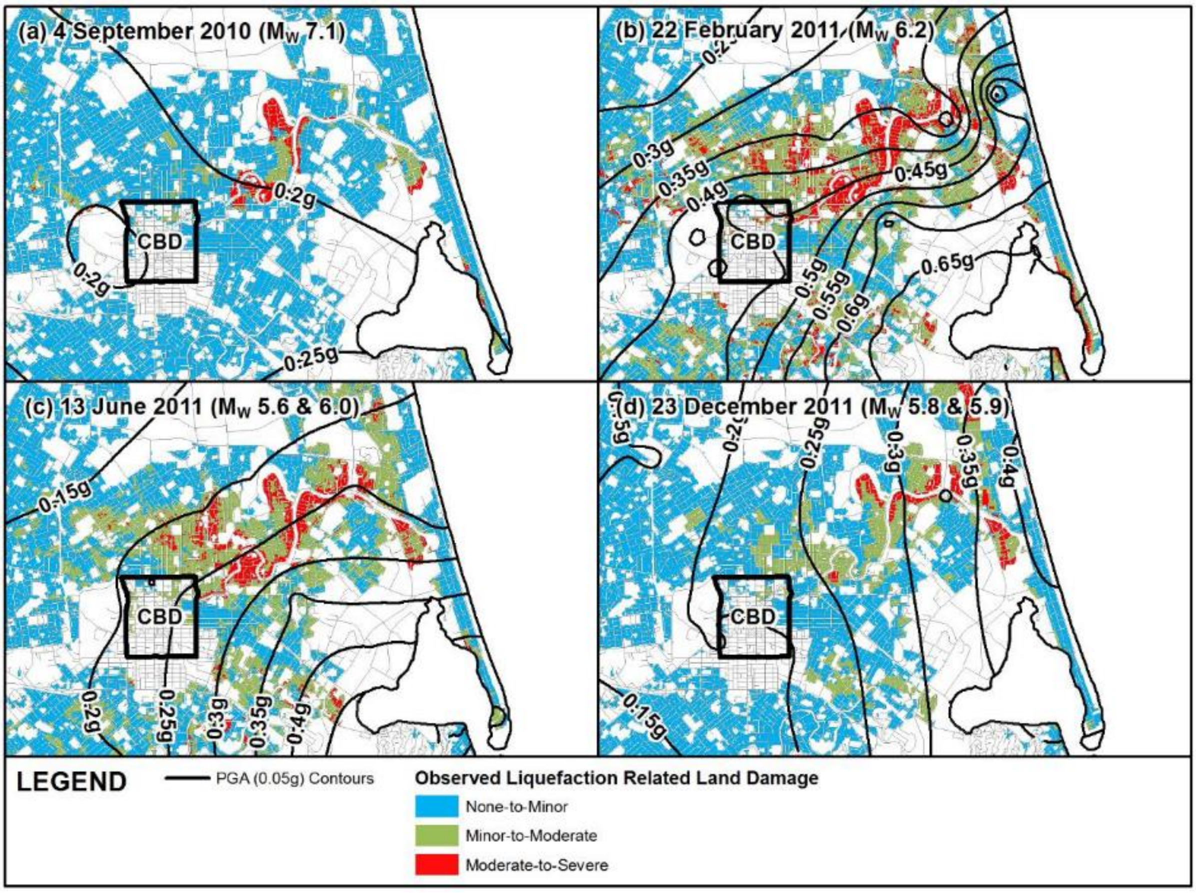


Figure 3.12: Maps showing the estimated intensity of earthquake shaking and the observed land damage for urban residential properties in Christchurch after the four main events of the Canterbury earthquakes (reproduced from Tonkin + Taylor, 2015).

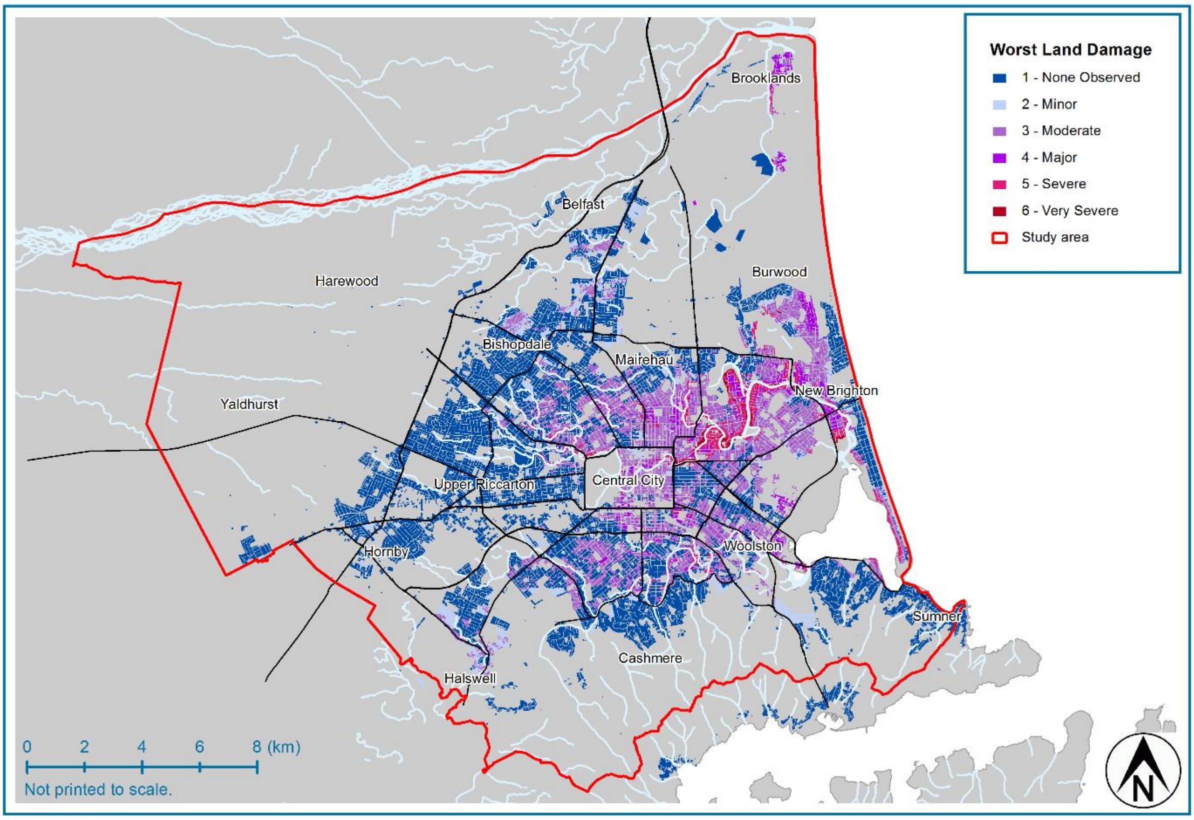


Figure 3.13: Worst land damage observations from the Canterbury earthquakes. Refer to Appendix A for larger map.

3.4 Level of detail supported by currently available base information

A liquefaction assessment draws on various sources of information to make a judgement as to the likely liquefaction vulnerability. For this study, the three key classes of information utilised relate to the soil profile, the groundwater level and the observed land performance in the Canterbury earthquakes. The types of available information are summarised in Table 3.5, along with the associated level of detail and residual uncertainty.

For each of these three types of information, a qualitative assessment was made of how the uncertainty varied spatially across the study area. The general pattern of uncertainty in available information across the study area is illustrated in Figure 3.14 (refer to Appendix A for more detailed maps). The uncertainty related to each type of information was then aggregated to show the combined uncertainty that flows through to the final assessment of liquefaction vulnerability. This aggregation recognised that liquefaction vulnerability can be assessed either by theoretical analysis (based on the soil profile and groundwater level) or by empirical analysis (based on observed performance). If there is more uncertainty in the soil or groundwater information, then the impacts on the final liquefaction assessment can be offset to some extent if there is less uncertainty in the observation information (and vice versa).

The resulting aggregation of uncertainty for the current liquefaction assessment study is illustrated in Figure 3.14(d). This map of aggregated uncertainty was used as a key input when nominating the final level of detail achieved for the liquefaction vulnerability categorisation for each assessment sub area (refer Section 4.8 and Figure 4.15).

The maps in Figure 3.14 relate to the absolute level of uncertainty in the base information itself, not the resulting impact of that uncertainty on the final liquefaction assessment. There are some locations across the study area where there is substantial uncertainty in the base information, but for one reason or another this uncertainty does not have a material impact on the liquefaction assessment. Examples of this include:

- Figure 3.14(a) shows there is "more" uncertainty in the ground conditions in the northwest portion of the study area. This is because there is limited ground investigation information available in this area, and it tends to be more qualitative information such as excavator pits and water well boreholes rather than quantitative geotechnical data such as CPT and SPT testing. However, based on the regional geology it is known that the soil profile in this area is typically gravel-dominated from shallow depths, and groundwater is typically deeper than 6m below ground. Therefore, even though there is substantial uncertainty regarding the exact profile of soil type and strength present at any particular location in this area, it is still possible to conclude with reasonable certainty that ***Liquefaction Damage is Unlikely***.
- Similarly, Figure 3.14(a) shows there is "more" uncertainty in the ground on the Port Hills in the south of the study area. Again, this is because of the limited quantitative ground investigation data available. However, the soil profile in this area typically comprises steeply sloping ground with a relatively thin layer of loess draped over rock, so it is still possible to conclude with reasonable certainty that ***Liquefaction Damage is Unlikely***.
- Figure 3.14(c) shows more uncertainty to the west of the CBD than the east. This is because in the east the land is low-lying with a gentle slope towards the sea, so groundwater levels are largely controlled by sea level and as a result there is less seasonal/annual and spatial variability. In the west the land is higher and more steeply sloping so groundwater levels are controlled more by seasonal/annual variations in rainfall with more spatial variability. While there is more uncertainty in the absolute groundwater level in the West, in some locations this uncertainty does not materially impact the final liquefaction vulnerability assessment. For example, an uncertainty of ±1m in groundwater level would have a more significant impact on the liquefaction assessment if groundwater was at 2m depth than if it was at 6m depth. Conversely, uncertainty in the absolute groundwater would have a less significant impact on the liquefaction assessment if the soil layers within the range of uncertainty are predominantly non-liquefiable (e.g. gravelly deposits to the west of the city or peat deposits at various locations to the north, east and south of the city).

As part of the manual engineering review process for calibrating the ground damage model and assigning a liquefaction vulnerability category to each sub-area, consideration was given to the residual uncertainty in the final liquefaction assessment after all the available information had been analysed (along with uncertainties implicit in the analysis itself). Where the residual uncertainty was less, a higher level of detail in the assessment was supported (refer Figure 4.15) and more precise liquefaction vulnerability categories were assigned (refer Figures 4.13 and 4.14).

Table 3.5: Types of information considered in the liquefaction assessment.

Type of information	High detail *Less uncertainty*	Moderate detail	Low detail *More uncertainty*
Information about the near-surface soil profile.	Quantitative subsurface information such as CPT data from closely spaced investigations.	Qualitative subsurface information such test pit and borehole logs, often widely spaced.	Inferences about the ground conditions based on the surface geomorphology.
Information about groundwater levels.	Groundwater monitoring from wells that are closely spaced or have a long monitoring history.	Groundwater monitoring from wells that are widely spaced or have a short monitoring history.	Inferences about groundwater depth based on general location and ground elevation.
Information from land performance observed in the Canterbury earthquakes.	Property-level mapping undertaken on foot following multiple earthquake events with sufficient shaking to be "well tested".	Property-level mapping undertaken on foot following only one earthquake event with sufficient shaking to be "well tested".	Road-level mapping undertaken by car or from aerial photography, or no earthquake event with sufficient shaking to be "well tested".

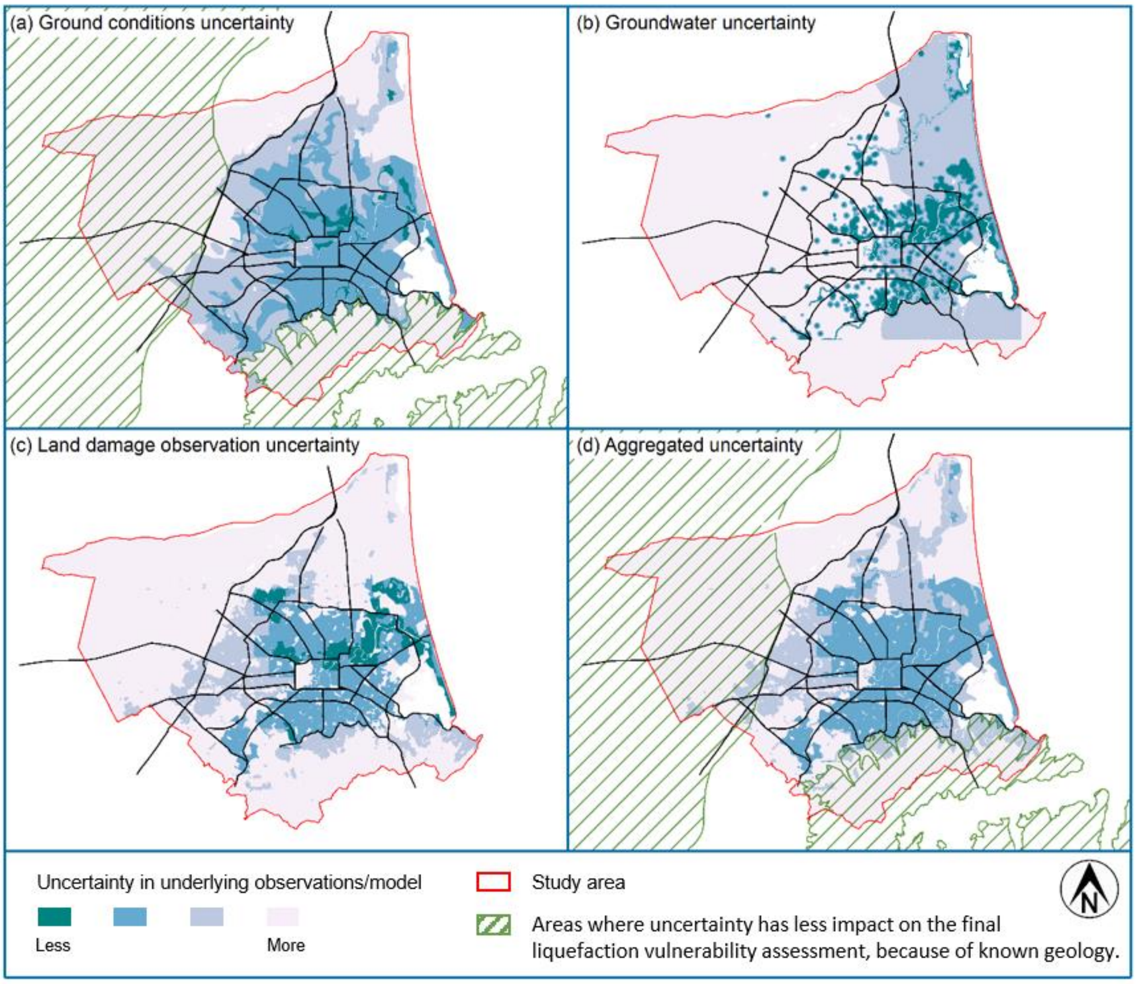


Figure 3.14: Summary of how uncertainty in the currently available information varies across the study area, and how uncertainty in each type of information was aggregated. There is less uncertainty in areas where detailed information is available, and more uncertainty in areas where the available information is limited. Refer to Appendix A for more detailed maps.

4 Risk analysis

The following sections outline the liquefaction assessment that has been carried out in this study. The initial focus was to develop an analytical model which estimated the severity of liquefaction-induced ground damage resulting from a range of groundwater and earthquake scenarios. This model, along with engineering judgement to weigh up the available information and uncertainties, was then used to categorise expected land performance relative to the criteria recommended in MBIE/MfE (2017).

The assessment was conducted in a series of stages in order to appropriately incorporate the available information. These stages are summarised below and largely happened sequentially, with iteration as required to incorporate interdependencies in the technical analysis and maintain consistency.

1. Delineation of the study area into sub areas of similar expected ground performance.
2. Generation of automated CPT-derived liquefaction damage response curves.
3. Calibration of liquefaction damage response curves.
4. Lateral spreading adjustments.
5. Groundwater adjustments.

4.1 Managing uncertainties in the liquefaction vulnerability assessment

We have considered the uncertainties in the liquefaction vulnerability assessment as they relate to the main steps in the assessment process. This process is outlined in Figure 4.1, with more detail of the uncertainties provided in Table 4.1.

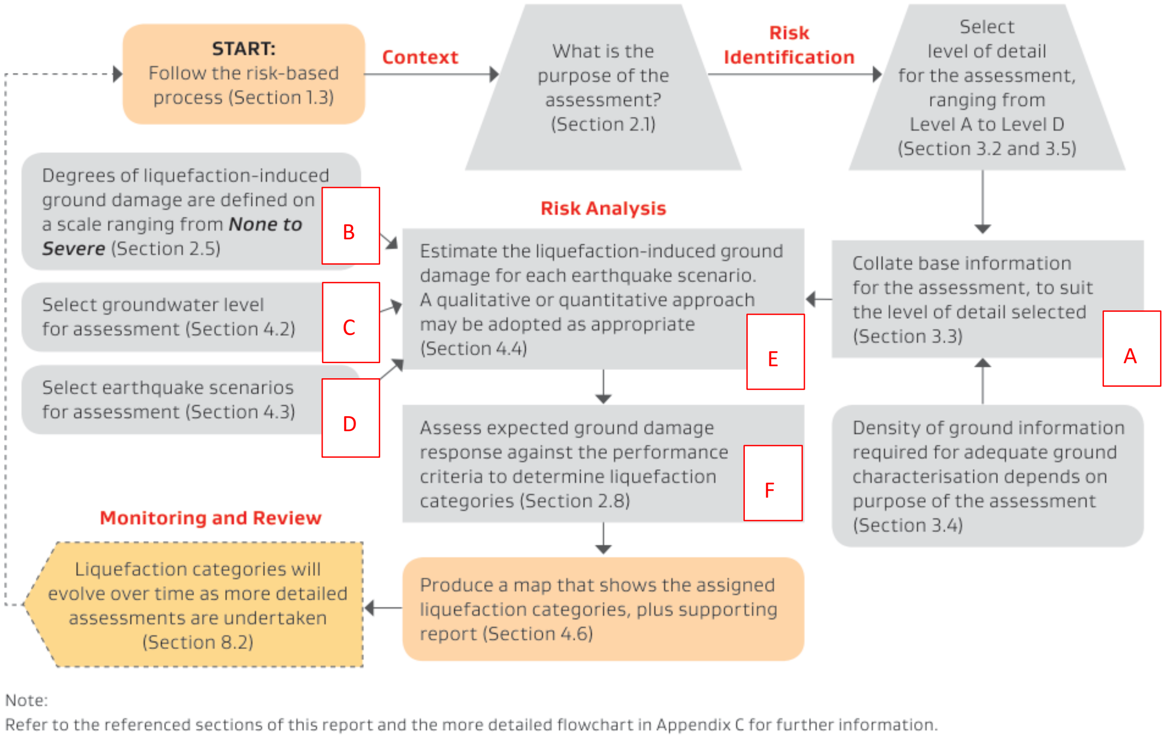


Figure 4.1: Liquefaction assessment methodology flowchart from MBIE/MfE (2017), with labels A to F relating to uncertainties identified in Table 4.1.

Table 4.1: Uncertainties in the liquefaction assessment

Aspect of the liquefaction assessment	Uncertainty	Consequence for the liquefaction assessment	Management of uncertainty in the liquefaction assessment
A. Collate base information for the assessment, to suit the level of detail selected.			
Geology and geomorphology	Scale/precision of mapping – delineation of boundaries.	Land at a particular location incorrectly characterised (placed into wrong geomorphology type) and hence expected ground performance.	Checking final map and boundaries against most detailed information to assist in delineation e.g. LiDAR, observations, groundwater depth.
Groundwater depth	Prediction of groundwater depth adopted for event specific analysis and future scenarios.	Over/under prediction in degree of land damage. Miscalibration based on observations and misprediction for future scenarios.	Calibration against observations. High level check of reasonableness of groundwater depths and representativeness of groundwater across polygon.
Regional seismicity	Prediction of event magnitude and PGA adopted for event specific analysis and future scenarios.	Over/under prediction in degree of land damage. Miscalibration based on observations and misprediction for future scenarios.	Understanding event model uncertainty and adopting multiple scenarios for forward analysis rather than single design event.
Historical observations	Mapping of land damage through the CES e.g. property specific versus area wide mapping, inconsistency in categorisation by different mappers,	Miscalibration of model leading to over/under prediction in degree of land damage.	High level check of reasonableness, understanding what causes difference between the model and observations.
Ground investigation data	Spatial variability in soil profile limits ability to characterise using discrete investigation points.	Land at a particular location incorrectly characterised (incorrect soil profile).	Checking final map and boundaries against most detailed information to assist in delineation e.g. LiDAR, observations, groundwater depth. Understanding spatial bias and density across the polygon.

Table 4.1 (continued): Uncertainties in the liquefaction assessment

Aspect of the liquefaction assessment	Uncertainty	Consequence for the liquefaction assessment	Management of uncertainty in the liquefaction assessment
B. Degree of liquefaction-induced ground damage are defined on a scale ranging from None to Severe.			
Land performance categorisation	Wide range of performance encompassed within each of the categories.	Limited resolution and precision in the description of consequences.	Clearly convey to end users the range and variability in land performance prediction.
Consequences of land damage	Link between ground damage and damage to building and infrastructure.	Over/under prediction of consequential damage resulting from land damage.	Clearly convey to end users the range and variability of the consequences of land performance prediction.
C. Groundwater level for assessment.			
Selection of groundwater levels for future scenarios.	Impact of climate change on groundwater levels.	Over/under prediction of land damage.	Clearly convey to end users the range and variability in groundwater and the impacts this has on future land performance prediction. Describe as groundwater scenarios rather than single predicted outcome.
Fluctuations of groundwater levels seasonally and from year to year.	Uncertainty in groundwater levels at the time of the event.	Over/under prediction of land damage.	Clearly convey to end users the range and variability in groundwater and the impacts this has on future land performance prediction. Describe as groundwater scenarios rather than single predicted outcome. High and low groundwater levels helps to convey significance of this to end users.
Selection of groundwater levels for future scenarios.	Partial saturation.	Miscalibration of model (under prediction if partially saturated for CES but not future event). Misprediction of future damage (over prediction if saturated for CES but not future event).	Clearly convey to end users the influence of partial saturation and the impacts this has on future land performance prediction.

Table 4.1 (continued): Uncertainties in the liquefaction assessment

Aspect of the liquefaction assessment	**Uncertainty**	**Consequence for the liquefaction assessment**	**Management of uncertainty in the liquefaction assessment**
D. Earthquake scenario for assessment.			
Selection of earthquake demand for future scenarios.	Uncertainty in duration and intensity of ground shaking at a particular location (source, path, and site effects).	Over/under prediction of land damage.	Clearly convey to end users the range and variability in earthquake demands. Various scenarios displayed help to convey this.
E. Estimate the liquefaction-induced ground damage for each earthquake scenario.			
Susceptibility	Uncertainty in the ability of the CPT to appropriately characterise soil type e.g. sand like versus clay lie (Ic = 2.6 assumed cut-off).	Over/under prediction of land damage.	Calibrate against observations with understanding of the soil types present. Cleary convey to end users the uncertainties in assessing liquefaction susceptibility for some soil types.
Triggering – cyclic demand	Characterising a complex and irregular earthquake loading and site/system response with a single demand number.	Over/under prediction of land damage.	Calibrate against observations. Cleary convey to end users the variability in response to potential future earthquake scenarios.
Triggering – cyclic resistance	Uncertainty in ability of the CPT to accurately characterise cyclic resistance, particularly for soils outside the case history database.	Over/under prediction of land damage.	Calibrate against observations with an understanding of the soil types present.
Consequence	Uncertainty in the ability of LSN to accurately characterise the degree of land damage.	Over/under prediction of land damage.	Calibrate against observations with an understanding of the soil types and profiles (interlayered silty-sand profiles versus clean sand profiles) and groundwater conditions.
Influence of lateral-spreading	Uncertainty in prediction of future lateral-spreading.	Uncertainty in future lateral-spreading.	Identify areas with zones of potential lateral-spreading and convey the uncertainties in expected land performance in these areas.
F. Assess expected ground damage response against the performance criteria			
Assigning liquefaction vulnerability categories to each polygon.	Spread in expected performance across a polygon	Land at a particular location incorrectly characterised (placed into wrong vulnerability category).	Refine polygons based on observations as appropriate and practical. Convey to end user the range of possible performances for each polygon.

4.2 Initial definition of liquefaction assessment sub areas

The study area was delineated into sub areas expected to have similar ground performance during earthquake shaking. The initial set of sub areas were established by utilising the surface geology map sourced from Begg et al. (2015) as shown in Figure 4.2. For the purposes of this study, this map was simplified where appropriate (reflecting the level of detail intended by the assessment). For example, geomorphic units which were sufficiently small (approximately <10,000 m^2) were merged with adjacent units having the same geomorphological characterisation.

Additional modifications were made following inspection of the ground elevation and groundwater depth across the study area. Sub areas were divided where significant changes in the ground elevation or groundwater were identified, to capture the variations in ground performance that these features can cause. For example, geological profiles that have deeper groundwater are expected to perform comparatively better due to having a thicker non-liquefying crust (refer Section 2.2). An example of division of sub areas based on these details is presented in Figure 4.3.

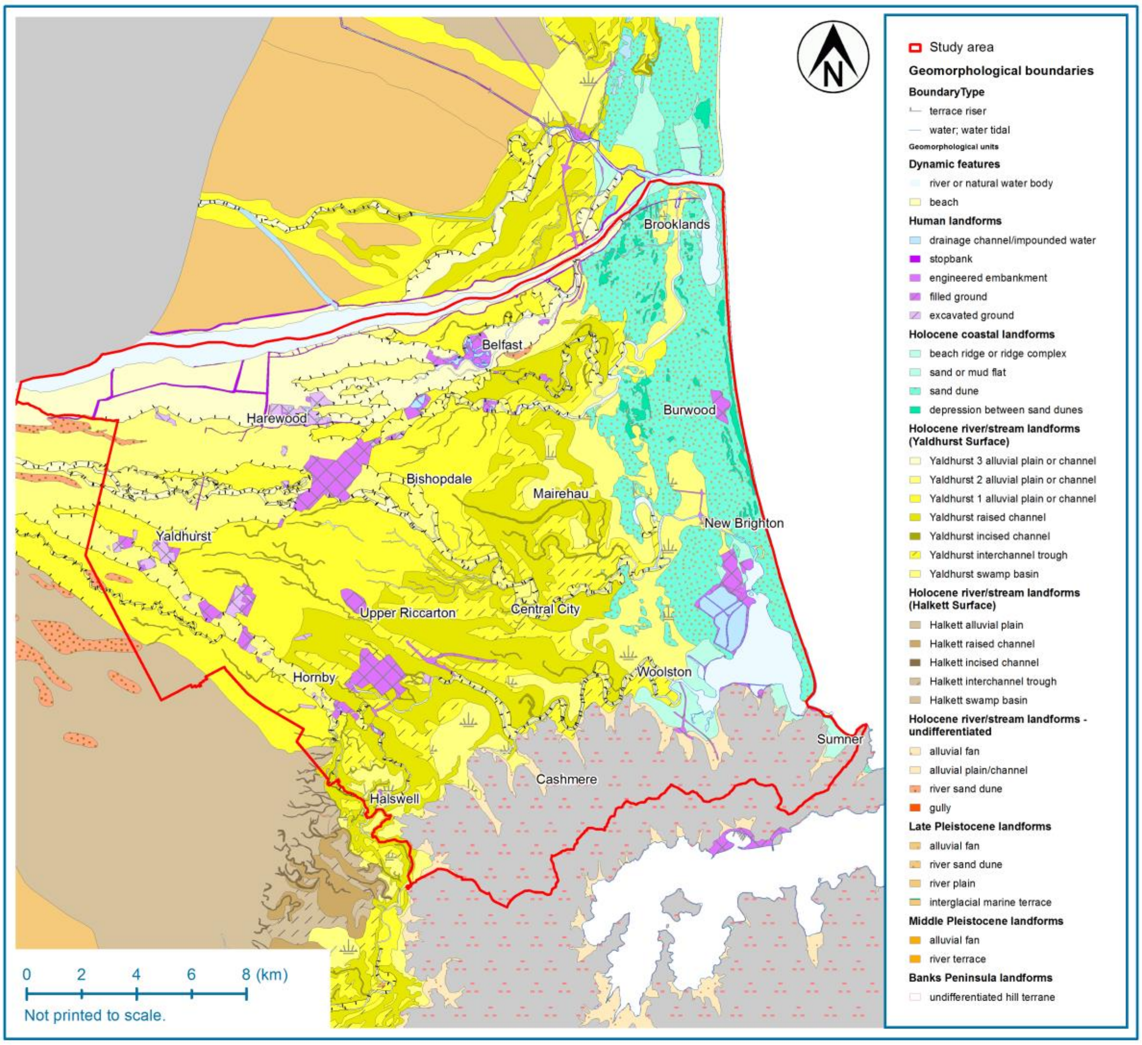


Figure 4.2: GNS geomorphological map of the eastern Canterbury area used as the initial iteration of the liquefaction assessment sub areas (data sourced from Begg et al., 2015). Refer to Appendix B for larger map.

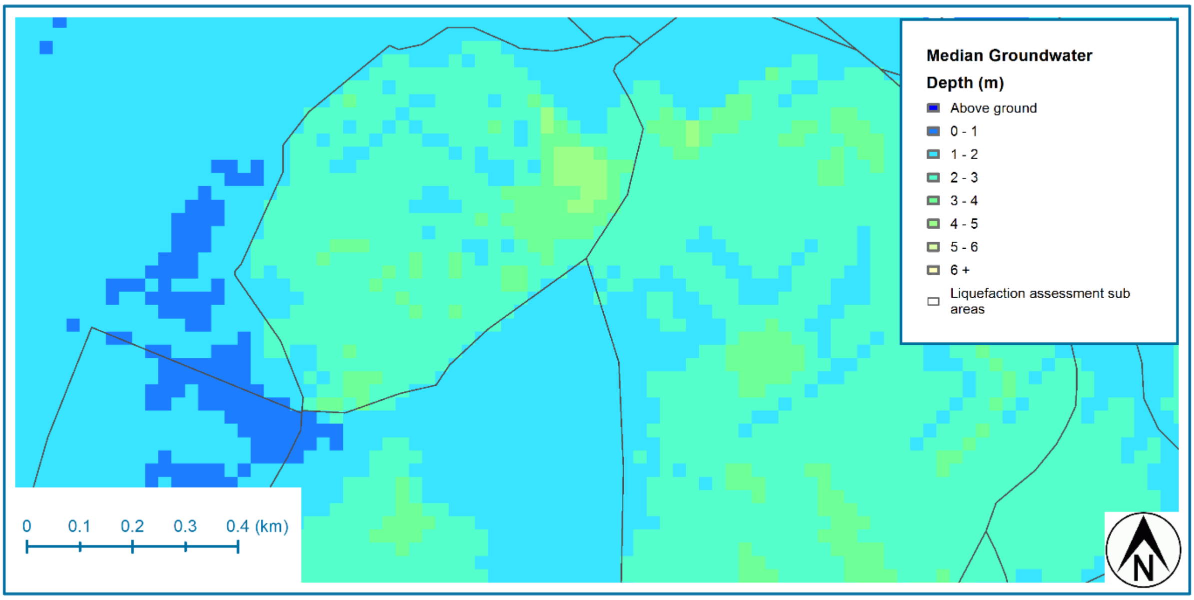


Figure 4.3: An example of delineating sub areas based on groundwater depth.

CPT and borehole investigations were then used to identify changes in the subsurface geology as a basis for further refinement of the sub areas. In areas with high CPT density, initial analyses could be used to separate out zones where different ground conditions are determined from the CPT traces or different liquefaction vulnerability indices are computed.

The initial definition of the sub areas included accounting for areas that are assumed to have the potential for lateral spreading. Lateral spreading is one of the most damaging consequences of liquefaction (refer Section 2.2). It most commonly occurs near rivers and watercourses where there is a free-face formed by the bank of the channel. Areas assumed to have the potential for lateral spreading were delineated using a buffer distance from river centrelines, as illustrated in Figure 4.4. The assumed buffer distance was dependent on the width and depth of the river channel with values of 50, 100, and 150 metres typically applied with increasing watercourse width and depth. These numbers were based on the typical pattern and extent of the most significant lateral spreading damage mapped across the study area following the Canterbury earthquakes.

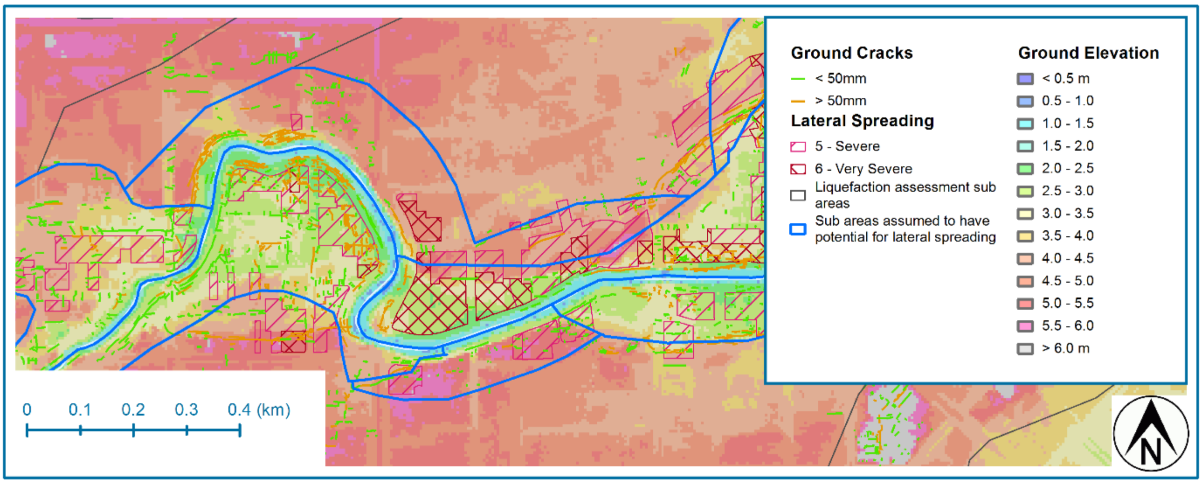


Figure 4.4: An example of delineating sub areas to identify areas assumed to have potential for lateral spreading, also showing the base information used in the assessment.

In some locations there was limited ground investigation information within a particular sub area, which made it difficult to undertake meaningful quantitative analysis. In this situation other subareas were identified which, while geographically separated, have similar geomorphology, ground elevation and groundwater depth, and therefore similar expected liquefaction vulnerability. In these cases an “association” was applied to pool the data across these similar areas for combined analysis. An example of this association process is presented in Figure 4.5.

A liquefaction assessment was carried out using an initial set of sub areas resulting from the above delineations. Following this, further refinement to the boundaries of these sub areas was made in order to more appropriately reflect any patterns in the expected liquefaction vulnerability (refer to Section 4.7).

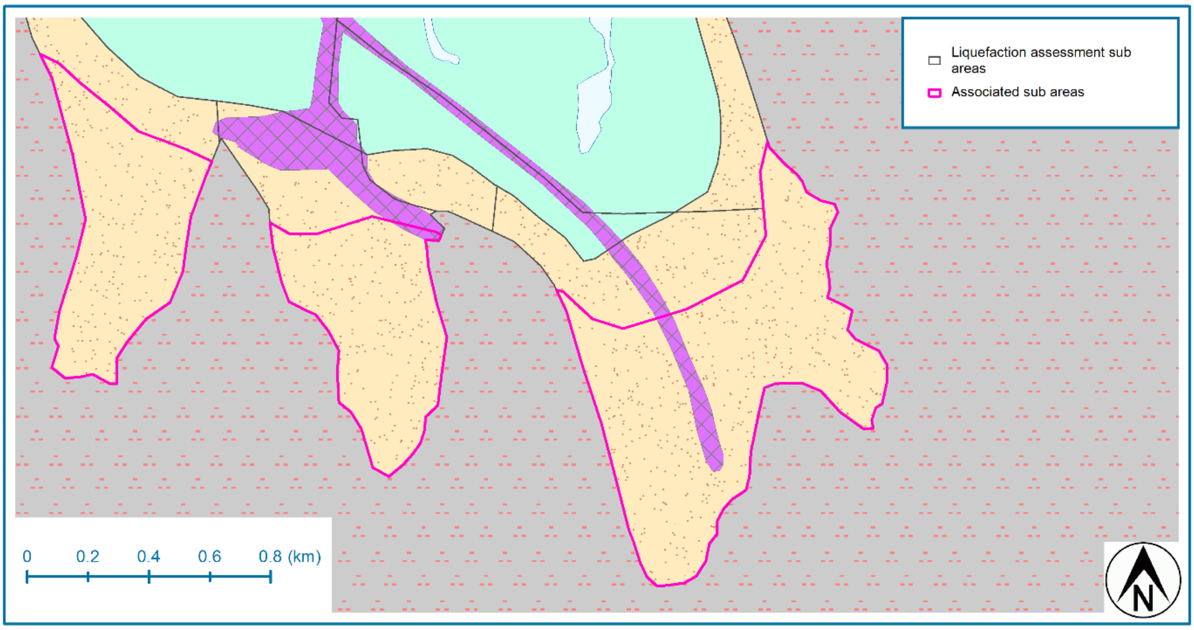


Figure 4.5: Association process for a set of polygons (highlighted) which are geographically separated, however are expected to exhibit similar ground performance based on geology, elevation and groundwater.

4.3 Groundwater scenarios

Groundwater scenarios for analysis have been defined using the groundwater model for Christchurch discussed in Section 3.3.3. Liquefaction-induced ground damage response curves were initially generated for this median base case.

As discussed in Section 3.3.3 there is significant uncertainty regarding groundwater conditions that could exist at some time in the future at the moment that an earthquake occurs. These uncertainties include:

- Variations over time (tidally, seasonally and from year to year).
- Localised spatial variations in groundwater levels not reflected in the area-wide model.
- The effects of climate change (including sea level rise and other climate-related changes).
- Hydraulic connectivity between soil strata meaning that the groundwater regime can be vastly more complicated than the simple hydrostatic conditions assumed in analysis.

For this current study it was not practical to attempt to explicitly model each of these uncertainties across the city and over time, and the combined effect on the liquefaction vulnerability assessment. Instead, a simple sensitivity analysis was undertaken to quantify the change in ground damage for scenarios with groundwater incrementally shallower or deeper than the current-day median (2014 model), as shown in Table 4.2.

This simple sensitivity analysis provides an initial understanding of locations across the city where uncertainty in groundwater assumptions has a material impact on the liquefaction vulnerability assessment, regardless of whether that uncertainty comes from climate, seasonal, annual, localised or other factors. In locations where this uncertainty matters, future work can then direct more focussed attention on resolving the specific factors contributing to the groundwater uncertainty.

Table 4.2: Groundwater sensitivity scenarios considered in this study.

Change in groundwater elevation	**Description**
1.0m deeper	Groundwater 1m below current-day median levels (2014 model). *This could represent very dry summer conditions.*
0.5m deeper	Groundwater 0.5m below current-day median levels (2014 model). *This could represent typical summer conditions.*
Average (median)	Groundwater at current-day median levels (2014 model). *Over the past 30 years (Note 1), groundwater has been higher than this half the time, and lower than this half the time.*
0.5m shallower	Groundwater 0.5m above current-day median levels (2014 model). *This could represent typical winter conditions, or the effects of climate change (including sea level rise and other climate-related changes) (Note 2).*
1.0m shallower	Groundwater 1m above current-day median levels (2014 model). *This could represent very wet winter conditions and/or the effects of climate change (including sea level rise and other climate-related changes) (Note 2).*
2.0m shallower	Groundwater 2m above current-day median levels (2014 model). *This could represent winter conditions in conjunction with the effects of climate change (including sea level rise and other climate-related changes) (Note 2).*

NOTES:

1) This is the duration of groundwater monitoring records analysed for development of the median groundwater model in van Ballegooy et al. (2014). This 30 year period also provides a reasonable representation of the variability in groundwater level over time for current-day conditions.
2) Sea level rise is likely to result in a greater rise in groundwater levels in the east of the city than the west. The net effect on groundwater levels once other climate factors are also included (e.g. changes in rainfall and evaporation) is particularly difficult to predict for the west of the city. Refer to Section 3.3.3 for further details.

4.4 Earthquake scenarios

As discussed in Section 3.3.4, there is considerable uncertainty in the estimation of seismic hazard for Christchurch city, and it is possible that values assumed for design values may reduce to less conservative levels in future. Accordingly, the current study took a “consequences first” approach – considering a series of simple earthquake scenarios to assess the potential consequences. This initial focus on consequences provides a useful starting point for broad discussions with stakeholders, and can be used to develop a good understanding of the relevant issues and potential mitigation options before progressing into more detailed analysis (if required) of the likelihood of particular events occurring.

The distribution of liquefaction-induced ground damage response curves for each sub area were computed over a range of Peak Ground Acceleration (PGA) values from 0.0 to 0.8 g for a design earthquake event with a magnitude of M_w=6.0, as shown in Table 4.3. This envelopes the full range of earthquake scenarios identified in Section 3.3.4, allowing the estimated ground damage to be readily interpolated for any PGA value across the range.

The likelihood values for each scenario listed in Table 4.3 have been estimated using the Bradley (2014) seismic hazard model. These likelihoods differ from the conservative MBIE design values in Table 3.3, however these best-estimate likelihood values are considered to be more appropriate for the public awareness purpose of the "Liquefaction Lab" website tool.

Table 4.3: Earthquake scenarios considered in this study.

Peak ground acceleration (g) (Site class D assumed)	**Earthquake magnitude**	**Approximate likelihood in next 50 years**
0.05	6.0	98%
0.10	6.0	79%
0.15	6.0	53%
0.20	6.0	33%
0.25	6.0	20%
0.30	6.0	12%
0.4	6.0	5%
0.5	6.0	2%
0.6	6.0	1%

4.5 Determining expected degree of liquefaction-induced ground damage

4.5.1 Simplified distribution of ground damage response curves

LSN vs PGA ground damage response curves

Once the initial sub areas had been defined, liquefaction-induced ground damage response curves were computed for each CPT at the groundwater and earthquake scenarios discussed above. This was initially performed using all the collated CPT investigations subject to the filtering presented in Section 3.3.2 and computed using the Boulanger & Idriss (2014) simplified deterministic liquefaction assessment procedure with the Liquefaction Severity Number (LSN) employed for the estimation of ground damage. In general, the default liquefaction triggering parameters were used such as a fines content correction of 0 and an I_C cut-off of 2.6. To provide a non-biased best-estimate starting point for the calibration process, the 50th percentile liquefaction triggering curve (PL50) was used for both the forward-analysis to predict damage and the back-analysis to set damage index LSN thresholds as shown in Table 4.4.

For each CPT, the ground damage response curve is simply the series of LSN values computed for a set of PGAs at a groundwater scenario (initially just the median). The response curves were then collated for each areas (or to all associated sub areas), producing a distribution of curves. There is dispersion in these curves, which can be substantial in some cases, because of the spatial variability in ground and groundwater conditions and therefore calculated vulnerability across a sub area.

At each PGA increment, a cross-section of the response curves gives rise to a distribution of LSNs. It is possible to characterise this distribution using statistical methods. For this study, the collection of response curves has been characterised in cumulative frequency distribution (CFD) space. That is, LSN values are calculated corresponding to 5% increments from 0 to 100% at each PGA increment. The result is a matrix representation of the liquefaction vulnerability with PGA on the horizontal axis and CFD percentile on the vertical axis. This process is demonstrated in Figure 4.6 which also shows how 15th, 50th, and 85th percentile LSNs values can be quickly obtained by reading horizontally across the matrix.

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

Because the PL50 triggering curve was used for this analysis (to provide un-biased data for calibration), the damage index LSN thresholds reported in previous literature cannot be used here (as they are based on PL85 back-analysis). Also, as outlined in the MBIE/MfE (2017) guidelines, when assigning liquefaction vulnerability categories for an area-wide hazard assessment it is important to account for the uncertainties within the assessment, and the potential consequences of over-estimating or under-estimating the liquefaction vulnerability. Accordingly, Table 4.4 and Appendix J of MBIE/MfE (2017) sets out a philosophy for evaluating performance based on the level of certainty in the estimated liquefaction-induced ground damage.

Taking the MBIE/MfE (2017) uncertainty philosophy into account, for the purposes of the current high-level hazard study we have adopted approximate characteristic LSN ranges for each degree of liquefaction-induced damage as shown in Table 4.4. These ranges were derived from a comprehensive back analysis of ground damage observations from the Canterbury earthquakes, using the available CPTs and the event specific groundwater and ground motion models (refer Tonkin & Taylor (2013) for details of these event models). Optimal LSN thresholds for estimating the severity of ground damage were established using receiver operating characteristic (ROC) analyses (refer Maurer et al., 2015)), taking into account the 85% and 50% confidence levels specified in the MBIE/MfE (2017) performance criteria.

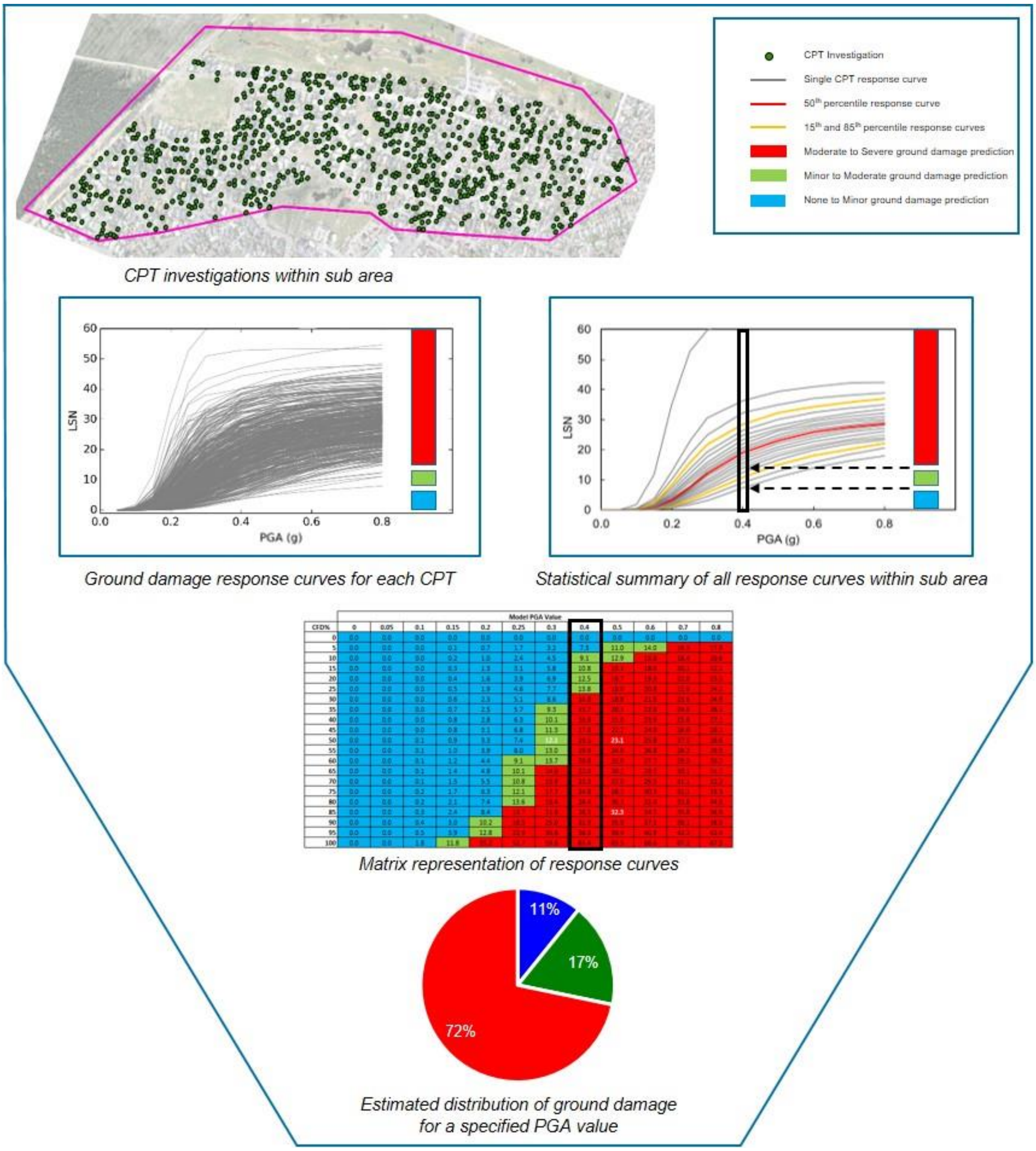
Comparing the distribution of the response curves with these thresholds in Table 4.4 provides an estimation of the ground damage for a given scenario. These thresholds are the basis for the colourisation of the matrix shown in Figure 4.6, to represent the degree of ground damage.

Table 4.4: LSN ranges used to estimate liquefaction-induced ground damage.

LSN range ***Calculated using the 50th percentile liquefaction triggering curve (PL_{50})***	**Typical range of liquefaction-induced ground damage**
0 – 9	*None to Minor*
9 – 14	*Minor to Moderate*
> 14	*Moderate to Severe*

NOTES:

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



CPT investigations within sub area

Ground damage response curves for each CPT

Statistical summary of all response curves within sub area

Matrix representation of response curves

Estimated distribution of ground damage for a specified PGA value

Figure 4.6: Distribution of ground damage response curves and associated matrix representation for an example sub area used in this study.

4.5.2 Calibration of liquefaction-induced ground damage response curves

The simplified CPT-methods have inherent tendencies to miss-predict, most commonly in the form of over-prediction, when used in ground conditions outside of those from which they were developed. This has now been recognised in a number of studies (Cubrinovski et al., 2017; Mellsop, 2017; Ogden, 2018) all of which highlighted the conditions in which the likelihood of incorrect predictions increased. These conditions include, but are not limited to, the following:

- Incorrect characterisation of liquefaction resistance of soils which deviate from clean sands through the CPT investigation method.
- Complex soil profiles where soil layer interactions and system response are not adequately captured by the simplified analysis methods.
- Shallow groundwater depths causing hypersensitive vulnerability parameters to be calculated (especially in the LSN framework which contains a hyperbolic function).
- Erroneous estimation of the cyclic shear stresses from within the soil profile.
- Complex groundwater flow conditions such as non-hydrostatic pressure profiles and disturbance of soil fabric development from an underlying artesian aquifer.

Because of this, any liquefaction vulnerability model developed directly from the CPT-based methods will be subject to the same limitations. For the most part in Christchurch, there is an overstating of the liquefaction vulnerability when the results of the simplified analysis are compared against observations through the Canterbury earthquakes. Fortunately the extensive data that is available from the Canterbury earthquakes provides an opportunity to calibrate the simplified analysis results to better reflect the observed ground performance.

The calibration process for this study required manual inspection of all the liquefaction assessment sub areas. Information was compiled pertaining to the observations of land damage, PGA and groundwater for the four main events during the Canterbury earthquakes. Engineering judgement (guided by a defined assessment process) was then used to determine if there was any basis to perform a calibration to the response curves.

The calibration assessment considered a number of aspects which could provide a physical explanation for differences between predicted and observed levels of liquefaction-induced damage, including:

1. Density of land damage observations and CPT investigations along with general comments regarding the nature of the automated model.
2. Any reasons for miss-prediction or uncertainty in the event-specific PGA models.
3. Any reasons for uncertainty in the event-specific and median GWD models.
4. Inspection of a selection of CPT profiles in order to generally describe the soil profile, such that comments about systematic over/under calculation of liquefaction vulnerability can be made.
5. LSN thresholds and if there are any reasons that they may not be appropriate for the polygon being assessed.
6. Hypersensitivity of LSN to shallow groundwater.
7. Influence of lateral spreading exacerbating damage.
8. Bias for CPTs to be located where damage occurred (as often CPTs were undertaken to inform assessment and repair of damage).
9. Variation from person to person undertaking the ground damage mapping giving a systemic overstating or understating of severity.
10. Extrapolation of land damage from road-based and aerial mapping for June and December events.

The outcome from understanding the above is a justification (or no-justification) for scaling the model up or down or for shifting helper points which are utilised in the subsequent calibration process. Helper points, crosses in Figure 4.7, were calculated for each of the 4 main events of the Canterbury earthquakes by translating the observed levels of land damage into LSN values through back analysis. By comparing these helper points with the response curves and considering the justification factors listed above, a 3-step calibration process was then applied to better align the model with the observations.

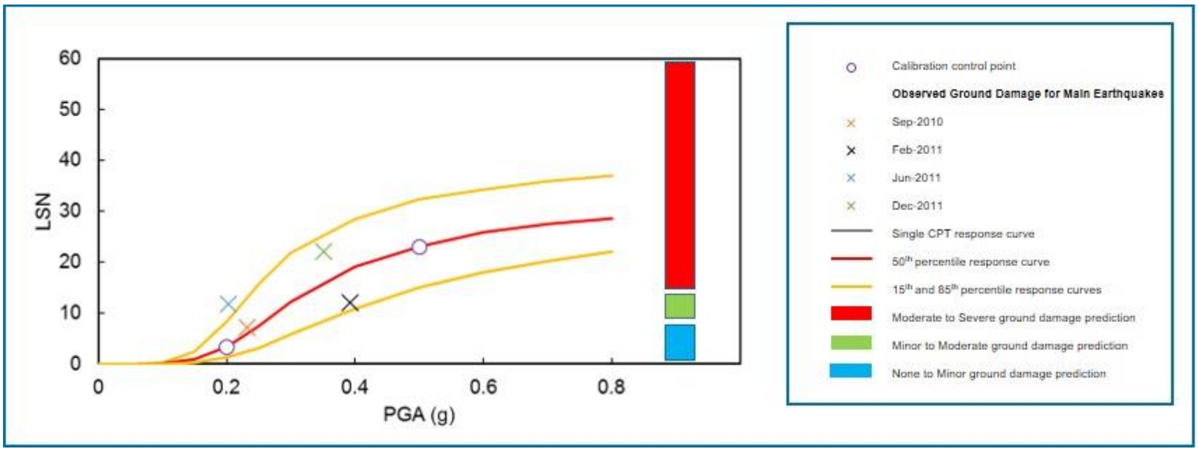


Figure 4.7: Example distribution of response curves (15,50th and 85th percentiles) and helpers (crosses) representing event-specific back analysed LSN values. If there is justification for calibration, then these helpers are used as reference points to transform the ground damage matrices to better align prediction and observation.

The objective for the process is to translate the response curves (or matrices), in a way that is physically consistent with the justification factors, such that the proportions of land damage (***None to Minor***, ***Minor to Moderate***, and ***Moderate to Severe***) better align with the proportions of land damage observed during the events of the Canterbury earthquakes.

Each of the steps targets a particular characteristic of the response curves:

- ***Step 1 – Shift trigger PGA left/right.*** If there is justification for early or late liquefaction triggering compared to what is calculated directly from the CPT-based methods, then the point at which the response curves start to rapidly increase with PGA can be shifted horizontally. For example, where the resistance of the soil profile is misrepresented by the LSN parameter and a more significant level of ground shaking is required to generate material forms of land damage.
- ***Step 2 – Scale overall severity up/down.*** The most commonly applied transformation to the matrices is a vertical shift in order to increase or decrease the predicted severity of ground damage. For example, where the soil profile comprises thin interbedded silt and sand layers the simplified analysis may over-predict the surface consequences of liquefaction.
- ***Step 3 – Increase/decrease variability in predicted severity.*** This transformation is used to better match the variability in performance predicted by the CPTs to the observations. The 15th and 85th percentile curves are used as references for increasing or decreasing the variability below and above the median, and can be independently lowered or raised while the median is kept fixed. Transformations are linearly distributed between the 15th and 85th percentile response curves.

The distribution of ground damage response curves is then translated into a liquefaction vulnerability category according to the MBIE/MfE(2017) guidance. This is discussed in more detail in Section 4.8.

Figure 4.8 presents an example comparing observed and predicted distributions of land damage. Appendix D presents case studies of the calibration process for three example sub-areas with different liquefaction characteristics.

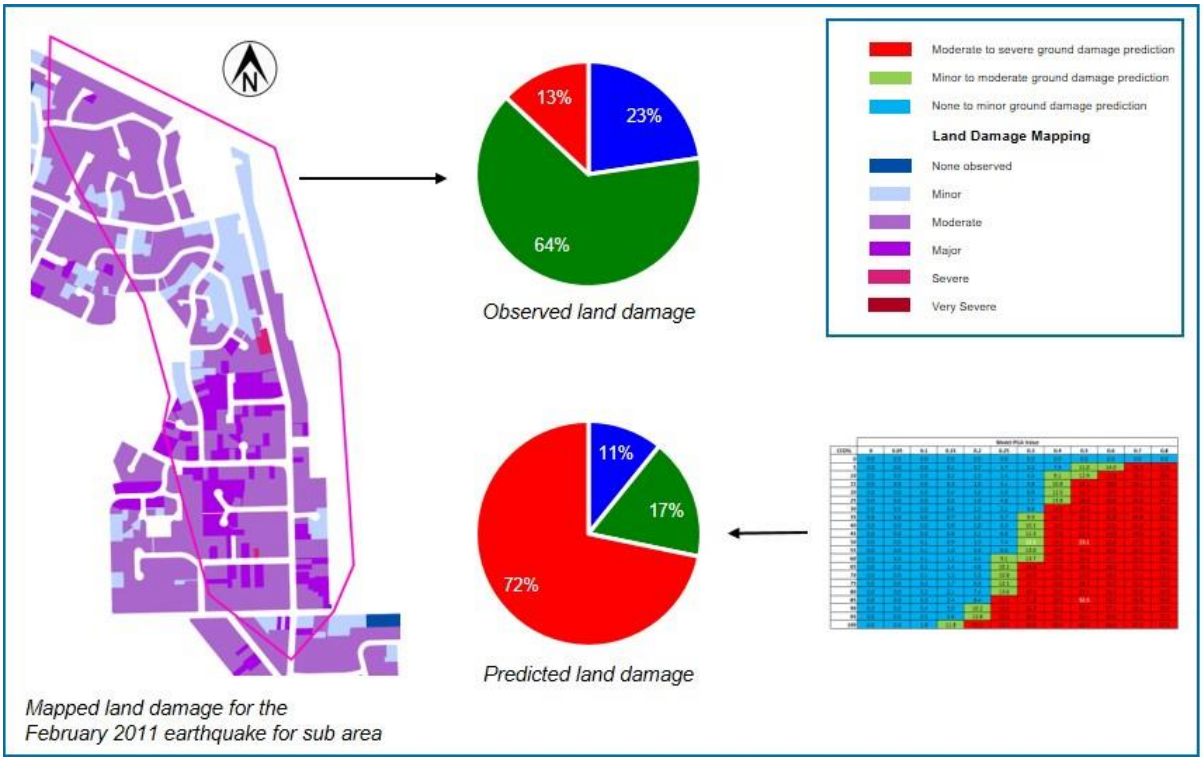


Figure 4.8: Observed and predicted land damage distributions for a particular sub area prior to the calibration process.

4.5.3 Lateral spreading adjustments

The initial calibration of the liquefaction-induced ground damage model was based on “level-ground” seismic performance, as the simplified analysis of CPT data that formed the basis of the response curves does not make any allowance for the increased severity of damage that can result from lateral spreading.

Once the response curves for “level-ground” seismic performance were calibrated, an adjustment to the predicted distribution of ground damage was applied for sub areas identified as having the potential for lateral spreading to occur (refer to Figures 4.4 and 4.1). This adjustment shifted the ground damage response curves (for all percentile bands) upwards, which results in a higher proportion of moderate to severe ground damage being predicted for the sub area.

The magnitude of the lateral spreading adjustment varied depending on the PGA for the earthquake scenario being analysed. For low PGA values (less than 0.15g at M_w=6.0) no adjustment was made, reflecting the observation that there is a threshold strength of shaking required to trigger sufficiently extensive liquefaction to allow lateral spreading to mobilise. For high PGA values (more than 0.5g at M_w=6.0), the adjustment resulted in a shift in the predicted distribution of ground damage equivalent to an increase of 5 LSN points.

4.5.4 Groundwater adjustments

Groundwater adjustments are needed for prediction of ground damage in scenarios with deeper and shallower groundwater. These adjustments were calculated as the difference in LSN values for groundwater levels 1 m deeper, 1 m shallower and 2 m shallower than the current-day median levels (2014 model).

To mitigate hypersensitivity in the calculated severity index parameters at very shallow groundwater depths, the hyperbolic component of the LSN function was removed (fixed at a value of 1.0) for depths of the soil profile less than 1 m below ground surface. The computed adjustments were then modified according to the model calibration applied for the respective sub area before a manual review of the adjustments was applied. Where appropriate, adjustments were changed in order to better reflect expected ground damage performance. For the plus/minus 0.5 m groundwater scenarios, adjustments were obtained by linearly interpolating between the median and the plus/minus 1 m cases. This interpolation approach was adopted, rather than a strict calculation of these LSN increments from the CPT data over 0.5 m increments, to avoid implying more precision than can be supported given the considerable uncertainty in groundwater level and spatial variations in soil profile.

For an example of how the groundwater affects the predicted ground damage see Figure 5.4.

4.6 Model validation

The liquefaction vulnerability model was validated by comparing charts and maps of predicted and observed ground damage for the September 2010 and February 2011 earthquake events. Where significant discrepancies were identified, the base information was revisited to explain the difference and accept the model result, or the model was re-calibrated in order to more appropriately reflect the observations of ground damage.

An example from one part of the model validation process is shown in Figure 4.9:

- Panels (a) and (b) of Figure 4.9 show the observations from property-by-property mapping of liquefaction-induced ground damage in the September 2010 and February 2011 earthquakes.
- These observations were aggregated over each liquefaction vulnerability sub-area to determine the proportion each sub-area affected by ***None to Minor***, ***Minor to Moderate***, and ***Moderate to Severe*** land damage. This distribution of damage for each sub-area was converted into the summary maps in panels (c) and (d) of Figure 4.9, using the 7-step gradational scale shown in Figure 5.2.
- The calibrated liquefaction model was run using the estimated pattern of earthquake shaking intensity experienced across the city in the September 2010 and February 2011 earthquakes (i.e. an event-specific PGA value was analysed for each sub-area independently). The predicted distribution of liquefaction-induced land damage in each sub-area was then mapped in panels (e) and (f) of Figure 4.9, using the same 7-step gradational scale.

Because of the nature of the assessment, the various uncertainties of the base information and the complexities associated with estimating liquefaction-induced ground damage there will always be some degree of miss-alignment between what this model estimates and that which was observed during the Canterbury earthquakes. Throughout the liquefaction assessment and notably in the calibration process we have endeavoured to strike a balance between the layers of base information, which at times can be at odds with the observed ground damage.

For example, Figure 4.9 shows that the calibrated model shows a slight tendency to over-predict damage in the southern part of the city compared to observations from these two particular earthquake events. This is because the observed performance was often better than suggested by simplified CPT-based liquefaction analysis. However, when calibrating the model we aimed to strike a balance between this conflicting information. We could not ignore the analytical information which suggested liquefaction damage was possible and simply adjust the model to perfectly match observations from one event (which might provide a more inaccurate prediction for other events). We only adjusted the CPT-based analysis model to the degree that could be justified by an understanding of the physical reasons why the observed performance was different to the analytical prediction.

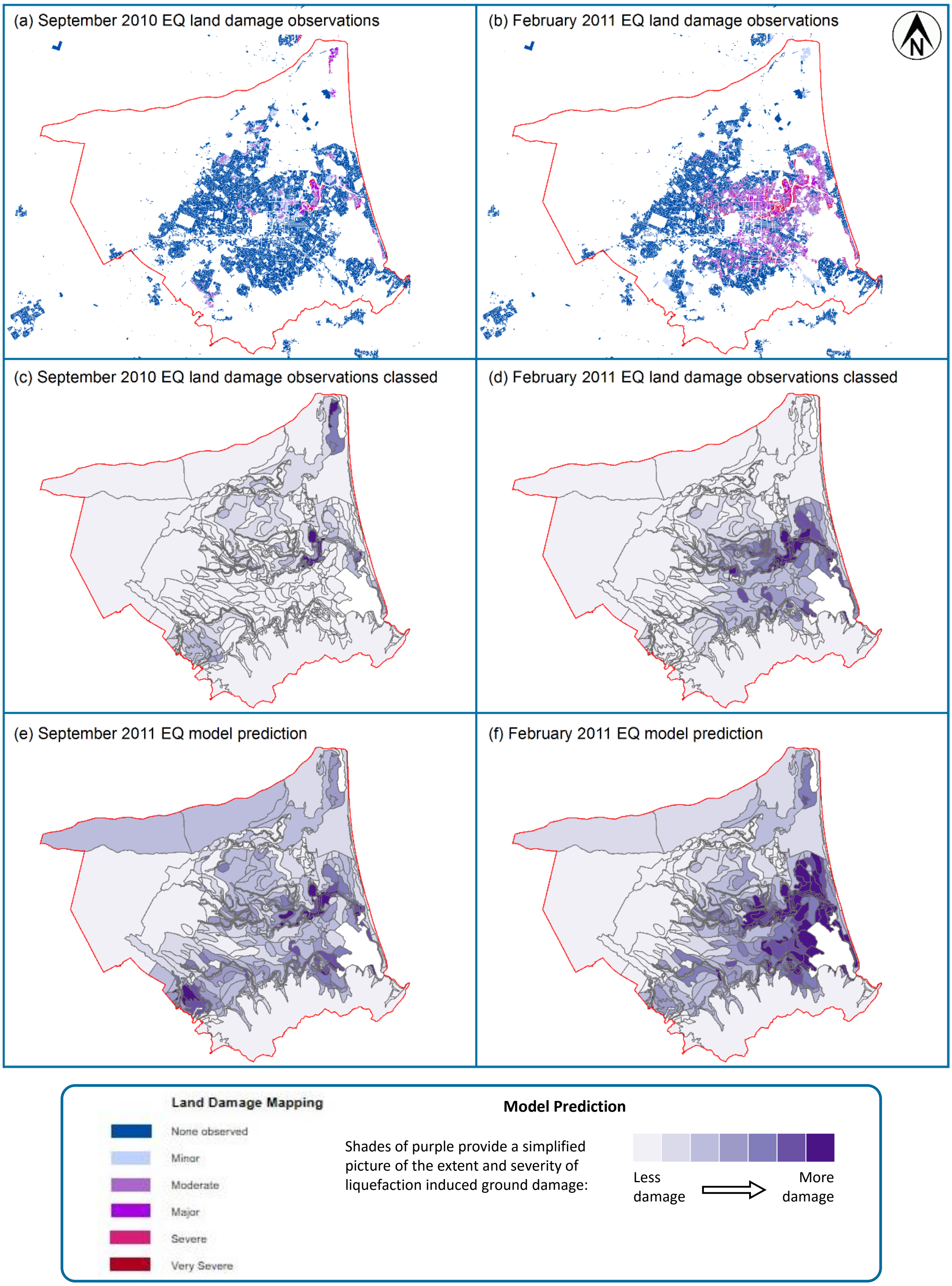


Figure 4.9: Comparison of land damage observations and model predictions for September 2010 and February 2011 earthquakes. Refer to Figure 5.2 for more detailed model prediction legend. Refer to Appendix B for more detailed map and statistical analysis of the prediction accuracy.

4.7 Refinement of liquefaction assessment sub area boundaries

Following calibration and validation of the liquefaction-induced ground damage model, the spatial delineation of each sub area was re-examined to confirm or refine the location of boundaries in the model. This typically involved:

- Slight shifts to the boundaries to better distinguish areas with different expected ground performance, particularly at the boundaries between ***Low***, ***Medium*** and ***High*** liquefaction vulnerability.
- Splitting large sub areas into smaller sub areas, particularly where detailed ground investigations were available in part of the area (e.g. new subdivisions) while the remainder of the sub area had limited data (so a less precise vulnerability category and lower level of detail needed to be assigned in the final mapping).

The final liquefaction vulnerability sub areas following this refinement are shown in Figure 4.10. This figure also identifies sub areas which are assumed to have the potential for lateral spreading to occur.

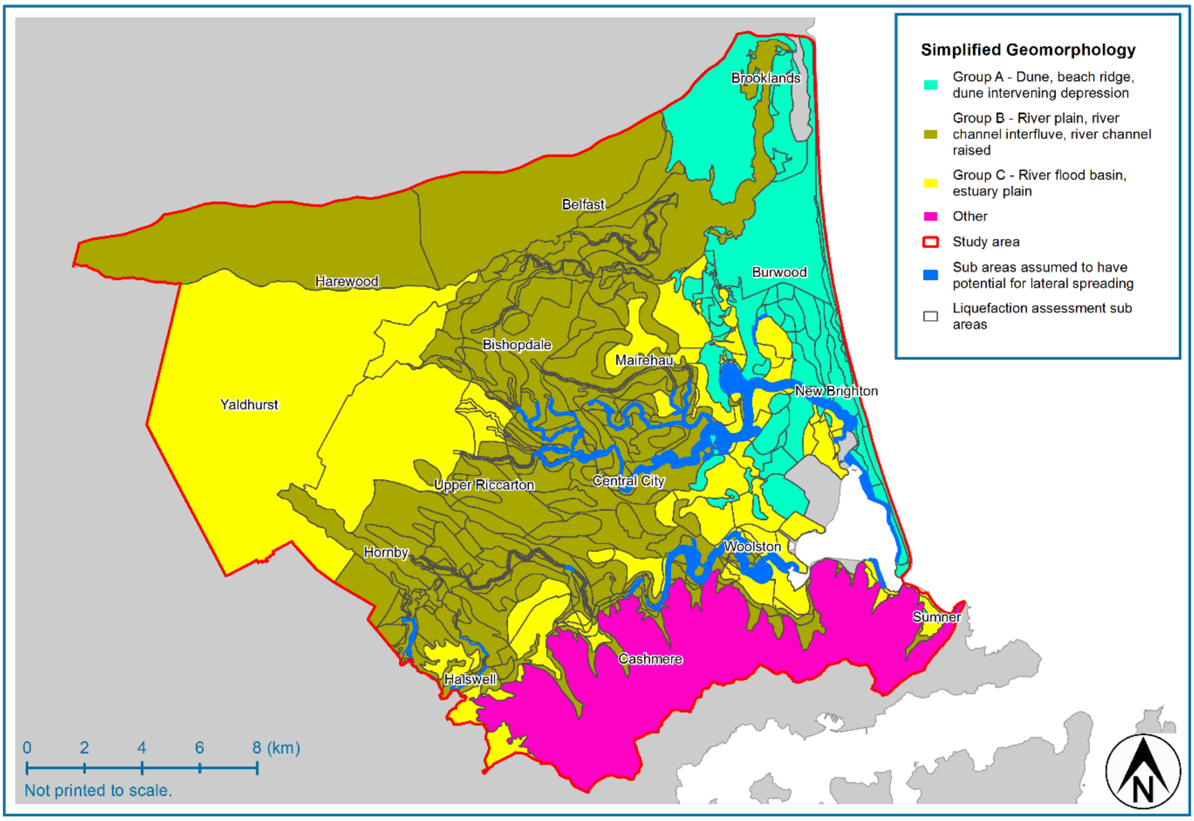


Figure 4.10: Current liquefaction assessment sub areas with those assumed to have potential for lateral spreading identified. Refer to Appendix A for larger map.

4.8 Liquefaction vulnerability assessed against performance criteria

4.8.1 Vulnerability assessment process

For each sub area a liquefaction vulnerability category has been assigned according to the framework recommended in MBIE/MfE(2017), as shown in Figures 4.11 to 4.13.

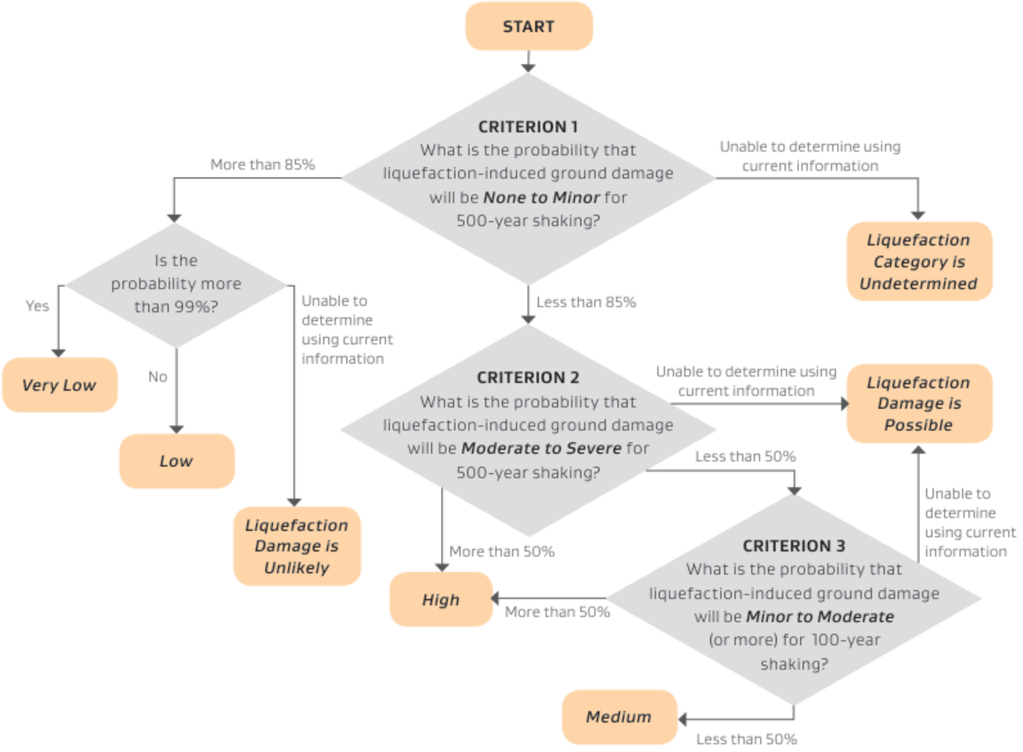


Figure 4.11: Flow chart for determining the liquefaction vulnerability category (from MBIE/MfE 2017).

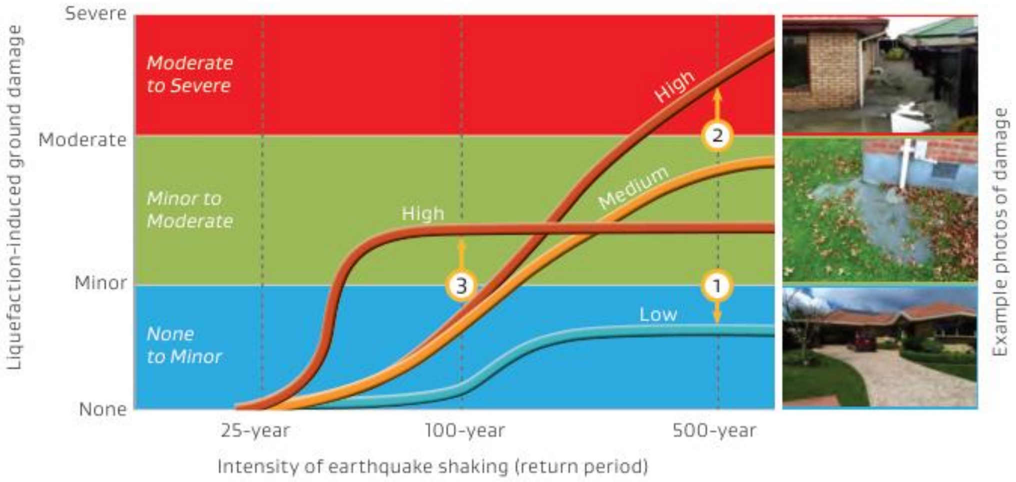


Figure 4.12: Example ground damage response curves for low, medium, and high liquefaction vulnerability categories, and performance criteria used for liquefaction categorisation (from MBIE/MfE, 2017).

4.8.2 Results

The end result of the assessment against the performance criteria is the assigned liquefaction vulnerability categories shown in Figure 4.14.

Taking into account the residual uncertainty for the categorisation of each sub area, achieved levels of detail have been designated as shown in Figure 4.15.

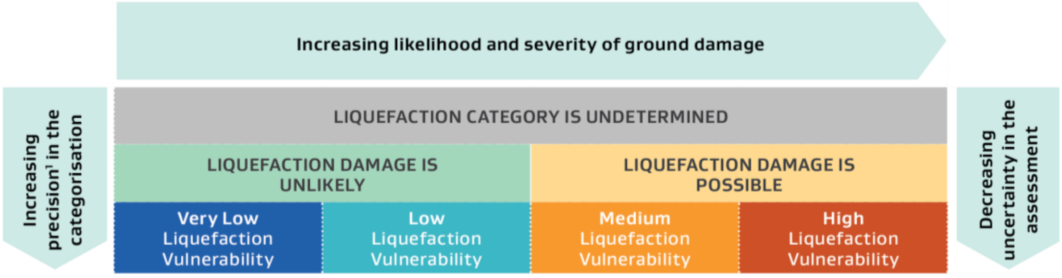


Figure 4.13: Liquefaction vulnerability categories (reproduced from MBIE/MfE, 2017).

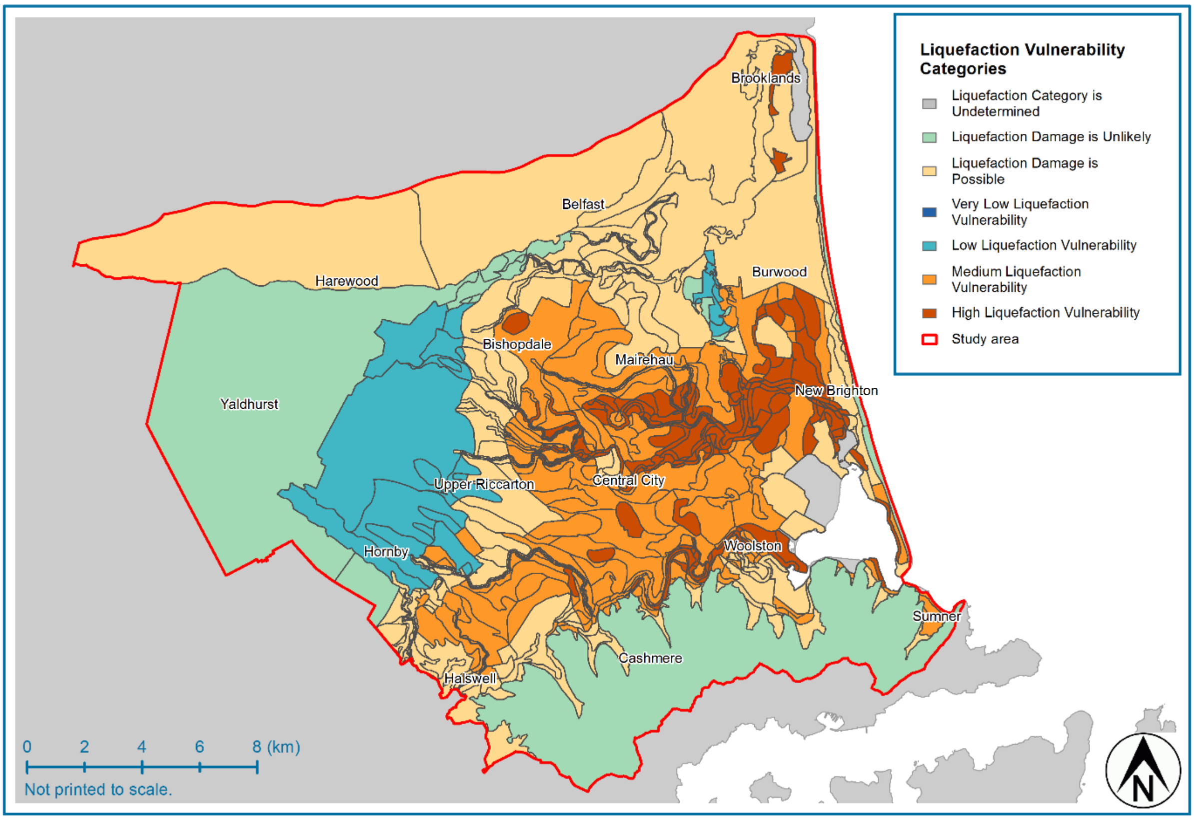


Figure 4.14: Liquefaction vulnerability categories for Christchurch city assigned in this study. Refer to Figure 4.13 for map legend. Level of detail in the assessment varies between Level A and Level C (refer Figure 4.15). Refer to Appendix B for larger map.

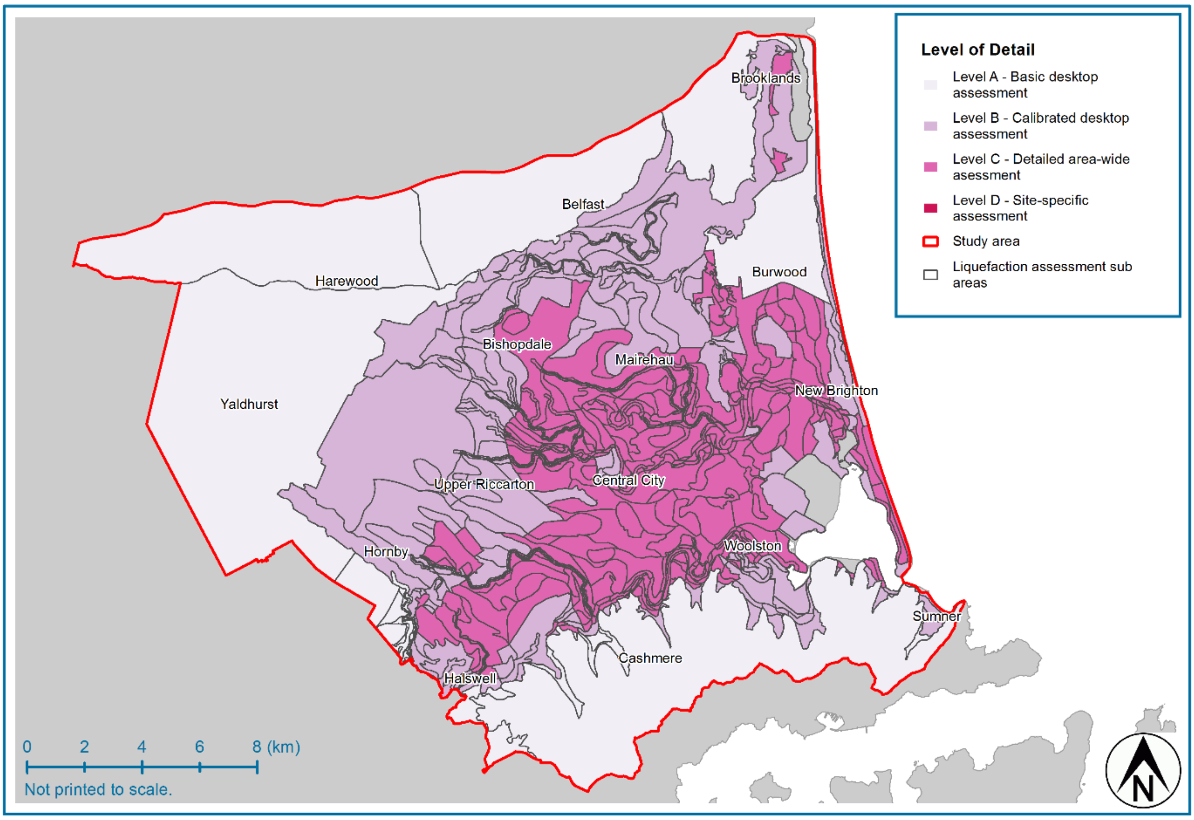


Figure 4.15: Level of detail supported by currently available base information, for the liquefaction vulnerability categories for Christchurch city determined through this study. Refer to Appendix B for larger map and a map comparing the ideal and the achieved level of detail.

4.8.3 Discussion

While for the most part the liquefaction vulnerability map in Figure 4.14 is self-explanatory and broadly consistent with previous liquefaction studies, there are several locations across the city where further discussion may be useful to explain the rationale for the assigned categories. These locations are identified with labels A to F in Figure 4.16 and discussed below.

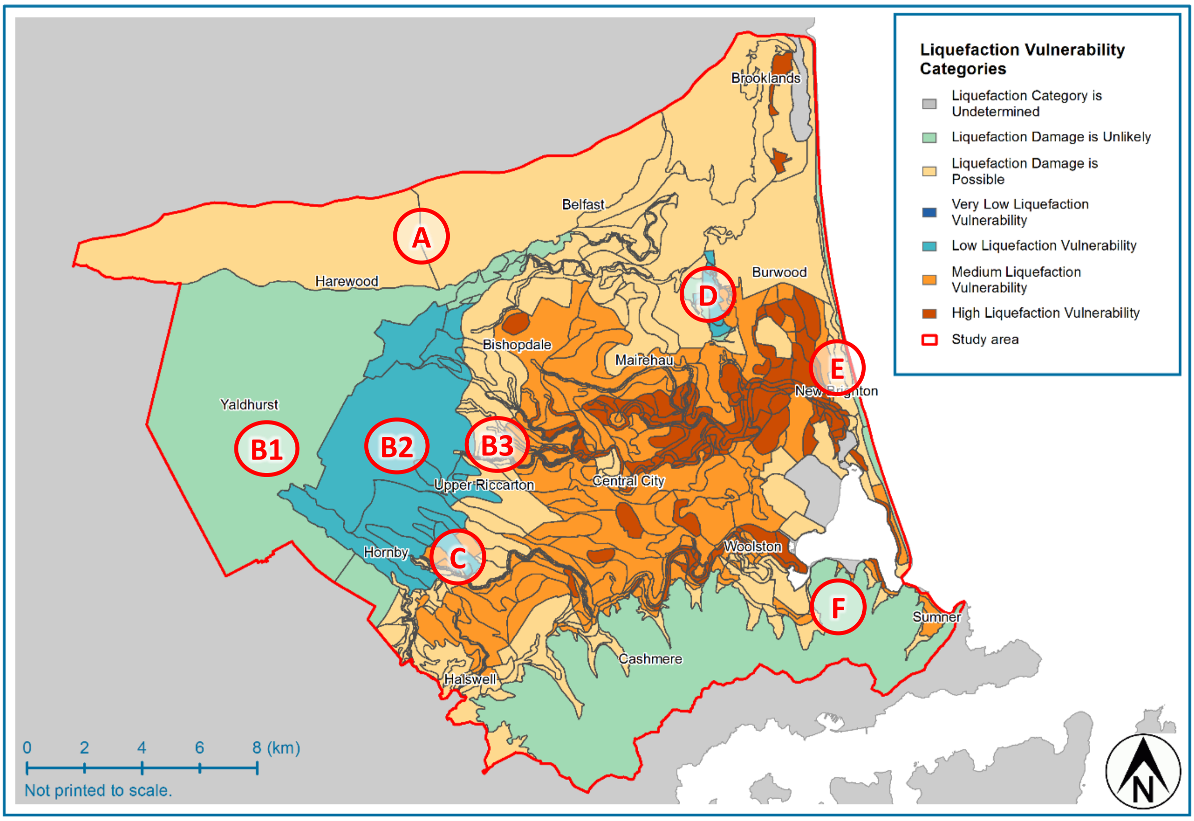


Figure 4.16: Liquefaction vulnerability categories for Christchurch city assigned in this study, showing locations discussed in Section 4.8.3. Refer to Figure 4.13 for map legend.

Area A – Lower terrace of Waimakariri River flood plain

These sub-areas have been assigned a vulnerability category of ***Liquefaction Damage is Possible***, in contrast to the neighbouring sub-areas to the south which were assigned ***Liquefaction Damage is Unlikely***. While the ground conditions in these sub-areas might appear similar at first glance, there is greater uncertainty in the northern sub-areas, which means that these did not meet the Criterion 1 criteria of more than 85% certainty specified in Figure 4.11. These sub areas are identified on the GNS geomorphic map as the most recent river plain (Yaldhurst 3 surface, ya3). The geomorphic description notes that this channel has carried river floodwater in recent history and was the Waimakariri River South Branch prior to 1868. The ground in this area is lower-lying than the older river terrace to the south, and as shown in Figure 3.9 the groundwater level in this area is typically shallower than 2m below ground. These features mean that there is more potential for younger liquefaction-prone soils to be present at some locations within in this sub-area.

Area B – Western Christchurch

The liquefaction vulnerability categories on the western side of the city reflects both the relative uncertainty in the base information and gradual changes in the ground conditions from West to East:

- **Area B1:** In this rural part of the study area there is little quantitative information about the ground conditions, so the liquefaction assessment was undertaken at a detail of Level A (the least detailed assessment level). However, known geology and topography indicates that the soil profile is typically gravel-dominated with deep groundwater. So despite the lack of detailed information it is possible to assign a vulnerability category of ***Liquefaction Damage is Unlikely***. Because of the lack of detail it is not possible to assign a more precise category (i.e. from the bottom tier of the hierarchy shown in Figure 4.13).
- **Area B2:** In this area there was more detailed information available regarding ground conditions and groundwater levels (including historic information from the ECan wells database) and more detailed earthquake damage observations, meaning that a Level B assessment could be undertaken. The analysis of this information was sufficiently conclusive to allow a more precise category of ***Low Liquefaction Vulnerability*** to be assigned.
- **Area B3:** In this area there is a gradual transition in ground conditions, with liquefaction vulnerability increasing from West to East. Ground conditions towards the West are dominated by deep groundwater and shallow gravel. Ground conditions towards the East are dominated by shallower groundwater and silt/sand soils. Across most of this area there was no visible surface evidence of liquefaction having occurred during the Canterbury earthquakes. However, analysis of the available ground information suggests that the potential for liquefaction cannot be completely ruled out at this stage so a category of ***Liquefaction Damage is Possible*** has been assigned to reflect this uncertainty. The current assessment is based on a calibrated desktop assessment (Level B). In future, more detailed area-wide assessments (Level C) or site-specific assessments (Level D) may reduce this uncertainty to a level where a different vulnerability category (e.g. *Low*) could be assigned in some locations.

Area C – Wigram subdivisions

In this area the vulnerability map shows a sharp transition between ***Low*** and ***Medium Liquefaction Vulnerability***. At first glance this could appear inconsistent with the adjacent areas of the map, which has a band of *Liquefaction Damage is Possible* running from Halswell to Belfast which represents the uncertainty in the transition from *Low* to the West and *Medium* to the east. It has been possible to map a more precise delineation of liquefaction vulnerability in this particular area because of the extensive ground investigations undertaken as part of post-earthquake subdivision development.

Area D – Marshland subdivisions

In this area the vulnerability map shows ***Low Liquefaction Vulnerability***, which at first glance might appear inconsistent with the mapped liquefaction vulnerability of the surrounding land. At this specific location there are three key factors which together provide sufficient certainty to assign this vulnerability category:

- Extensive ground investigations undertaken as part of post-earthquake subdivision development indicate that the ground conditions are dominated by dense dune sand deposits.

- Post-earthquake aerial photography shows no visible surface evidence of liquefaction having occurred during the Canterbury earthquakes.

- Shallow ground improvement works were undertaken as part of subdivision earthworks.

Area E – Coastal margin

The liquefaction vulnerability categories along the eastern coastal margin of the city reflects both the relative uncertainty in the base information and gradual changes in the ground conditions from East to West:

- The high-energy depositional environment means that the coastal sand dunes are expected to be well compacted, the elevation of the dunes above sea level means that groundwater is expected to be deep, and there was no surface evidence of liquefaction having occurred in the Canterbury earthquakes. This provides sufficient certainty to assign a vulnerability category of ***Liquefaction Damage is Unlikely***, but a lack of quantitative information (e.g. CPT testing) means that a more precise category (e.g. *Low*) cannot be assigned.
- Moving westwards from the coastal dunes there is a transition to inter-dune troughs deposits which are more vulnerable to liquefaction. However, the low density of ground investigations, variability in ground conditions, and masking of the original geomorphology by land development means there is insufficient certainty to delineate a sharp transition between *Low* and *Medium*/*High* vulnerability categories. This uncertainty is reflected in the ***Liquefaction Damage is Possible*** category assigned to this area. In future, more detailed assessments may reduce this uncertainty to a level where a different vulnerability category (e.g. *Low*) could be assigned in some locations.

Area F – Heathcote

This residential area at the bottom of the Heathcote valley has been assigned a category of ***Medium Liquefaction Vulnerability***, which at first glance appears inconsistent with the less precise category of *Liquefaction Damage is Possible* assigned to the industrial/rural land to the north/west and the valley floor further upslope to the south. It has been possible to assign this more precise vulnerability category because of the more detailed information available from CPT testing and land damage mapping. In comparison:

- For the industrial/rural land there is a low density of ground investigation and there was limited ground-based mapping (and interpretation from air photos was difficult because of the nature of the land uses). This means there was insufficient certainty to distinguish between *Medium* and *High* vulnerability.
- For the upslope valley floor areas there remains uncertainty regarding the potential for liquefaction or cyclic softening to occur (a potential contributing factor to toe slump damage observed in mass movement areas around base of the Port Hills). This means there was insufficient certainty to distinguish between *Low* and *Medium* vulnerability.

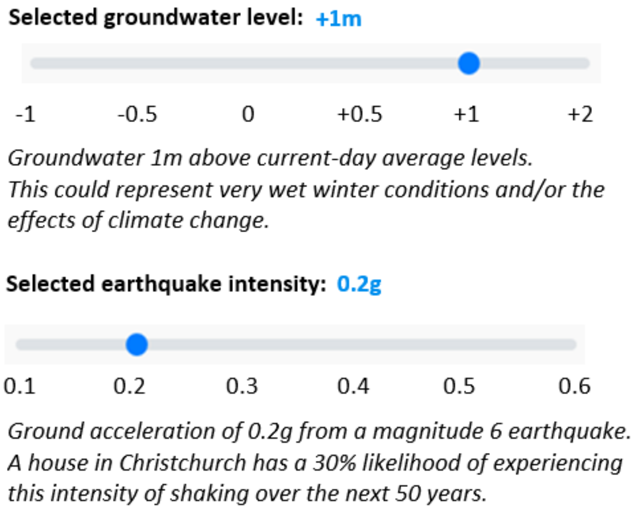
5 Communication and consultation

One of the intended outcomes of the study is to provide technical information to support public awareness initiatives. This includes an online liquefaction awareness “Liquefaction Lab” tool, along with associated story-maps which describe the observed consequences of liquefaction during the Canterbury earthquakes and the base information used for this study. In future this website could be expanded to include further resources about liquefaction, and to provide information and collect feedback as part of engagement and consultation processes.

5.1 “Liquefaction Lab” public awareness website tool

The calibrated liquefaction-induced ground damage response model presented in Section 4 allows a range of earthquake and groundwater scenarios (and the associated uncertainties) to be explored in the “Liquefaction Lab” public awareness website tool.

This tool communicates the spatially varying nature of the liquefaction hazard across Christchurch city. Users can select different combinations of scenarios (refer Figure 5.1) to see how variation of these parameters can result in significant differences in the severity of ground damage that occurs.



Selected groundwater level: +1m

Groundwater 1m above current-day average levels.
This could represent very wet winter conditions and/or the effects of climate change.

Selected earthquake intensity: 0.2g

Ground acceleration of 0.2g from a magnitude 6 earthquake.
A house in Christchurch has a 30% likelihood of experiencing this intensity of shaking over the next 50 years.

Figure 5.1: Selecting ground and shaking scenarios on the "Liquefaction Lab" website.

When the user selects scenarios, the tool updates the map to represent the modelled distribution of liquefaction-induced ground damage. The relative proportions of the three different degrees of damage (refer Table 4.4) is represented by a 7-step gradient colour scale as shown in Figure 5.2. Users can also click on any of the liquefaction assessment sub areas to view a pie chart showing the modelled distribution of damage. Figure 5.3 demonstrates the results for a current-day median (2014 model) groundwater scenario at 0.3 g, while Figure 5.4 shows how the results vary in response to different groundwater and shaking levels.

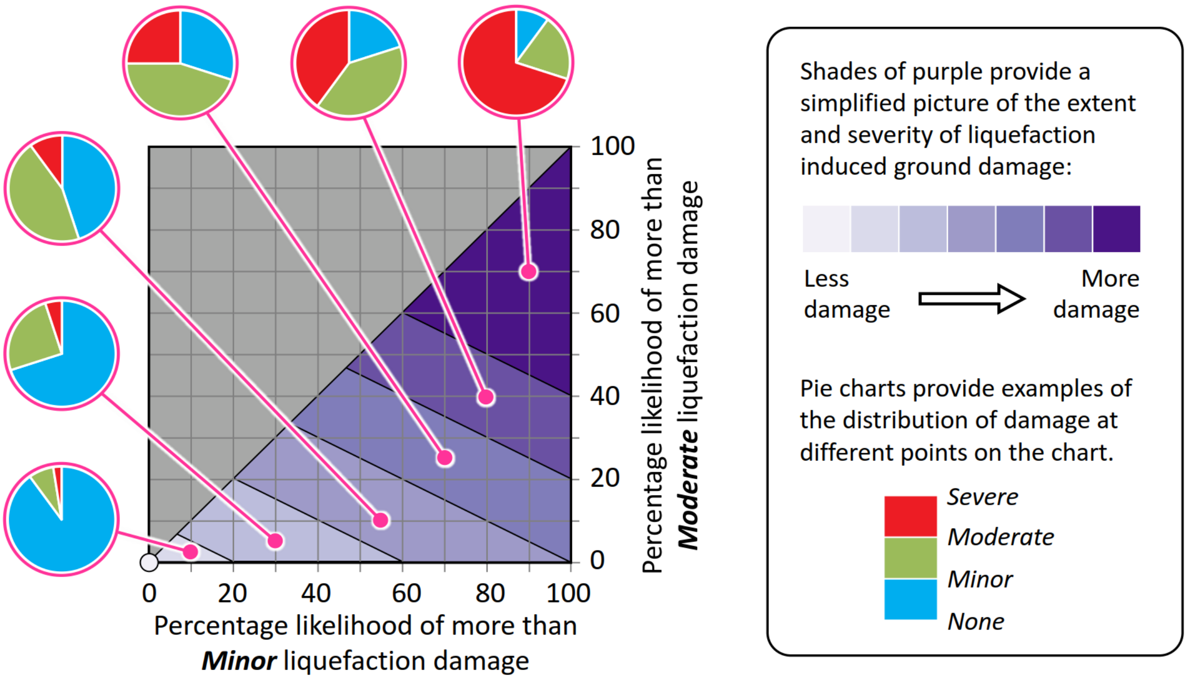


Figure 5.2: Colouring of sub areas for the "Liquefaction Lab" for the various distributions of predicted liquefaction-induced ground damage.

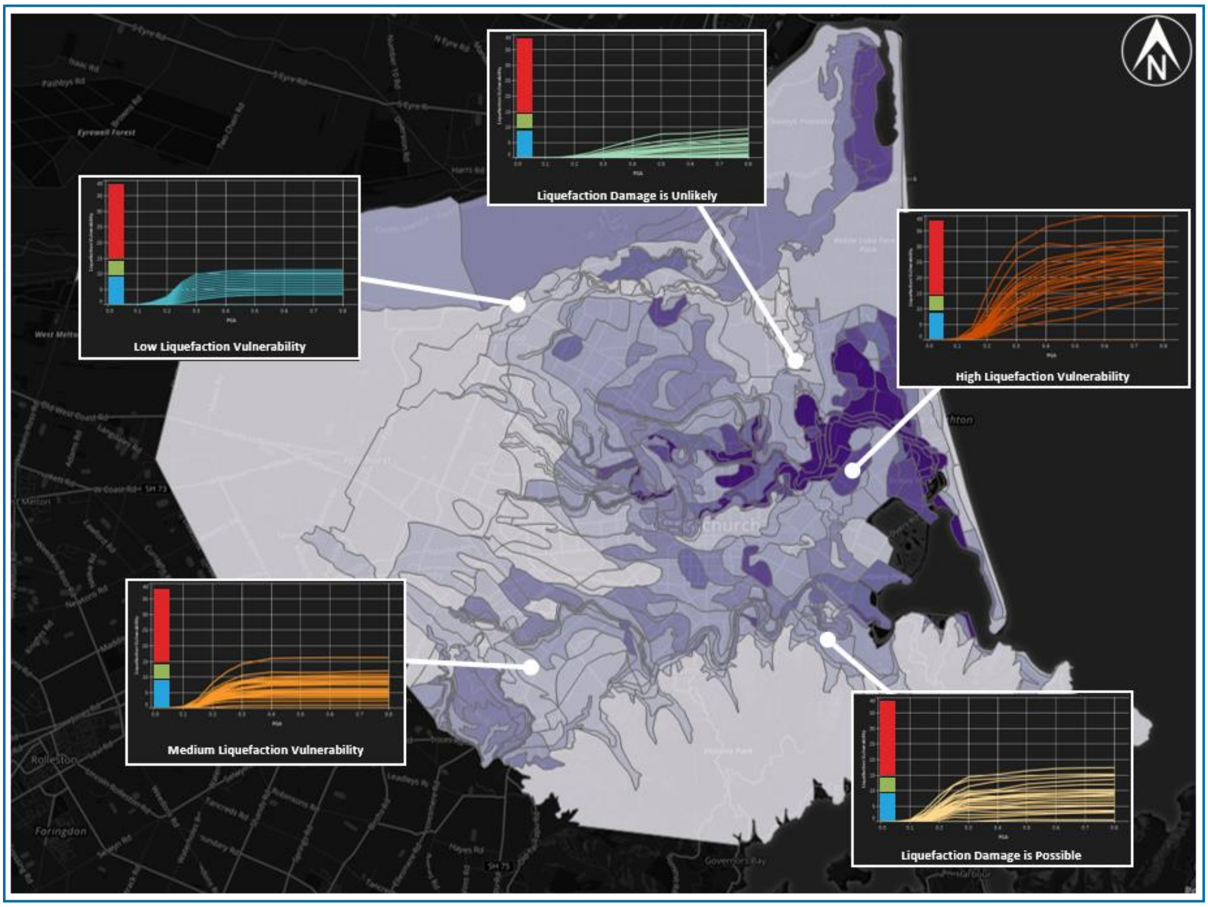


Figure 5.3: Example of the liquefaction vulnerability data driving the "Liquefaction Lab" public awareness website tool, for a current-day median (2014 model) groundwater scenario at 0.3 g. Also shown are distributions of liquefaction damage response curves for some example sub areas, highlighting the spatially varying liquefaction vulnerability. Refer to Figure 5.2 for legend.

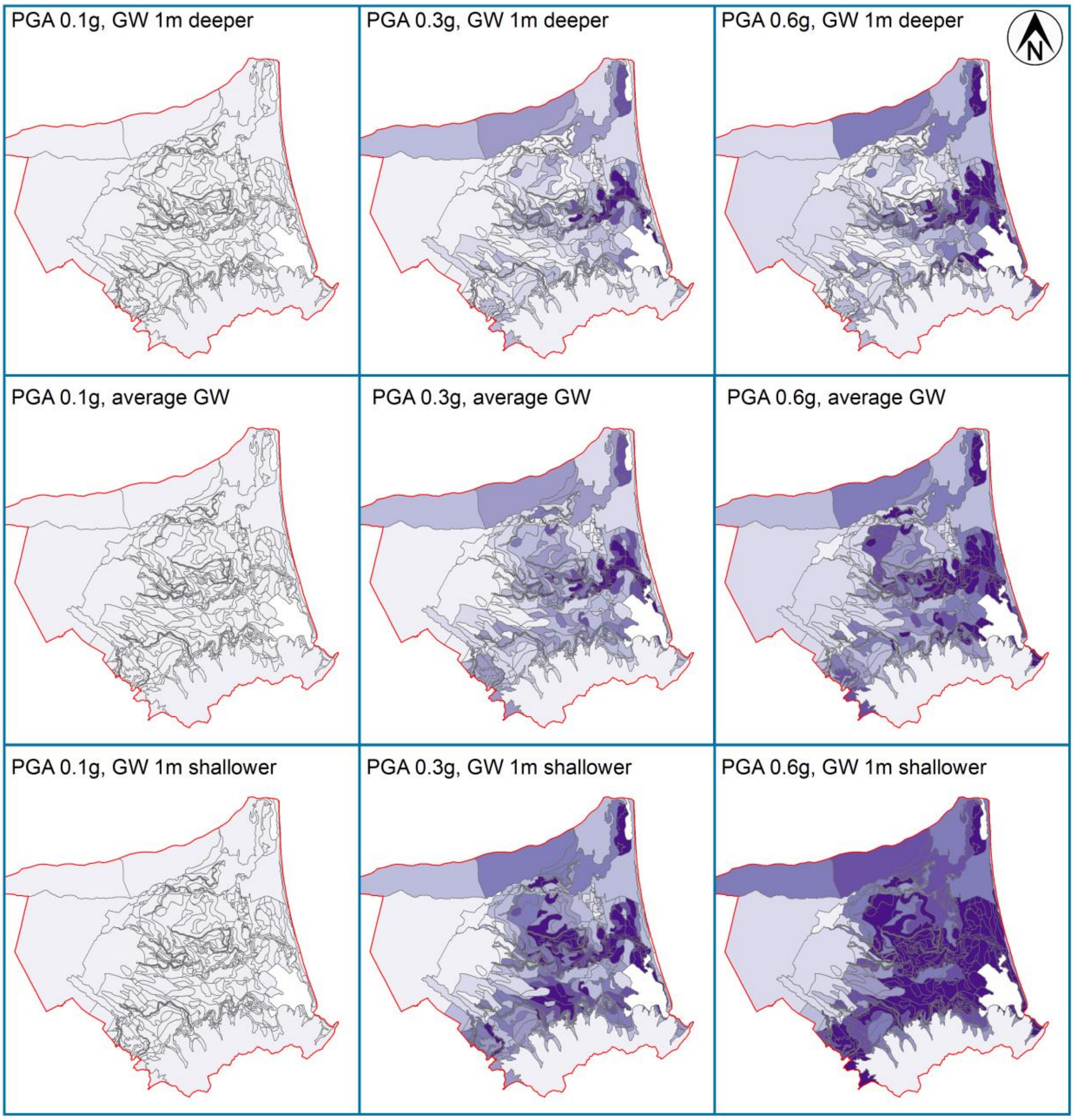


Figure 5.4: Example ground damage scenarios from the "Liquefaction Lab" public awareness website tool. Three shaking scenarios (0.1, 0.3 and 0.6g) are presented, combined with three groundwater scenarios (1 m below current-day median levels (2014 model), current-day median, and 1 m above current-day median levels). Refer to Figure 5.2 for legend. Refer to Appendix C for larger map.

6 Risk evaluation and risk treatment

6.1 Scope of the current assessment

The scope of the current liquefaction assessment is focussed on the technical aspects of identification and analysis of liquefaction-related risk. The Liquefaction Vulnerability Study provides base hazard information, which is intended to inform a wide range of purposes. In general, the use of this information will include a stage of interpreting and evaluating the information as it relates to the specific context (e.g. building consent, resource consent and district plan).

This study does not seek to draw conclusions about how this risk should be managed. Rather, this technical information should help inform the broader considerations of risk evaluation and risk treatment decisions, where the effects of liquefaction and potential management options can be weighed up alongside other factors that impact on the community's objectives.

6.2 Incorporating this hazard information into existing risk treatment options

As outlined in Section 2.3, Christchurch already has an existing framework for managing liquefaction-related risk, established by various policy, planning and consenting processes and updated following the Canterbury earthquakes. This means that much of the background work associated with risk evaluation and risk treatment decisions has been previously undertaken. Accordingly, the updated technical information presented in this study is likely to be of most significance for refining the spatial definition of risk treatments, rather than triggering extensive re-evaluation of the current risk management approach.

For example, in future district plan reviews the current broad-scale definition of the Liquefaction Management Area in the district plan could be updated with the more detailed spatial mapping of liquefaction vulnerability provided by this study. The greater precision in liquefaction vulnerability categorisation could also provide opportunities to refine the existing risk treatment measures to better target assessment and mitigation effort to match the need.

There is an opportunity to incorporate the technical information from this study into council's natural hazards risk management efforts. In doing so, it will be important for all parties to establish a shared understanding of how uncertainties in the technical assessment could impact council's risk evaluation and risk treatment decision-making. This will allow more robust evaluation of potential risk mitigation measures and their likely efficiency and effectiveness.

6.3 The difference between "hazard maps" and "hazard management maps"

There are varied perceptions and understanding of hazard maps and how they can and should be used. It is helpful to distinguish two different types of maps:

- maps that are prepared to capture knowledge and understanding of natural hazard processes in a particular area or location (hazard maps); and
- maps that contain information about the location of different management responses or controls (hazard management maps).

"Hazard maps" capture a lot of different information reflecting the location (physical features) and overlay this with a range of scenarios that show how natural hazard processes interact in that location and how varied the hazard can be. These could include different types and severity of earthquake events or groundwater scenarios. The purpose of these maps is to build understanding of the spatial and temporal variability of the hazard and its potential physical impacts. This information is dynamic, and needs to be frequently updated to reflect new information and test new or different scenarios. The maps can be used to help develop and test possible hazard management options and responses.

"Hazard management maps" capture location-specific information about proposed or agreed management responses. They can demonstrate where, for example, different policy frameworks, rules or consenting pathways apply. They capture the outcome of processes to develop and agree management responses (such as evaluation of benefits and costs of various risk treatment options). Once these are agreed the maps can be included in plans such as under the Resource Management Act 1991 (RMA) or compliance/guidance documents such as for Building Consent. They should only be subject to change that follows the same process of consultation and agreement by which they were developed and agreed. Where these maps are included in RMA plans they have statutory status and can only be changed following formal plan change processes.

6.4 MBIE Technical Categories and District Plan Liquefaction Management Area

The Liquefaction Vulnerability Categories (LVC's) presented in this report do not supersede the 2011 MBIE Technical Categories (TC's) or the Christchurch District Plan Liquefaction Management Area (LMA). They are fundamentally different types of information – the LVC's are a "hazard map", and the TC's and LMA are a "hazard management map":

- The TC's and the accompanying guidance (MBIE, 2015) used the base technical information about liquefaction vulnerability that was known in 2011 (primarily based on observed ground performance) and interpreted this hazard information for the specific context of repair and rebuilding of damaged homes to define a process to manage the hazard which if followed provided "reasonable grounds" that the building code would be met. Section 3.1 of the guidance notes that the TC's were established as a recovery measure and were intended to have a limited life. They were intended to facilitate the recovery by providing an indication of what geotechnical assessments are required, directing scarce engineering resources appropriately and providing guidance on appropriate foundation solutions. The TC's are not a hazard map.

- The LMA is used to establish District Plan policies and rules to manage the hazard by providing for re-zoning, subdivision, use and development on flat land where liquefaction risk has been appropriately identified and assessed, and can be adequately remedied or mitigated.

- The LVC's represent an update of the raw hazard information. However, they do not take the next step that the TC's and LMA did, of interpreting the hazard information for specific purposes such as building consenting and resource consenting.

In summary, the LVC information is one of a range of inputs that will help guide future refinements of Council's building consent processes and district plan provisions.

7 Monitoring and review

The framework for liquefaction vulnerability assessment used in this study has been designed to facilitate the refinement of the liquefaction categorisations across Christchurch city over time as more detailed information becomes available. The liquefaction vulnerability map presented in this report is not intended to be frozen in time, rather it should continually evolve.

This is one of the reasons why the concepts of intended purpose and level of detail are given particular attention in this report. This enables an assessment undertaken at a higher level of detail or for a more specific purpose to take precedence over other assessments. For example, a particular location might be initially categorised as ***Liquefaction Damage is Possible*** with ***Level B*** detail in this current district-wide assessment, then subsequently re-categorised as ***Medium Liquefaction Vulnerability*** in a more detailed ***Level C*** assessment under taken for subdivision consent.

We recommend that Council collate liquefaction assessment information that they receive (e.g. from this current study, and from plan and consent submissions) into a form that can be readily referenced and updated in future. This could be as simple as a list of reports containing liquefaction assessment information, or as sophisticated as a GIS database that maps the extent, liquefaction vulnerability categories and level of detail for each liquefaction assessment in real-time.

This could also provide the ability to monitor the accuracy of the liquefaction vulnerability categories assigned in the current study. If patterns are observed where more detailed assessments indicate higher or lower liquefaction vulnerability than this study, then this could trigger a proactive review of the categories assigned by this study in those areas. Localised review might also be required where land development activities change the natural performance of the land as assessed in this study (e.g. subdivision earthworks and ground compaction).

Monitoring and review should also extend to the appropriateness of the risk evaluation and the adopted risk treatments, as well as any changes in the context or the community’s objectives.

8 Recording and reporting

Table 8.1 summarises a range of potential recording and reporting activities to support the technical information about liquefaction vulnerability from this current study, as well as Council's wider approach to natural hazard risk management.

Table 8.1: Potential recording and reporting activities

Purpose	Potential activities
Communicating risk management activities and outcomes across the organisation.	• Technical briefings for Council elected members and strategy, communications, planning, resource/building consent and customer services staff.
Providing information for decision-making.	• Technical inputs into Council district plan reviews and RMA Section 32 analysis regarding liquefaction vulnerability assessment, risk evaluation and risk treatment options. • Develop a "Land Performance Standard" which clarifies the level of land performance (either of natural ground or after ground improvement work) that Council will require in order for consent to be granted in various situations.
Improving risk management activities.	• Encourage property owners to incorporate improved resilience measures into buildings beyond existing use rights or minimum building standards to avoid or mitigate natural hazards affecting their property. This could include providing information about the location and consequences of liquefaction, and potential cost-effective measures for reducing these consequences.
Providing risk information and interacting with stakeholders.	• Public awareness "Liquefaction Laboratory" website (in development). • Refinement of liquefaction information provided on LIMs. • Developing information resources such as simple factsheets, Newsline articles, media briefings, case studies, workshops, and briefing material for councillors, officials and customer service staff to engage with the community. • Provide open GIS access to the liquefaction vulnerability assessment data for each sub area. For example, this could provide useful background information on key uncertainties to help focus future technical assessment to support land development. • Work with the land development sector to establish land performance expectations and the process for managing evolution of the liquefaction categories over time. • Drawing on feedback from the land development sector (both technical and commercial), and the wider community, regarding the efficiency and effectiveness of adopted risk treatment measures.
Understand risk culture, appetite, and tolerance.	• Collect user feedback from the "Liquefaction Laboratory" website to explore community attitudes to acceptable risks and the need for mitigation.

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10 Applicability

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

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

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

This assessment has been made at a broad scale across the 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 may be required for some purposes (e.g. for design of building foundations).

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