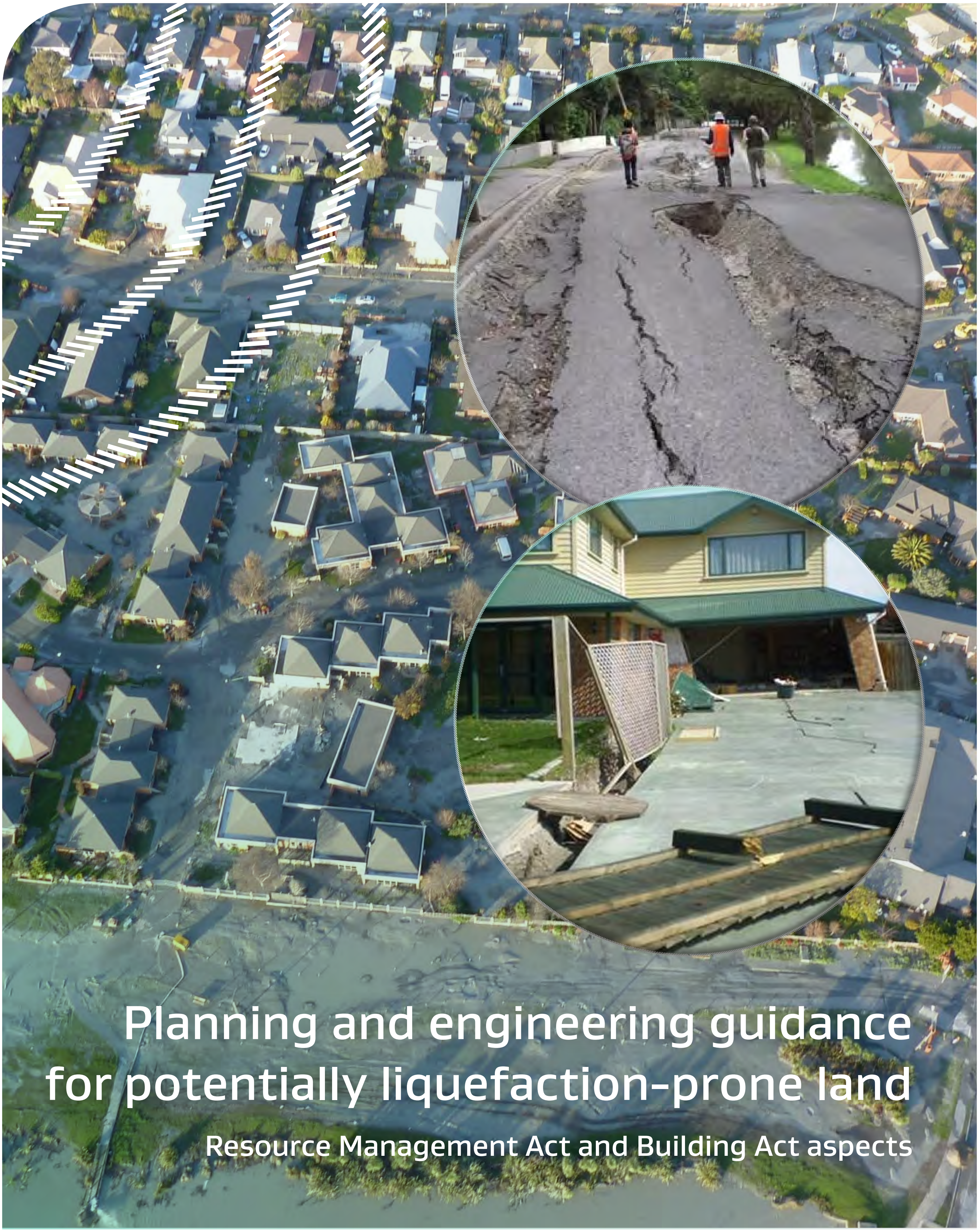

Planning and engineering guidance for potentially liquefaction-prone land

Resource Management Act and Building Act aspects

EQC
EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

Ministry for the Environment
Manatū Mō Te Taiao

Document development

The development of this document was a collaborative effort between the Ministry for the Environment and Ministry of Business, Innovation and Employment in response to the Canterbury Earthquake Royal Commission recommendations. The document was developed using the following structure:

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Acknowledgements

Input from a number of technical specialists and territorial authorities has been provided as this document evolved and this input is greatly acknowledged. The support of the Earthquake Commission for assistance in the training associated with the reference of this document is acknowledged.

Document status

ISBN (print) 978-1-98-851771-1
ISBN (online) 978-1-98-851770-4

Rev 0.1

Issue date September 2017

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It is not mandatory to follow the guidance, but if followed:

- it does not relieve any person of the obligation to consider any matter to which that information relates according to the circumstances of the particular case
- the building consent authority may have regard to the guidance, but is not bound to accept the guidance as demonstrating compliance with the Building Code
- users should consider taking appropriate professional advice prior to entering into a construction contract which incorporates all or parts of this document.

While MfE and MBIE have taken care in preparing this document, professional judgment is required.

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Important notice

This document is preliminary and the contents should be treated as draft guidelines. Submissions on its content by the natural hazard communities to MfE and MBIE is encouraged, after which a further review will be undertaken. The contents may be subject to further changes, additions, and deletions. Feedback may be provided to:

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CONTENTS

1 INTRODUCTION

1.1 Purpose of the guidance

This document provides guidance for a risk-based process to manage liquefaction-related risk in land use planning and development decision-making. While this guidance specifically focuses on liquefaction and its consequences, it is part of a broader objective that buildings and infrastructure be located and built with appropriate consideration of all aspects of the land conditions and natural hazards. This document builds on the understanding that there are equally important parts to be played by resource management land use planning (covered by the Resource Management Act (RMA)) and engineering design (covered by the Building Act).

This guidance examines adverse effects from earthquake-induced liquefaction, with a focus on identifying if the liquefaction is likely to be consequential to land, buildings and infrastructure. This links in to the broader consideration of natural hazards provided by the RMA, relating to the effects on life, property and other aspects of the environment.

The focus on liquefaction is a result of the experience of the Canterbury Earthquake Sequence 2010–2011 and responds to recommendations 186 to 189 made by the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes. These recommendations relate to the role of regional councils and territorial authorities in managing liquefaction-related risk, with a focus on regional policy guidance, regional and district plans, resource and subdivision consents. This guidance has a corresponding focus on this regulatory framework, but it should be appreciated that there are a variety of other tools that are also available as part of a comprehensive approach to natural hazards management (eg broader central and local government planning, infrastructure and asset management strategies, and provision of information).

In some locations around New Zealand there has already been significant work undertaken over the past 30 years to identify and manage liquefaction-related risk. However, different methodologies and categorisations have been used in different regions. This guidance seeks to encourage consistency in the approaches used across New Zealand, to make it easier to transfer knowledge and develop efficient standardised solutions.

This document does not address other earthquake effects, natural hazards or geotechnical issues – so it is important to also consider whether these are relevant for a particular case. It does not provide detailed technical guidance on liquefaction analysis or earthquake engineering – for this technical detail refer to the NZGS/MBIE Earthquake Geotechnical Engineering Practice series (NZGS 2016a to 2016d).

1.2 Ways information about liquefaction is used

There are numerous ways information about the potential for liquefaction-induced ground damage might be used, for example:

- long term strategic land use planning
- developing planning processes to manage risks and the effects of natural hazard events
- design of land development, building and infrastructure works
- informing earthquake-prone building assessments
- improving infrastructure and lifeline resilience
- civil defence and emergency management planning
- catastrophe loss modelling for insurance, disaster risk reduction and recovery planning.

When undertaking a liquefaction assessment it is essential that the intended purpose (or range of purposes) of the resulting information is clearly defined, as this will govern many aspects of the scope and detail of the technical work that needs to be undertaken. For example, a generic liquefaction hazard map or detailed geological model may be of limited practical use if it is not developed with a clear purpose and understanding of how it will be applied. As part of defining the purpose of the work, the spatial extent of the area to be assessed should also be carefully delineated.

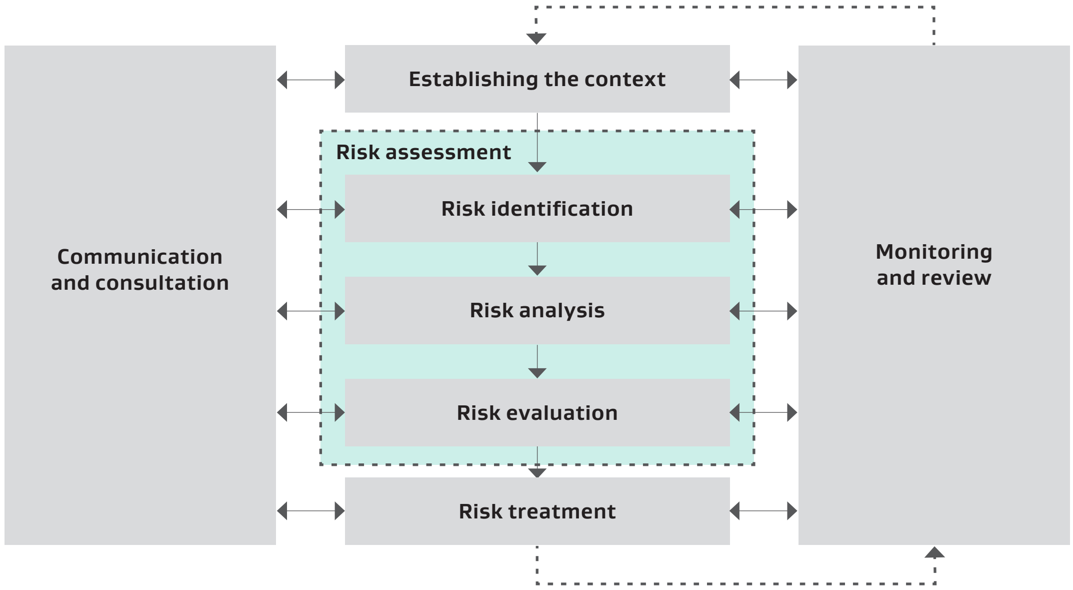
This guidance document focuses on assessing the potential for liquefaction-induced ground damage to inform RMA and Building Act planning and consenting processes. As outlined in Section 2.1, this process involves a hierarchy of tools, with higher-level regional policy statement and plans providing an overarching framework that empowers the management of liquefaction-related risk via the lower-level district plan and consent processes. The purposes that liquefaction assessments could be used for, and the refinement of this information over time, are further illustrated by the examples in Appendix B.

As demonstrated in the list of examples above, there is a range of other ways in which liquefaction information might be used that are outside the planning and consenting process. Not all of this guidance document will be directly applicable for the specific needs of these other situations. However, many of the concepts presented here may be relevant, and it is recommended that a consistent approach is adopted where possible, to provide compatibility of information for various purposes.

1.3 Structure of this document

The structure of this document mirrors the risk management process defined in the joint Australian and New Zealand International Standard for Risk management (AS/NZS ISO 31000:2009), as outlined in Figure 1.1.

Figure 1.1: Risk management process defined in AS/NZS ISO 31000:2009, and the corresponding structure of this guidance document



1.4 Overview of technical aspects of the risk assessment framework

As shown in Figure 1.1, the key technical inputs into the risk management process are developed during the risk assessment stages (primarily risk identification and risk analysis). There are significant complexities and interrelationships in the technical aspects of the risk assessment framework presented in this guidance, so it is useful to develop an initial high-level understanding of how the individual components connect together before examining the technical recommendations in more detail.

Figure 1.2 provides a simplified overview of the technical process for scoping, undertaking and reporting a liquefaction assessment to inform planning processes, including refinement of the categorisation over time as additional information becomes available. A more detailed version of this flowchart is included in Appendix C.

This guidance provides a performance-based framework for categorising the liquefaction vulnerability of land to inform planning and consenting processes. This framework is based on the severity of liquefaction-induced ground damage (Section 2.5) that is expected to occur at various intensities of earthquake shaking (Section 4.3). The degree of ground damage is estimated using qualitative or quantitative methods as appropriate (Section 4.4). The expected ground response is compared to a set of performance criteria to select the appropriate liquefaction vulnerability category from the standardised options shown in Table 1.1 (refer Section 4.5 for details).

Liquefaction assessments are undertaken at a wide range of scales and detail, ranging from a high-level assessment of an entire region down to site-specific analysis for a specific building. To allow this information to be effectively integrated and refined over time, this framework uses consistent terminology to describe the level of detail in a liquefaction assessment, as shown in Table 1.2 (refer Section 3.2 for details). The key feature defining each level of detail is the degree of residual uncertainty in the assessment. This uncertainty is primarily related to the types of information assessed, how subsurface data is used to 'ground truth' assumed conditions, the variability in the ground conditions, and nature and reliability of the methods used to assess liquefaction vulnerability.

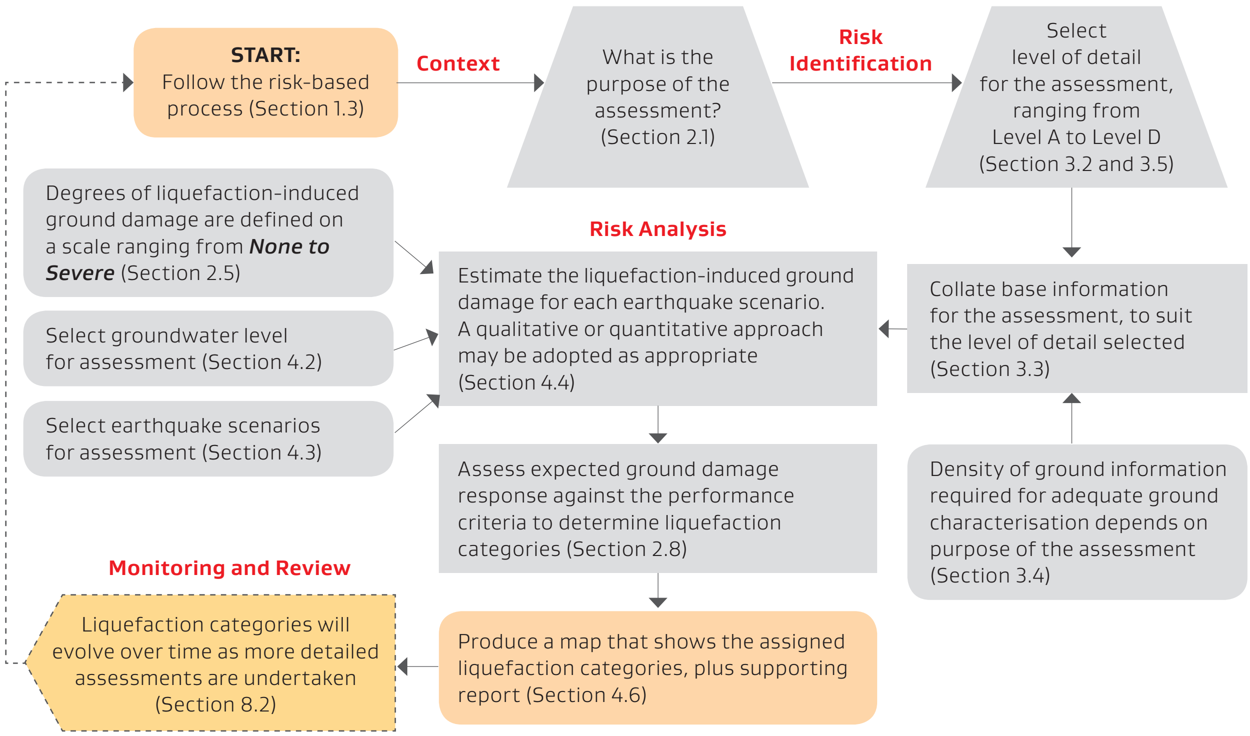
One way of conceptualising liquefaction-related risk is to consider how uncertainties in the land performance impact on a community's objectives and decision-making. This guidance recognises that the impact of this uncertainty is more significant in some situations than in others. For example, from an overall community resilience perspective, the exposure (and thus the potential impact) is greater for a large high-density urban development than for a single building in a sparsely populated rural area.

Accordingly, recommendations are given for the minimum level of detail in liquefaction assessments to inform planning and consenting processes for a range of scenarios (Section 3.5). The recommended level of detail in the liquefaction assessment increases as the likelihood, severity and exposure to ground damage increases. The recommended level of detail also increases as the intended purpose becomes more site-specific (eg a higher level of detail for subdivision consent than for a regional plan).

The targeted approach outlined in this guidance aims for efficiency by investing effort in reducing the uncertainty in situations where the overall impact of the liquefaction-related risk is the greatest. It also aims to incorporate management of liquefaction-related risk in a progressive manner throughout the land use planning and development framework, with appropriate risk treatments implemented at the point in the framework where they can be the most efficient and effective.

Liquefaction assessment is a complex task, which can require substantial expert technical judgement. This guidance recommends that peer review should be included where a liquefaction assessment is of particular importance or complexity (eg a district-wide assessment to assist the council to develop planning provisions). Peer review may also be particularly valuable in locations where there is little pre-existing liquefaction assessment information. Peer review is most useful as an ongoing collaborative process while the work is being scoped and undertaken, rather than simply a review of the final end product. Recommendations for scoping and procuring a liquefaction assessment study are discussed further in Appendix H.

Figure 1.2: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage



Note:
Refer to the referenced sections of this report and the more detailed flowchart in Appendix C for further information.

Table 1.1: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes (refer to Section 4.5 for details)

Increasing likelihood and severity of ground damage

<table>
<tr><td rowspan="3">Increasing precision[1] in the categorisation</td><td colspan="4">LIQUEFACTION CATEGORY IS UNDETERMINED</td><td rowspan="3">Decreasing uncertainty in the assessment</td></tr>
<tr><td colspan="2">LIQUEFACTION DAMAGE IS UNLIKELY</td><td colspan="2">LIQUEFACTION DAMAGE IS POSSIBLE</td></tr>
<tr><td>Very Low
Liquefaction Vulnerability</td><td>Low
Liquefaction Vulnerability</td><td>Medium
Liquefaction Vulnerability</td><td>High
Liquefaction Vulnerability</td></tr>
</table>

Note:

1 In this context the 'precision' of the categorisation means how explicitly the level of liquefaction vulnerability is described. The precision is different to the accuracy (ie trueness) of the categorisation.

Table 1.2: Levels of detail for liquefaction assessment studies

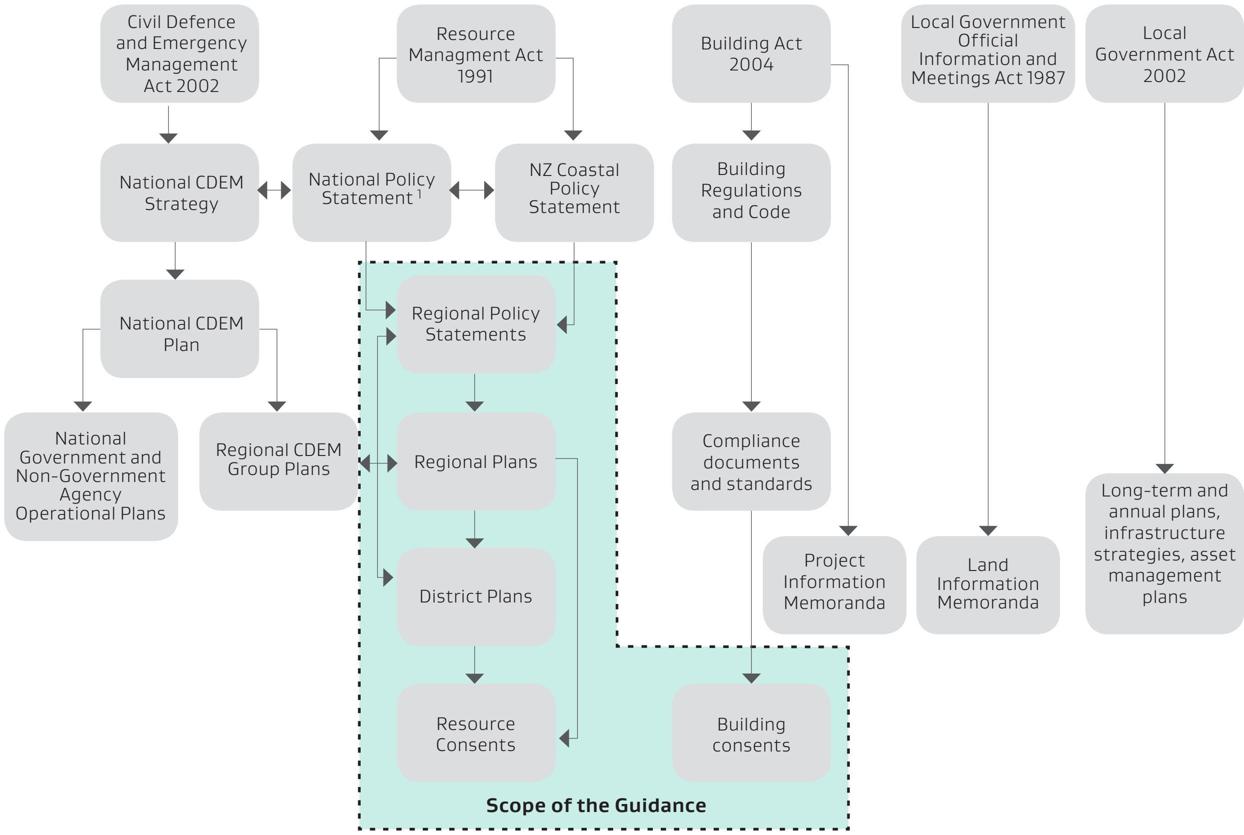
LEVEL OF DETAIL
Level A – Basic Desktop Assessment
Level B – Calibrated Desktop Assessment
Level C – Detailed Area-Wide Assessment
Level D – Site-Specific Assessment

2 ESTABLISHING THE CONTEXT

2.1 New Zealand regulatory framework

Management of natural hazards in New Zealand is influenced by five main statutes, as summarised in Figure 2.1. For a detailed description of the regulatory context see Tonkin + Taylor (2016). This guidance is focused on part of the regulatory framework under the RMA and the Building Act, as shown in the green shading in Figure 2.1.

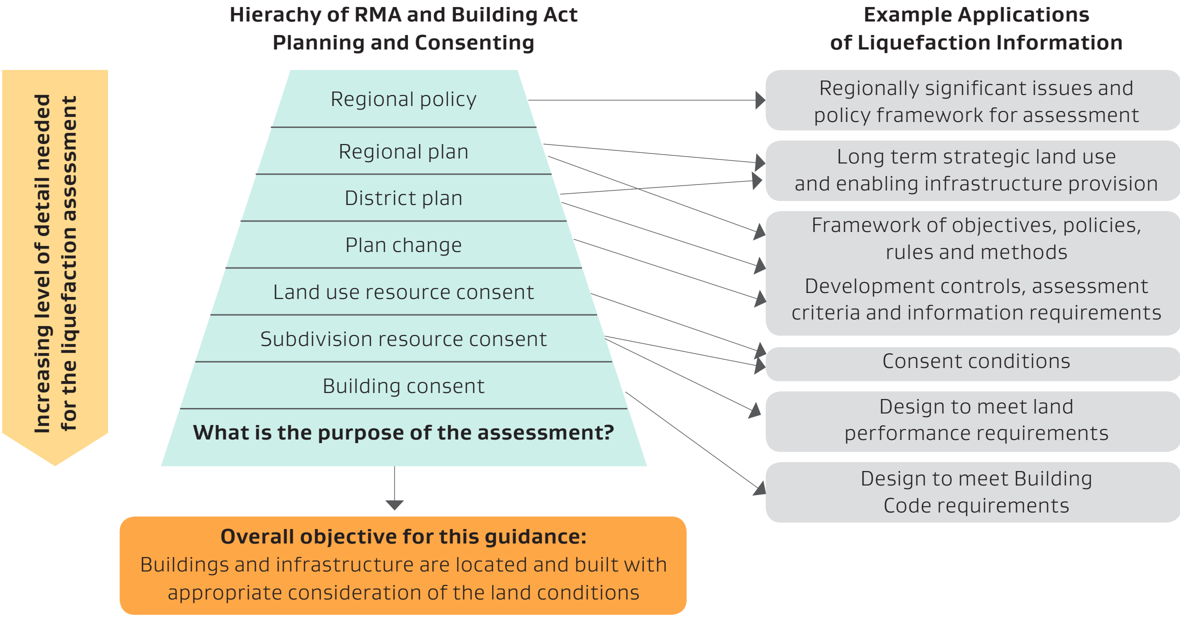
Figure 2.1: Legislative framework for natural hazards management in New Zealand. The scope of this guidance is indicated by the green box (adapted from GWRC 2017 and the National Civil Defence and Emergency Management Strategy 2007)



Note:

1 The government has announced an intention to develop a National Policy Statement on natural hazards.

Figure 2.2: Simplified hierarchy of RMA and Building Act planning and consenting processes, and example applications of information about the potential for liquefaction-induced ground damage



The regional and district policy and planning instruments and resource consenting processes operate as a hierarchy that requires progressively more detailed information to support decision-making, as illustrated in Figure 2.2.

The context for each level of the hierarchy will differ, so at the start of a risk-based approach the relevant context needs to be established, for example for a:

- regional policy statement, the relevant RMA context is the Part 2 (purpose and principles) of the RMA and the functions of regional councils under the RMA
- district plan, the relevant context will be objectives and policies set in the applicable regional policy statement and the functions of district councils under the RMA.

Establishing the context will also include identifying the relevant stakeholders. Stakeholder engagement will help the community identify its objectives, build awareness and understanding, and explore attitudes to the effects and risks associated with liquefaction. The wider objectives of different communities will vary, particularly the development pressures faced by different regions, districts or cities. Some, for example, will be considering Special Housing Areas to meet needs for additional housing.

2.2 Mechanism of liquefaction

'Soil' consists of solid particles and the voids between them, as illustrated in Figure 2.3. The particles can be either loosely or tightly packed, and the voids can be either air-filled or water-filled. In loosely packed soils strong earthquake shaking can cause rearrangement of the particles, and if the voids are filled with water then high water pressures can develop as a result.

This high water pressure reduces the contact forces between the particles, reducing the strength and stiffness of the soil. This effect is only temporary – once earthquake shaking has stopped the soil is able to drain and the water pressure and soil strength gradually return to normal over a period of hours or days (although the ground may continue to creep for some weeks after the event).

Figure 2.3: Schematic representation of the mechanism of liquefaction (from Tonkin + Taylor 2015)

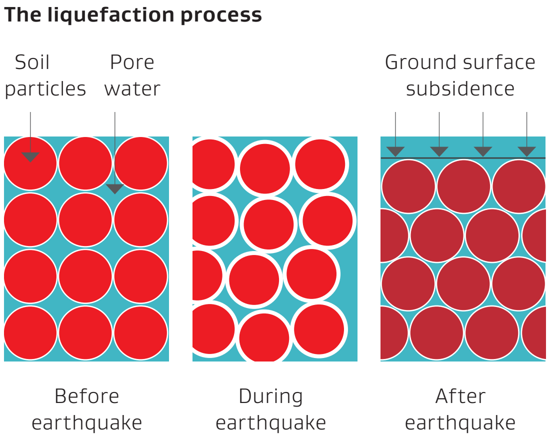


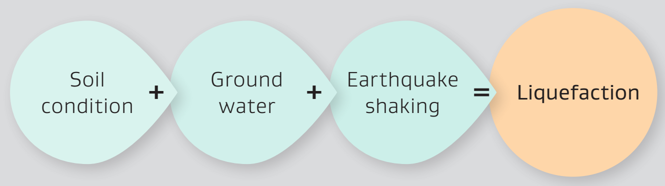
Figure 2.4: The key elements required for liquefaction

Three key elements are all required for liquefaction to occur:

1 Loose non-plastic soil (typically sands and silts, or in rare cases gravel)

2 Saturated soil (ie below the groundwater table)

3 Sufficient ground shaking (a combination of the duration and intensity of shaking).



2.3 Landforms commonly susceptible to liquefaction

Because liquefaction requires specific soil and groundwater conditions to occur (given sufficient earthquake shaking), some types of landforms are more likely to be susceptible than others. This is illustrated in Figure 2.5.

Soil types that are susceptible to liquefaction are typically those that are geologically young (ie <11,000 years old) and deposited in low energy environments, forming loose and soft layers. While granular sandy soils are the most likely to liquefy, silts that are of low plasticity or 'cohesiveness' can also liquefy. In addition to sandy and silty soils, some gravelly soils are potentially susceptible to liquefaction.

Most gravelly soils drain relatively well (hence no increase in pore pressure can occur), however, when:

a their voids are filled with finer particles, or

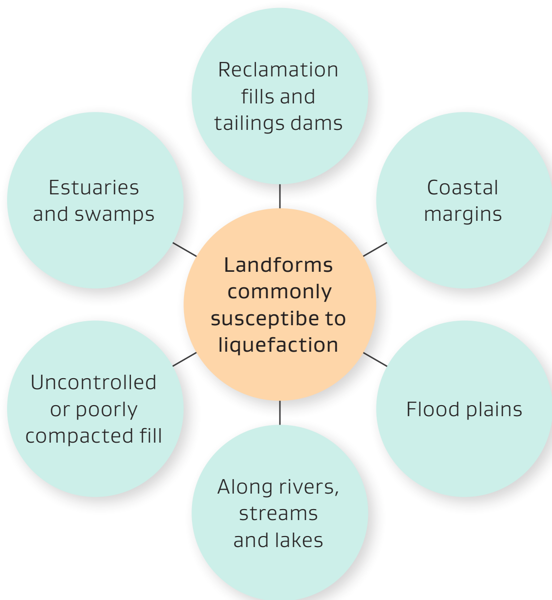
b they are surrounded by less pervious soils

drainage can be impeded and they may be susceptible to liquefaction.

Some clay soils can also exhibit liquefaction-like behaviour (ie cyclic softening).

The areas containing significant deposits of potentially liquefiable soils are often relatively flat and close to waterways, which have historically made for attractive places to settle and build. Reclaimed land formed by placing uncompacted or poorly compacted fill within existing waterways is particularly susceptible to liquefaction as it is often relatively loose and saturated.

Figure 2.5: Landforms commonly susceptible to liquefaction (this list is not exhaustive, liquefaction is still able to occur in other types of landforms)



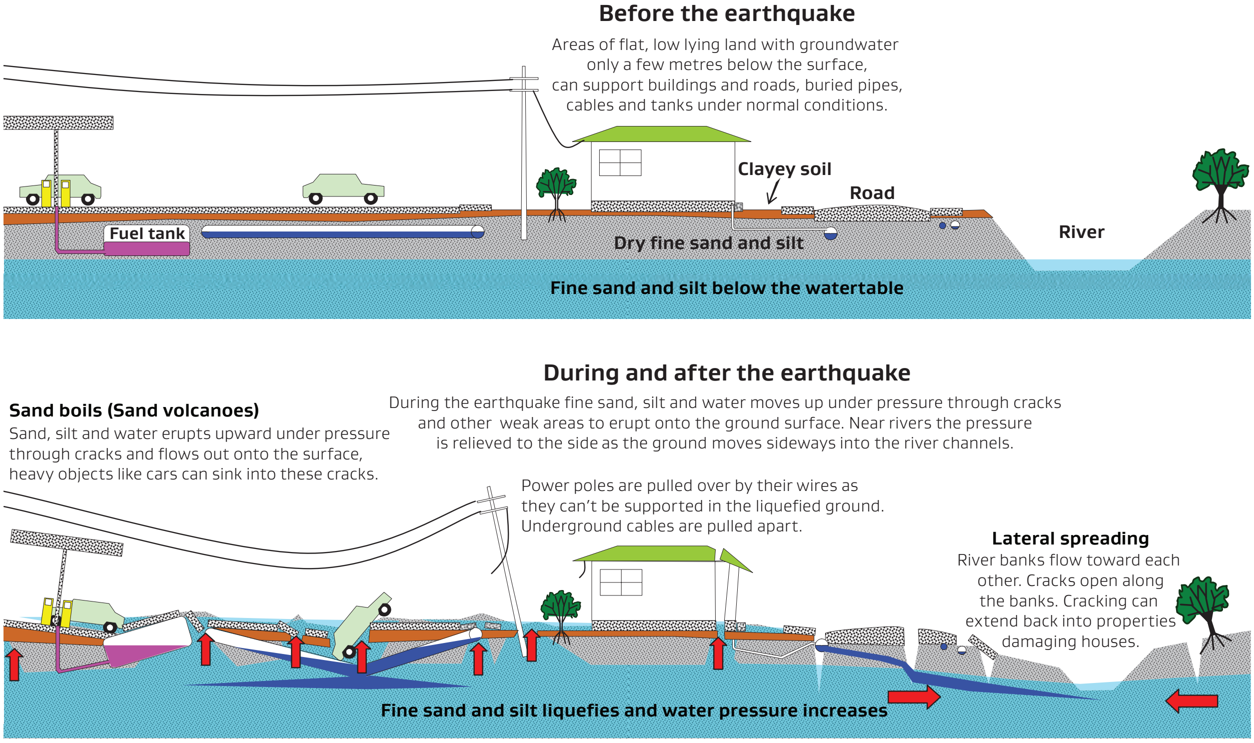
2.4 Consequences of liquefaction

While the immediate effects of liquefaction relate primarily to land damage, it can also cause a wide range of flow-on consequences as summarised in Table 2.1 and Figure 2.6.

Table 2.1: Overview of the potential consequences of liquefaction

Land	– Sand boils, where pressurised liquefied material is ejected to the surface (ejecta). – Ground settlement and undulation, due to consolidation and ejection of liquefied soil. – Ground cracking from lateral spreading, where the ground moves downslope or towards an unsupported face (eg a river channel or terrace edge).
Environment	– Discharge of sediment into waterways, impacting water quality and habitat. – Fine airborne dust from dried ejecta, impacting air quality. – Potential contamination issues from ejected soil. – Potential alteration of groundwater flow paths and formation of new springs.
Buildings	– Distortion of the structure due to differential settlement of the underlying ground, impacting the amenity and weathertightness of the building. – Loss of foundation-bearing capacity, resulting in settlement of the structure. *In some cases this can result in tilting or overturning of multi-level buildings.* – Stretch of the foundation due to lateral spreading, pulling the structure apart. *In some cases this can result in collapse or near-collapse of buildings.* – Damage to piles due to lateral ground movements, and settlement of piles due to 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 deformation (eg 'three waters', power and gas networks). – Ongoing issues with sediment blocking pipes and chambers. – Uplift of buoyant buried structures (eg 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 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 (eg respiratory and psychological health issues).

Figure 2.6: Liquefaction and its effects (Source: IPENZ)



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

2.5 Classification of the degree of liquefaction-induced ground damage

The land performance framework presented in this guidance is based on assessment of the degree of liquefaction-induced ground damage that is expected to occur at various intensities of earthquake shaking. Therefore it is important to establish consistent classification terminology to describe various degrees of damage.

Three degrees of liquefaction-induced ground damage are described in Table 2.2, with example photos presented in Appendix A. This classification of ground damage was developed based on observations from the Canterbury earthquake sequence, as outlined in Tonkin + Taylor (2013 and 2015).

Table 2.2: Degrees of liquefaction-induced ground damage used in the land performance framework. Additional example photos of land damage are presented in Appendix A

DEGREE OF LIQUEFACTION-INDUCED GROUND DAMAGE (example photographs)	TYPICAL CONSEQUENCES AT THE GROUND SURFACE These are examples of the type of damage that would be expected, they are not intended to be criteria for calculation
None to Minor 	– ***None to Minor*** no signs of ejected liquefied material at the ground surface[1]. – No more than minor differential settlement of the ground surface (eg undulations less than 25 mm in height). – No apparent lateral spreading ground movement (eg only hairline ground cracks). – Liquefaction causes no or only cosmetic damage to buildings and infrastructure (but damage may still occur due to other earthquake effects).
Minor to Moderate 	– ***Minor to Moderate*** quantities of ejected liquefied material at the ground surface (eg less than 25 percent of a typical residential site covered[2]); and/or – Moderate differential settlement of the ground surface (eg undulations 25–100 mm in height). – No significant lateral spreading ground movement (eg ground cracks less than 50 mm wide may be present, but pattern of cracking suggests the cause is primarily ground oscillation or settlement rather than lateral spreading). – Liquefaction causes moderate but typically repairable damage to buildings and infrastructure. Damage may be substantially less where liquefaction was addressed during design (eg enhanced foundations).
Moderate to Severe 	– Large quantities of ejected liquefied material at the ground surface (eg more than 25 percent of a typical residential site covered[2]); and/or – ***Moderate to Severe*** differential settlement of the ground surface (eg undulations more than 100 mm in height); and/or – Significant lateral spreading ground movement (eg ground cracks greater than 50 mm wide, with pattern of cracking suggesting direction of movement downslope or towards a free-face). – Liquefaction causes substantial damage and disruption to buildings and infrastructure, and repair may be difficult or uneconomic in some cases. Damage may be substantially less, and more likely to be repairable, where liquefaction was addressed during design (eg enhanced foundations and robust infrastructure detailing).

Notes:

1 An absence of ejecta at the ground surface does not necessarily mean that liquefaction has not occurred. Liquefaction may still occur at depth, potentially causing ground settlement.

2 The coverage of the site with ejected liquefied material does not in itself represent ground damage in an engineering sense, however there is a strong correlation between the volume of ejecta and the severity of differential ground settlement and foundation/infrastructure damage.

3 RISK IDENTIFICATION

3.1 Risk assessment process

As outlined in Figure 1.1, the first step in the risk assessment process is risk identification. In the context of liquefaction-related risk, the aim of this step is to identify land where there is potential for liquefaction-induced ground damage to occur (or just as importantly, identify areas where it is unlikely so no further assessment is required). A liquefaction assessment study draws on a range of existing information, and collects new information where appropriate, to identify this land.

It is difficult to precisely and accurately identify liquefaction-prone land, so an important part of the risk assessment process is to understand and manage this uncertainty. The primary factors that influence the degree of uncertainty for a liquefaction assessment are:

- the types of information examined in the assessment
- the amount and spatial density of subsurface investigation data used to 'ground truth' assumptions about soil type, soil strength, subsurface profile and groundwater conditions
- the degree of variability in the ground conditions
- how well the seismic behaviour can be predicted for the particular soil types present (eg there is particular uncertainty regarding the influence of fines content and interbedded silty soil layers, so for liquefaction analysis in present-day engineering practice it is common to allow for this uncertainty by making conservative assumptions
- how much is known about how an area has been or will be developed (eg the types of land preparation, infrastructure and buildings).

In most circumstances the primary means for reducing this uncertainty is to increase the level of detail in the liquefaction assessment study, however there are cost and practical limitations to this. Therefore the focus of this section of the guidance is selecting a level of detail for a liquefaction assessment study (and the corresponding information requirements) to provide an appropriate balance between the benefits and the costs of identifying liquefaction-prone land.

3.2 Level of detail for liquefaction assessment studies

The level of detail that is required for a liquefaction assessment will be governed by the intended purpose (or purposes), and how uncertainty in the assessment could affect objectives and the decisions to be made. For example, a region-wide liquefaction assessment for a regional policy statement would require a lower level of detail than a site-specific liquefaction assessment for design of a new residential subdivision. However, the overall principles of liquefaction assessment remain the same regardless of scale.

With increasing level of detail or increasing area of study there is an increase in time and cost – so ideally the detail and extent of a liquefaction assessment study would be sufficient, but not excessive, for the intended purpose. However it is not simple to apply this concept in practice, as information about liquefaction at various levels of detail will often be required for a range of purposes at different times over various parts of a region. Therefore this guidance presents an assessment framework that allows the liquefaction categorisation to be progressively refined over time as needed in specific locations and as more detailed information becomes available (examples of this iterative process are provided in Appendix B).

A key goal of the framework presented in this guidance is providing clarity about the level of detail and purpose for each liquefaction assessment study that is undertaken. This allows a liquefaction assessment undertaken at a higher level of detail or more specific purpose to take precedence over an assessment with a lower level of detail or more general purpose. It also seeks to avoid situations where a liquefaction assessment that was undertaken with sufficient detail for one purpose is inappropriately used for a different purpose that requires greater detail.

This guidance recommends that when a liquefaction assessment study is commissioned, the client and the geotechnical professional should discuss the advantages and disadvantages of moving from one level of assessment detail to the next. This should include consideration of the potential consequences associated with different levels of residual uncertainty. This will allow the client to make an informed decision as to the level of detail for the assessment. The chosen level of detail should also be reviewed periodically as the work progresses and the uncertainties and consequences become better understood.

To establish consistent terminology four levels of liquefaction assessment are defined in Table 3.1, with the level of detail increasing from a *Basic Desktop Assessment* (Level A) up to a *Site Specific Assessment* (Level D). **The key feature defining each level of detail is the degree of residual uncertainty in the assessment.**

As the level of detail increases the uncertainty associated with the liquefaction assessment generally also decreases, so the liquefaction vulnerability category can be determined more precisely and the degree of conservatism in application of the results can be decreased. However, there is no 'one size fits all' guidance for the appropriate degree of conservatism (as this depends on the specific details of the situation and the potential consequences of the uncertainty). In many cases it may be more appropriate to adopt 'most likely' assumptions and clearly communicate the uncertainties (and potential consequences) to information users, rather than making blanket conservative assumptions.

Figure 3.1 demonstrates conceptually how increasing the level of detail reduces the uncertainty about the ground conditions.

It is recommended that territorial authorities maintain a record of all liquefaction assessments they receive. Ideally this would be in a geospatial information system that records the extent, level of detail and categorisation results for each assessment. As a minimum, copies of all technical reports and ground investigation data should be permanently retained. For consistency across New Zealand, it is recommended that the descriptions and colours shown in Table 3.1 are used when preparing maps that show the level of detail in liquefaction assessments. Refer to Appendix E for standard data format details.

Table 3.1: Levels of detail for liquefaction assessment studies, and the key defining features

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

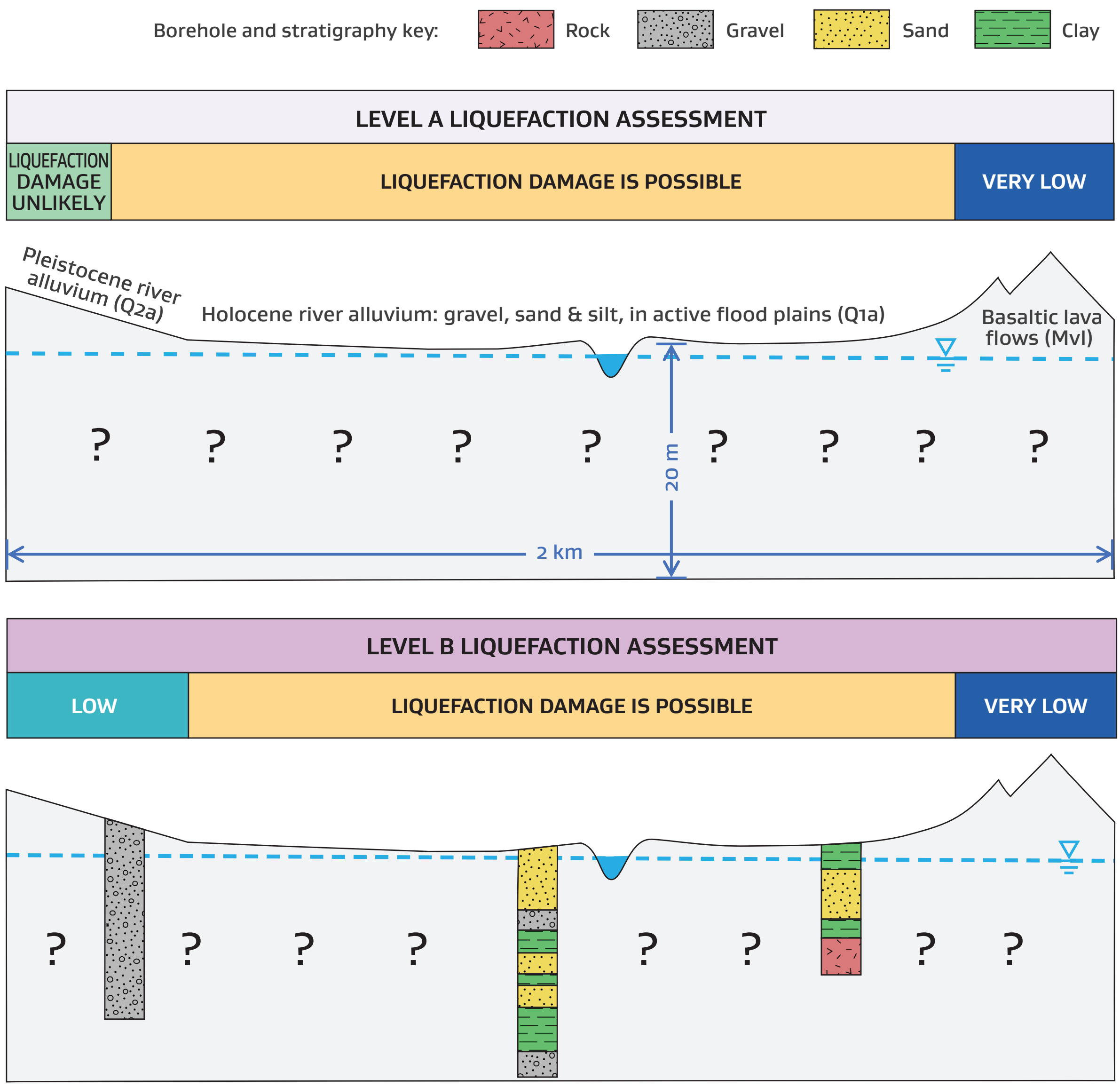
Figure 3.1: Conceptual example of the difference in subsurface ground information for Level A, B, C and D liquefaction assessments:

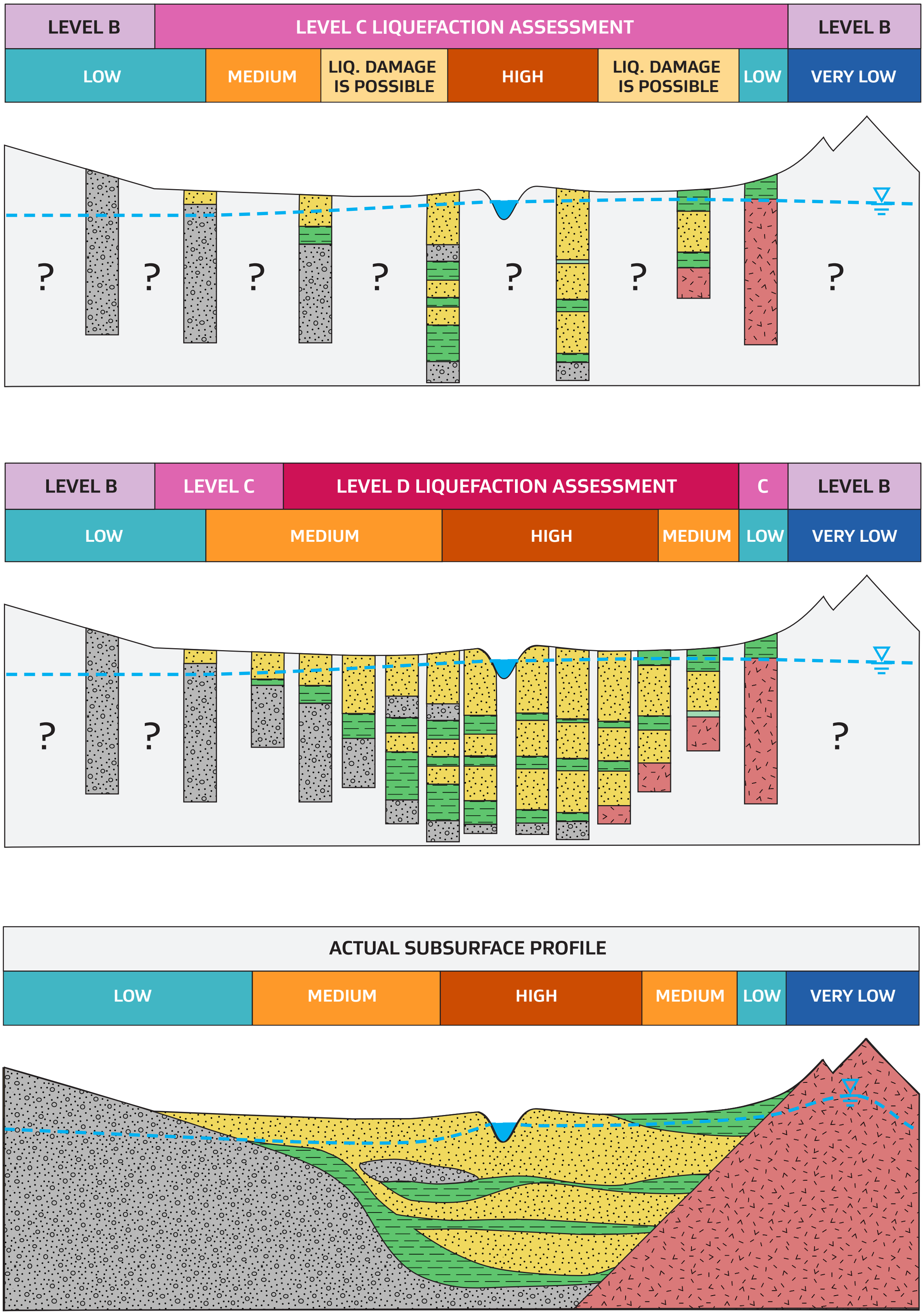
Level A – Only basic surface geology and groundwater information is available. Areas are identified where ***Liquefaction Damage Is Unlikely*** (Pleistocene deposits with groundwater deeper than 4 m) and with ***Very Low*** liquefaction vulnerability (exposed rock). Substantial uncertainty remains regarding subsurface conditions elsewhere, but the nature of the deposits means that ***Liquefaction Damage Is Possible***.

Level B – A small number of subsurface investigations provides a better understanding of liquefaction susceptibility for the mapped deposits. This shows that the Pleistocene deposits comprise gravel to the surface, with ***Low*** liquefaction vulnerability. Significant uncertainty remains regarding the level of liquefaction-related risk for the Holocene deposits and how ground conditions vary across the area.

Level C – A more refined groundwater model indicates ***Low*** liquefaction vulnerability in areas where the groundwater table is within the gravel. A ***Medium*** category is assigned in areas where there is a moderate thickness of surface crust and a small thickness of sand below the water table. The higher density of ground investigations identifies an area at the foot of the hill where clay overlies rock, so a ***Low*** category is assigned. The potential for lateral spreading is confirmed along the riverbanks, so a ***High*** category is assigned.

Level D – Analysis of the high density of subsurface testing data allows the area ***High*** liquefaction vulnerability to be delineated from the surrounding ***Medium*** areas.




LEVEL B
LEVEL C LIQUEFACTION ASSESSMENT
LEVEL B
LOW
MEDIUM
LIQ. DAMAGE IS POSSIBLE
HIGH
LIQ. DAMAGE IS POSSIBLE
LOW
VERY LOW
LEVEL B
LEVEL C
LEVEL D LIQUEFACTION ASSESSMENT
C
LEVEL B
LOW
MEDIUM
HIGH
MEDIUM
LOW
VERY LOW
ACTUAL SUBSURFACE PROFILE
LOW
MEDIUM
HIGH
MEDIUM
LOW
VERY LOW

3.3 Information used for liquefaction assessment

Table 3.2 summarises the types of information typically used for liquefaction assessment at each level of detail.

Table 3.2: Information typically used for liquefaction assessment

LEVEL OF DETAIL	INFORMATION TYPICALLY USED [1]
Level A **Basic desktop assessment**	Basic regional-scale information: – Large-scale regional maps of geology and geomorphology. – Large-scale regional maps of depth to groundwater. – Regional seismicity information. – Historical observations of liquefaction in previous earthquakes (will only sometimes be available) eg Fairless & Berrill (1984). – Assessment using simple screening criteria based on geological age, seismicity and groundwater levels, to identify areas where significant liquefaction-induced ground damage is unlikely to occur. – Qualitative assessment using simple screening criteria based on geomorphology to identify areas where there is potential for lateral spreading to occur, or the landform suggests it may have occurred in the past. – Local experience of typical ground conditions across an area. – 'Walkover' examination of the area being mapped (for small study areas) or of typical examples of key geological features (for large study areas).
Level B **Calibrated desktop assessment**	As above, plus high-level 'ground-truthing': – Information from a small number of subsurface investigation points to provide high-level understanding of the nature and variability of the key geological units. – Qualitative (or possibly quantitative) assessment of subsurface ground information to provide high-level understanding of the potential for liquefaction triggering to occur, and potential severity of the consequences. – Information from a small number of groundwater monitoring points to provide high-level understanding of variation in groundwater level over time.
Level C **Detailed area-wide assessment**	As above, plus detailed information on ground conditions and groundwater levels with good coverage across the entire study area: – Area-specific mapping of geology and geomorphology. – Historical information, such as previous land use, fills, and pre-development landscape features (eg buried streams and swamps). – Ground investigation and groundwater monitoring at sufficient density and coverage to adequately characterise the typical range of soil strength and groundwater depth for the critical geological units. – Laboratory testing where necessary to confirm liquefaction susceptibility for marginal soil types (eg to assess fines content and plasticity of silty soils). – Detailed quantitative analysis of subsurface testing data to assess liquefaction triggering and consequences for the general types of development proposed in the area. – Simplified quantitative analysis to identify areas where there is potential for lateral spreading, and consequences for the general types of development proposed in the area.
Level D **Site-specific assessment**	– As above, plus specific information about the particular site and proposed development being considered, to provide a high degree of site-specific confidence in the assessment. – Site-specific mapping of geology and geomorphology. – Detailed site-specific quantitative analysis of subsurface testing data (within or very close to the building footprint) to assess liquefaction triggering and likely consequences for the particular development proposed at the site. – Detailed quantitative analysis to identify potential for lateral spreading to occur, and likely consequences for the particular development proposed at the site.

Note:

1 The key feature defining each level of detail is the degree of residual uncertainty in the assessment (refer Table 3.1), not necessarily the types of information used. In some cases, some types of information may be unavailable or not applicable, other types of information might also be relevant, or it might be more appropriate to bring in information at higher or lower levels of detail.

3.4 Required spatial density of ground information

Table 3.3 and Figure 3.2 provide indicative guidance on the spatial density of deep ground investigation that is likely to be required to achieve the target degree of certainty for each level of detail.

It is emphasised that the key features which define the level of detail for a particular assessment are the nature of the assessment undertaken and the residual uncertainties (refer Table 3.1), not simply the investigation density. Meeting the indicative minimum investigation density does not in itself 'qualify' an assessment for the corresponding level of detail. Similarly, falling short of the indicative density does not necessary 'disqualify' an assessment. **The key requirement is that the investigations should be sufficient for adequate ground characterisation for the specific purpose of the assessment and the ground conditions encountered.**

When applying Table 3.3, ground investigations should only be considered to contribute towards the calculated investigation density where they are of a suitable type and sufficient quality and depth to adequately characterise the potential severity of liquefaction-induced ground damage:

- CPT (Cone Penetrometer Test) and physical drilling and sampling with SPT (Standard Penetration Testing) are typically the most useful deep investigation methods for assessing liquefaction.
- Investigations should be deep enough to characterise the ground to at least 10–15 m depth below ground level for residential or light commercial development, or at least 20–25 m for heavier structures or critical facilities.
- In some circumstances Scala Penetrometer Testing may be useful to help understand the shallow subsurface profile (eg to confirm the presence of rock at shallow depth), but it is not considered appropriate as a tool for evaluation of liquefaction triggering.
- In some areas it may be expected that that the ground is not susceptible to liquefaction from shallower depths (eg areas underlain by competent gravels and a deep groundwater table, or with shallow bedrock). In such cases the geotechnical professional should first confirm that this is the case (eg by examining existing deep investigations in the area, site-specific geological mapping, or undertaking a small number of targeted deep investigations). Once confirmed, ground investigations can in most cases then be designed primarily for the assessment of other geotechnical issues (further deep investigations might or might not be required, depending on the specific ground conditions and proposed development).

For further discussion regarding the technical details of geotechnical investigations for earthquake engineering purposes, refer to NZGS (2016b). A case study demonstrating how these different investigation densities are intended to identify variation of ground conditions at a range of scales is included in Appendix D.

Table 3.3: Indicative spatial density of deep ground investigation for adequate ground characterisation for liquefaction assessments to inform planning and consenting processes

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

Notes:

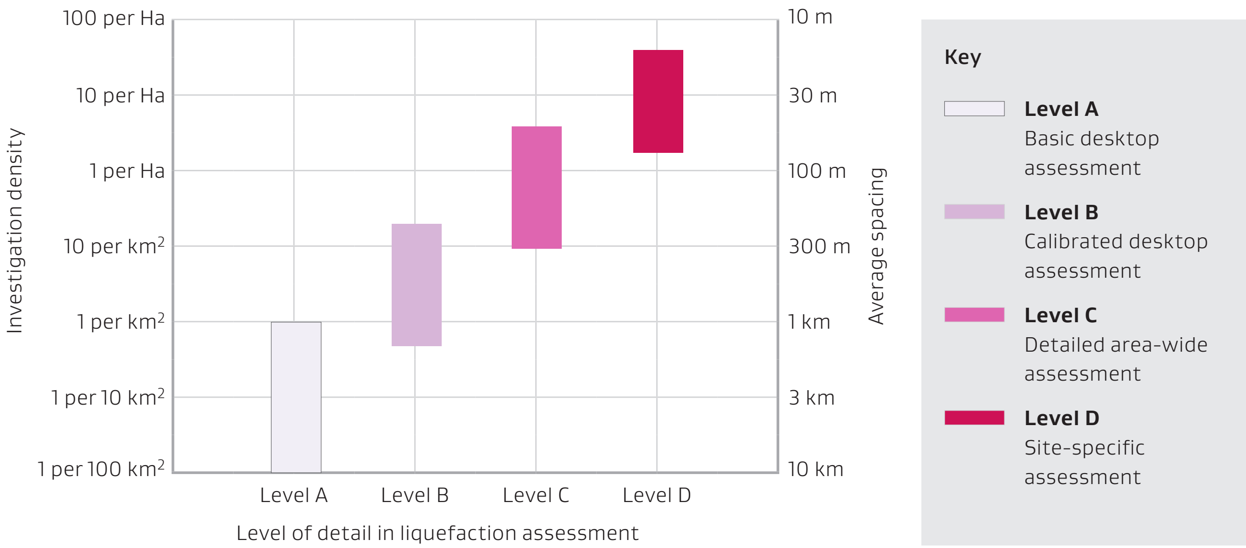
1 Investigation densities listed in this table are cumulative – suitable data from investigations undertaken in previous stages of work should be incorporated in subsequent stages.

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

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

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

Figure 3.2: Indicative spatial density of deep ground investigation for adequate ground characterisation for liquefaction assessments to inform planning and consenting processes



3.5 Minimum level of detail required for the intended purpose

Once the intended purpose (or purposes) of a liquefaction assessment study has been established, an assessment should be made of the minimum level of detail that is necessary to adequately fulfil that purpose.

The tables on the following pages provide general guidance on the likely requirements for liquefaction assessments for various planning and consenting purposes. However, the exact details of what is required will vary depending on the specific circumstances of each situation, so this is a matter of judgement for the engineering and planning experts, and relevant decision-makers to determine on a case-by-case basis.

Table 3.4 indicates that for regional policies and plans, and district plans, ***Level A*** assessment may be sufficiently detailed to provide an initial general screening for liquefaction-related risk (however a ***Level B*** assessment might offer a significant reduction in uncertainty with only minor additional effort).

As demonstrated in Table 3.5 to Table 3.7, for plan change and consenting there are a greater range of specific scenarios and scales that need to be taken into account when determining the appropriate level of detail for a liquefaction assessment. The recommended level of detail in the liquefaction assessment increases as the likelihood, severity and exposure to ground damage increases. In some scenarios there may not be a need for liquefaction assessment at all (eg land uses that do not involve buildings, such as agriculture).

This targeted approach aims for efficiency by investing effort in reducing the uncertainty in situations where the overall impact of the liquefaction-related risk is the greatest. For example, urban residential development requires particularly careful consideration of liquefaction-related risk, due to the concentration of assets exposed and the potential for extensive and prolonged community disruption if buildings and infrastructure are damaged.

Some iteration may be required when using Table 3.5 to Table 3.7, because the minimum level of detail required for a liquefaction assessment depends on the liquefaction vulnerability category, but the liquefaction vulnerability category won't be confirmed until the assessment is completed. A suggested iterative process is demonstrated in Figure 3.3.

When undertaking a liquefaction assessment it is often useful to start with an initial phase of work at a lower level of detail than is expected to be required, to provide an initial indication of the liquefaction vulnerability category (eg using only existing ground investigation data, or a small number of new investigations). This allows any additional investigations to be tailored to match the level of detail required, and to target key uncertainties identified in the initial assessment.

Table 3.4: General guidance on the likely requirements for liquefaction assessments

	PURPOSE THAT THE LIQUEFACTION ASSESSMENT WILL BE USED FOR						
	Regional policy	**Regional plan**	**District plan**	**Plan change**	**Land use consent**	**Subdivision consent**	**Building consent**
Typical map scale[1]	1:25,000 or greater		1:10,000 to 1:5,000		1:1250 to 1:500		1:500 or less
Typical extent of liquefaction study (km^2)	5,000 to 50,000		100 to 10,000	Less than 20	Less than 5		Less than 1
Minimum level of detail required	Level A[2]		Level A[2]	Refer Table 3.5	Refer Table 3.6		Refer Table 3.7

Notes:

1 The values shown in this table are indicative only, and territorial authorities may wish to customise details to suit local circumstances.

2 For regional and district plan purposes it is recommended that an initial region or district-wide liquefaction assessment be undertaken to provide a broad overview of how the potential for liquefaction damage varies across the area. In particular, this initial assessment should identify any areas or land use scenarios where further liquefaction assessment is not required. A ***Level A*** assessment may be sufficient for this initial screening, however a ***Level B*** assessment might offer a significant reduction in uncertainty with only minor additional effort, and allow the territorial authority to take a more active lead in management of liquefaction-related risk. The territorial authority may then wish to consider whether there are any specific areas where the uncertainty about potential liquefaction damage is significant in relation to its objectives (eg proposed future growth areas). In these key areas it may be useful to undertake more detailed liquefaction assessments (eg at the level of detail recommended for plan change) to help better inform land use strategy and district plan processes.

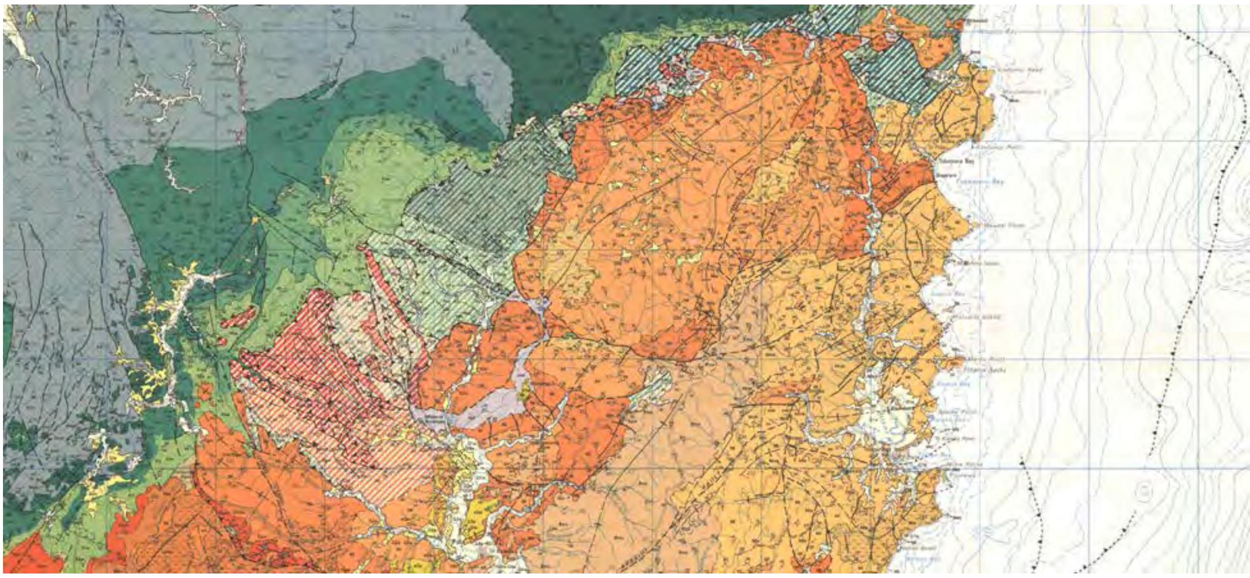


Figure 3.3: Flow chart demonstrating iterative process when using Tables 3.5 to Table 3.7 to determine the level of detail required and confirm the liquefaction vulnerability category

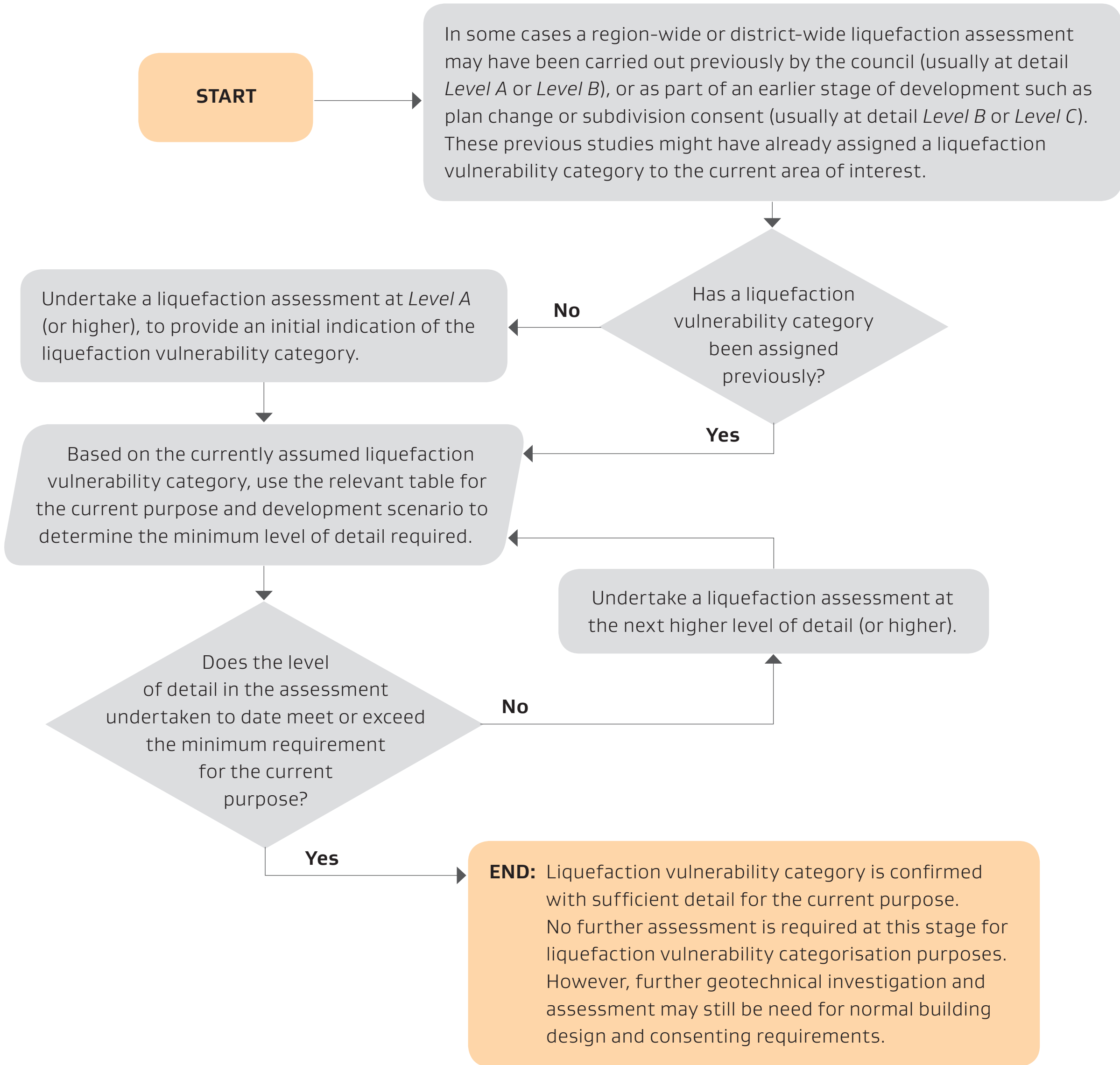


Table 3.5: Example matrix for determining minimum level of detail required for plan change

Increasing likelihood andseverity of ground damage

Increasing new capital investment and total exposure to a single event

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 Change of rules to allow increasing intensity of land use, buildings and population	Level A	Level A	Level A	Level A
Rural-residential setting (lot size of 1 to 4 Ha) eg Change of rules to reduce the minimum lot size for a residential dwelling	Level A	Level A	Level A	Level A
Small-scale urban infill (original lot size less than 2500 m^2) eg Relaxing minimum lot size limits in a residential area near the CBD to promote intensification	Level A	Level B	Level B	Level B
Commercial or industrial development eg Rezoning urban fringe land from rural to business zoning	Level A	Level B	Level B	Level B
Urban residential development (typically 15–60 households per Ha) eg Rezoning vacant industrial land from business to residential zoning	Level A	Level B	Level B	Level B

Notes:

1 These scenarios are indicative only, and territorial authorities may wish to add or delete scenarios or customise details and definitions to suit local circumstances. For some types of land use or subdivision consent, liquefaction might not be a relevant consideration (ie no liquefaction assessment would be required).

2 Refer to Section 4 for details about how liquefaction vulnerability categories are determined. Some iteration may be required when using this table, because the minimum level of detail required for a liquefaction assessment depends on the liquefaction vulnerability category, but the category won't be confirmed until the assessment is completed. A suggested iterative process is demonstrated in Figure 3.3.

3 In some cases an area will be assigned one of the lower-precision liquefaction vulnerability categories, particularly for ***Level A*** and ***Level B*** assessments. In the case of ***Liquefaction Category is Undetermined***, ***Liquefaction Damage is Unlikely*** or ***Liquefaction Damage is Possible***, the requirements for the upper end of the applicable range should be adopted. Alternatively, the iterative process outlined in Figure 3.3 can be used to incrementally increase the level of detail in the liquefaction assessment until it is possible to assign a more precise liquefaction vulnerability category, and the requirements for that category can be adopted.

Table 3.6: Example matrix for determining minimum level of detail required for land use or subdivision consent

Increasing likelihood and severity of ground damage →

Increasing new capital investment and total exposure to a single event ↓

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

Notes:

1 These scenarios are indicative only, and territorial authorities may wish to add or delete scenarios or customise details and definitions to suit local circumstances. For some types of land use or subdivision consent, liquefaction might not be a relevant consideration (eg land use consent for agricultural purposes might not require a liquefaction assessment).

2 Refer to Section 4 for details about how liquefaction vulnerability categories are determined. Some iteration may be required when using this table, because the minimum level of detail required for a liquefaction assessment depends on the liquefaction vulnerability category, but the category won't be confirmed until the assessment is completed. A suggested iterative process is demonstrated in Figure 3.3.

3 In some cases an area will be assigned one of the lower-precision liquefaction vulnerability categories, particularly for ***Level A*** and ***Level B*** assessments. In the case of ***Liquefaction Category is Undetermined***, ***Liquefaction Damage is Unlikely*** or ***Liquefaction Damage is Possible***, the requirements for the upper end of the applicable range should be adopted. Alternatively, the iterative process outlined in Figure 3.3 can be used to incrementally increase the level of detail in the liquefaction assessment until it is possible to assign a more precise liquefaction vulnerability category, and the requirements for that category can be adopted.

Table 3.7: Example matrix for determining minimum level of detail required for liquefaction categorisation at building consent stage

Increasing likelihood and severity of ground damage

Increasing new capital investment and total exposure to a single event

	LIQUEFACTION VULNERABILITY CATEGORY[1,3,4]			
	LIQUEFACTION CATEGORY IS UNDETERMINED			
	LIQUEFACTION DAMAGE IS UNLIKELY		LIQUEFACTION DAMAGE IS POSSIBLE	
DEVELOPMENT SCENARIO[2]	**Very Low**	**Low**	**Medium**	**High**
Sparsely populated rural area (lot size more than 4 Ha) eg A new farm building	Level A	Level A	Level A[5]	Level A[6]
Rural-residential setting (lot size of 1 to 4 Ha) eg A 'lifestyle' property	Level A	Level B	Level B[5]	Level B[6]
Small-scale urban infill (original lot size less than 2500 m^2) eg Demolish old house and replace with four townhouses	Level B	Level B	Level B[5]	Level D
Commercial or industrial development[7] eg A warehouse building in an industrial park	Level B	Level B	Level C	Level D
Urban residential development (lot size less than 1 Ha; typically <1000 m^2) eg Home in a new subdivision	Level B	Level C[8]	Level C	Level D

Notes:

1 The recommended level of detail relates only to liquefaction assessment for the purposes of determining a liquefaction vulnerability category. Further geotechnical investigation and assessment may still be needed for normal building design and consenting requirements (eg for specific design of foundations).

2 These scenarios are indicative only, and territorial authorities may wish to add or delete scenarios or customise details and definitions to suit local circumstances.

3 Refer to Section 4 for details about how liquefaction vulnerability categories are determined. Some iteration may be required when using this table, because the minimum level of detail required for a liquefaction assessment depends on the liquefaction vulnerability category, but the category won't be confirmed until the assessment is completed. A suggested iterative process is demonstrated in Figure 3.3.

4 In some cases an area will be assigned one of the lower-precision liquefaction vulnerability categories, particularly for ***Level A*** and ***Level B*** assessments. In the case of ***Liquefaction Category is Undetermined***, ***Liquefaction Damage is Unlikely*** or ***Liquefaction Damage is Possible***, the requirements for the upper end of the applicable range should be adopted. Alternatively, the iterative process outlined in Figure 3.3 can be used to incrementally increase the level of detail in the liquefaction assessment until it is possible to assign a more precise liquefaction vulnerability category, and the requirements for that category can be adopted.

5 This level of detail is sufficient provided that: visual assessment and reasonable enquiry does not indicate the original Medium category is inappropriate; normal geotechnical investigations are undertaken for the purposes of evaluating all other potential geotechnical issues; and a hybrid technical categories (TC) 2/TC3 foundation or TC3 surface structure foundation is used (MBIE 2015). Alternatively, a liquefaction assessment at the next higher level of detail can be undertaken and the foundation selected in accordance with the results.

6 This level of detail is sufficient provided that: normal geotechnical investigations are undertaken for the purposes of evaluating all other potential geotechnical issues; and a TC3 foundation or ground improvement (MBIE 2015) or specific engineering design foundation is used. Alternatively, a liquefaction assessment at the next higher level of detail can be undertaken and the foundation selected in accordance with the results. Geotechnical engineering advice will be required to select an appropriate foundation solution for the specific ground conditions at the site. Site-specific deep ground investigations may be required to inform foundation design (depending on the site details and the foundation option selected).

7 The geotechnical assessment needed for commercial and industrial buildings will vary depending on the specific details of the site, the proposed building and foundation type, and the particular functional requirements. Specific engineering input is typically required, including recommendations for addressing liquefaction damage potential and any other geotechnical issues. The engineer may judge that a higher or lower level of detail is appropriate for a particular situation.

8 In some situations it may not be cost-effective to undertake deep ground investigations for liquefaction assessment in areas categorised ***Low*** (eg for a small development in a remote area where it is costly to mobilise a CPT rig). In these circumstances, a site-specific ***Level B*** assessment may be sufficient, provided that it confirms the Low category is appropriate and a TC2 foundation is used (MBIE 2015).

3.6 Selecting the extent and level of detail for a liquefaction assessment study

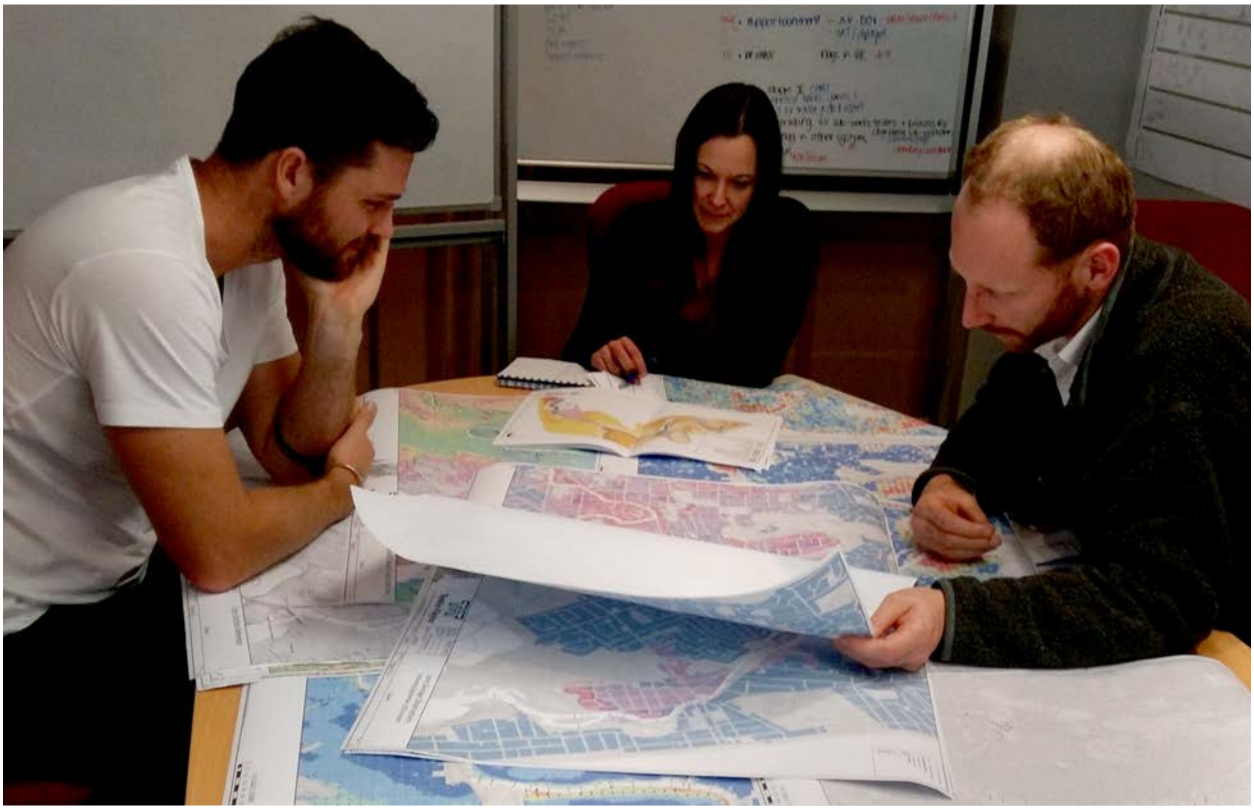
Once the minimum level of detail required for the intended purpose (or purposes) has been determined, consideration should be given to whether a better overall outcome can be achieved by adopting a higher level of detail than the minimum requirements.

Some examples of where this might be the case are:

- The degree of uncertainty will generally decrease as the assessment becomes more detailed, which may allow reduced conservatism when assigning liquefaction categories and delineating areas.
- In identified future growth areas, if more detailed ground information is available earlier in the process then this may encourage development and assist strategic land use planning.
- In some cases the liquefaction information might also be intended to assist with other purposes beyond planning and consenting (refer Section 1.2).
- It may be possible to achieve economies of scale by collaborating with other parties to undertake an assessment that can fulfil multiple purposes.
- If there is already detailed ground investigation information available in an area then there may be only minor additional cost in including this information in the assessment.

Taking into account the intended purpose, and balancing up the benefits and costs of possible options, the spatial extent and target level of detail for the liquefaction assessment study should be decided.

It is possible that the target level of detail might vary across the study area, to reflect differences in planning needs and the pre-existing information available.



4 RISK ANALYSIS

4.1 Risk assessment process

4.1.1 Overview

As outlined in Figure 1.1, the second step in the risk assessment process is risk analysis. In the context of liquefaction-related risk, the aim of this step is to analyse the collated information to determine how vulnerable the land is to liquefaction-induced ground damage.

This guidance recommends the following analysis framework:

- use the collated information to develop a model of the ground conditions (Sections 3.3 and 3.4)
- select groundwater scenarios for analysis (Section 4.2)
- select earthquake scenarios for analysis (Section 4.3)
- estimate the degree of liquefaction-induced ground damage for each scenario (Section 4.4)
- assess the expected ground damage against liquefaction vulnerability performance criteria (Section 4.5)

The end output of this analysis is to delineate areas of land with similar liquefaction vulnerability, and assign one of the liquefaction vulnerability categories specified in Table 4.1 to each of these areas of land.

As detailed in Table 3.1, there is usually significant residual uncertainty in the results of a liquefaction assessment, regardless of the level of detail. Uncertainties in each of the five analysis stages listed above can compound, increasing the overall uncertainty regarding the level of liquefaction-related risk, how it varies across each mapped area, and the delineation of boundaries between different areas. A liquefaction risk analysis should clearly communicate what these uncertainties are for the specific area being examined, and explain the potential consequences if the actual conditions vary from the assumed model.

Table 4.1: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes

Increasing likelihood and severity of ground damage

Increasing precision[1] in the categorisation

LIQUEFACTION CATEGORY IS UNDETERMINED			
LIQUEFACTION DAMAGE IS UNLIKELY		LIQUEFACTION DAMAGE IS POSSIBLE	
Very Low Liquefaction Vulnerability	Low Liquefaction Vulnerability	Medium Liquefaction Vulnerability	High Liquefaction Vulnerability

Decreasing uncertainty in the assessment

Notes:

1 In this context the 'precision' of the categorisation means how explicitly the level of liquefaction vulnerability is described. The precision is different to the accuracy (ie trueness) of the categorisation.

Refer to Table 4.4 for the technical performance criteria defining each liquefaction vulnerability category.

For consistency across New Zealand, it is recommended that the category names and colours shown in this table are used for liquefaction vulnerability category maps. Refer to Appendix E for standard data format details.

4.1.2 Precision and confidence in the liquefaction vulnerability categorisation

As indicated by the arrows on Table 4.1, the liquefaction categories relate to the likelihood and severity of ground damage (from left to right) and the precision[1] the vulnerability has been determined with (from top to bottom).

The purpose of this matrix-like approach is to enable the precision of the liquefaction categorisation to vary in response to the uncertainties and level of detail of the assessment:

- a more precise category can be assigned when there is sufficient certainty to do so (refer Table 4.4 for indicative confidence levels)
- where the uncertainty is too great for a precise category to be determined a more generalised category can be assigned (or the category can be identified as undetermined). More detailed assessment can then be undertaken to update the category in future if the need arises.

This means that regardless of the level of detail and uncertainties in the assessment, a liquefaction vulnerability category can be assigned with an appropriate degree of confidence to inform planning and decision-making processes. Robust analysis and clear communication of precision and uncertainty is particularly important when the technical information is used as part of communication and consultation processes (refer Section 7).

In practice the precision with which it is possible to determine the liquefaction vulnerability, and delineate boundaries between areas with different vulnerability, will depend on the uncertainties and level of detail in the liquefaction assessment. However, when undertaking a liquefaction assessment to inform planning processes, it is often not necessary to precisely determine the liquefaction vulnerability. For many purposes, it is sufficient to simply determine whether ***Liquefaction Damage is Unlikely*** (in which case one set of planning rules would apply) or ***Liquefaction Damage is Possible*** (in which case a different set of planning rules would apply). For ***Level A*** and ***Level B*** assessments it is often not possible to assign liquefaction vulnerability categories with any more precision than this.

It is only necessary to determine a more specific category when the intended purpose requires this higher level of detail (eg subdivision design or building design). The purpose of the planning rules would be to direct that this more detailed assessment is undertaken when required, and any liquefaction issues identified are appropriately managed.

It can be counterproductive to assign more precise liquefaction vulnerability categories (ie ***Very Low*** to ***High***) when there is insufficient technical certainty to do so. For example:

- assigning a less favourable category (eg ***High***) 'just to be safe' when there is uncertainty can result in significant opportunity costs. It can also undermine the scientific credibility of the assessment with a perception of over-extrapolating or misrepresenting the technical information
- assigning one of the more precise categories (eg ***Medium***) based on overextrapolation of limited but favourable information might result in buildings and infrastructure being constructed with insufficient resilience for the actual ground conditions.

In both examples above, it might be more appropriate to assign a liquefaction vulnerability category of ***Liquefaction Damage is Possible***, rather than ***High*** or ***Medium***. If more precise categorisation is needed for a particular purpose, then further liquefaction assessment and ground investigation should be undertaken to provide the appropriate level of certainty.

1 In this context the 'precision' of the categorisation means how explicitly the level of liquefaction vulnerability is described. The precision is different to the accuracy (ie trueness) of the categorisation.

4.2 Groundwater

4.2.1 Background

Groundwater information is an important input into a liquefaction assessment, as liquefaction can only occur if a soil is saturated. Key groundwater features that may be relevant for a liquefaction assessment include:

- the depth below ground of the water table
- changes with depth (eg perched water table, or pressurised aquifer)
- variations over time (eg seasonally, climatically and from year to year).

Council groundwater well databases and local knowledge may assist in some areas, but often there is little existing information about groundwater conditions, particularly relating to changes with depth and variations over time. Therefore it will often be necessary to either collect new groundwater information or make suitably conservative assumptions in the liquefaction assessment to allow for this uncertainty.

4.2.2 Groundwater monitoring

Liquefaction assessment requires an understanding of the groundwater level in the near-surface groundwater aquifer. Accurate knowledge of this level usually requires measurements from shallow piezometers or standpipes (these usually have a measurement point shallower than approximately 10 m depth). The majority of monitored groundwater wells in New Zealand are installed into deeper confined aquifers, so groundwater measurements from these wells may not be directly relevant for liquefaction assessment.

Regular monitoring of groundwater levels is beneficial as it builds confidence in the accuracy of the measurements and can provide information on seasonal fluctuations. If sufficient data is available, development of a regional groundwater model may be useful to help inform liquefaction assessments and encourage consistency of approach.

Care should be taken to understand the groundwater regime when interpreting piezometer pressures and standpipe levels. For example, measurement of a perched water table could lead to the incorrect assumption that all of the underlying soil profile is saturated. Similarly, if there is a layer of low-permeability soil near the surface the overlying soil might not be saturated even if the groundwater pressure measured in the underlying confined aquifer suggests it would be.

For some soil types, the range of long-term groundwater fluctuation can also be inferred from visual assessment of soil weathering in excavator pits or drill core.

4.2.3 Selecting a groundwater level for liquefaction analysis

The depth of the water table often dictates the position of the first potentially liquefiable layer. The closer this liquefiable layer is to the surface, the greater its potential contribution to ground surface damage. If groundwater levels are deep then liquefaction-induced ground surface damage, such as differential ground settlement, is unlikely (refer to Section 4.4.4 for initial screening criteria). Conversely, if groundwater levels can rise close to the ground surface (eg within about 2 m) then consideration of variations over time may be important (eg seasonal fluctuation or long-term sea level rise).

Care should be taken to understand the effect of compounding conservative assumptions when selecting groundwater levels for the liquefaction assessment. For example, there is a low likelihood (much less than 1 in 500) that a 500-year earthquake would occur at the same time as the groundwater level is at its highest seasonal level. Accordingly, it is often appropriate to assume an average (median) groundwater level as the primary analysis case for liquefaction categorisation. The effects of high and low groundwater levels should then be examined as a sensitivity analysis, and used to inform engineering judgement when determining the appropriate liquefaction vulnerability category (although this information is typically only available for ***Level C*** or ***Level D*** assessments).

For example, if changing from the median to the typical seasonal high groundwater level results in a large step-change worsening of land performance then this might indicate higher liquefaction vulnerability than a situation where raising the groundwater level results in only moderate incremental change to the land performance. As with other uncertainties in the liquefaction assessment, it is important to communicate this sensitivity and its potential significance to those who will use the information for decision-making.

4.2.4 Climate change and sea level rise

Background

For areas close to the coast where groundwater levels are strongly influenced by sea level, a rise in sea level may cause an increased risk of liquefaction damage in future (eg by reducing the thickness of the non-liquefying 'crust' of soil at the ground surface). Liquefaction-induced ground surface damage may be more likely and/or more severe in areas which already have a water table level (and susceptible soils) within about 2 m of the ground surface.

Increases or decreases in rainfall as a result of climate change may also affect groundwater levels in future, however the magnitude of any change is difficult to predict and would also depend on interaction with a range of other factors (eg changes in groundwater abstraction or river flows).

Initial sensitivity analysis

For the purposes of liquefaction assessment to inform planning and consenting processes, it is recommended that the significance of potentially higher groundwater levels is first assessed using a simple sensitivity analysis.

There are various ways that this sensitivity analysis could be performed, for example:

- by raising the groundwater level assumed in the analysis by a nominal distance above the current-day median (eg by 0.5 m across the entire study area), and examining the change in predicted liquefaction-induced damage. This will help develop an understanding of where rising groundwater levels might have a significant impact on liquefaction-related risk, or where this impact is likely to be less significant
- by raising the groundwater level assumed in the analysis in a number of smaller increments (eg in five increments of 0.2 m each across the entire study area) to examine in more detail how the predicted liquefaction-induced damage responds to rising groundwater. This will help develop an understanding of how much change in groundwater level is required to cause a significant impact on liquefaction-related risk, or for the risk to cross a particular tolerance threshold.

For this initial sensitivity analysis, the precise amount the groundwater is raised is of only secondary importance. The values suggested in the examples above are likely to provide a useful starting point in most circumstances, subject to confirmation by the regional and/or district council of any scenarios they require to be considered. The primary aim of this initial analysis is to develop a better understanding of the potential consequences of changing groundwater levels. In particular, it is useful to understand whether rising groundwater levels could result in a large step-change worsening in land performance (eg enough to materially impact the engineering solution that would be adopted).

This initial focus on consequences provides a useful starting point for broad discussions with stakeholders. The approach can be used to develop a good understanding of the relevant issues and potential adaptation options before progressing into more detailed consideration of precisely how much groundwater rise should be assumed for planning and consenting purposes (and the related issues of the time period to be considered and the likelihood of different scenarios occurring in future).

Detailed analysis

If the initial sensitivity analysis indicates that a rise in groundwater levels could result in significant worsening of liquefaction-induced damage, and uncertainty about the magnitude of this worsening could have a significant impact on objectives and decision-making, then more detailed analysis may be warranted.

In most cases the starting point for this analysis will be an assumed increase in sea level. If rainfall is a significant factor determining groundwater levels in an area, then assumptions may also need to be made about changes in rainfall patterns (climate change may result in increased or decreased rainfall, depending on the location, and the direction of change may be different for summer and winter).

These assumptions should be defined by the regional and/or district council:

- because this is typically outside the area of expertise of the geotechnical engineers and engineering geologists who would undertake the liquefaction analysis; and
- to maintain consistency in assessments.

The assumptions should be consistent with the approach adopted by the relevant council for the assessment of other impacts of climate change (eg for flood analysis), and with relevant national policy statements and technical guidance.

With these assumptions defined, a hydrogeological model can be developed to estimate the groundwater level in a future scenario, and analysis undertaken to predict the degree of liquefaction-induced ground damage and assign liquefaction vulnerability categories. It is important to appreciate that there are significant uncertainties involved in modelling even the current-day groundwater conditions, so there will be substantial uncertainty when attempting to extrapolate this model to reflect future conditions. To decide whether development of such a model is warranted, consideration should be given to the results of the initial sensitivity analysis, the information available or able to be practically collected, and how useful the results would be for the intended purpose given the likely level of uncertainty.

It may be useful to present the results of this analysis both in absolute terms (ie the assigned liquefaction vulnerability categories) and in terms of the change in vulnerability due to the assumed change in groundwater levels.

4.3 Seismic hazard

4.3.1 Background

The expected severity and frequency of future earthquake shaking varies across New Zealand, so an important part of most liquefaction assessment studies will be determining the details of the earthquake scenarios to be considered. Key features of interest are:

- the likelihood of earthquake shaking in the future
- the most likely and maximum sizes of earthquakes that could affect the region
- how the strength of shaking could vary over a region
- the uncertainties in the seismic hazard assessment.

Further technical detail regarding estimation of ground motion parameters for liquefaction analysis purposes is provided in NZGS (2016c).

Seismic hazard information

The New Zealand National Seismic Hazard Model (NSHM) aggregates information on seismicity into a model that can be used to calculate the likelihood of earthquakes occurring within a region. The information considered includes:

- historical records of large earthquakes from people's observations
- past occurrence of earthquakes recorded using seismic instruments
- the location of known faults capable of producing moderate to large earthquakes and assessment of their average rupture reoccurrence. This is inferred from field investigation of the faults and evidence of their past displacements and effects (eg old landslides and topography changes)
- other known earthquake sources such as volcanic activity and subduction zones
- regional scale displacement of the land from tectonic plate movement
- distribution of shaking in previous earthquakes, from felt observations and instrumental recordings.

Uncertainty

There is considerable uncertainty in the assessment of seismic hazard – it's not possible to predict exactly when and where earthquakes will occur, and how strong the ground shaking will be. When assessing liquefaction-related risk as part of land use planning and development decision-making it is important to understand and communicate the potential implications of this uncertainty. This allows appropriate judgement to be applied, and more detailed assessment can be requested if necessary. If uncertainties in the seismic hazard are critical for decision-making, then a regional or site-specific probabilistic seismic hazard assessment (PSHA) may be useful to help constrain this uncertainty.

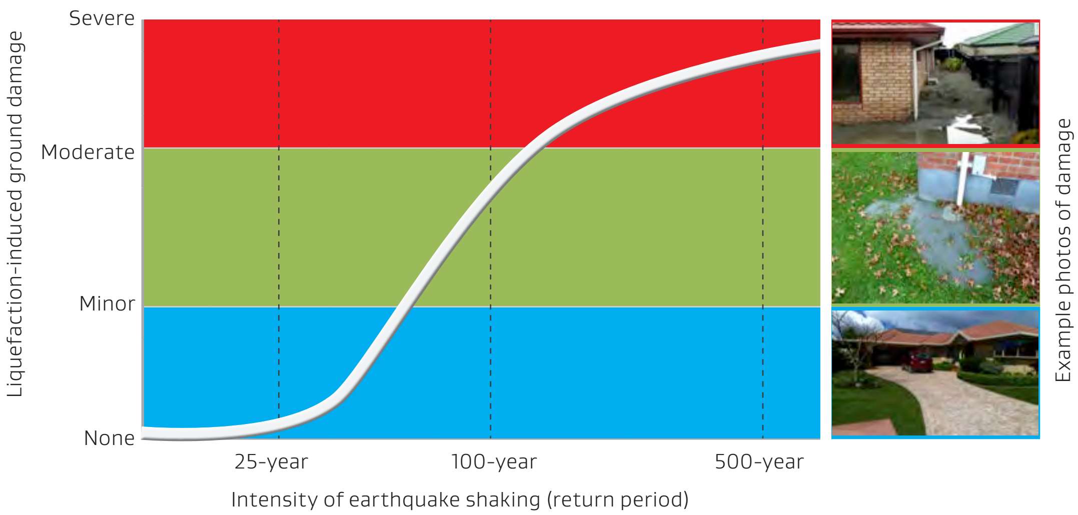
One way to accommodate this uncertainty is to consider a series of simple earthquake scenarios and assess what the consequences could be – for example small, moderate and extreme (low probability) events could be examined. This initial focus on consequences provides a useful starting point for broad 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 of the likelihood of particular events occurring.

4.3.2 Ground damage response curves and the need for multiple earthquake scenarios

The relationship between the intensity of earthquake shaking and the severity of liquefaction-induced ground damage can be highly non-linear, as illustrated by the example conceptual response curve plotted in Figure 4.1.

This happens because when the intensity of earthquake shaking is less than required to trigger liquefaction then it has little effect on the strength of the soil. As soon as the intensity of earthquake shaking is enough to trigger liquefaction in a soil layer there is a rapid reduction in its strength. However, further increases in shaking intensity beyond the point of liquefaction triggering may only result in minor additional strength loss in that soil layer.

Figure 4.1: Example conceptual response curve showing the degree of liquefaction-induced ground damage at different strengths of earthquake shaking



Notes:

The response curve shown is for a site with High liquefaction vulnerability (refer Section 4.5.2) – the shape of the curve and degree of damage will be different for sites with lower liquefaction vulnerability.

Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

The response can be further complicated by the presence of various soil layers of differing strengths. In this situation increasing shaking intensity may progressively trigger liquefaction in stronger soil layers, increasing the cumulative thickness of liquefaction within the overall soil profile.

Due to this complexity, assessing only a single earthquake scenario is often insufficient to properly understand the overall liquefaction-induced ground damage response curve. The most common exception to this is where ***Liquefaction Damage is Unlikely*** (eg rock or dense gravel that is simply not susceptible to liquefaction), in which case it is usually sufficient to only consider a large earthquake scenario and demonstrate that liquefaction does not occur.

Therefore to assess the overall level of liquefaction-related risk in situations where liquefaction damage is possible the categorisation of land to inform planning processes and engineering design needs to consider a range of earthquake scenarios, to identify multiple points along the response curve. Guidance regarding scenarios for analysis is provided in Sections 4.3.3 and 4.3.4.

4.3.3 Minimum requirements for earthquake scenarios

Return periods for earthquake scenarios

Earthquake scenarios for detailed liquefaction analysis are typically characterised in terms of the intensity of ground shaking that has a particular likelihood of occurring over a given length of time.

For example, one earthquake scenario that is often used for liquefaction analysis is a 500-year 'return period'. For this scenario, a particular intensity of ground shaking would be predicted at a particular location. This does not mean that this earthquake or this level of shaking will only occur once every 500 years – it could happen at any time, potentially multiple times or not at all over that period. The return period is simply a convenient way of saying that the probability of a particular intensity of shaking occurring (or being exceeded) in any one year is 1 in 500. This is often termed the Annual Exceedance Probability (AEP), which for a 500-year event would be 0.2 percent.

Earthquake scenarios for land use planning purposes

For land use planning it is important to recognise that once a land use is established then it might continue in perpetuity (ie use of the land becomes effectively permanent). While the exact nature of the land use might change over time, once the investment is made in buildings and infrastructure it becomes very difficult to withdraw from an area. It is also difficult to retrospectively improve the performance of the land once subdivided and occupied, as this is most effectively achieved on an area-wide clear-site basis. This is different to a building consent situation, where any individual building might have a much shorter nominal design life (eg 50 or 100 years, although many remain in use longer) and the building stock can be incrementally improved over time as old buildings are replaced with new.

Recognising the need to consider a long time frame for land use planning (centuries, rather than decades), where this guidance is adopted it is recommended that the earthquake scenarios outlined in Table 4.2 are considered as a minimum.

The 500-year earthquake scenario represents an intensity of shaking that is considered to have a low likelihood of being exceeded in the area within the land use planning horizon. There is a 0.2 percent probability that this will be exceeded in any given year, or approximately 10 percent probability over a 50-year period and 18 percent probability over a 100-year period. This scenario aligns with the Ultimate Limit State design case for most 'normal' buildings specified in the New Zealand Standard for structural design actions (NZS 1170.0:2002).

The 100-year earthquake scenario represents an intensity of shaking that is considered to have a high likelihood of occurring in the area within the land use planning horizon. There is a 1 percent probability that this will be exceeded in any given year, or approximately 10 percent probability in any given decade. Estimating the likely land performance at 100-year levels of shaking usually requires detailed quantitative analysis of subsurface test data, because the performance is very sensitive to details such as the soil strength and the minimum intensity of shaking required to trigger liquefaction for each soil[2]. This detailed analysis would usually only be carried out for ***Level C*** and ***Level D*** assessments (and sometimes to a minor extent for calibration at ***Level B***).

4.3.4 Additional earthquake scenarios and sensitivity studies

Additional earthquake scenarios might also be relevant for consideration in a liquefaction assessment study, however this will be a matter of judgement based on the specific details of each case. Several example scenarios are discussed below.

25-year earthquake scenario

For most buildings, the New Zealand standard for structural design actions (NZS 1170.0:2002) specifies a 25-year earthquake scenario for the Serviceability Limit State design case. A key focus of this design case is the potential for loss of amenity during the lifetime of the building.

So while the 25-year earthquake scenario might not be directly relevant for land use planning (as it needs to consider a longer time frame than individual buildings), it can be helpful to proactively consider this earthquake scenario during the planning process to confirm the land performance will be suitable for building purposes.

Extreme (low probability) earthquake scenario

The design of most 'normal' buildings and structures takes into account a 500-year level of earthquake shaking. While there is a low likelihood of this level of shaking of being exceeded in any given area within the land use planning horizon, there remains a chance that stronger earthquake shaking could occur.

For routine situations it would usually be overly conservative and cost-prohibitive to design for low-probability extreme earthquake scenarios. However, critical or high-impact facilities (eg hospitals or large dams) typically have their own specific design requirements which go well beyond those for routine project purposes.

As shown in Figure 4.1, increasing the earthquake shaking above 500-year level often results in only minor worsening in the expected land performance. Therefore for routine situations it will often be most appropriate for extreme earthquake scenarios to be considered as a sensitivity check to provide additional background information (eg 'what if' questions) to help guide development of natural hazard management strategies, rather than as a primary factor determining the liquefaction categorisation.

2 The performance is often less sensitive to these details at shorter return periods (eg 25-year) in cases where there is no significant liquefaction triggering at this low level of shaking, and at longer return periods (eg 500-year) in cases where all susceptible soils would liquefy at this high level of shaking.

Table 4.2: Recommended minimum earthquake scenarios for liquefaction assessment

LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT	RECOMMENDED MINIMUM EARTHQUAKE SCENARIOS
Level A Basic desktop assessment	500-year return period (0.2 percent AEP)
Level B Calibrated desktop assessment	
Level C Detailed area-wide assessment	100-year return period (1 percent AEP), and 500-year return period (0.2 percent AEP)
Level D Site-specific assessment	

For the purposes of applying the land performance framework presented in this document for routine situations, if an extreme earthquake scenario is adopted as a sensitivity check then a nominal earthquake scenario with peak ground acceleration at 150 percent of the 500-year level is recommended[3]. If the extreme scenario results in a large step-change worsening of land performance compared to the 500-year scenario (eg enough to materially impact the engineering solution that would be adopted), then this might indicate higher liquefaction vulnerability than a situation where there is only a minor incremental change to the land performance.

As with other uncertainties in the liquefaction assessment, it is important to communicate this sensitivity and its potential significance to those who will use the information for decision-making. This may be particularly relevant when planning for urban-density residential development and critical infrastructure.

Sensitivity analysis to determine onset of damage

In many cases it may be useful to undertake a sensitivity analysis to determine the intensity of shaking required to induce certain degrees of liquefaction-induced ground damage, as this can vary significantly depending on ground conditions.

This is usually of most relevance in situations where there is a significant step-change in performance (eg where no ground damage is expected at 25-year intensity of shaking, but this rapidly increases to moderate damage at 50-year intensity).

3 It is noted that for high-importance projects a site-specific seismic hazard study is sometimes undertaken to determine the Maximum Credible Earthquake event (MCE), however this additional complexity is unlikely to be warranted for the simple sensitivity check suggested here.

4.4 Estimation of potential liquefaction-induced ground damage

4.4.1 Overview

Once the base information is collated, the next step in the liquefaction assessment is to estimate the degree of liquefaction-induced ground damage likely to occur for each earthquake scenario considered. Depending on the information available, the nature of the ground conditions and the detail and purpose of the assessment, this may require the study area to be divided into sub-areas, and the approach taken might be qualitative or quantitative (or a mixture of both).

The following sections provide general guidance on approaches that can be used to categorise liquefaction vulnerability to inform planning and consenting processes. For further discussion regarding the technical details of analysis of liquefaction and its consequences, refer to NZGS (2016c).

4.4.2 Delineate sub-areas for assessment

The predicted degree of liquefaction-induced land damage will often vary across the study area due to variations in ground conditions, particularly for broader-scale assessments. In this case it can be useful to divide the study area up into smaller sub-areas, each with similar liquefaction characteristics. The number and size of these sub-areas will depend on knowledge about variability of ground conditions and the detail and extent of the study.

Sub-areas would typically be defined initially based on geological, depositional and geomorphic features. For assessments at higher levels of detail it may be possible to then refine the sub-areas based on analysis of ground investigation information. There will often be considerable uncertainty regarding the location of boundaries between sub-areas, so they should be defined with an appropriate level of conservatism taking into account the detail, scale and purpose of the assessment and the specific uncertainties associated with the ground conditions and assessment method. The liquefaction assessment report should clearly explain the basis and assumptions for delineating boundaries between sub-areas, and this should be given particular attention during peer review.

In cases where there is sufficient information it may be more appropriate to provide a best-estimate delineation of boundaries, rather than define conservative boundaries that may over-state the likely extent and severity of liquefaction vulnerability. In this case it would be important to clearly communicate this uncertainty (and potential consequences), to draw attention to the need to refine this boundary in more detailed subsequent assessments (eg in the assessment report and as part of the Geospatial Information System (GIS) metadata for each area recommended in Appendix E).

4.4.3 Qualitative approaches

There are a range of qualitative approaches for assessing the potential for liquefaction-induced land damage, which can be applied at various levels of detail as required. The most common approaches are outlined below.

It should be appreciated that simple large-scale qualitative assessments are generally only intended to identify broad geological units where there is a greater or lesser likelihood that potentially liquefiable sediments may be present within part (but not necessarily all) of a given area. This type of assessment will not be able to delineate the actual extent of liquefiable soil deposits or determine the actual potential for liquefaction at a specific site.

Therefore care is essential when using qualitative approaches for assigning liquefaction vulnerability categories, requiring informed judgement by a suitably experienced engineering professional. Conservative assumptions should be made where appropriate, guided by an understanding of the potential consequences of incorrect categorisation. These uncertainties and assumptions in the liquefaction assessment (and potential consequences) should be clearly communicated to the users of the information.

Simple geological screening

The most basic qualitative approach is to apply a simple screening test based on geological maps. The primary aim of this initial screening is to identify geological units that are fundamentally not susceptible to liquefaction (eg rock or dense gravel). The approach adopted for qualitative screening will vary slightly depending on the specifics of each region, however the key concepts are well established in the technical literature, eg Youd and Perkins (1978), Kramer (1996), Idriss and Boulanger (2008).

Liquefaction vulnerability categories can be determined as follows:

- The identified non-susceptible geological units would be typically be assigned a liquefaction vulnerability category of ***Liquefaction Damage is Unlikely***. Alternatively, if the available information is sufficiently detailed and conclusive, it may be possible to assign a liquefaction vulnerability category of ***Very Low*** or ***Low***.
- In some cases the available geological information might be sufficiently detailed and conclusive to allow a liquefaction vulnerability category of ***High*** to be applied (eg for a known deep estuarine deposit where it is clear that ***Moderate to Severe*** land damage is likely).
- In almost all cases a simple geological screening will not provide sufficient information to assign a liquefaction vulnerability category of ***Medium***, as this typically requires detailed quantitative analysis to determine how the degree of ground damage varies for different intensities of earthquake shaking (refer Section 4.5).
- All other geological units would typically be assigned a liquefaction vulnerability category of ***Liquefaction Category is Undetermined*** or ***Liquefaction Damage is Possible*** as appropriate, awaiting more detailed assessment and recategorisation in future if the need arises.

It should be appreciated that large-scale geological maps (eg the 1:250,000 QMAP series) might not identify small deposits of susceptible soils within larger geological units (eg infilled river channels). This means that there is still potential for localised areas of liquefaction-induced damage to occur even within areas that are screened out using this approach. In many cases this damage is likely to be limited in extent and severity, and the building design and consenting process will often identify particular problem sites, so this uncertainty in the categorisation presents a relatively low level of overall risk. Nonetheless, it is important to communicate this uncertainty and the potential consequences to users of the information so they can identify situations where it may be important for their purposes.

When applying this geological screening approach, it is important to bear in mind that geological maps primarily only show the material present at the ground surface; they typically provide little or no information about the subsurface ground profile.

For example, an area mapped as having clay (which is non-liquefiable) at the surface might have thick deposits of liquefiable sand just beneath the surface. Therefore it is important to supplement geological maps with a broader understanding of the subsurface conditions and the land forming processes involved (eg good knowledge of local ground conditions).

Geological screening with qualitative calibration

The geological screening process outlined above can be significantly enhanced by targeted calibration of the geological maps using ground investigation information to better understand the subsurface soil profile and the liquefaction susceptibility of the soil types present.

For example geologically recent river floodplain deposits might be all mapped as the same geological unit (with the symbol Q1a), but some parts of the unit might comprise dense gravels right from the surface while other parts might have thick deposits of loose sand at the surface. In this case examining borehole logs across the area to see whether material is logged as sand or gravel would help understand the spatial distribution of material types that are susceptible to liquefaction.

One challenge with calibration of geological maps is how to use information from sparsely distributed point locations to understand the ground conditions elsewhere without over-extrapolating. Inappropriate extrapolation can easily result in incorrect assumptions being made. Particular care should be taken to avoid inadvertently extrapolating data across geologic boundaries. The nature of the depositional processes involved (both vertically and horizontally) should be taken into account when considering the details of the extrapolation. For example river deposits tend to be more variable than marine deposits. Also, different extrapolation techniques might be appropriate for different types of deposit. For instance marine deposits are often best extrapolated based on elevation relative to sea level, while airfall deposits might be better extrapolated based on layer thickness.

Careful judgement is required, balancing up a broad range of factors – this is a situation where peer review and a good understanding of local ground conditions are especially useful.

Simple geomorphic screening for lateral spreading

Observations from previous earthquakes indicate that severe damage to ground, buildings, infrastructure and the environment can be caused by liquefaction-induced lateral spreading (refer Section 2.4). Therefore the potential for lateral spreading should be considered when assigning liquefaction vulnerability categories.

If it is determined that ***Liquefaction Damage is Unlikely***, then lateral spreading damage is usually also unlikely (except in specific circumstances, such as a thin liquefiable layer that allows the overlying material to slide towards the free-face).

If ***Liquefaction Damage is Possible***, then lateral spreading has the potential to increase the severity of damage resulting from liquefaction. A simple qualitative approach for initial screening purposes is to identify geomorphic features such as free-faces or sloping ground that would enable lateral spreading to occur if liquefaction is triggered, or where the landform suggests it may have occurred in the past.

When considering the potential for lateral spreading adjacent to a free-face, the location of potentially liquefiable material within the soil profile can be important. It is less likely (but not impossible) for lateral spreading to occur if there is no liquefied soil within a depth of 2H of the ground surface (where H is the height of the free-face).

Lateral spreading can extend to large distances away from the free-face – extents of hundreds of metres or more have been observed in previous earthquakes. The spatial extent of lateral spreading is influenced by a range of factors, such as variations in the underlying geological formation and soil characteristics, extent of lenses of liquefied soil, ground topography and the three-dimensional geometry of the free-face. There are no firm guidelines for the extent of lateral spreading that could occur. However, as a starting point for simplified lateral spreading screening, particular attention should be given to liquefaction-susceptible land that is within 200 m of a free-face greater than 2 m high; or within 100 m of a free-face less than 2 m high.

Where the potential for lateral spreading is identified, the liquefaction vulnerability category should be updated as necessary to reflect the potential for increased damage (eg areas that would otherwise have been categorised as ***Medium*** liquefaction vulnerability might be updated to ***High***).

Table 4.3: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground surface damage is unlikely

TYPE OF SOIL DEPOSIT	A LIQUEFACTION VULNERABILITY CATEGORY OF LIQUEFACTION DAMAGE IS UNLIKELY CAN BE ASSIGNED IF EITHER OF THESE CONDITIONS IS MET:	
	DESIGN PEAK GROUND ACCELERATION (PGA) FOR 500-YEAR INTENSITY OF EARTHQUAKE SHAKING[1]	DEPTH TO GROUNDWATER[2]
Late Holocene age Current river channels and their historical floodplains, marshes and estuaries, reclamation fills	Less than 0.1 g[3]	More than 8 m
Holocene age Less than 11,000 years old	Less than 0.2 g	More than 6 m
Latest Pleistocene age Between 11,000 and 15,000 years old	Less than 0.3 g	More than 4 m

Notes:

1 The listed PGA values correspond to a magnitude 7.5 earthquake. For screening purposes using this table, earthquake scenarios with different magnitudes may be scaled using the magnitude scaling factor (MSF) proposed by Idriss and Boulanger (2008): MSF = [6.9 exp (-M/4) – 0.058], up to a maximum value of 1.8.

2 For screening purposes using this table, a high groundwater scenario should be assumed (eg a typical seasonal high groundwater level).

3 For many types of late Holocene age deposits (and especially reclamation fills), if liquefaction is triggered then ***Moderate to Severe*** ground damage often results. Therefore careful consideration should be given to the uncertainties in the seismic hazard estimate before screening out these soils on the basis of the expected intensity of earthquake shaking. It is important to understand the potential consequences if earthquake shaking is stronger than expected.

These criteria are adapted (with modifications) from California Department of Conservation (2004).

4.4.4 Semi-quantitative approaches

Geological screening based on seismic hazard or groundwater depth

By considering the regional seismicity and depth to groundwater in conjunction with the depositional process and the age of soil deposits, the semi-quantitative screening criteria in Table 4.3 can be used to identify geological units where significant liquefaction-induced ground damage is unlikely to occur. A soil deposit of the specified type may be assigned a liquefaction vulnerability category of ***Liquefaction Damage is Unlikely*** if the 500-year peak ground acceleration (PGA) is less than the value listed, or if the depth to groundwater is more than the value listed. Alternatively, if the available information is sufficiently detailed and conclusive then it may be possible to assign a liquefaction vulnerability category of ***Low***.

Geological screening with quantitative calibration

The calibration of geological maps can be further improved by targeted analysis of subsurface test data (eg CPT or SPT) to help understand the intensity of earthquake shaking required to trigger liquefaction and the resulting degree of ground damage.

As discussed in Section 4.4.3, care is required when extrapolating sparse information in this way, as inappropriate extrapolation can easily result in incorrect assumptions being made. This is particularly challenging for quantitative liquefaction analysis, as soil strength can vary significantly within a geological unit, particularly for river deposits. A robust technical methodology applied by a suitably experienced engineering geologist or geotechnical engineer is required for this type of calibration, preferably with the benefit of expert peer review.

Historic observations of liquefaction or lateral spreading

Observations of liquefaction having occurred, or not occurred, in a previous earthquake can provide useful information about liquefaction susceptibility and triggering. A collection of observations from previous New Zealand earthquakes is provided in Fairless and Berrill (1984).

Ambraseys (1988) collated liquefaction observation information from a number of previous earthquakes, and found no examples of liquefaction observed at a distance from the epicentre of more than approximately 20 km for a magnitude 6 earthquake, 100 km for magnitude 7, or 300 km for magnitude 8. So if the distance between a site and the epicentre of a previous earthquake is less than these limits then observations of the site performance might be useful.

If liquefaction was observed to have occurred at a particular location, it clearly indicates that the soil is susceptible to liquefaction. In addition to this qualitative assessment of susceptibility, observations can also enable semi-quantitative calibration of the liquefaction analysis. The observation demonstrates that the intensity of shaking required to trigger liquefaction is less than or equal to the intensity of shaking experienced in that earthquake – possibly enabling the triggering PGA to be calibrated. Observations about the degree of ground damage that occurred might also allow the analysis of liquefaction severity to be calibrated.

If a site experienced an earthquake and evidence of liquefaction was not observed then this provides some information about the potential for liquefaction to occur in future, but there are particular complexities in interpreting this information. It is possible that soil is susceptible but the strength of the soil is such that the intensity or duration of shaking was not sufficient to trigger liquefaction. It is also possible that liquefaction was triggered in the soil at depth but there was no surface evidence of liquefaction having occurred, and greater ground damage might occur in longer-duration earthquakes. In some cases there might have been surface evidence of liquefaction occurring, but the observation was not recorded or photographed, or it was attributed to other causes (eg flooding, landslip or fault rupture) because of a lack of knowledge about liquefaction in the past.

A similar approach can be applied for observations about the occurrence or non-occurrence of lateral spreading (with the same challenges in interpretation as discussed above).

Empirical or semi-empirical assessment of lateral spreading

Depending on the available information and the scale and purpose of the assessment, suitable simplified lateral spreading assessment approaches could include:

- Empirical correlations based on regression analysis of lateral spreading displacements observed in previous earthquakes (eg Youd et al., 2002, Bardet et al., 2002). There are major uncertainties and limitations with these methods, so care is required when interpreting the results. These methods depend entirely on a limited database of case histories, so the results might not be applicable if extrapolated beyond that database. This is often the case for New Zealand conditions because of a lack of local case histories at the time these methods were developed, making local application of these methods challenging.
- Semi-empirical assessment based on integration of estimated permanent shear strains within the soil profile, normally based on correlations with penetration test data and calibration to case history observations (eg Tokimatsu and Asaka 1998, Zhang et al., 2004).

Both of these approaches provide an indication of the potential magnitude of lateral ground displacement, although there are substantial uncertainties in these estimates. This information could be incorporated into the liquefaction vulnerability categorisation in either of two ways:

- Qualitatively – eg by simply setting the liquefaction vulnerability category to ***High*** wherever there is a potential for material lateral spreading displacements to occur.
- Quantitatively – eg by evaluating the predicted magnitude of lateral displacement against lateral ground stretch limits for each liquefaction vulnerability category (refer Section 2.5).

4.4.5 Quantitative approaches

Liquefaction severity index parameters

Quantitative liquefaction analysis of subsurface test data such CPT or SPT can be undertaken to estimate the degree of liquefaction-induced ground damage for various earthquake scenarios. If there is sufficient spatial density and coverage of ground information (refer Section 3.4) then the ground performance across the study area can be assessed directly from the analysis results, rather than relying on extrapolation across geological units (as is required for the qualitative and semi-quantitative approaches). In some cases, the analysis might also adopt a probabilistic approach for managing uncertainties in the base information and damage correlations.

There are a range of liquefaction analysis methods that may be suitable for estimating the degree of liquefaction-induced ground settlement damage, depending on the specific circumstances of each assessment. Examples of such methods include:

- S_{V1D} – Post-liquefaction volumetric consolidation settlement (Zhang et al., 2002)
- LPI – Liquefaction Potential Index (Iwasaki et al., 1978)
- LPI_{ISH} – Ishihara-inspired LPI (Maurer et al., 2015)
- LSN – Liquefaction Severity Number (van Ballegooy et al., 2014)

This guidance document does not require that any particular analysis method must be used, or specify any fixed threshold index values for land categorisation. Rather, it establishes performance criteria based on the degree of damage expected for various intensities of earthquake shaking (refer Section 4.5), and allows the technical experts flexibility to evaluate these criteria as appropriate for the specific situation.

One of the key aspects of a quantitative liquefaction assessment is understanding the correlation between liquefaction analysis results and the ground damage that is likely to occur. A common approach is to select threshold values of a calculated index parameter to indicate different degrees of damage. There can be considerable variability in the correlation between liquefaction calculations and the actual damage that occurs, so appropriate understanding and management of this uncertainty (and potential consequences) is an important part of this process. Appendix I provides an example of this approach using the LSN.

Analytical assessment of lateral spreading

In some situations detailed analysis of potential lateral spreading ground displacements will be warranted – such as to delineate areas where particular building requirements apply, or for specific engineering design of foundations and infrastructure. This would often include more detailed application of the semi-quantitative approaches outlined in Section 4.4.4, supplemented where required with site-specific stability analysis using methods such as:

- static slope stability analysis using liquefied soil strengths, to assess the potential for static flow slide failure to occur
- sliding block analysis, where lateral displacements are assumed to accumulate incrementally during earthquake shaking whenever the ground acceleration exceeds a calculated yield value
- detailed numerical analysis (eg nonlinear finite-element time-history analysis).

The results of this analysis would be evaluated against the lateral ground stretch limits for each liquefaction vulnerability category (refer Section 2.5), or the specific deformation tolerances of the proposed buildings and infrastructure.

4.5 Assessing expected ground damage against performance criteria

4.5.1 Overview of the performance-based framework for liquefaction categorisation

This guidance provides a performance-based framework for categorising land to inform planning and consenting processes for managing liquefaction-related risk. This is conceptually similar to the performance-based approach taken by the New Zealand Building Code.

This means that rather than requiring a single fixed assessment methodology to be used, this guidance establishes performance criteria that can be evaluated using various methods as appropriate for the specific circumstances of each case. This flexibility is particularly important for liquefaction assessment as the scientific understanding is rapidly evolving, assessment tools are being continually improved, and soil characteristics vary significantly across the country.

The performance-based framework in this guidance is based on the degree of liquefaction-induced ground damage (refer Section 2.5) that is expected to occur at various intensities of earthquake shaking (refer Section 4.3). The degree of ground damage for each earthquake scenario is estimated using qualitative or quantitative methods as appropriate for the level of detail in the assessment (refer Section 4.4). The expected ground response is then compared to the performance criteria defined in Section 4.5.2 to determine the appropriate liquefaction vulnerability category.

Throughout this risk analysis process there should be careful consideration of the uncertainties in the input parameters and analysis tools, as they relate specifically to the area being examined, and the potential consequences if the actual conditions vary from the assumed model. These uncertainties and consequences should be taken into account when evaluating the probabilities of ground damage listed in Table 4.4, and communicated to the users of the liquefaction assessment information.

4.5.2 Performance criteria for liquefaction vulnerability categorisation

The recommended performance criteria for determining the liquefaction vulnerability category for a particular area of land are presented in Table 4.4 (refer to Section 4.4 for methods to estimate the degree of ground damage).

The liquefaction vulnerability category can be determined by applying three tests to compare the expected liquefaction response against the performance criteria. This is demonstrated in the process flowchart in Figure 4.2, and the conceptual liquefaction-induced ground damage response curves in Figure 4.3.

The performance criteria make reference to particular probabilities of a certain degree of damage occurring. These probabilities are intended to provide a general indication of the level of confidence required to assign a particular category, rather than to be a specific numerical criteria for calculation. In most cases the level of confidence will be evaluated qualitatively, rather than by rigorous probabilistic analysis. These indicative probabilities have been selected to help manage the consequences of uncertainty in the liquefaction vulnerability categorisation (ie under-prediction and over-prediction of the vulnerability), as detailed in Appendix J.

4.5.3 Implementation of the performance-based framework in practice

In practice, determining the applicable liquefaction category for a particular area of land will be more complex that in the conceptual examples presented in Figure 4.3.

In those conceptual examples there is a single response curve that represents the land performance at a location, the degree of damage is precisely known and the curve is defined over its entire length. But in practice there may be considerable variability in the response curves across a particular area of land, there is uncertainty in the degree of damage that could occur, and only a limited number of points on the response curve will be known. These complexities are discussed further in Appendix J.

Table 4.4: Performance criteria for determining the liquefaction vulnerability category

<table>
<tr><td colspan="4">LIQUEFACTION CATEGORY IS UNDETERMINED
A liquefaction vulnerability category has not been assigned at this stage, either because a liquefaction assessment has not been undertaken for this area, or there is not enough information to determine the appropriate category with the required level of confidence.</td></tr>
<tr><td colspan="2">LIQUEFACTION DAMAGE IS UNLIKELY
There is a probability of more than 85 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking.
At this stage there is not enough information to distinguish between Very Low and Low. More detailed assessment would be required to assign a more specific liquefaction category.</td><td colspan="2">LIQUEFACTION DAMAGE IS POSSIBLE
There is a probability of more than 15 percent that liquefaction-induced ground damage will be Minor to Moderate (or more) for 500-year shaking.
At this stage there is not enough information to distinguish between Medium and High. More detailed assessment would be required to assign a more specific liquefaction category.</td></tr>
<tr><td>Very Low Liquefaction Vulnerability
There is a probability of more than 99 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking.</td><td>Low Liquefaction Vulnerability
There is a probability of more than 85 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking.</td><td>Medium Liquefaction Vulnerability
There is a probability of more than 50 percent that liquefaction-induced ground damage will be:
Minor to Moderate (or less) for 500-year shaking; and
None to Minor for 100-year shaking.</td><td>High Liquefaction Vulnerability
There is a probability of more than 50 percent that liquefaction-induced ground damage will be:
Moderate to Severe for 500-year shaking; and/or
Minor to Moderate (or more) for 100-year shaking.</td></tr>
</table>

Notes:

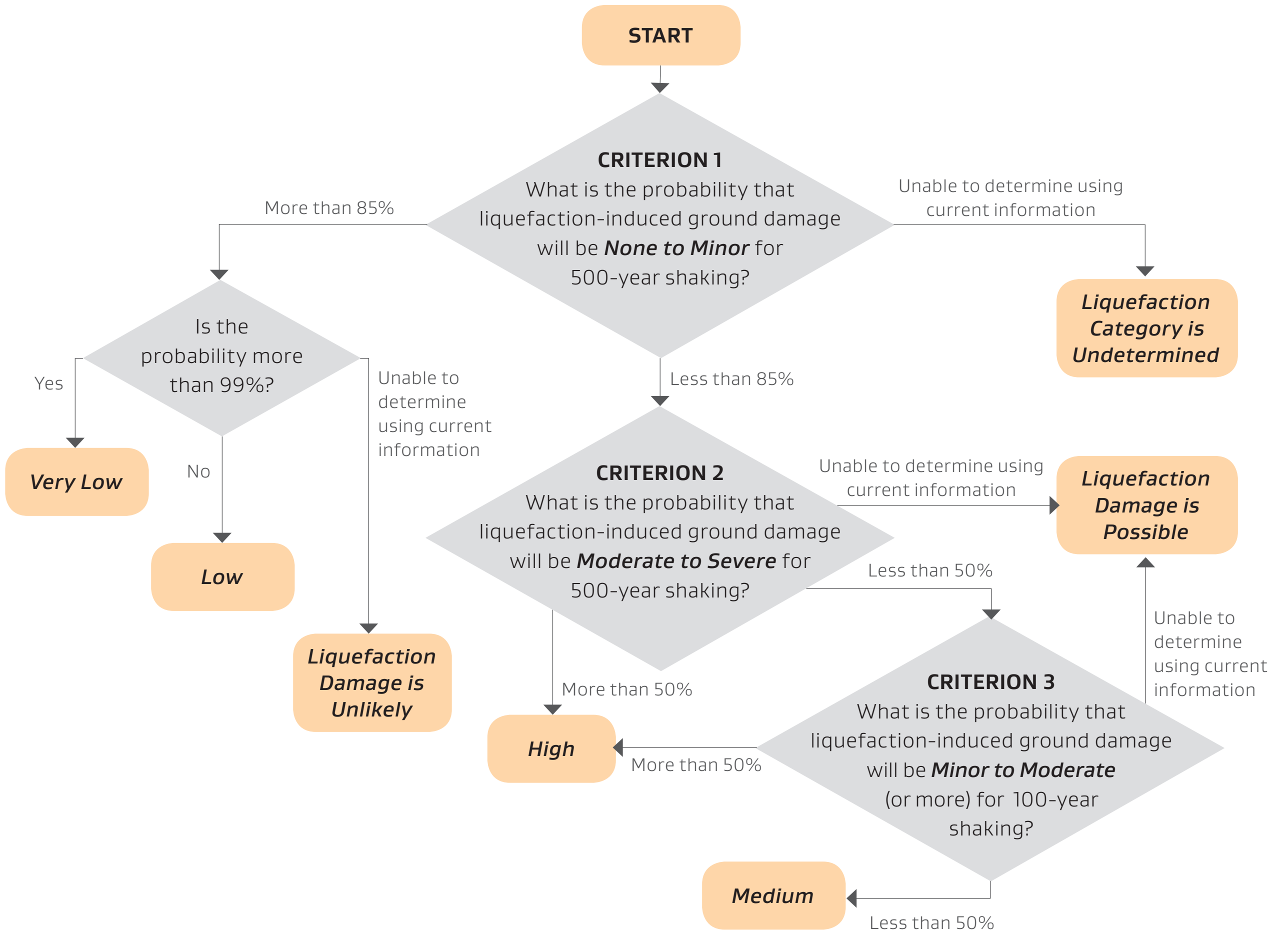
This table describes the degree of damage that is expected to occur on average across the area, but due to natural ground variability some locations within an area may have more or less damage. This is discussed further in Appendix J.

Refer to Section 2.5 for description of degrees of ground damage, Section 4.3 for discussion on earthquake scenarios, and Section 4.4 for methods to estimate the degree of ground damage.

The probabilities listed in this table are intended to provide a general indication of the level of confidence required to assign a particular category, rather than to be a specific numerical criteria for calculation. Conceptually, these probabilities relate to the total effect of all uncertainties in the assessment (ie more than just the probability of liquefaction assumed in the simplified liquefaction triggering analysis method).

It may be appropriate for other threshold values to be adopted for the performance criteria (eg for probability, degree of damage and earthquake scenarios) depending on the specific details of the assessment methodology, the purpose and level of detail of the liquefaction assessment, local ground conditions, and the relative costs of under-prediction and over-prediction (refer Appendix J). However, to maintain consistency across the country it is important that the overarching principles of this performance based framework are retained, and any alternative criteria are developed with the benefit of expert peer review.

Figure 4.2: Flow chart for determining the liquefaction vulnerability category



4.6 Production of a liquefaction vulnerability category map and supporting report

This guidance seeks to encourage consistency in the assessment, documentation and communication of liquefaction risk across New Zealand. An important part of this is for consistent terminology to be used for mapping and reporting the results of a liquefaction assessment.

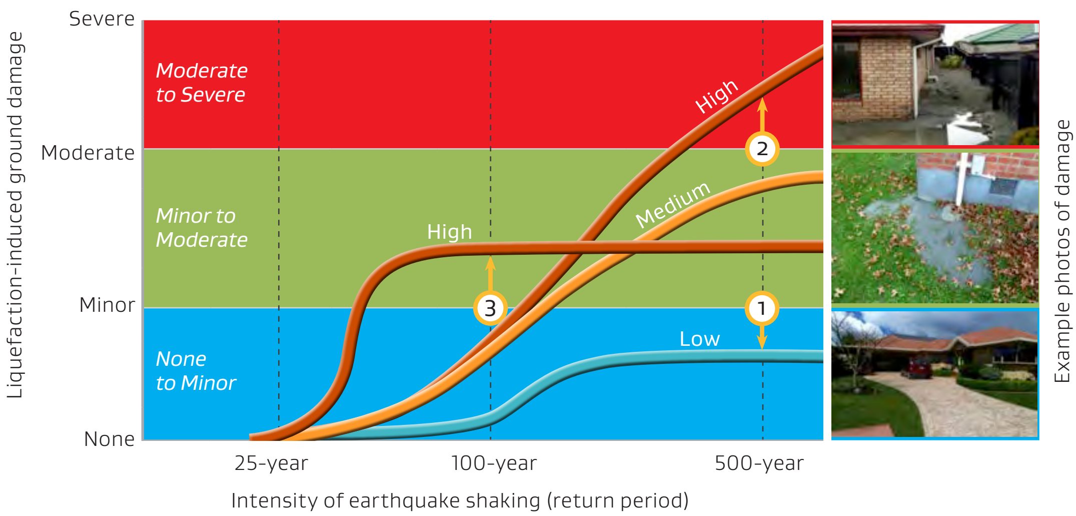
This guidance recommends that every liquefaction assessment should include a map that clearly defines the spatial extent of the study area, the delineation of any sub-areas, and the liquefaction vulnerability categories assigned. The category descriptions and colour scheme shown in Table 4.1 should be used where possible (refer to Appendix E for the relevant colour codes). Because these descriptions are by necessity very simplified, the map should also reference the full liquefaction assessment report (or other public information resources) for further detail.

The purpose, methodology and results of a liquefaction assessment should be clearly documented in a report. This may be a stand-alone report specifically for the liquefaction assessment (eg for a district-wide study), or as part of a broader report (eg as part of a subdivision geotechnical report). In either case, there are a number of key details that should be clearly identified in the report. For example it is important to explain the purpose and level of detail of the assessment, so that it is only used for appropriate purposes and so it is clear when a more detailed assessment supersedes a previous assessment for a particular location.

It is recommended that information about the liquefaction assessment is collated into a summary table such as the example in Appendix E, to make it easy for readers of the report to understand the scope of the assessment. As the liquefaction vulnerability categories across a region will be incrementally refined over time as further assessments are undertaken, councils may wish to use this summary table, along with GIS metadata for each area and sub-area, to collate liquefaction assessment information for ease of reference and updating in future.

One of the key aspects of a liquefaction assessment that will evolve over time is the available subsurface ground information (eg CPT testing and boreholes). Therefore the report should clearly identify the ground investigations that were used in the assessment (eg a list or map of investigation locations). This can help future readers of the report understand if there is new information in an area that may be useful to consider when updating the liquefaction assessment.

Figure 4.3: Conceptual example of ground damage response curves for low, medium and high liquefaction vulnerability categories, and performance criteria used for liquefaction categorisation



Performance criteria for liquefaction categorisation

Select the highest category from these three criteria. If none apply then the liquefaction vulnerability category is ***Medium***

1. If less than ***Minor*** ground damage at 500-year level of shaking then the liquefaction vulnerability category is ***Low***
2. If more than ***Moderate*** ground damage at 500-year level of shaking then the liquefaction vulnerability category is ***High***
3. If more than ***Minor*** ground damage at 100-year level of shaking then the liquefaction vulnerability category is ***High***

Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

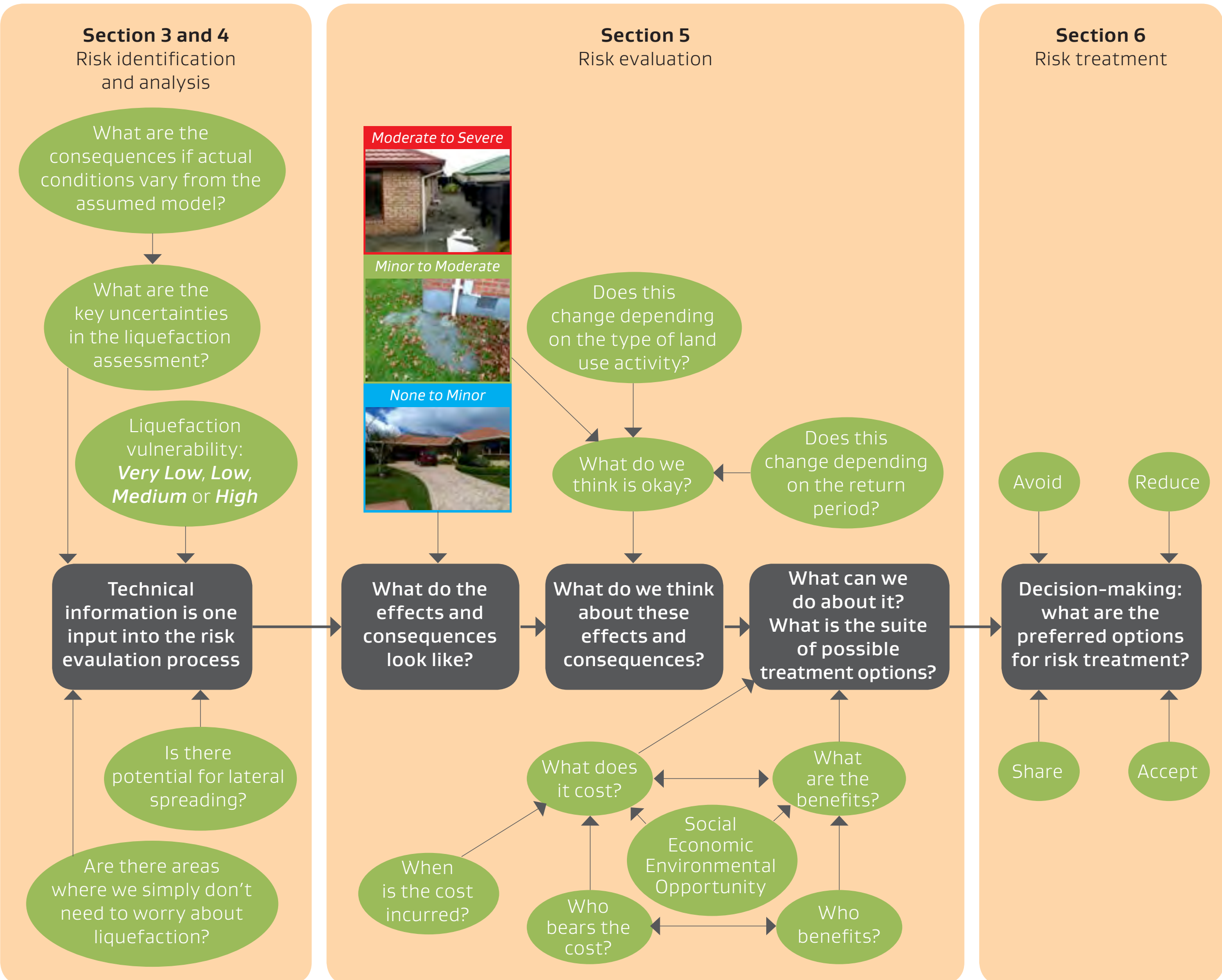
5 RISK EVALUATION

As outlined in Figure 1.1, risk evaluation is the third and final step in the risk assessment process. This is where the largely technical and factual information about the potential effects and risk of liquefaction is communicated and given meaning. The process moves from a technical stage to the beginning of a decision-making stage and so needs to involve the relevant stakeholders and decision-makers.

Risk evaluation examines the information about the risks that have been identified and analysed to understand how they may impact on stakeholders and the applicable regulatory and community objectives. Effective communication about the technical assessment information and associated uncertainty (and potential consequences of this uncertainty) is vital so that all stakeholders and decision-makers can evaluate how that uncertainty may affect their objectives.

As illustrated in Figure 5.1, it is at this point that attitudes to risk and uncertainty need to be explored to inform decisions that will need to be made about the most appropriate risk treatment options. For RMA processes, this evaluation should form part of the benefits and costs evaluation required by Section 32 of the Act (see Section 6.6).

Figure 5.1: Example process for risk evaluation



6 RISK TREATMENT

6.1 Overview of risk treatment options

As outlined in Figure 1.1, once risks have been assessed (identified, analysed and evaluated) consideration should be given to whether some form of risk treatment is appropriate.

ISO 31000 provides examples of a range of options for responding to risks. These examples are summarised in Table 6.1, together with discussion of their applicability in the specific context of managing liquefaction-related risk.

As the focus of this guidance document is on managing liquefaction-related risk as part of land use planning and decision-making, Sections 6.2 through to 6.7 will concentrate on ways that risk treatment can be implemented using the available planning and decision-making tools within the RMA and Building Act framework.

It should be appreciated that there are a variety of other planning and decision-making tools that are also available as part of a comprehensive approach to natural hazards management (eg broader central and local government planning, infrastructure and asset management strategies, and provision of information).

There are also engineering approaches available for managing liquefaction-related risk. For discussion of the technical engineering details of risk treatment options (primarily ***Reduce*** or ***Mitigate***) refer to the NZGS/MBIE Earthquake Geotechnical Engineering Practice series (NZGS 2016a to 2016d).

An important part of land use planning in areas where ***Liquefaction Damage is Possible*** is enabling the provision of infrastructure that is suitably resilient and affordable. Therefore more specific guidance relating to infrastructure strategy is provided in Section 6.9.

Table 6.1: Example risk treatment options for liquefaction-related risk

RISK TREATMENT OPTION		APPLICABILITY TO MANAGING LIQUEFACTION-RELATED RISK
AVOID OR ELIMINATE	**Avoiding risk by deciding not to start or continue with the activity that gives rise to the risk**	This typically takes the form of land use controls that simply avoid creating new areas of built land use (or intensifying existing areas) on land where the liquefaction-related risk is considered not tolerable. This could also include measures to avoid (where practical) locating critical infrastructure in areas with greater liquefaction vulnerability, or to avoid higher-density or higher-consequence land uses in these areas. In some regions it may be possible to locate activities in areas where earthquake shaking is expected to be weaker and/or less frequent, although there would be a residual risk that an unforeseen event or site response could cause stronger shaking than predicted. Avoiding liquefaction-prone land altogether might come at the cost of lost opportunity to benefit from that activity, so this treatment option should be evaluated in the context of the broader objectives of a district.
	Removing the risk source	It is not possible to stop earthquakes (ie the fundamental natural hazard event that triggers liquefaction), so removing the risk source not possible in this case.
REDUCE OR MITIGATE	**Changing the likelihood**	It is not possible to change the likelihood of earthquakes, so instead the focus of this risk treatment is to reduce the likelihood of liquefaction occurring. This would require changing one or both of the other key elements detailed in Figure 2.4: – It may be possible to change the soil condition (eg by deep compaction or reinforcement of the ground) so that a higher level of earthquake shaking is required to trigger liquefaction. In some cases it may be possible to change the fundamental behaviour of the ground (eg by physically removing or cementing susceptible soil) so that liquefaction will not occur even under the highest levels of earthquake shaking. – Changing the groundwater conditions sufficiently to materially reduce the likelihood of liquefaction occurring is unlikely to be practical in most cases.

RISK TREATMENT OPTION		APPLICABILITY TO MANAGING LIQUEFACTION-RELATED RISK
REDUCE OR MITIGATE	Changing the consequences	There are two primary engineering approaches for changing the consequences that result once liquefaction is triggered (refer also to MBIE 2015). – Improve the ground to reduce severity of ground deformation and strength loss. Targeted ground improvement can reduce the aspects of liquefaction that are most damaging for the types of buildings and infrastructure that are proposed (eg shallow foundations can be sensitive to differential ground settlement and weak soil, so a strong and stiff building platform could be provided to reduce the potential for strength loss and sand boils beneath footings and to distribute ground settlement more smoothly across the building footprint). – Improve the structure so it is better able to tolerate ground deformation. Thoughtful building design can provide solutions that are less vulnerable to liquefaction-induced damage, and are more readily repairable following an event (eg lightweight buildings with stiff foundation slabs which limit the distortion of a building and are more practical to relevel after an event). Similar concepts apply to infrastructure, to provide solutions which are more resilient to ground deformation (eg polyethylene pipes and pressure wastewater systems) and networks that offer redundancy to better tolerate damage to one part of the network. Another means of reducing the consequences is to control the type and intensity of land development, to limit the assets that are exposed to the hazard.
SHARE OR TRANSFER	Sharing the risk with other parties	This often takes the form of insurance, but can include a range of other risk financing mechanisms or contractual arrangements (eg sharing of infrastructure repair costs between local and central government). This requires a good understanding of the potential damage and cost of reinstatement. It is usually not possible to completely transfer all liquefaction-related risk (eg even if insurance covers the cost of repair, a risk of community disruption from liquefaction-induced damage remains). There also remains a risk that the other party will dispute or be unable to meet its obligations when an event occurs.
RETAIN OR ACCEPT	Taking or increasing the risk in order to pursue an opportunity	Situations might arise where an opportunity can only be realised by building on liquefaction-prone land, but it would not be practical or cost-effective to reduce the potential for liquefaction-induced damage to occur (eg due to a lack of available land, the need to build in a specific location or critical infrastructure that cannot functionally be located elsewhere). This situation would require careful assessment to determine whether the benefits of the opportunity were so great that they outweighed a level of liquefaction-related risk that would ordinarily not be tolerable.
	Retaining the risk by informed decision	In some cases it may be appropriate to not insure (or self-insure) non-critical assets that can be affordably repaired or replaced following an event as part of normal operations. This requires a good understanding of the likelihood and consequences of liquefaction-induced damage and the cost of reinstatement. Sometimes a risk might be retained unknowingly because it was not identified or not well understood, so alternative risk treatments were not implemented. This underscores the importance of a rigorous process to identify the full range of risks that might be present.

Note:
These options are not mutually exclusive, and some options might be less effective or inappropriate in some circumstances, so it is often useful to apply a combination of risk treatments to reduce the residual risk to a tolerable level.

6.2 Managing liquefaction-related risk in land use planning and decision-making

Managing significant risks from natural hazards is a Matter of National Importance under the RMA and so needs to be addressed at all levels of planning and decision-making. In addition, the formal functions of councils are also part of the context relevant to different parts of the planning and decision-making hierarchy established by the RMA.

The RMA assigns regional and district councils' functions and responsibilities related to natural hazards as follows:

- regional councils are charged with 'the control of the use of land for the purpose of . . . the avoidance or mitigation of natural hazards' (RMA Section 30).
- district councils are charged with 'the control of any actual or potential effects of the use, development, or protection of land, including for the purpose of. . .the avoidance or mitigation of natural hazards' (RMA Section 31).

The RMA provides for regional councils to take a lead role on natural hazards, using their regional policy statements as a means to allocate responsibilities and set the policy framework for regional and district plans. The following sections address each level of the planning and decision-making hierarchy. Some detail in the form of examples is provided in Appendix F.

The Resource Legislation Amendment Act 2017 has introduced an extensive range of changes to planning processes, in addition to the new requirement to manage significant risks from natural hazards as a Matter of National Importance. The Act provides for new collaborative and streamlined approaches to preparing policies and plans. Councils should consider the implications of these changes when using the guidance in the following sections.

6.3 Regional policy statements

6.3.1 Introduction

Regional policy statements are a key element in the RMA planning framework. Their purpose is to:

> *achieve the purpose of the Act by providing an overview of the resource management issues of the region and policies and methods to achieve integrated management of the natural and physical resources of the whole region (RMA Section 59).*

The sustainable management purpose of the RMA includes enabling 'people and communities to provide for their social, economic, and cultural well-being and for their health and safety'. Managing significant risks from natural hazards is also now a Matter of National Importance. As evidenced by the Canterbury Earthquake Sequence, liquefaction can have a significant impact on the well-beings and on health and safety.

The Canterbury Earthquakes Royal Commission's (CERC) recommendations recognised the importance of a regional-level understanding of risk related to liquefaction and of regional councils taking a lead role as follows:

> *Since seismicity should be considered and understood at a regional level, regional councils should take a lead role in this respect, and provide policy guidance as to where and how liquefaction risk ought to be avoided or mitigated (CERC Recommendation 187).*

As described in Sections 2.2 and 2.3, liquefaction-related risk exists only in some specific places – where there is the necessary combination of susceptible soil, groundwater and earthquake hazard. The regional scale is an appropriate scale to identify broadly where there is the potential for liquefaction to occur and where material liquefaction-induced damage is unlikely. The purpose of making this distinction is to provide guidance about those areas in the region where further consideration of liquefaction-related risk is required, and as importantly, where it is not.

6.3.2 Guidance

Assessment and mapping

Where liquefaction-related risk has not been assessed or mapped, regional councils might choose to complete a high-level assessment and prepare technical assessment maps as described in Section 3. Regional councils have choices about the scale and nature of the assessment they may wish to carry out at the regional policy statement level as discussed in Section 3. At regional policy statement stage, the purpose of the technical assessment and maps is primarily to differentiate land where ***Liquefaction Damage is Unlikely*** from land where ***Liquefaction Damage is Possible***. The maps and any supporting technical information should be an input to the consultation and engagement process with stakeholders (including planners and decision-makers) about the appropriate provisions to be included in the regional policy statement.

Where technical assessment maps have been prepared, the information they contain can provide a basis for different approaches to managing the two broad types of land. They could be used to identify land where further assessment should be carried out to support decisions on future use, subdivision and development and, importantly, where further assessment is not, or is unlikely to be required. Subject to engagement outcomes with stakeholders, planning maps could be prepared, to support objectives and policies in the regional policy statement. The maps should be called 'Regional Policy Statement – Liquefaction Assessment Requirement Maps', with the legend as shown in Table 6.2.

Table 6.2: Recommended legend for regional policy statement – liquefaction assessment requirement maps

Legend
Liquefaction assessment required ***Liquefaction Damage is Possible*** – further liquefaction assessment will be needed as part of the planning and consenting process for any intensification of land use or buildings in this area.
Liquefaction assessment not required ***Liquefaction damage is unlikely*** – there is no need for further liquefaction assessment as part of the planning and consenting process unless: a more detailed or site-specific information indicates otherwise, or b specific high-intensity or high-importance activities are proposed.

It is important to appreciate that these planning maps are separate from the technical analysis maps. The technical risk analysis (refer Section 4) will have assigned liquefaction vulnerability categories to land, however a risk evaluation process (refer Section 5) is required before decisions can be made regarding the appropriate risk treatment response (refer Section 6). It is the eventual output of this process that will be shown on the regional policy statement planning maps.

In many cases, the approach adopted might simply be for land shown on technical maps as ***Liquefaction Damage is Unlikely***, ***Very Low*** or ***Low*** to be included in the regional policy statement planning map as 'Liquefaction assessment not required'. However, this guidance recommends that for higher-intensity land use a certain minimum level of liquefaction assessment is undertaken to confirm the categorisation, even if the initial broad-scale assessment indicates that ***Liquefaction Damage is Unlikely*** (refer Section 3.5). Territorial authorities might choose to undertake or facilitate this more detailed liquefaction assessment in specific areas (eg proposed future growth areas). Alternatively, they might choose to include provisions in their plans to require this additional information to be provided as part of the plan change or consenting process for specified types of high-intensity and high-importance activities.

Information in, or supporting the regional policy statement

Supporting, simple and brief text (and photographs/diagrams) should be included in the regional policy statement and/or supporting documents (such as issues and options papers and the Section 32 evaluation report) to explain:

- what liquefaction is, how it occurs and its effects
- how the regional council has assessed and determined what is a significant risk from liquefaction (if the council has expressly done this) and identified areas where further liquefaction assessment is required
- what is shown on the planning map(s) in the regional policy statement
- the purpose of the information and
- the uncertainties associated with the technical assessment and mapping, and its use to prepare the planning map(s).

This text may be based on information included in this guidance document and should be supplemented with relevant region-specific information produced as part of the liquefaction assessment completed by the regional council.

Objectives and policies

Regional policy statements should include objectives that cover the following matters:

- that development, subdivision, use of land and construction of buildings and infrastructure is managed to avoid or mitigate the adverse effects of liquefaction consistent with the community's view on the level of risk that is acceptable. This should include the basis on which the council has, or intends to, require district councils to determine the significance of the risk associated with those effects. For example, where a community has a low risk acceptance level the objective could be expressed as avoiding development, etc in areas where ***Moderate to Severe*** land damage is expected to occur in the event of low or moderate level earthquake shaking. A community with a greater risk acceptance level could set an objective to require mitigation measures to ensure that earthquake shaking (at extreme/high, moderate or low levels) will result in ***Minor to Moderate*** land damage (or better). The descriptions and example photographs of different degrees of liquefaction-induced ground damage provided in Section 2.5 and Appendix A could be used to communicate clearly the level of performance the mitigation is to achieve
- that decisions about development, subdivision, use of land and building on land that may be subject to liquefaction are informed by appropriate information about the liquefaction-related risk
- that requirements for investigations (and the associated costs) are focused on areas where there is significant liquefaction-related risk.

Regional policy statements should include policies that cover the following matters:

- how the significance of risks from liquefaction have been or are to be determined
- that investigations related to liquefaction-related risk will only be required for land that is identified on the Regional Policy Statement Liquefaction Assessment Requirement Maps
- the regional council's intentions/commitment to gather/maintain information on liquefaction-related risk in the region
- the regional council's intentions/commitments to itself complete or to assist district councils to carry-out (and/or require consent applicants to carry-out) more detailed assessment and mapping
- the regional council's direction regarding the allocation of responsibilities between the regional council and district councils for investigating and managing liquefaction-related risk (including how community acceptance of risk is to be determined).

6.3.3 Commentary

The approach that is appropriate will vary between regions for a range of reasons. Unitary councils will necessarily take a different approach to other regional councils.

For unitary councils, a key decision will be whether to address liquefaction in regional or district provisions of their resource management plan or plans. The extent to which a regional council wishes to take, or it is most effective and efficient to take a leadership role will be an important determinant. Approaches may also vary depending on how the regional council wishes to structure its framework for objectives and policies, including whether to have stand-alone objectives and policies on individual natural hazards.

This guidance recommends a relatively strong leadership role by regional councils. This is consistent with the Royal Commission's recommendation and should enable cost-effective work to identify, assess and map land that either does, or does not require further investigation.

There are several examples of regional policy statement objectives and policies specifically addressing liquefaction. These are included in Appendix F.

6.4 Regional plans

6.4.1 Introduction

Regional councils have discretion about whether to prepare regional plans (other than a regional coastal plan, which is mandatory). A regional plan can provide a mechanism for more detailed assessment and mapping of liquefaction-related risk. It can provide for more specific objectives and policies and, importantly, it can establish regional rules.

Regional plans and rules can address a wider range of potential effects of liquefaction than are able to be addressed in district plan rules (eg effects on water and other elements of the natural environment). Importantly, regional rules are not constrained by existing use rights established under Section 10 of the RMA. This means that regional rules can be used to address issues associated with existing development.

Where a regional council elects to take a lead role in more detailed assessment, mapping and management of liquefaction-related risk, this should be accomplished through provisions in a regional plan.

6.4.2 Guidance

Assessment and mapping

If regional councils wish to take an active lead in management of liquefaction-related risk, they can do so via provisions in their regional plan. This will typically need more detailed technical assessment than was required to support their regional policy statements. The purpose of the additional technical assessment is to refine the assessment of liquefaction-related risk and provide a basis for more specific policies and rules. Refinement may involve:

- being able to classify land that was previously uncategorised
- being able to reclassify land based on more detailed information
- being able to assign more precise liquefaction vulnerability categories (ie ***Medium*** vs ***High***)

- targeted ground investigations and assessment to provide greater detail and certainty in areas with increasing development pressure
- being able to refine boundaries between categories (eg in areas where there is uncertainty regarding the transition between different ground conditions)
- being able to delineate boundaries between categories on a cadastral basemap to enable their use for property-specific planning purposes (being clear that this is not a property-specific assessment, but that boundaries between areas need to be defined so it is possible to determine the particular planning requirements that apply for a specific property).

Refined technical assessment and mapping information should be part of engagement with stakeholders about the appropriate planning response in a regional plan. That engagement will also influence choices about the nature and level of detail needed. The regional council may choose to assess and map some parts of its region in more detail than others. That choice will most likely reflect existing development and current or expected development pressure, and the nature and level of control regional council wishes to apply through the regional plan.

Regional councils should use the technical mapping information, as appropriate, to develop planning maps for their regional plans. There will be a range of options, which could:

- be more refined versions of the map(s) in the regional policy statement, providing a more refined basis for determining where and when further technical assessment is required
- provide a means to represent decisions made in engagement processes about the significance of potential effects and levels of acceptance or tolerance for those effects occurring
- provide a basis for area and/or site-specific policies and rules about avoidance or mitigation required.

Information in, or supporting the regional plan

Simple, brief and supporting text (and photographs) should be included in the regional plan and/or supporting documents (such as issues and options papers and the Section 32 evaluation report) to explain:

- if required, new environmental effects information (not addressed in the regional policy statement)
- earthquake scenarios and expected/likely land damage and relate this to information about the performance of standard foundation specifications
- how the council has or intends to determine the significance of risks associated with liquefaction effects
- what is shown on the maps
- the purpose of the information
- the uncertainties associated with the assessment and mapping.

Objectives and policies

The regional plan should include (as relevant) objectives that cover the following matters:

- that development (including spatial planning and site selection for special housing areas), subdivision, use of land and construction buildings and infrastructure are informed by appropriate information on liquefaction-related risk
- environmental outcome statements for environmental effects resulting from liquefaction that are particularly relevant to the region (eg protection of groundwater resources from physical disruption and contamination, protection of water bodies and habitats from the effects of sediment and contaminant discharges, etc).

The regional plan should include (as relevant) policies that cover the following matters:

- directing where future urban development is to be encouraged/avoided (based on liquefaction-related risk)
- requirements for more detailed liquefaction assessments (where land use change or subdivision is proposed)
- requirements for district plans to set activity status for different classes of land as determined by the regional council or allow for councils to set these
- where, what and when standard foundation specifications or ground treatment options can be used as the management option for liquefaction-related risk
- storage use and management of hazardous substances in areas subject to liquefaction-related risk
- management of recharge areas and/or areas for extraction of groundwater

- use and management of riparian areas, including reserves to minimise potential effects on water bodies from lateral spreading and discharges of sediment and contaminants associated with liquefaction.

General information on foundation and ground treatment options and costs is summarised in Chapter 5 and 6 of EQC (2015). Detailed technical guidance is provided in the NZGS/MBIE Earthquake Geotechnical Engineering Practice series (NZGS 2016a to 2016d).

The content of these policies should reflect the community's risk appetite, established through engagement with the relevant stakeholders and decision-makers.

Rules

The regional plan may have rules that cover the following matters:

- obligations for any information on liquefaction assessments carried out by other parties to be provided to the regional council and/or the national Geotechnical Database
- establishing activity status for different classes of land
- performance standards or specific requirements for foundation and ground improvement options
- requirements that apply to existing uses
- storage use and management of contaminants (including hazardous substances) in areas subject to liquefaction-related risk
- management of recharge areas and/or areas for extraction of groundwater
- use and management of riparian areas, including reserves.

6.4.3 Commentary

As with the regional policy statement, the approach different regional or unitary councils may take will vary depending on their circumstances and decisions about the level of leadership and/or control the council wishes to exercise. It will also need to reflect the council's overall approach to preparing regional plans, for example, topic-specific plans, more comprehensive regional plans or unitary/combined plans.

More detailed assessment and mapping could be completed and incorporated in the regional policy statement, with supporting objectives and policies. This would require earlier investment in the more detailed assessment, so that it would be available to inform a review or change to the regional policy statement. If a regional or unitary council wishes to take a stronger leadership role and exercise more control, the option of a regional plan with rules will be more appropriate.

This guidance recommends that regional councils take a strong leadership role and consider developing regional plan provisions where:

- completing detailed assessment and mapping would be more effective and cost-efficient in the context of the region's development aspirations and resource capacity and capability of the regional and district councils
- there are concerns about the risk of specific adverse effects on other aspects of the environment that justify intervention using regional objectives, policies, rules or other methods
- there are concerns about the risk associated with existing activities that justify intervention using regional rules.

6.5 District plans

6.5.1 Introduction

District plans provide the most extensive opportunities to establish provisions to address liquefaction-related risk associated with land use, subdivision and development. All district councils (territorial authorities) must have a district plan (or plans) for their districts.

District plans are required to include objectives, policies and rules (if there are rules) and may include other information. Of most relevance to this guidance, district plans can include:

- information on the significant resource management issues for the district
- reasons for adopting the policies and methods
- requirements for the information to be included with an application for a resource consent.

Controlling subdivision of land is an important function of district councils and the RMA provides specific powers related to subdivision consenting that are relevant for avoiding or mitigating the effects of liquefaction. These include Section 106 powers to refuse or place conditions on subdivision consents where there is a significant risk from natural hazards and Sections 220 and 229–232 that provide for conditions to be set on subdivision consents.

Section 106 requires an assessment of risk to be completed. The assessment needs to include the likelihood of a natural hazard occurring and the material damage that could occur to the land concerned or other structures. It also needs to address any likely subsequent use of the land that would accelerate, worsen or result in material damage. The assessment processes described in Section 3 should support the specific planning assessment required in Section 106.

Section 106 is an important and powerful backstop provision to address natural hazards in subdivision consents. This is because Section 87A (2) provides an override to the Section 104A obligation on councils to grant consents for controlled activities. The restriction on conditions being limited to the matters identified in rules, however, still applies.

In the case of subdivision consent applications, Sections 220 and 229 provide additional scope to include conditions on consents, including:

- to require esplanade strips or reserves to mitigate natural hazards
- on bulk, location, foundations and floor-level heights for buildings
- to protect land from natural hazards
- to require filling, compaction or earthworks.

Obligations can also be established on an ongoing basis through consent notices under Section 221. District plan provisions can set out how the council intends to use these powers to manage liquefaction-related risk.

6.5.2 Guidance

The approach taken and provisions in the district plan must sit within the framework and context established by the regional council. In particular, the RMA requires the district plan to give effect to the regional policy statement and to not be inconsistent with a regional plan.

Assessment and mapping

The district council should complete additional technical assessment and mapping as required to meet requirements in the relevant regional policy statement and, if relevant, any regional plan. Generally, assessment should be sufficient to be able to map information at a property level (at the scale of 1:10,000–1:5000) for areas in the district of existing or likely future development. Other land could be assessed and mapped at a 1:25,000 or greater scale.

The technical assessment information and maps should be an input to the engagement with stakeholders to develop appropriate district plan provisions. That engagement and decisions about appropriate provisions will also inform the exact nature and level of detail of technical assessment that is required.

Based on the technical assessment information and stakeholder engagement, district councils should prepare planning maps to support the planning response determined to manage the liquefaction-related risk. For a district plan, maps are most likely to be required at a level of refinement to support a detailed and specific rules framework.

Information in, or supporting the district plan

Simple, brief and supporting text (and photographs) should be included in the district plan and/or supporting documents (such as issues and options papers and the Section 32 report) to:

- explain earthquake scenarios and expected/likely land damage and relate this to information about the performance of standard foundation specifications
- explain what is shown on the map
- identify the purpose of the information
- identify the uncertainties associated with the assessment and mapping.

This text should be based on information from the technical assessments, stakeholder engagement and the requirements established in the applicable regional policy statement and regional plan.

Objectives and policies

District plans should include objectives covering the following matters:

- expressing the council (and community's) risk appetite by using, as appropriate language – to avoid/control/manage/allow – development, subdivision, use of land and construction of buildings and infrastructure on land of different classifications for liquefaction potential
- that decisions on development, subdivision, use of land and construction of buildings and infrastructure are informed by appropriate information on liquefaction-related risk.

District plans should include policies that cover the following matters:

- directing where future urban development is to be encouraged/avoided
- requirements for more rigorous liquefaction assessments (for example for subdivision proposals and more intensive land use changes)
- how the council will exercise its discretion to grant or refuse consent under Section 106 (including expectations on the risk assessment information to be provided by applicants and the level of mitigation council is likely to consider acceptable)

- where, what and when standard foundation specifications or ground improvement solutions can be used as the management option for liquefaction-related risk – for information on options and costs refer to EQC (2015) and NZGS (2016a to 2016d)
- requirements to provide/take esplanade reserves for the purpose of avoiding, mitigating or managing the effects of liquefaction and lateral spreading
- use and management of riparian areas, including reserves.

Rules

The district plan should have rules that cover the following matters:

- establishing activity status for different classes of land
- consents required for subdivision of land that may be subject to liquefaction, including application of Section 106
- performance standards, including foundation treatments and ground improvement for permitted activities
- requirements for esplanade reserves or strips
- assessment criteria for controlled, restricted discretionary, discretionary or non-complying activities relevant to liquefaction
- requirements for liquefaction assessments to support applications for consents (including assessment under Section 106 for subdivision consent applications) – referencing the relevant more detailed assessments set out in Section 3
- obligations for any information on liquefaction assessments carried out by other parties to be provided to the regional council and/or the national Geotechnical Database.

6.5.3 Commentary

The approach of district councils in their district plans will vary as they respond to the lead of the relevant regional council and their own local context, needs and community aspirations and risk appetite. This guidance recommends that district council include specific and targeted provisions in their district plans, in particular assigning appropriate activity status and setting detailed performance standards and assessment criteria.

It will be important that district councils expressly consider consenting requirements for subdivision to ensure requirements for express consent are in place, as appropriate. This is because changes to Section 11 of the RMA, which come into effect from 1 October 2017 provide for subdivision as a permitted activity unless restricted by rules.

Examples of district plan objectives and policies related to natural hazards are included in Appendix F.

6.6 Section 32 evaluation

Section 32 of the RMA requires an evaluation to be carried out to support the development of policy statements, regional and district plans and plan changes. The evaluation is to assess the:

- appropriateness of the objectives in achieving the purpose of the RMA
- the appropriateness of the policies and methods (provisions) in achieving the objectives in terms of efficiency and effectiveness.

The assessment needs to be completed at a level of detail that corresponds to the scale and significance of the effects anticipated from the proposed policy statement, plan or plan change. It is also to include an assessment of the benefits and costs (environmental, economic, social and cultural) of the proposed provisions, and for these to be quantified where practicable.

Information from the technical assessments described in this guidance should assist and provide a significant input to the section 32 evaluation. In addition, general information about foundation and ground improvement options, their effectiveness and constraints, and indicative costs are provided in Chapter 5 and 6 of EQC (2015). To complete an appropriate Section 32 evaluation, councils will need to review with appropriate expertise the relevance and applicability of this general information, as specific details are likely to vary around the country and over time.

6.7 Resource consent processes

6.7.1 Introduction

The guidance in Section 6.2 to 6.5 for council-level RMA policies and plans recommends a framework for objectives, policies and rules in regional policy statements, regional plans and district plans. That framework will likely result in requirements for regional-level land use consents, district-level land use consents and subdivision consents.

Rules will have established:

- activity status for land uses and for subdivision, thereby triggering the need for resource consent applications
- for any controlled or restricted discretionary activities, the matters the relevant council will exercise its control over or restrict its discretion
- information requirements to support applications for consents, triggering the need for different levels of detail in liquefaction assessments (as described in Section 3 of this guidance)
- assessment criteria that the council will apply to consider applications for resource consents, including appropriate mitigation measures.

Objectives and policies should have established and provided guidance on:

- council and community risk appetite associated with the potential effects of liquefaction occurring, including where and what activities or development are to be avoided or encouraged and in what locations (that may be subject to liquefaction effects)
- expectations on mitigation that may be required and the level of performance they should achieve in avoiding or minimising adverse effects and damage from liquefaction.

Processing of applications for consents should be relatively straightforward where this framework is established appropriately. The necessary information, of the required quality, should be available from the applicant to support the consent officer processing the application, submitters considering or making submissions (if an application has been notified) and decision-makers determining the application. The matters that are relevant to the decision and any conditions that may be applied will also be clear and transparent.

Establishing the policy and plan framework recommended in the guidance will take some time. In the interim, councils will be required to process applications under the provisions of their existing policy and plan framework and relevant provisions of the RMA. The guidance provided here is focused on the situation where the recommended framework is not yet in place.

6.7.2 Guidance

Addressing liquefaction before a new policy and rules framework is in place

The RMA includes provisions that may enable a council to address liquefaction in the absence of express provisions on liquefaction being included in the applicable policy and rule framework. The extent to which a council can do this will depend on whether the existing policy and rule framework has restricted the council's ability to require or obtain information, or determine applications.

Restrictions or limitations on discretion

The applicable existing policy and rule framework may restrict or limit councils' ability to address liquefaction when applications for resource consents are considered and determined. This will most likely occur where the rules establish controlled or restricted discretionary status for the activity for which consent is required and/or include assessment criteria that do not identify natural hazard matters. These limitations could impact on the information applicants provide, a council's ability to require or obtain information and its ability to determine the consent and its conditions, including as follows under:

- Clause 7 (2) of Schedule 4, the requirement for an AEE to address '*any risk to the neighbourhood, the wider community, or the environment through natural hazards*' is subject to the provisions of any policy statement or plan
- Clause 104A council is obliged to grant consent for a controlled activity and can only impose conditions related to the matters it has reserved control over (as identified in the relevant rules)
- Clause 104C council may only consider and impose conditions on the matters it has restricted its discretion over (as identified in the relevant rules).

This guidance recommends that councils review their existing policy and plan frameworks to determine if those frameworks have restricted the council's ability to address liquefaction. If appropriate, councils may need to obtain legal advice on the extent of any limitations that may result from the construction and wording of their policies and rules.

Where discretion has not been limited

Section 88 of the RMA requires all applications for resource consents to be include an assessment of effects on the environment (AEE) as required by Schedule 4. Clause 7 (1) (f) or Schedule 4 requires an AEE to address '*any risk to the neighbourhood, the wider community, or the environment through natural hazards*'. Applications for resource consents should therefore address liquefaction-related risk. Where this information is not provided, the council may:

- return the incomplete application to the applicant under Section 88 (3A) or
- request further information from the applicant under Section 92.

Requesting or obtaining further information

Section 92A allows an applicant to refuse to provide the further information requested. Where this occurs, the council is obliged to proceed to determine the application without that information. Section 92 (2) provides for a council to commission a report on any matter relating to an application where the council considers the activity will have a significant adverse effect on the environment and the application has been notified. The applicant may, however, refuse to agree to the report being commissioned (Section 92 (2) (c)).

Determining applications for consent

Section 104 sets provisions for councils to consider applications for consent. These include the ability for councils to have regard to other matters they consider relevant and reasonably necessary to determine the application (Section 104 (1) (c)). These provisions give councils the opportunity to have regard to this guidance. Where a council has not restricted its discretion (for example through controlled or restricted discretionary activity status), it has wide discretion under Section 108 to approve or decline, or impose conditions on the consent. The extent of this discretion includes many possible means to obtain more information on liquefaction-related risk and ensure appropriate mitigation measures are provided, for example requiring:

- a bond
- works to be provided
- a covenant (for a land use consent)
- information to be provided to council
- measurements, investigations or inspections to be carried out.

In the case of subdivision consent applications, Sections 220 and 229 provide additional scope to include conditions on consents, including:

- to require esplanade strips or reserves to mitigate natural hazards
- on bulk, location, foundations and floor level heights for buildings
- to protect land from natural hazards
- to require filling, compaction or earthworks.

Subject to any limitations established by the existing policy and plan framework, this guidance recommends that councils:

- provide information to assist applicants for resource consents to prepare adequate AEEs (at pre-lodgement meetings with resource consent applicants and more widely) including about:
  - liquefaction-related risk in their region/district
  - the nature of investigations and information that is required to identify and assess the risk, including referencing the guidance in this document on different levels of assessment that may be relevant in any particular circumstance
  - mitigation measures that may be appropriate to address liquefaction-related risk
- return incomplete applications for resource consents to applicants where liquefaction is a relevant potential concern, directing the applicants to information council has made available about liquefaction (above)
- issue requests for further information, based on this guidance (in particular requiring more detailed assessment where this is appropriate)
- consider commissioning reports on liquefaction-related risk and mitigation for applications where liquefaction-related risk has not been addressed or not adequately addressed
- consider engaging specialist advice to assist in processing applications for consents and preparing Section 42A reports

- identify and consider this guidance document as an 'other matter' that is relevant to determining a consent application under Section 104 (1) (c)
- decline applications for consent where there is inadequate information about liquefaction-related risk and/or mitigation measures
- decline, or place appropriate conditions on, consents to avoid or mitigate the adverse effects of liquefaction to a specified level (consistent with the community's view on the level of risk that is acceptable).

Section 106

Section 106 gives territorial authorities the power to refuse or place conditions on subdivision consents where there is a significant risk from natural hazards. It requires an assessment of risk to be completed. The assessment needs to include the likelihood of a natural hazard occurring and the material damage that could occur to the land concerned or other structures. It also needs to address any likely subsequent use of the land that would accelerate, worsen or result in material damage.

The conditions that can be imposed must be for avoiding or mitigating those effects. Section 106 is an important and powerful backstop provision to address natural hazards in subdivision consents. This is because Section 87A (2) provides an override to the Section 104A obligation on councils to grant consents for controlled activities. The restriction on conditions being limited to the matters identified in rules, however, still applies.

This guidance recommends that councils use the Section 106 backstop to refuse consents for controlled activity consents where suitable conditions cannot be imposed to mitigate the effects identified.

6.7.3 Commentary

The Resource Legislation Amendment Act 2017 has introduced a wide range of changes to the RMA consenting processes. Some of these had immediate effect. Others, such as the new permitted activity status of subdivisions, have delayed effect. Councils will need to carefully consider the implications of changes to the RMA alongside the guidance above and seek legal advice if required.

6.8 Building consent

As discussed in Section 6.7.1 the framework recommended in this guidance establishes objectives, policies and rules in regional policy statements and regional and district plans, and requirements for land use and subdivision consents. With this framework in place, appropriate management of liquefaction-related risk will have been established in earlier stages of the land development process.

Therefore, by the time a project reaches building consent stage all that should remain is to confirm that the proposed building work satisfies the Building Code. Technical guidance regarding the engineering details of liquefaction mitigation and earthquake resistant foundation design are provided in NZGS (2016c & 2016d).

Acceptable Solution B1/AS1 is a commonly used means of demonstrating compliance with the Building Code for structures not requiring specific engineering design. Several of the cited material standards are limited to situations where 'good ground' is confirmed. Following the Canterbury earthquakes, modifications were made to this Acceptable Solution, as an interim measure applying only to the Canterbury earthquake region. For this region the definition of 'good ground' was changed to exclude ground subject to liquefaction and/or lateral spread, and stronger foundations were required. Further work is ongoing to determine if and how the definition of 'good ground' should be amended for the remainder of the country. In the meantime, without a regulatory back-stop in the Building Code to identify liquefaction issues, it is even more important for councils to understand, communicate and manage liquefaction-related risk through a framework as outlined in this guidance, using planning provisions to ensure liquefaction issues are properly addressed for individual buildings.

As part of the planning and consenting framework, rules or conditions may have been put in place that require particular land treatment or building details to manage liquefaction-related risk (eg ground improvement or resilient foundations and service connections). The territorial authority should check at this stage to confirm that any such requirements have been satisfied (bearing in mind that it is obliged to issue a building consent if the work satisfies the Building Code).

6.9 Infrastructure

The 2010/2011 Canterbury earthquakes highlighted the vulnerability of critical horizontal infrastructure to damage induced by liquefaction and associated ground deformation. The greatest damage to buried three waters assets (wastewater, water supply and stormwater) occurred in areas of extensive liquefaction. Damage varied regionally and could be correlated to ground deformation resulting from a combination of post liquefaction reconsolidation and lateral spread, localised instability and loss of ground support associated with release of ejecta.

Structural damage to infrastructure leads to a reduction or loss of functionality and hence the ability to provide a minimum level of service. The effect on the overall network varies between failure of a critical asset or assets, systemic failure of network elements or widespread degradation of the whole network. The social consequences can be severe and continue over an extended period, as occurred during and following the Canterbury earthquakes.

Hence it is important to consider the resilience of critical infrastructure in planning, design and the operations and maintenance of any development. Cubrinovski et al (2014) carried out a review of water supply, wastewater and road network damage that occurred during the Canterbury earthquakes, which provides pertinent data and includes the following summary observations:

- modern pipe materials and flexible pipelines, such as polyvinyl chloride (PVC) and polyethylene (PE), performed significantly better than more brittle pipelines such as asbestos cement (AC) and galvanised iron (GI)
- for all pipe materials there is a direct link between increasing liquefaction and pipeline damage
- granular backfill significantly improved the performance for PE and AC pipelines compared to potentially liquefiable native soil backfill
- damage rates reduce with increasing pipeline diameter (for the same pipe materials)
- a significant proportion of damage was associated with a failure of fittings and connections
- comprehensive and accurate GIS databases are essential for disaster response/recovery management.

Following the 2011 Canterbury earthquakes the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) was established to carry out the assessment of damage, subsequent design and delivery of horizontal infrastructure. The lessons learned, which have been captured in a learning legacy (https://scirtlearninglegacy.org.nz/), are a key resource in understanding failure mechanisms and how these can be mitigated by developing resilient infrastructure designs.

The typical configuration of infrastructure assets often means that designing to prevent damage is not technically feasible or economically justifiable, when considering the objectives of the owner or operator of the asset. Gibson and Newby (2015) advise that the key to good design is to provide an appropriate level of resilience in the right locations. Consideration of resilience should incorporate input from the asset owner/operator, technical design disciplines and constructors (where appropriate) and be undertaken during all stages of development. Often the greatest value can be achieved during the early planning and design phases of a project where the overall strategy

Table 6.3: Key considerations when reviewing appropriate level of resilience

ITEMS	DETAILS FOR CONSIDERATION
Requirements and responsibilities of the asset owner	– Legal obligations – Budget constraints – Asset owner/operator requirements of post disaster functionality, prioritisation and repair costs
Influence of spatial location	– Significance of the asset within the wider network, and resulting consequences to dependent infrastructure – Spatial variance of liquefaction and resulting ground deformation
Earthquake hazard	– Earthquake severity and annual probability of exceedance
Failure mechanisms and consequence	– Geotechnical hazards at the site and influence on asset performance – Identify likely modes of failure and severity/consequence within the wider network and within the specific asset – Prioritise hazards and failure mechanisms for resilience improvement
Engineering solutions to improve resilience	– Technical feasibility, reliability and complexity of resilient solutions – Ability to exhibit improved resilience for multiple earthquakes
Value	– Estimate improvement in seismic performance and post disaster functionality and compare to requirements – Identify critical drivers for resilience, eg cost, seismic performance and/or post disaster functionality – Demonstrate efficient use of capital considering the net present value of the asset for a range of earthquake hazards

of a development is established. The ability to improve resilience for an asset or sector of a network diminishes rapidly as the development progresses.

The level of resilience adopted must be compatible with the development, the objectives of the parties responsible and the needs of the community (refer Table 6.3).

In a wider context, and particularly in their early stages of development, consideration should be given to the following:

- greatest resilience improvement can be achieved by configuring the layout of infrastructure to avoid land with predicted large ground deformation
- incorporating a level of redundancy within a system, or ability to provide an alternative route
- adoption of appropriate infrastructure technology eg pressure or vacuum sewers in areas with predicted large ground deformation
- careful detailing of materials and joints/ connections to reduce the severity of damage and to facilitate the ease and speed of repair.

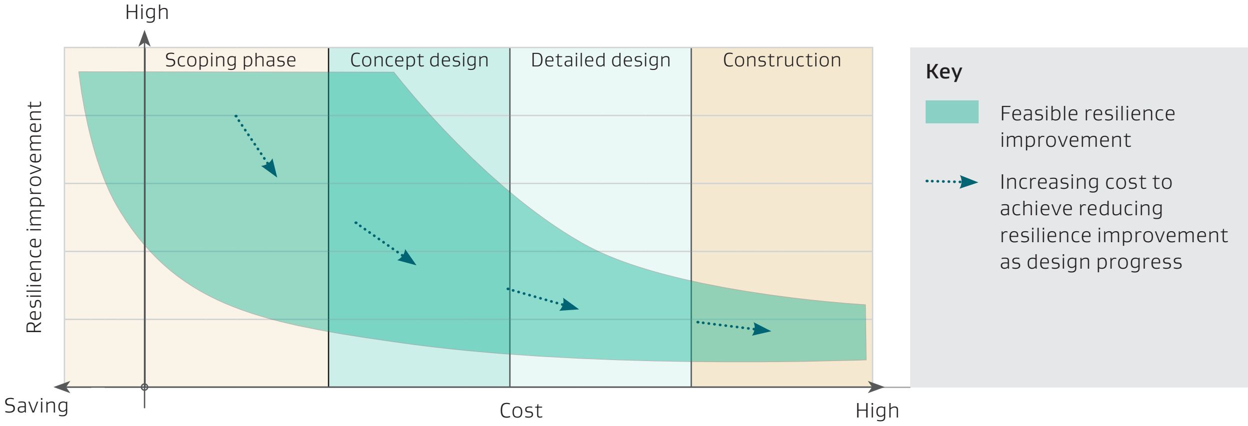
Often significant step changes in resilience can be achieved with a minor design change. Within SCIRT there were cases where the early optimisation of an appropriate design strategy provided a net cost saving in addition to providing a network with lower vulnerability to earthquakes. This concept is illustrated in Figure 6.1.

The level of resilience appropriate for a particular asset in a specific network is directly proportional to the percentage of the total network that relies upon that asset remaining functional. In the case of a wastewater network the sewage treatment facility, terminal pump stations and major trunk sewers will generally require the highest level of resilience. Understanding modes of failure is important for infrastructure design. Specifics will vary with asset type, performance requirements and specific location and project conditions (refer Appendix G).

The resilience of critical infrastructure should consider all network components that influence the level of service experienced by the end user, including components of the wider network that may be owned and/or operated by another party. In addition improving the ability to access and repair potential earthquake damage should be considered.

Adoption of a resilience prioritisation method can assist with the selection and incorporation of appropriate resilience measures into infrastructure design. The resilience prioritisation method is a structured process of assessment and design (refer Appendix G).

Figure 6.1: Schematic generalisation of feasible resilience improvement versus cost to implement (Gibson and Newby, 2015)



6.10 General recommendations for geotechnical assessments

Care should be taken to ensure that a focus on earthquake and liquefaction issues when assessing a particular site does not result in the 'normal' geotechnical and regulatory issues being overlooked. Some issues of particular significance are discussed below.

6.10.1 Plan change and subdivision consent

In support of plan change applications and subdivision consent applications, it is recommended that appropriate geotechnical investigations are carried out, and stand-alone geotechnical reports are prepared.

This work should be overseen by a Chartered Professional Engineer (CPEng) with current accreditation in the geotechnical practice field as administered by the Institution of Professional Engineers New Zealand (IPENZ) and/or a Professional Engineering Geologist with current registration on the IPENZ PEngGeol register. The reports should include all relevant factual and interpretative geotechnical information, clearly distinguishing between fact and interpretation and providing a commentary on uncertainty (and potential consequences). The reports should address the pertinent geotechnical aspects of all natural hazards relevant to the site.

The general requirements for geotechnical assessments for subdivisions are set out to a certain degree in various Engineering Codes of Practice or Infrastructure Design Standards published by territorial authorities throughout the country. Additional guidance is also given in the following standards (available from Standards New Zealand):

- NZS 4431:1989 *Code of Practice for Earth Fill for Residential Development*
- NZS 4404:2010 *Land Development and Subdivision Infrastructure*.

6.10.2 Building consent

Reliance on liquefaction information from previous stages of work

The ground investigations and engineering assessment required at building consent stage will vary depending on the information already available from earlier stages of the land development process.

Where the framework recommended in this guidance is implemented, liquefaction assessment may have already been completed for planning and consenting purposes (eg plan change or subdivision consent). However it is recommended that territorial authorities implement 'backstop measures' in the building consent process to confirm that liquefaction and other geotechnical issues have been appropriately considered as part of building design. 'Normal' geotechnical investigations should also be undertaken as required for evaluating other potential geotechnical issues (eg foundation bearing capacity, site stability, etc).

As demonstrated in Section 3.5 there are some situations in the recommended framework where a project can reach building consent stage with only a broad-scale ***Level A*** or ***Level B*** assessment having been undertaken (eg for rural areas, or areas categorised as ***Liquefaction Damage is Unlikely***). In this situation, there will typically have been no site-specific ground investigations or liquefaction assessment undertaken prior to the building consent stage – so a final 'ground-truthing' of assumptions is of even greater importance.

It is recommended that building consent applicants be required to demonstrate that a visual assessment of the site has been undertaken and reasonable efforts made to check that there are no obvious reasons why the previously assigned area-wide liquefaction vulnerability category might be inappropriate. For example, if a site was previously categorised as ***Liquefaction Damage is Unlikely***, but liquefaction was observed in a previous earthquake, or investigations on a neighbouring site discovered thick deposits of liquefiable soil, then further assessment may be warranted to confirm the liquefaction vulnerability of the site.

Land where a liquefaction category has not yet been assigned

In some cases an application for building consent might be received for a location where an area-wide liquefaction assessment has not yet been undertaken (eg as part of the regional or district plan process). In this scenario it is recommended that the process outlined in Figure 3.3 is followed, to provide a level of information about liquefaction vulnerability that is sufficient for the proposed development.

Exemptions from requirements for more detailed liquefaction assessment

In particular situations, territorial authorities may wish to establish rules that allow building consents to be issued in areas where ***Liquefaction Damage is Possible***, without the need for more detailed liquefaction assessment, subject to certain conditions (eg particular ground treatment or foundations). This might be the case in situations where the costs of more detailed liquefaction assessment would be disproportionate to the benefits, and the money would be better spent improving the land or foundations. This is discussed further in Table 3.7.

For example, in an area categorised as ***Medium*** in a previous area-wide ***Level B*** assessment, a council might allow replacement of an existing building or a new infill building without further liquefaction assessment, provided that a resilient building and foundation is constructed (and reasonable enquiry confirms that this is appropriate). A resilient building and foundation might be defined as a regular lightweight structure with ability to span over lost ground support or to be relevelled, for example a 'TC2-type' foundation in the MBIE (2012) Canterbury foundation guidance. Recent experience in Canterbury suggests that these types of foundations generally incur no or only minor additional cost compared to conventional NZS 3604 foundations.

Land assigned a liquefaction vulnerability category of *High*

In areas assigned a liquefaction category of ***High***, it is recommended that a geotechnical engineer should provide input into the design of all buildings. This should include a site-specific assessment of liquefaction issues, including assessment of new or existing subsurface ground investigations.

Typically this would require information from a minimum of two deep investigations within or very close to the building footprint. Building foundations are likely to require specific engineering design or selection of the appropriate standardised foundation solution – refer to NZGS (2016 b to d) for more detail).

Multi-storey, commercial and industrial buildings

Multi-storey, commercial and industrial buildings typically require specific engineering design regardless of the ground conditions. In most cases this should include geotechnical assessment for foundation design, including appropriate ground investigations customised to the particular details of the site and building.

7 COMMUNICATION AND CONSULTATION

Communication and consultation right through the risk management process is a key requirement for effective outcomes. Stakeholder engagement is an important element of RMA planning and decision-making processes. Engagement needs to involve a wide range of stakeholders, including:

- RMA decision-makers (councillors and key council staff)
- professional advisors (planners, engineers, scientist, lawyers, economists)
- individuals (property owners, rate payers, citizens)
- business interests (business owners, employees, developers)
- community groups (environmental, social non-government organisations (NGOs) or other interest groups).

The views, awareness, and objectives of all of these groups shape individual and collective understanding about and attitudes to risk and uncertainty.

Engagement with stakeholders should begin when establishing the context for a risk management process. This should focus on correctly understanding the relevant environmental, social, cultural, economic, political and regulatory context; and the relevant objectives of stakeholders. It should confirm the types of decisions that need to be made and the nature, type and detail of information that will be required to inform those decisions.

Understanding risk associated with natural hazards requires technical expertise on the natural processes that are involved in natural hazards, how hazard events play out and who or what they may affect. Technical assessment is therefore an important element of the risk process for managing natural hazards. The technical assessment requires input from stakeholders who will have specific knowledge and experience, particularly about consequences and effects.

Stakeholder engagement is also a vital part of the step to evaluate risk and provides the basis for decision-making about how risks should be treated (managed). For risk assessment, and evaluation in particular, to be effective it is important that the science and engineering (and other technical specialist) expertise associated with risk identification and analysis is clearly and effectively communicated to stakeholders. This includes communicating information about uncertainty and assumptions within the analysis, and the potential consequences if the actual conditions vary from the assumed model. This is important so all stakeholders can understand and reach a view on the reliance they can place on the assessment information, determine their attitude to risk and uncertainty and how this can best be addressed in decision-making.

Stakeholder engagement is likely to be most focused and formal (including statutory consultation processes) through the steps in the risk management process where treatment options are being proposed, evaluated and decisions are being made. The evaluation under formal RMA processes for policies and plans includes considering benefits and costs and who benefits and on whom costs fall.

Stakeholder engagement should also feature in ongoing processes to monitor and review the impact and effectiveness of decisions (policy settings, plan provisions and consenting decisions) in meeting the intended outcomes and impacts on stakeholder objectives.

Communication and consultation aspects of the risk based approach are discussed further in the following references:

- Johnson, L., Samant, L.D., and Frew, S. (2005). *Planning for the unexpected – Land use development and risk*. American Planning Association, Planning Advisory Service, Report number 531.
- SNZ HB 327:2010. *Communicating and consulting about risk*. Standards New Zealand, 2010.
- NIWA, MWH, GNS and BRANZ (2012). *Impacts of Climate Change on Urban Infrastructure and the Built Environment: Toolbox Handbook*.
- Kilvington, M., and Saunders W. (2015). *I can live with this*, The Bay of Plenty Regional Council Public Engagement on Acceptable Risk.

8 MONITORING AND REVIEW

All steps in the risk management process should be subject to monitoring and review processes. These should be focused on the quality of inputs, processes (engagement, assessment and decision-making) and outputs. Some of those review processes will involve formal technical or peer review. Others may involve stakeholder feedback and formalised decision criteria and authority delegations.

8.1 RMA requirements

The RMA has formal requirements for monitoring and review, set out in Section 35. These include obligations for councils to monitor the following matters and take appropriate action in response to that monitoring:

- the state of the environment in its region or district
- the efficiency and effectiveness of policies, rules or other methods in policy statements and plans
- the exercise of its functions, powers or duties
- the exercise of resource consents.

Councils are required to report at least every five years on their monitoring of the effectiveness of policies and plans. They are also obliged to keep information and records to support administration of their policies and plans, consenting and other duties, functions and powers.

The Resource Legislation Amendment Act 2017 has added a new specific requirement to Section 35 for councils to monitor the efficiency and effectiveness of processes they use to exercise powers and perform functions or duties. This includes considering timeliness, cost and the overall satisfaction of stakeholders (described in the Act as 'those persons or bodies in respect of whom the powers, functions or duties are exercised or performed). This requirement aligns with the new provision inserted as Section 18A in the RMA establishing procedural principles. These establish obligations for those who exercise powers or perform functions to take all practicable steps to:

- use timely, efficient, consistent and cost-effective processes that are proportionate
- ensure policy statements and plans include only those matters relevant to the purpose of the RMA and are worded in a way that is clear and concise
- promote collaboration between local authorities.

Section 79 of the RMA also establishes an obligation for a 10-year review of the provisions of policy statements and plans. Sections 128 through 133A of the RMA also set out requirements for review of resource consent. Under the Building Act 2004 provisions in Sections 91–95A establish processes through code compliance certificates to monitor and review compliance with building consents.

8.2 Refinement of the liquefaction categorisation over time

The liquefaction assessment framework outlined in this guidance has been designed to facilitate the refinement of the liquefaction categorisations across an area over time as more detailed information becomes available. This is one of the reasons why the concepts of scale, purpose and detail of each liquefaction assessment are given particular attention in the framework.

This enables an assessment undertaken at a higher level of detail or for a more specific purpose to take precedence over previous assessments. For example, a particular location might be initially identified as ***Liquefaction Damage is Possible*** as part of a regional ***Level B*** assessment for district plan purposes, then subsequently recategorised as ***Medium Liquefaction Vulnerability*** in a more detailed ***Level C*** assessment undertaken for subdivision consent.

This guidance recommends that councils collate liquefaction assessment information that they receive from regional hazard studies and plan/consent submissions into a form that can be readily referenced and updated in future. This could be as simple as a list referencing reports containing liquefaction, or as sophisticated as a GIS database that maps the extent, liquefaction vulnerability categories and level of detail for each liquefaction assessment (refer Appendix E).

The refinement of liquefaction categorisation over time is demonstrated by the examples in Appendix B.

9 REFERENCES

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APPENDIX A.
EXAMPLE PHOTOGRAPHS OF DIFFERENT DEGREES OF LIQUEFACTION-INDUCED GROUND SURFACE DAMAGE

The photographs on the following pages are sourced from Appendix B of Tonkin + Taylor (2015), reproduced with permission of EQC. Tonkin + Taylor Ltd. (2015) *Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology*. Report to Earthquake Commission, Tonkin + Taylor ref. 52010.140/v1.0. Available at: http://www.eqc.govt.nz/canterbury-earthquakes/land-claims/flat-land/increased-risk-of-liquefaction.

Table A1: Degrees of liquefaction-induced ground damage used in the land performance framework

DEGREE OF LIQUEFACTION-INDUCED GROUND DAMAGE (example photographs)	TYPICAL CONSEQUENCES AT THE GROUND SURFACE[1,2] These are examples of the type of damage that would be expected, they are not intended to be criteria for calculation
None to Minor 	– ***None to Minor*** no signs of ejected liquefied material at the ground surface[1]. – No more than minor differential settlement of the ground surface (eg undulations less than 25 mm in height). – No apparent lateral spreading ground movement (eg only hairline ground cracks). – Liquefaction causes no or only cosmetic damage to buildings and infrastructure (but damage may still occur due to other earthquake effects).
Minor to Moderate 	– ***Minor to Moderate*** quantities of ejected liquefied material at the ground surface (eg less than 25 percent of a typical residential site covered[2]); and/or – Moderate differential settlement of the ground surface (eg undulations 25–100 mm in height). – No significant lateral spreading ground movement (eg ground cracks less than 50 mm wide may be present, but pattern of cracking suggests the cause is primarily ground oscillation or settlement rather than lateral spreading). – Liquefaction causes moderate but typically repairable damage to buildings and infrastructure. Damage may be substantially less where liquefaction was addressed during design (eg enhanced foundations).
Moderate to Severe 	– Large quantities of ejected liquefied material at the ground surface (eg more than 25 percent of a typical residential site covered[2]); and/or – ***Moderate to Severe*** differential settlement of the ground surface (eg undulations more than 100 mm in height); and/or – Significant lateral spreading ground movement (eg ground cracks greater than 50 mm wide, with pattern of cracking suggesting direction of movement downslope or towards a free-face). – Liquefaction causes substantial damage and disruption to buildings and infrastructure, and repair may be difficult or uneconomic in some cases. Damage may be substantially less, and more likely to be repairable, where liquefaction was addressed during design (eg enhanced foundations and robust infrastructure detailing).

Notes:

1 An absence of ejecta at the ground surface does not necessarily mean that liquefaction has not occurred. Liquefaction may still occur at depth, potentially causing ground settlement.

2 The coverage of the site with ejected liquefied material does not in itself represent ground damage in an engineering sense, however there is a strong correlation between the volume of ejecta and the severity of differential ground settlement and foundation/infrastructure damage.

Figures A1 to A2: Photos of land with *None to Minor* liquefaction-related land damage

Figure A1: Photos of land with None to Minor liquefaction-related land damage

None to Minor land damage

Even lawns and undamaged pavers

Undamaged asphalt driveway

Undamaged concrete driveway and kerbing

Aerial shot of Broomfield area showing no liquefaction ejecta on the roads or Broomfield Common

View of Aston Drive with little damage

View of Centaurus Road with little damage

Figure A2: Photos of land with None to Minor liquefaction-related land damage

None to Minor land damage

Flat lawn

Slightly undulating lawn and driveway

Slightly undulating lawn

Undulating lawn

Undulating lawn

Aerial photo of North New Brighton showing little damage

Figures A3 to A10: Photos of land with *Minor to Moderate* liquefaction-related land damage

Figure A3: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Undulating lawns and liquefaction ejecta

Piles of sand along the footpath

Cracking and ejected sand on driveway

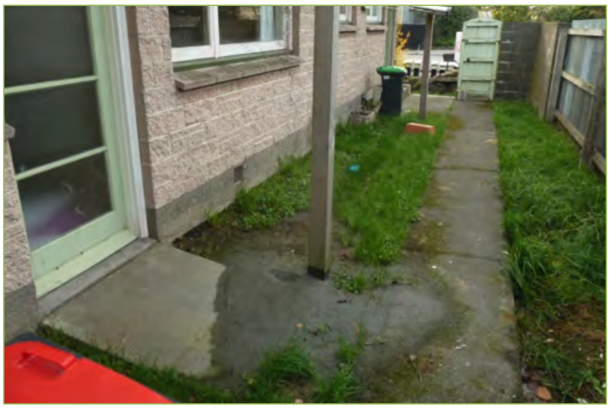
Liquefaction ejecta pile on road

Isolated area of liquefaction ejecta on lawn

Isolated area of liquefaction ejecta on lawn

Figure A4: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage



Liquefaction ejecta around washing line pole

Liquefaction ejecta on lawn

Foundation damage

Undulating paving slabs

Liquefaction ejecta on lawn

Foundation damage

Figure A5: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Foundation damage

Liquefaction ejecta on lawn

Liquefaction ejecta on lawn

Liquefaction ejecta in planter

Liquefaction ejecta in planter with undulating pavers

Foundation damage

Figure A6: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Liquefaction ejecta at a New Brighton Road junction

Aerial photo of liquefaction ejecta at Cashmere High School

Liquefaction ejecta on lawn

Liquefaction ejecta on lawn

Liquefaction ejecta on lawn

Isolated area of liquefaction ejecta

Figure A7: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Damage to asphalt

Liquefaction ejecta on lawn

Liquefaction ejecta in piles on road

Undulating paving bricks

Isolated area of liquefaction ejecta

Foundation damage

Figure A8: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Foundation damage

Liquefaction ejecta on lawn

Liquefaction ejecta in many places on lawn

Large area of liquefaction ejecta on lawn

Foundation and brickwork damage

Liquefaction ejecta and brickwork damage

Figure A9: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Liquefaction ejecta in many areas on lawn

Undulations in lawn

Liquefaction ejecta covering driveway

Undulations in paving area

Liquefaction ejecta on lawn

Undulations in lawn, liquefaction ejecta removed

Figure A10: Photos of land with Minor to Moderate liquefaction-related land damage

Minor to Moderate land damage

Foundation damage

Liquefaction ejecta alongside culvert

Liquefaction ejecta on lawn

Foundation damage

Liquefaction ejecta, dwelling tilting

Liquefaction ejecta, dwelling tilting

Figures A11 to A15: Photos of land with *Moderate to Severe* liquefaction-related land damage

Figure A11: Photos of land with Moderate to Severe liquefaction-related land damage

Moderate to Severe land damage


Large patch of liquefaction ejecta


Foundation damage


Liquefaction ejecta piles along Androssan Street

Liquefaction ejecta piles along Avonside Drive


Liquefaction ejecta around property


Foundation damage

Figure A12: Photos of land with Moderate to Severe liquefaction-related land damage

Moderate to Severe land damage

Aerial photo showing liquefaction ejecta on Seabreeze Close

Liquefaction ejecta in turning circle of Seabreeze Close

Outside of dwelling showing level liquefaction ejecta reached on brickwork and windows

Large amounts of liquefaction ejecta

Large amounts of liquefaction ejecta and tilting dwelling

Large amounts of liquefaction ejecta around property

Figure A13: Photos of land with Moderate to Severe liquefaction-related land damage

Moderate to Severe land damage

Large amounts of liquefaction ejecta

Large amounts of liquefaction ejecta

Large amounts of liquefaction ejecta

Large amounts of liquefaction ejecta inside dwelling

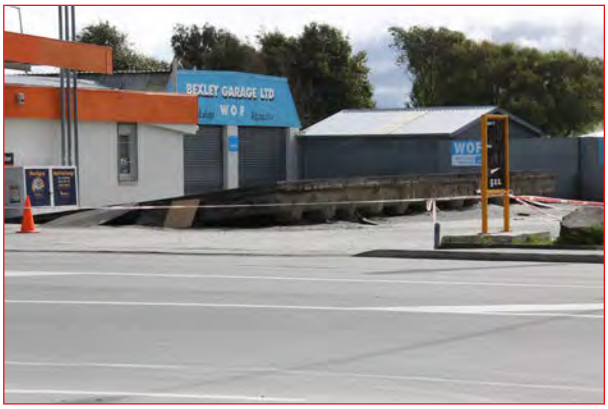
Close up photo of road damage seen in aerial photo of Woolston

Foundation damage, tilting dwelling

Figure A14: Photos of land with Moderate to Severe liquefaction-related land damage

Moderate to Severe land damage

Lateral spreading damage to power lines



Flotation of underground petrol tank

1 m wide crack from lateral spreading

House deformed by lateral spreading

Bridge damaged by lateral spreading

Carport pulled apart by lateral spreading

Figure A15: Photos of land with Moderate to Severe liquefaction-related land damage

Moderate to Severe land damage

Drive and garages deformed by lateral spreading

Liquefaction ejecta inside house

Lateral spreading damage to road and powerlines

Power substation punched into ground

Flooding and lateral spreading damage to power lines

Buckling of bridge caused by lateral spreading

APPENDIX B.
EXAMPLE APPLICATIONS OF LIQUEFACTION ASSESSMENTS AND REFINEMENT OF THE LIQUEFACTION CATEGORISATION OVER TIME

EXAMPLE ASSESSMENT PURPOSE	EXAMPLE LIQUEFACTION ASSESSMENT DETAILS AND OUTCOMES
The regional council wishes to provide strategic direction on the management of liquefaction-related risk in their regional policy statement	– A ***Basic Desktop Assessment*** (***Level A***) is undertaken that covers the entire region. – The assessment is based primarily on large-scale geological maps and expert local knowledge. – This shows that for a large part of the region ***Liquefaction Damage is Unlikely***. But for the coastal margins ***Liquefaction Damage is Possible***, so the regional council includes provisions in the regional policy statement to direct that more detailed liquefaction assessment be undertaken as part of future land use planning in those areas.
The district council wishes to include appropriate liquefaction assessment provisions in their district plan	– A ***Calibrated Desktop Assessment*** (***Level B***) is undertaken covering the part of the district where the regional study indicated ***Liquefaction Damage is Possible***. – The calibration uses selected existing subsurface investigations (typically at a spacing of ~1 km). – This demonstrates that some inland parts of the study area can be recategorised as ***Liquefaction Damage is Unlikely***. – For the remainder of the area ***Liquefaction Damage is Possible***. The district council includes provisions in the district plan to require that any plan change or consent applications in this area be supported by a sufficiently detailed liquefaction assessment.
A regional council is working with several of its district councils to formulate an urban development strategy as part of the regional plan. They wish to evaluate the liquefaction vulnerability for five potential future growth areas that are under consideration, as part of understanding the relative merits of each area	– One area was categorised in the previous region-wide ***Level A*** assessment as ***Liquefaction Damage is Unlikely***, so is not assessed further at this stage. – Four areas were identified in previous district-wide ***Level B*** assessments as ***Liquefaction Damage is Possible***, so for these areas a more focused ***Calibrated Desktop Assessment*** (***Level B***) is undertaken. – This time the calibration uses all existing subsurface investigations in each area, and a small number of new investigations are undertaken where existing data is sparse (to give a maximum spacing between investigations of ~500 m). – The more detailed ground information shows the change in geology is closer to the coast than conservatively assumed previously. This allows one area to be recategorised as ***Liquefaction Damage is Unlikely***. – The study confirms ***Liquefaction Damage is Possible*** in three areas. Two areas are categorised as ***Medium***. One area appears to be a mix of both ***Medium*** and ***High***, but there is insufficient spatial detail to confidently delineate the boundaries between these categories, so for the meantime it remains categorised as ***Liquefaction Damage is Possible***. – This information about liquefaction is taken into account as part of strategic planning for the region.

EXAMPLE ASSESSMENT PURPOSE	EXAMPLE LIQUEFACTION ASSESSMENT DETAILS AND OUTCOMES
The owner of a large rural property in one of the growth areas categorised as *Medium* wishes to subdivide the land for urban residential development	– The previous ***Calibrated Desktop Assessment*** (***Level B***) undertaken for the growth area by the regional council provides sufficient information about liquefaction to support a plan change application in this case, so no additional liquefaction assessment is required at this stage. The owner submits a private plan change application, which is approved. – To provide information to support the subdivision consent application, a ***Detailed Area-Wide Assessment*** (***Level C***) is undertaken focusing on this specific property. – The investigations previously undertaken by the council for regional plan purposes are too widely spaced for subdivision consent purposes, so additional new ground investigations are undertaken (to give a maximum spacing between investigations of ~250 m). The investigations show that the ground conditions are relatively consistent across the site, so this investigation density (at the lower end of the recommended range for ***Level C***) is considered appropriate. – The study confirms that the previous ***Medium*** category is appropriate. The liquefaction assessment report is provided to the district council as part of the subdivision consent submission.
The owner of an orchard on the fringe of the urban area wishes to subdivide the land for urban residential development (an earlier district plan had already changed the land use zoning to residential)	– A previous ***Calibrated Desktop Assessment*** (***Level B***) undertaken by the city council indicates that ***Liquefaction Damage is Possible***. – A ***Detailed Area-Wide Assessment*** (***Level C***) is undertaken, with additional new ground investigations (on a 250 m grid). These investigations show that there are areas of better and worse ground across the property, but there is still insufficient spatial detail to confidently delineate the boundaries between ***Medium*** and ***High*** liquefaction categories, so it remains as ***Liquefaction Damage is Possible***. – The district plan subdivision rules require that any land with a ***High*** liquefaction category is identified and either remediated or avoided for residential use. So the owner undertakes a more detailed ***Level C*** assessment, with additional ground investigations (on a 125 m grid). – This provides sufficient detail to delineate areas of ***Medium*** and ***High***. The subdivision is designed with ***Medium*** land used for residential lots, and ***High*** land used for reserves and stormwater management.
The owner of a large rural property at the foot of a hill wishes to develop a small four-lot 'lifestyle block' subdivision	– The region-wide ***Basic Desktop Assessment*** (***Level A***) that was undertaken previously by the regional council indicated that ***Liquefaction Damage is Unlikely***. – This existing liquefaction categorisation is sufficient for plan change purposes in this case, so no further liquefaction assessment is required to support the plan change application. – The previous ***Level A*** assessment notes that there is uncertainty regarding the location of the transition between a thick wedge of windblown soil at the foot of the hill and shallow rock further up the hill slope. It suggests that subsurface investigations would be required before a more precise category could be assigned in this area (ie to distinguish between ***Very Low*** and ***Low***). – However, the district council has implemented rules that allow small, low-density residential developments in areas categorised as ***Liquefaction Damage is Unlikely*** in the region-wide ***Level A*** assessment, without the need for additional liquefaction assessment, provided that robust foundations (eg 'TC2-type') are used for all dwellings. – By satisfying these conditions the development is able to proceed through subdivision and building consent without the need for any more detailed liquefaction assessment.

EXAMPLE ASSESSMENT PURPOSE	EXAMPLE LIQUEFACTION ASSESSMENT DETAILS AND OUTCOMES
The owner of a 8 Ha rural property close to the coast wishes to develop a 100-lot medium-density residential subdivision	– The region-wide ***Basic Desktop Assessment*** (***Level A***) that was undertaken previously by the regional council indicated that ***Liquefaction Damage is Possible***. The district council for this area has not yet undertaken any more detailed liquefaction assessment. – The existing liquefaction assessment is not detailed enough for plan change purposes in this case, so the landowner commissions an engineer to undertake a liquefaction assessment focusing on the specific property. The landowner wishes to minimise investigation costs until they understand the potential severity of liquefaction issues and have obtained plan change approval, so a staged assessment is undertaken. – The engineer first checks if there is sufficient existing subsurface investigation information in the surrounding area to undertake a ***Calibrated Desktop Assessment*** (***Level B***). There are some investigations nearby, but they are in a different geological unit to the site, so cannot be used to calibrate the desktop assessment. There are two investigations in the same geological unit within 1 km of the site, so one new investigation is undertaken on the site to meet the minimum ***Level B*** requirement of three investigations for each geological sub-unit (refer Table 3.3). – The ***Level B*** assessment indicates that ***Liquefaction Damage is Possible***. The liquefaction assessment report is provided to the district council as part of the plan change application, which is approved. – To support the subdivision consent application, a ***Detailed Area-Wide Assessment*** (***Level C***) is undertaken. Four additional ground investigations are undertaken – this gives a total of five investigations across the site with an investigation density of 0.6 per Ha (meeting the minimum ***Level C*** requirements in Table 3.3). – The ***Level C*** assessment indicates a liquefaction vulnerability category of ***High***. The liquefaction assessment report is provided to the district council as part of the subdivision consent application. – The subdivision consent is approved, with conditions requiring resilient design for infrastructure and dwellings. – Half of the lots are purchased by a group home builder who undertakes a ***Site-specific Assessment*** (***Level D***) to provide the ground information needed for foundation design. They undertake additional ground investigations on a 50 m grid across the areas they have purchased (a density of 4 per Ha). This confirms the ***High*** category. – The grid of investigations demonstrates that the ground conditions are relatively consistent across most of the area. So in these areas there is now adequate ground characterisation for foundation design and building consent for each dwelling. – There is one area where ground conditions are more variable, and the previous grid of investigations is not sufficient for foundation design. Additional ground investigations are undertaken in this area, to give two investigations within each building footprint. Based on the results of this investigation, a ground improvement solution is specifically designed for each dwelling.

EXAMPLE ASSESSMENT PURPOSE	EXAMPLE LIQUEFACTION ASSESSMENT DETAILS AND OUTCOMES
The owner of a large inner-city industrial site wishes to subdivide part of the site for a new commercial development	– A previous ***Calibrated Desktop Assessment*** (***Level B***) undertaken by the city council indicates that ***Liquefaction Damage is Possible***. – It has not yet been determined whether the liquefaction vulnerability category is ***Medium*** (in which case Table 6.3 would require a ***Level B*** assessment for subdivision consent) or ***High*** (in which case ***Level C*** would be required). So following Table 3.3, a ***Level C*** assessment is undertaken. – This more detailed assessment allows the land to be categorised as ***Medium***. The benefit of this more precise categorisation is that it provides a more straightforward path for the subdivision consent to be approved, as the city council has implemented rules that require liquefaction mitigation if land with ***High*** liquefaction vulnerability is subdivided.
A city council wishes to encourage housing intensification in an existing residential suburb close to the city centre	– A previous ***Calibrated Desktop Assessment*** (***Level B***) undertaken by the city council indicates that ***Liquefaction Damage is Possible***. – There is limited existing ground investigation information in the area, so the council undertakes new investigations. The investigations are located in the roadside, at a typical spacing of 300–400 m (25 CPTs over an area of 3 km²). In addition to providing information for this liquefaction assessment, these investigations also assist with development of the council's infrastructure renewal strategy. – With this additional ground investigation information, a more detailed ***Level B*** assessment is undertaken, including quantitative analysis, which indicates a liquefaction vulnerability category of ***Medium***. – The council amends the district plan rules, relaxing minimum lot size limits in this area to promote intensification. – The council amends its building consent process so that more detailed liquefaction assessment is not required for infill developments in this area, provided that a hybrid TC2/TC3 foundation or TC3 surface structure foundation is used (MBIE 2015).
The owner of an inner-city residential property wishes to subdivide the back half of their section and build a new townhouse	– The previous ***Calibrated Desktop Assessment*** (***Level B***) undertaken for this suburb by the city council indicates a liquefaction vulnerability category of ***Medium***. – This previous assessment provides sufficient information about liquefaction to support a subdivision consent application in this case, so no additional liquefaction assessment is required at this stage. The owner submits a subdivision consent application, which is approved. – The owner discusses foundation options for the new townhouse with their builder and engineer. They weigh up the extra cost and construction time of a hybrid TC2/TC3 foundation (compared to a simple TC2 slab) against the cost and time of more detailed liquefaction investigations (and the chance that these investigations might or might not allow a simple TC2 slab to be adopted). – The owner decides to adopt a hybrid TC2/TC3 foundation without any further liquefaction assessment. They complete their foundation design and submit their building consent application on this basis.

APPENDIX C.
FLOWCHART FOR LIQUEFACTION ASSESSMENT TO INFORM PLANNING PROCESSES

START
follow the risk-based process (Section 1.3)

Context

Regional policy
Regional plan
District change
Land use consent
Subdivision consent
Building consent
What is the purpose of the assessment? (Section 2.1)

Risk identification

Identify minimum level of detail required for the indended purpose (Section 3.5)

			ASSESSMENT PURPOSE				
			Regional ⟶ Site-specific				
Level of detail	Low	A	✓				
	↓	B	✓	✓	✓		
		C		✓	✓	✓	
	High	D			✓	✓	✓

Consider whether additional earthquake scenarios or sensitivity studies would be useful to inform decision-making or strategic planning (eg 25-year shaking, or level of shaking required to cause damage) Section 4.3.4

Select earthquake scenarios for assessment (Section 4.3)

Minimum requirements:

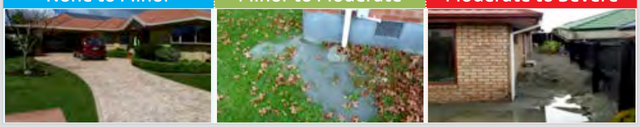
- 500-year shaking for Level A and B
- 100 and 500-year shaking for Level C and D.

Estimate liquefaction-induced ground damage (Section 4.4)

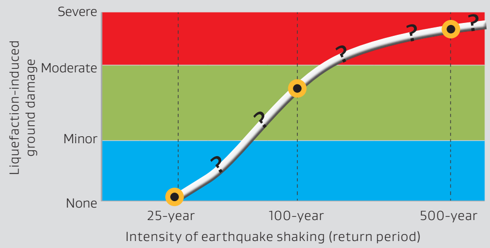
- Based on analysis of available information, divide the study area into sub-areas with similar liquefaction characteristics. The number and size of sub-areas will depend on the ground variability and the extent and detail of the study.
- For each sub-area, determine the expected degree of liquefaction-induced ground damage for each earthquake scenario considered.

Degrees of liquefaction-induced ground damage are defined on a scale ranging from *None to Severe*, with example photos (Section 2.5)

None to Minor | Minor to Moderate | Moderate to Severe

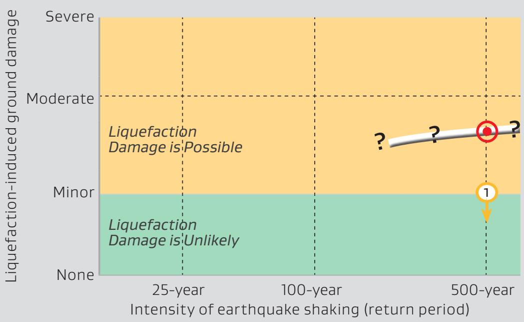


Produce simplified liquefaction-induced ground damage response curve for each sub-area (Section 4.3.2)



Typical *Level A* and *Level B* assessments (Appendix J3)

- The limited information means that only a simply assessment of performance is possible
- Areas are first identified where ***Liquefaction Damage is Unlikely***
- In the remaining areas ***Liquefaction Damage is Possible***, but the information used in the assessment is not detailed enough to determine the severity of potential damage.



Performance criteria for liquefaction categorisation

1. If less than ***Minor*** ground damage at 500-year level of shaking then ***Liquefaction Damage is Unlikely***

Level A and B

Assess expected ground damage response against the performance criteria to determine the liquefaction category for each sub-area (Section 4.5)

Increasing likelihood and severity of ground damage

Increasing precision in the categorisation

LIQUEFACTION CATEGORY IS UNDETERMINED			
LIQUEFACTION DAMAGE IS UNLIKELY		LIQUEFACTION DAMAGE IS POSSIBLE	
Very Low Liquefaction Vulnerability	Low Liquefaction Vulnerability	Medium Liquefaction Vulnerability	High Liquefaction Vulnerability

Decreasing uncertainty in the assessment

Produce a map that shows the liquefaction category assigned to each sub-area (Section 4.6)

The liquefaction category map will evolve over time as additional liquefaction assessments are completed as part of ongoing planning and consenting processess (ie return to START – Section 8.2)

Level A: Basic desktop

Level B: Calibrated desktop

Level C: Detailed area-wide

Level D: Site-specific

Select level of detail for the assessment (Section 3.6)

Consider whether a better overall outcome can be achieved by adopting a higher level of detail than the miniumum requirements (eg reduced conservatism, better information to encourage development) (Section 3.6)

Collate base information for the assessment, to suit the level of detail selected (Section 3.3)

Level A
- *Geology and geomorphology*
- *Groundwater depth*
- *Regional seismicity*
- *Historical observations*

+

Level B
Calibration using limited ground investigation data

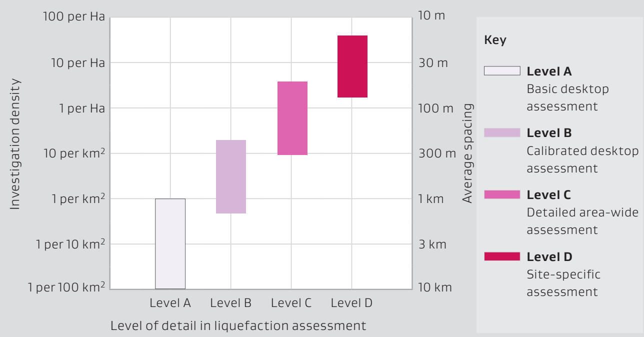
+

Level C
Detailed information on ground conditions and groundwater levels with good coverage across the entire study area

+

Level D
Specific information about particular site and proposed development, to provide a high degree of site-specific confidence

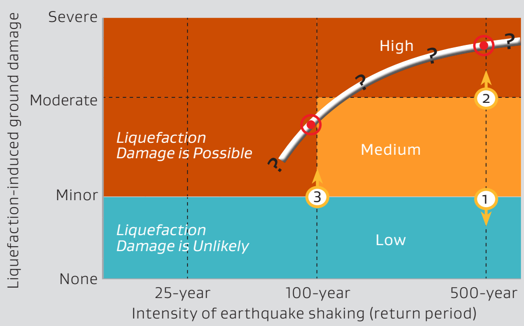
Minimum spatial density of ground investigations required depends on level of detail and purpose of the assessment, and the ground conditions encountered (Section 3.5)



Level C and D

Typical *Level C* and *Level D* assessments (Appendix J3)

- The additional information means that a more detailed assessment of performance is possible
- Areas are first identified where liquefaction damage is unlikely (***Low***)
- The remaining areas are categorised as either ***Medium*** or ***High***, depending on severity and frequency of potential liquefaction damage



Performance criteria for liquefaction categorisation

Select the highest category from these three criteria, if none apply then liquefaction category is ***Medium***

1. If less than ***Minor*** ground damage at 500-year level of shaking then liquefaction category is ***Low***
2. If more than ***Moderate*** ground damage at 500-year level of shaking then liquefaction category is ***High***
3. If more than ***Minor*** ground damage at 100-year level of shaking then liquefaction category is ***High***

APPENDIX D. CASE STUDY OF GROUND INVESTIGATION DENSITY

The following case study of an area of Christchurch shows how different investigation densities are intended to identify variation of ground conditions at a range of scales.

The different coloured triangles represent different investigations densities, as recommended for different purposes. The coloured shading on the map represents the observed land damage in this area resulting from the 2010 Darfield Earthquake.

Looking at the large-scale maps there appears to be a localised feature running across this area, potentially associated with historic river channel or swamp deposits. This case study shows that if ground investigations are too widely spaced then they might not identify this feature. The smaller scale maps show that as the investigation density increases, it becomes possible to identify smaller and more localised variations in ground conditions.

Ground surface observations

LEGEND

- No observed ground cracking or ejected liquefied material
- Minor ground cracking but no observed ejected liquefied material
- No lateral spreading but minor to moderate quantities of ejected material
- Moderate to major lateral spreading or large quantities of ejected material
- Severe lateral spreading; ejected material often observed
- No observations (uncoloured)

Figure D1: Investigations at approximately 2 km spacing, or 0.25 per km^2 (eg Level A)

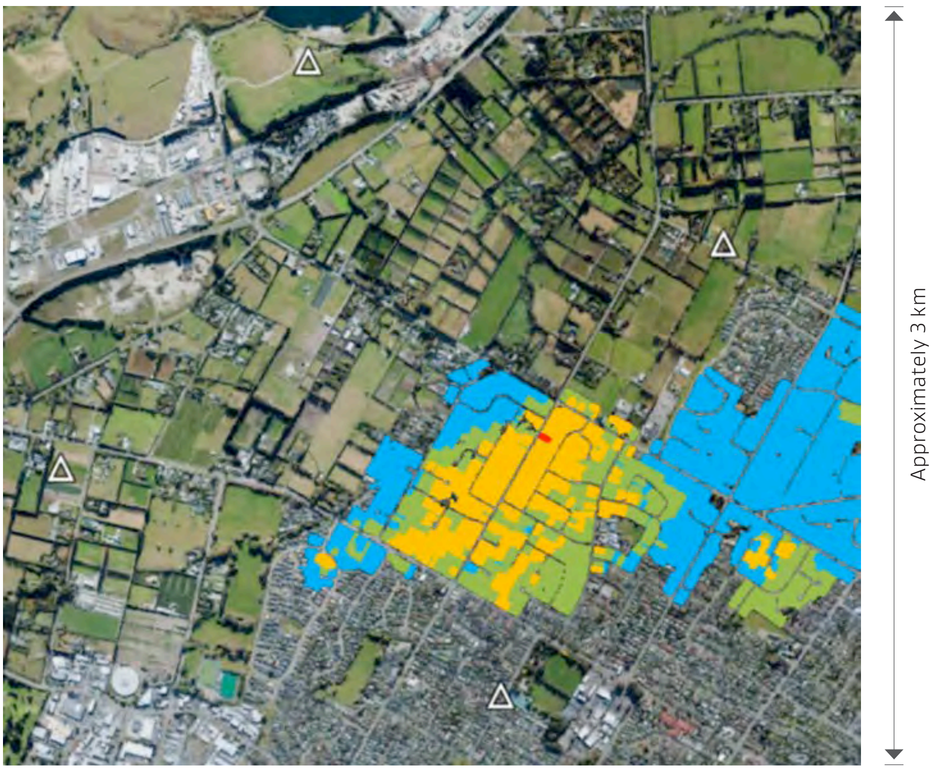
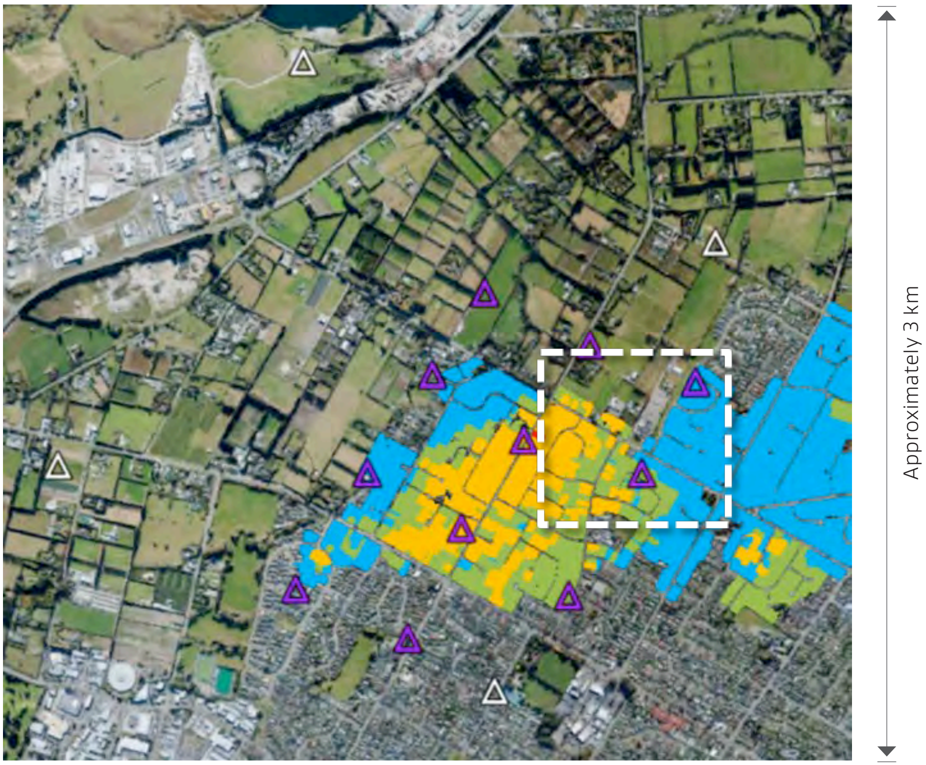


Figure D2: Investigations at approximately 500 m spacing, or 4 per km^2 (eg Level B)



See detail below

Figure D3: Investigations at approximately 100 m spacing, or 1 per Ha (eg Level C)

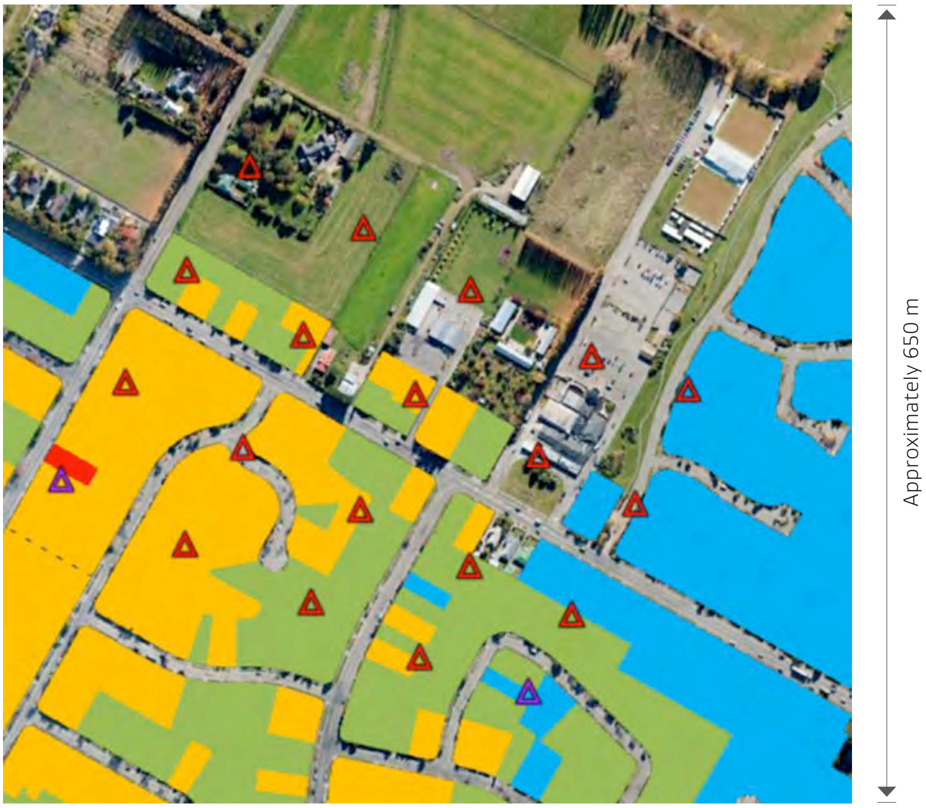


Figure D4: Investigations at approximately 50 m spacing, or 4 per Ha (eg Level C or D)

See detail below

Figure D5: Investigations at approximately 50 m spacing, or 4 per Ha (eg Level C or D)

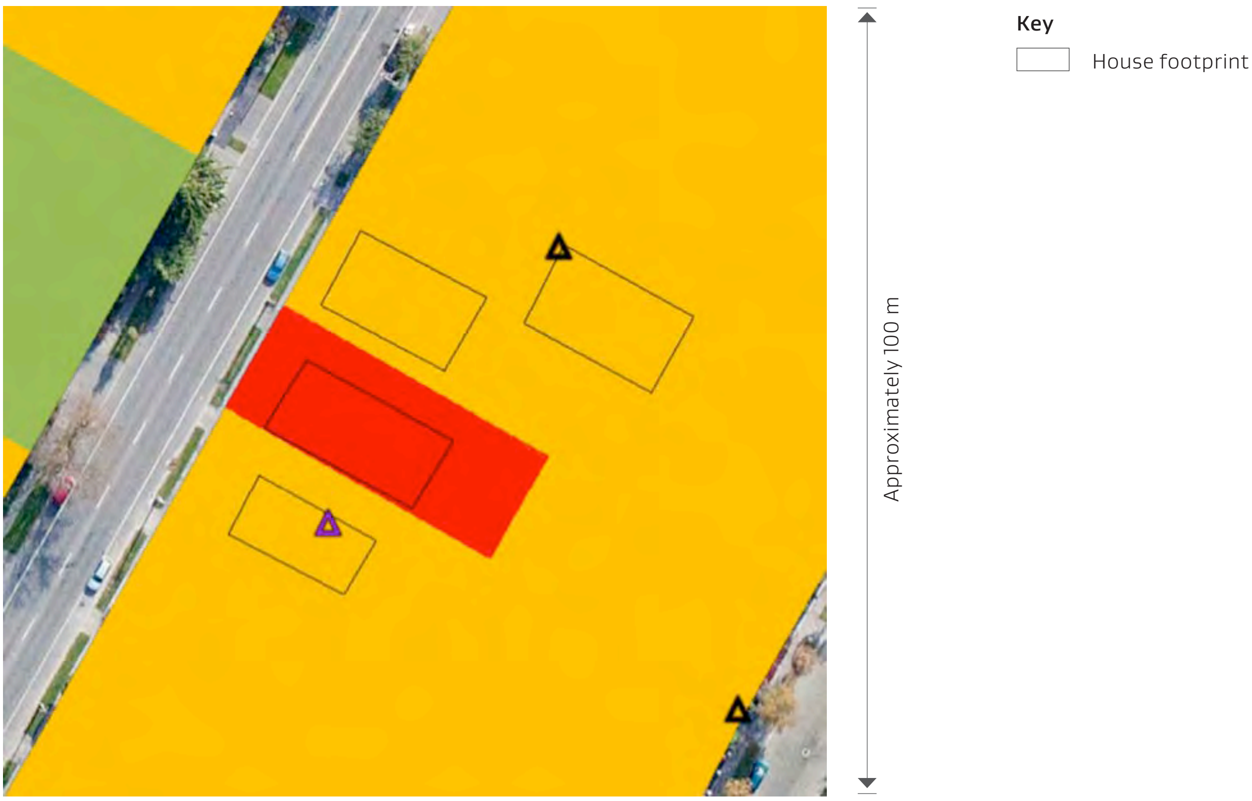


Figure D6: Two investigations within each building footprint (eg Level D)

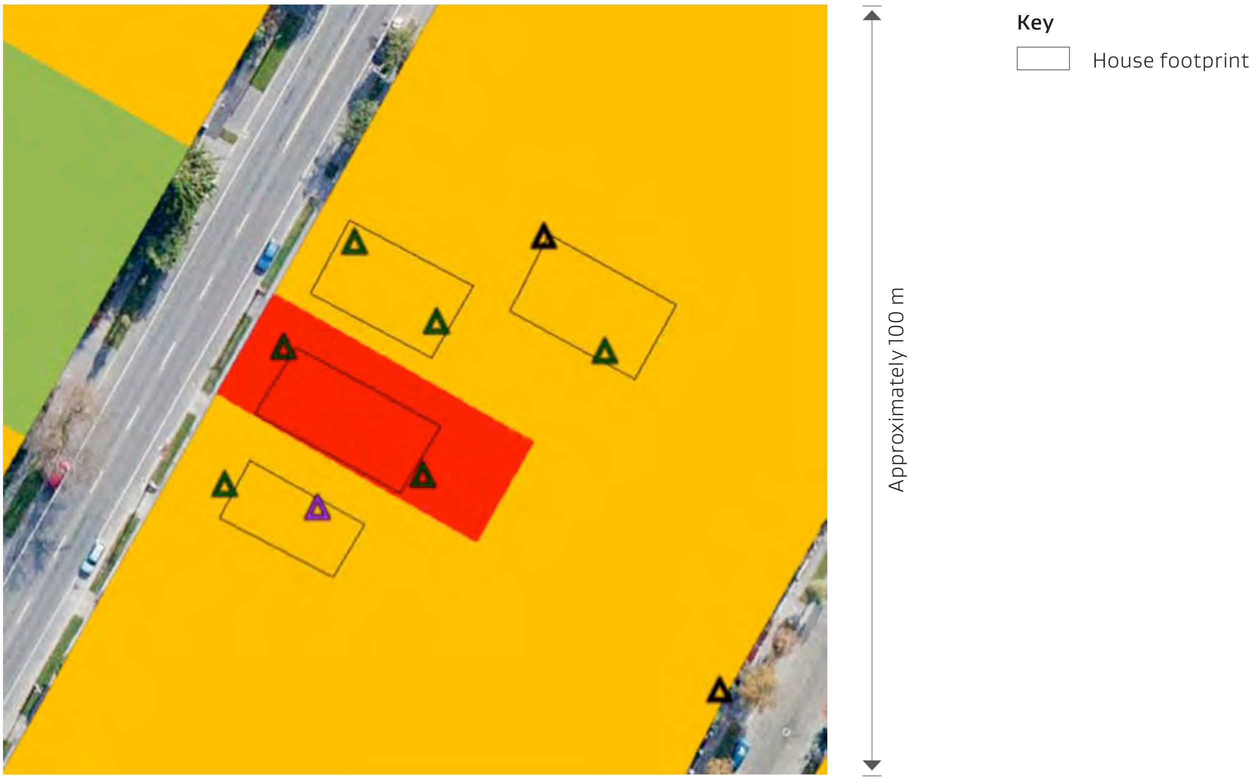


Figure D7: Overview of resulting pattern of investigation

APPENDIX E. STANDARD DATA FORMAT FOR MANAGING INFORMATION FROM LIQUEFACTION ASSESSMENTS

For consistency across New Zealand, this guidance recommends that the descriptions and colours shown in Tables E1 and E2 are used when preparing liquefaction assessment maps to inform planning processes.

These colours have been selected to be clearly distinguishable when reproduced on desktop printers and computer monitors, and for those with red-green colour blindness (for further details refer to Thompson et al., 2015 and http://colorbrewer2.org).

This guidance also recommends that information about each liquefaction assessment is collated into summary tables such as the example in Table E3, to make it easy to understand the scope of the assessment. As the liquefaction vulnerability categories across a region will be incrementally refined over time as further assessments are undertaken, councils may wish to use this summary table, along with GIS metadata for each area and sub-area, to collate liquefaction assessment information for ease of reference and updating in future. Table E4 provides an example of GIS metadata that should be captured for each area assessed.

Table E1: Levels of detail for liquefaction assessment studies

SHORT DESCRIPTION	LONG DESCRIPTION	RGB COLOUR CODE FOR MAPS
Level A	Level A – Basic desktop assessment	241, 238, 246
Level B	Level B – Calibrated desktop assessment	215, 181, 216
Level C	Level C – Detailed area-wide assessment	223, 101, 176
Level D	Level D – Site-specific assessment	206, 18, 86

Table E2: Recommended categories for use in liquefaction assessment studies

SHORT DESCRIPTION	LONG DESCRIPTION	RGB COLOUR CODE FOR MAPS
Liquefaction Category is Undetermined	A liquefaction vulnerability category has not been assigned at this stage, either because a liquefaction assessment has not been undertaken for this area, or there is not enough information to determine the appropriate category with the required level of confidence.	191, 191, 191
Liquefaction Damage is Unlikely	There is a probability of more than 85 percent that liquefaction-induced ground damage will be ***None to Minor*** for 500-year shaking. At this stage there is not enough information to distinguish between ***Very Low*** and ***Low***. More detailed assessment would be required to assign a more specific liquefaction category.	161, 218, 180
Liquefaction Damage is Possible	There is a probability of more than 15 percent that liquefaction-induced ground damage will be ***Minor to Moderate*** (or more) for 500-year shaking. At this stage there is not enough information to distinguish between ***Medium*** and ***High***. More detailed assessment would be required to assign a more specific liquefaction category.	254, 217, 142
Very Low Liquefaction Vulnerability	There is a probability of more than 99 percent that liquefaction-induced ground damage will be ***None to Minor*** for 500-year shaking.	34, 94, 168
Low Liquefaction Vulnerability	There is a probability of more than 85 percent that liquefaction-induced ground damage will be ***None to Minor*** for 500-year shaking.	65, 182, 196
Medium Liquefaction Vulnerability	There is a probability of more than 50 percent that liquefaction-induced ground damage will be: – ***Minor to Moderate*** (or less) for 500-year shaking; and – ***None to Minor*** for 100-year shaking.	254, 153, 41
High Liquefaction Vulnerability	There is a probability of more than 50 percent that liquefaction-induced ground damage will be: – ***Moderate to Severe*** for 500-year shaking; and/or – ***Minor to Moderate*** (or more) for 100-year shaking.	204, 76, 2

Note:
Where practical it is recommended that the map legend for liquefaction assessments is presented in the matrix form shown in Table 4.1, as this helps to better convey the meaning and range of uncertainty associated with each category.

Table E3: Example summary information table recommended for liquefaction assessment reports

LIQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Assessment of Liquefaction-Induced Ground Damage to Inform Planning Processes' published by the Ministry of Business, Innovation and Employment in 2017. **https://www.building.govt.nz/building-code-compliance/geotechnical-education**	
Client	ABC City Council & DEF Regional Council
Assessment undertaken by	XYZ Consulting Ltd. PO Box 123, ABC
Report date	29 February 2016
Extent of the study area	– Coastal margins of ABC District. – Refer to map in Figure 1.
Intended RMA planning and consenting purposes	– Rural areas = Regional Plan – Urban areas and future growth areas = District Plan – Refer to map in Figure 2.
Other intended purposes	– ABC City Council infrastructure resilience strategy – Greater ABC urban development strategy
Level of detail	– Rural areas = Level B (General Assessment). – Urban areas and future growth areas = Level C (Detailed Assessment). – Refer to map in Figure 2.
Notes regarding base information	– The assessment included all CPT and borehole investigations greater than 1 m depth within the study area that were available on the NZ Geotechnical Database as at 12 December 2015. Refer to maps in Appendix 2 for investigation location details. – Depth to groundwater was based on data from the DEF Regional Council shallow groundwater monitoring network up to 30 November 2015.
Other notes	– Parts of this work were supported by funding from the GHI foundation.

Table E4: Recommended GIS metadata for each area defined in a liquefaction assessment study

FIELD DESCRIPTION	FIELD NAME	DATA TYPE	EXAMPLE DATA
Liquefaction category assigned to this area	LIQ-CAT	Text (50 char)	***Liquefaction Damage is Possible***
Level of detail in the liquefaction assessment for this area	DETAIL	Text (50 char)	Level B – Calibrated Desktop Assessment
Date of liquefaction assessment	DATE	Date	29 February 2016
Name of the organisation that undertook the assessment	AUTHOR	Text (200 char)	XYZ Consulting Ltd. PO Box 123, ABC. www.xyz.com
Liquefaction assessment report reference	REPT-REF	Text (500 char)	'Liquefaction assessment for eastern ABC district', Report for ABC City Council by XYZ Consulting, February 2016, Ref:12345.6. available at www.abc.govt.nz/liq2016
Intended RMA planning and consenting purposes	PURPOSE	Text (200 char)	District plan
Other intended purposes	PURP-OTH	Text (200 char)	ABC City Council infrastructure resilience strategy. Greater ABC urban development strategy.
Notes regarding base information used in the liquefaction assessment for this area	BASE-INF	Text (5000 char)	The liquefaction assessment included four CPT and two borehole investigations within this area (depths between 3 m and 18 m) available on the NZGD as at 12 December 2015. The historic presence of a swamp in this area is recorded in the 1885 district survey map, however this was not mapped with sufficient precision to accurately define boundaries. Depth to groundwater was based on the DEF Regional Council groundwater model, which considered monitoring data up to 30 November 2015. The modelled groundwater level was confirmed by an existing standpipe in the north of the area, which showed variation of 0.8 m above and 0.5 m below the modelled median value over the period 2009 to 2015.
Notes regarding key uncertainties in the liquefaction assessment for this area, and potential consequences of this uncertainty	UNCERT	Text (5000 char)	There is uncertainty regarding the location of the boundary between this area of swamp deposits and the adjacent area of ***Low Liquefaction Vulnerability*** defined to the south where gravel deposits become dominant. The boundary between these areas has been defined conservatively based on three existing boreholes, more detailed ground investigations in future might allow the location of this boundary to be refined and shifted north slightly.
Other notes regarding the liquefaction assessment for this area	NOTES	Text (5000 char)	The interlayering of liquefiable and non-liquefiable material that is expected within the swamp deposits may act to reduce the severity of liquefaction-induced damage that occurs. The effect of this could be examined further in more detailed liquefaction assessments in future.

APPENDIX F.
EXAMPLES OF DEVELOPMENT CONTROLS

F1 Regional policy statement examples

There are several examples of regional policy statement objectives and policies specifically addressing liquefaction (operative in mid-2017). The Canterbury Regional Policy Statement 2013 has the most specific provisions as illustrated in the example extracts in the box below. References to liquefaction are highlighted in blue. In this example the Regional Council taking a supporting rather than leading role and is allocating responsibility for delineating (mapping) to the territorial authorities. The Canterbury Regional Policy Statement also includes some useful text providing reasons and explanation for the provisions.

Example: Canterbury Regional Policy Statement

Policy 11.3.3 – Earthquake hazards

New subdivision, use and development of land on or close to an active earthquake fault trace, or in areas susceptible to liquefaction and lateral spreading, shall be managed in order to avoid or mitigate the adverse effects of fault rupture, liquefaction and lateral spreading.

Methods

The Canterbury Regional Council will:

1. Assist territorial authorities to delineate fault avoidance zones along known active fault traces.
2. Assist territorial authorities to delineate areas susceptible to liquefaction and lateral spreading.
3. Make available, upon request, any information that it holds about natural hazards.

Territorial authorities will:

4. Set out objectives and policies, and may include methods in district plans to manage new subdivision, use and development of land in areas on or adjacent to a known active earthquake fault trace.
5. Set out objectives and policies, and may include methods in district plans to manage new subdivision, use and development of land in areas known to be potentially susceptible to liquefaction and lateral spreading.
6. Ensure that the risk of earthquake fault rupture, 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.

Territorial authorities should:

7. Supply information to the Regional Council captured at time of subdivision in relation to active earthquake fault trace, areas susceptible to liquefaction and lateral spreading.

The Bay of Plenty Regional Policy Statement example below is one where liquefaction is addressed. The Regional Council is taking a leadership role in assessing and mapping land that is susceptible to liquefaction and indicating that it will do this mapping in a staged manner.

Example: Bay of Plenty Regional Policy Statement

Policy NH 7A: Identifying areas susceptible to natural hazards

Identify natural hazards and the locations where those natural hazards could affect people, property and lifeline utilities by mapping hazard susceptibility areas for the following natural hazards:

a Volcanic activity

 i . . ..

b Earthquake

 i Liquefaction and lateral spreading. . .

c Coastal/marine processes. . ..

d Extreme rainfall. . .

Hazard susceptibility mapping may be undertaken in stages allowing for prioritisation of effort taking into account demand for land use change or intensification.

Policy NH 13 C: Allocation of responsibility for natural hazard identification and risk assessment

Require the natural hazard identification and risk assessment approach described in Policies NH 1B, NH 2B and NH 7A to NH 10B above to be given effect to by:

a Regional Council undertaking area-based natural hazard risk analysis and evaluation in accordance with Policy NH 4A for:

 i Liquefaction

In the Hawke's Bay Regional Policy Statement example, the Regional Council is taking a lead with mapping and providing information to territorial authorities. It provides direction on where hazard avoidance and mitigation should be focused and sets requirements for provisions to be included in district plans.

Example: Hawke's Bay Regional Resource Management Plan – Regional Policy Provisions

Section 3.12 Natural hazards

OBJECTIVE

OBJ 31 The avoidance or mitigation of the adverse effects of natural hazards on people's safety, property, and economic livelihood.

Explanation and reasons

Earthquakes

3.12.5 Earthquakes are a significant risk to the Hawke's Bay region, given the regular occurrence of tectonic movement in the area. Although large earthquakes such as the 1931 event occur infrequently, they have a high potential to impact on people and their livelihood. Development in Hawke's Bay has continued with little or no regard to the effects that earthquakes have on different ground conditions. The HBRC has commissioned studies into the risk posed by earthquakes, and the effect of earthquakes on different areas, particularly in relation to liquefaction, ground shaking, subsidence and uplift. This information has been provided to territorial local authorities, in order that they use it in the production of district plans and the establishment of building design standards.

POLICIES

POL 55 Role of non-regulatory methods

3.12.10 To use non-regulatory methods set out in Chapter 4, as the principal means of addressing hazard avoidance and mitigation, in particular:

a Liaison with territorial authorities – To provide information on natural hazard risk to territorial authorities, and advocate that future development is managed in such a way that the risk of exposure to natural hazards is avoided, remedied or mitigated.

b Works and services – To provide hazard mitigation measures, in particular flood mitigation measures, where the benefits can be shown to outweigh the costs and the identified beneficiaries can meet the costs.

c Natural hazard priorities – To focus both hazard avoidance and mitigation on areas of high human population density as a first priority.

Explanation and reasons

3.12.11 Policy 55 sets out the role of the HBRC in providing information to territorial authorities, providing works and services where these are cost-effective, and prioritising natural hazard responses as the principal means of addressing natural hazard avoidance and mitigation. This policy recognises the need for an integrated approach by territorial authorities and the HBRC to address land use planning and service provision with the view of minimising the risk and impact of natural hazards. The HBRC will provide hazard mitigation measures (eg stopbanks for flooding) where the benefits outweigh the costs, and the costs can be recovered from those who will benefit from the works. Furthermore, the HBRC will, as a first priority, focus hazard avoidance and mitigation on the areas of high human population density (eg cities and towns) as these areas are likely to experience significant effects on people's safety and economic livelihood as a result of a natural hazard event.

3.1B Managing the built environment

POLICIES

Provision for business activities (Heretaunga plains sub-region)

POL UD2 In the Heretaunga Plains sub-region, district plans shall provide for business activities to 2045, in a manner which: . . .

1 Avoids or mitigates the following locational constraints:

- i projected sea level rise as a result of climatic changes
- ii active coastal erosion and inundation
- iii stormwater infrastructure that is unable to mitigate identified flooding risk
- iv flood control and drainage schemes that are at or over capacity
- v active earthquake faults
- vi high liquefaction potential
- vii nearby sensitive waterbodies that are susceptible to potential contamination from runoff, stormwater discharges, or wastewater treatment and disposal.
- viii no current wastewater reticulation and the land is poor draining
- ix water short areas affecting the provision of adequate water supply.

Note: The same requirement on locational constraints is included in two other policies:

- New Residential Greenfield Growth Area Criteria (Heretaunga Plains Sub-Region) POL UD4.2
- Provision for Papakainga and Marae-Based Development (Region) POL UD6.1

F2 District plan examples

There are several examples of district plans addressing liquefaction. Three examples have provisions at an objective and/or policy level only. Just two have provisions that include rules. Of these the Christchurch Replacement District Plan provides the most useful example. However, it relies on guidance that was developed specifically for the Canterbury recovery and this may not be directly applicable to other parts of New Zealand.

The Tauranga example has an objective and policy which provide for avoidance or mitigation options, without differentiating when or in what situations each of the options should apply. Appropriate solutions are expected to be applied through subdivision, use and development processes. However, the objective and policy provide no basis to help determine what might be appropriate.

Example: Tauranga City Plan

Section 8 Natural hazard provisions

8A.1.2 Objective– Avoidance or mitigation of compressible and liquefiable soils

The risk to life, property and the environment resulting from the subdivision, use and development of land subject to, or likely to be subject to, induced subsidence from liquefaction, peat or other highly compressible soils is avoided or mitigated.

8A.1.2.1 Policy – Avoidance or mitigation of compressible and liquefiable soils

a By ensuring that land comprised of peat, highly compressible soils or soils subject to liquefaction are avoided or mitigated through the subdivision, use and development process

b By ensuring subdivision, use and development avoids or mitigates against the alteration of drainage patterns, or the physical characteristics of the peat or compressible soils

c By ensuring appropriate solutions are applied through the subdivision, use and development process to avoid or mitigate the adverse effects of peat and other compressible or liquefiable soils.

The Invercargill District Plan includes a map showing liquefaction susceptibility using a five-point scale from Negligible to Very High. There is some limited explanatory text and one policy. A 475-year return period event is set as the basis for hazard planning, but no further provisions are included in the plan.

Example: Invercargill Proposed District Plan

The district, like the rest of New Zealand, is susceptible to seismic activity. A major rupture of the south-west segment of the Alpine Fault is understood to have a 6–14% probability occurrence within the next 20 years. The best information available to the Council indicates that a MM VIII earthquake is the 475 year return period earthquake event. The lower lying areas of the Invercargill district have a high, or very high, susceptibility to liquefaction.

Policy 5 Identification – earthquake:

a To identify the Modified Mercelli VIII earthquake as the 475 year return period event, around which hazard planning for earthquake should be based.

b To also identify areas at risk from liquefaction.

Explanation: The best information available to the Council indicates that the biggest earthquake risk to Invercargill is from an earthquake originating in Fiordland and that the shaking felt in Invercargill from a 475 year return period event is likely to be of Modified Mercelli VIII. Generally, the lower lying areas of Invercargill are known to be at significantly greater risk from liquefaction than the areas above the three metre contour.

The Hutt City District Plan includes some explanatory material about liquefaction and how it occurs. A single policy addresses liquefaction and this simply requires suitable engineering measures to safeguard people and their property. There are no further provision to expand on the level of protection required or what would represent suitable engineering measures. Reference is made to information that will be provided on Land Information Memorandums (LIMs) and the Council relying on compliance with the Building Code to manage liquefaction-related risk.

Example: Hutt City District Plan

Section 14H

14H 1.1.1 Risk associated with natural hazards

Policies

a That the area at risk from fault rupture causing permanent ground deformation along the Wellington Fault be managed by the Wellington Fault Special Study Area to address the effects of subdivision and development on the safety of people and their property.

b That suitable engineering and emergency management measures be adopted to safeguard people and their property from liquefaction, ground-shaking and tsunami hazards.

c That where areas susceptible to landslide have been identified, appropriate conditions of compliance will be provided to mitigate the adverse effects of subdivision and development on the vulnerability of people and their property.

d That suitable engineering, emergency management and land use control measures be adopted to reduce the vulnerability of people and their property to flood hazards.

e That suitable engineering, emergency management and land use control measures be adopted to reduce vulnerability of development along the coast.

Explanation: Liquefaction hazard

Research shows that some subsurface soils have a high probability of liquefaction occurring during strong earthquake shaking. Liquefaction is the situation where the soil becomes like liquid due to seismic action. During liquefaction, the soil loses its ability to support buildings, causing damage to the buildings. The types of soil most susceptible to liquefaction are low to medium density sands and silts, generally within 12 to 15 m of the ground surface. These soils are known as flexible soils. Shallow groundwater level is also an important requirement for liquefaction to occur. Seaview/Gracefield and the southern portions of Petone, Moera and Woburn have such flexible soils and shallow ground water conditions. Details of liquefaction potential will be provided in Land Information Memoranda. Any proposed structures will be required to comply with the New Zealand Building Code.

The Palmerston North City District Plan includes identified liquefaction susceptibility zones. These and some explanatory information in the Plan are intended to raise awareness. There are no objectives, policies, rules or other planning provisions.

Example: Palmerston North City Council District Plan

Section 22 Natural hazards

Liquefaction susceptibility zones have also been included in the District plan. The maps are intended to broadly raise public awareness of the potential ground shaking and liquefaction hazard but there are no specific rules.

In terms of liquefaction hazard, the City is also divided into four liquefaction susceptibility zones (refer Map 22.6.2). Areas within Zone 1 are considered to have the highest susceptibility to soil liquefaction. This zone contains most of the known sites of liquefaction-induced ground damage reported in historical earthquakes in the Manawatu Wanganui Region. It also includes areas covered with stream and swamp sediments which have a documented susceptibility to this phenomenon. Areas covered by Zone 2 have a moderate susceptibility to liquefaction. Zones 3 and 4 contain areas with low and negligible susceptibility to liquefaction, respectively. Ashhurst largely falls within zone 4. It is important to note that in areas considered to be highly susceptible to liquefaction (Zone 1), this phenomenon is only likely to occur where ground shaking of Modified Mercalli (MM) intensity VII, or greater, is experienced. To provide some perspective as to the frequency or annual probability of experiencing such shaking, between 1840 and 1994 MM VII shaking has only been experienced within part or parts of the Manawatu-Wanganui Region, which includes Palmerston North City, Tararua, Horowhenua, Manawatu, Rangitikei, Wanganui, and Ruapehu and parts of Stratford, Taupo and Waitomo District, 11 times. Liquefaction-induced ground damage has been reported at various sites in the region in only 8 of these cases. In most cases recorded liquefaction ground damage effects associated with these events has been relatively minor. Palmerston North's general exposure to MM VII shaking, under average ground conditions, has been estimated at a 10% probability over a 15 year period (sometimes termed a 1 in 150 year event). However, given the City's general positioning on sediments prone to amplifying earth shaking events, shaking intensities experienced across the city with such an event are likely to exceed this level. It is therefore likely that shaking of MM VII or higher will be experienced within parts the city, on average, somewhat more frequently than once in 150 years.

For further information and explanation of terms related to Palmerston North's susceptibility to earth shaking, ground shaking amplification and liquefaction plan users are advised to contact Manawatu-Wanganui Regional Council relating to the hazard analysis work that has been undertaken in this area.

There are two examples of district plans that have provisions, including rules, covering liquefaction:

- the Christchurch City Replacement District Plan
- the Waimakiriri District Plan.

The Christchurch Plan has the most comprehensive provisions. The rules section in the example has been directly copied and pasted from the Independent Hearings Panel General Documents website and is the version updated 8 March 2017.

Example: Christchurch Replacement District Plan

Policy 5.3.3.1 – Management of liquefaction risk

a Map the Liquefaction Management Area based on a district-wide assessment of where damaging liquefaction is more likely to occur.

b Provide 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.

5.6 Rules – Liquefaction hazard

Liquefaction is a process that can occur during strong earthquake shaking which causes loss of stiffness and strength in generally loosely consolidated fine grained water saturated soils and can result in ground damage from lateral spreading, settlement, ground cracking, sand boils and deposition of sediment, as well as localised flooding.

5.6.1 Permitted activities

All activities in the Liquefaction Management Area are a permitted activity unless specified in Rules 5.6.2 or 5.6.3, or as otherwise specified elsewhere in the District Plan.

5.6.2 Controlled activities

The activities listed below are controlled activities within the area shown on the Planning Maps as the Liquefaction Management Area.

Discretion to impose conditions is restricted to the matters over which control is reserved as set out in the following table.

Where subdivision is specified, a subdivision consent is also required under Chapter 8 Subdivision, Development and Earthworks.

There may be other areas that are not identified at the district scale that are susceptible to liquefaction risk based on site specific characteristics – these may require specific geotechnical investigations as part of subdivision to satisfy the Council with respect to Section 104 and Section 106 of the RMA.

Table 5.6.2a

ACTIVITY		THE MATTERS OVER WHICH COUNCIL RESERVES ITS CONTROL
C1	Any subdivision which creates an additional vacant allotment or allotments in the Liquefaction Management Area. Note: This rule does not apply to boundary adjustments, amalgamations, or the creation of unit titles. Any resource consent application arising from this rule shall not be limited or publicly notified.	a The Council's control is limited to the following matters: i location, size and design of allotments, structures, roads, access, services or foundations as they relate to the liquefaction hazard ii timing, location, scale and nature of earthworks as they relate to the liquefaction hazard iii liquefaction hazard remediation methods. b These controlled activities will be assessed against the following criteria: i Whether techniques proposed for remediation and/or mitigation of the effects of any liquefaction hazard identified are appropriate, including but not limited to: A provision for ground-strengthening, foundation design, provision of resilient services and the ability of these to be incorporated into the subdivision consent as conditions or consent notices; and B setbacks in relation to any waterway or water body, or any sharp change in ground elevation, sloping ground or free-face. Alternatively, whether ground-strengthening or other proposed engineering or geotechnical solutions are identified to address any identified potential for lateral spread. ii The extent to which the layout of the subdivision in relation to the liquefaction hazard is appropriate, including the proposed location of earthworks, roads, access, servicing and building platforms in relation to the liquefaction hazards identified. iii The effect of the remediation and/or mitigation on the reasonable use of the site.

5.6.3 Restricted discretionary activities

The activities listed below are restricted discretionary activities in any zone within the area shown on the Planning Maps as the Liquefaction Management Area.

Discretion to grant or decline consent and impose conditions is restricted to the matters of discretion set out in the following table.

Table 5.6.3a

ACTIVITY		THE COUNCIL'S DISCRETION SHALL BE LIMITED TO THE FOLLOWING MATTERS
RD1	Any activity located on a site with an area of 1500 m^2 or more, qualifying as a controlled or restricted discretionary activity under any of the following residential rules: 1 Enhanced Development Mechanism Rule 14.11.3.3 RD1, RD2 2 Community Housing Redevelopment Mechanism Rule 14.12.2.3 RD1, RD2 3 Residential Suburban Zone and Residential Suburban Density Transition Zone Rule 14.2.2.3 RD7, RD8, RD10 4 Residential Medium Density Zone Rule 14.3.2.3 RD2 5 Residential Banks Peninsula Zone Rule 14.4.2.3 RD14 6 Residential New Neighbourhood Zone Rule 14.9.2.2 C1 or Rule 14.9.2.3 RD3. Any application arising from this rule in respect to the Enhanced Development Mechanism or the Community Housing Redevelopment Mechanism shall not be limited or publicly notified.	a The Council's discretion is limited to the following matters: i Location, siting and layout, design of buildings, car parking areas, access, services or foundations as they relate to the liquefaction hazard ii Timing, location, scale and nature of earthworks as they relate to the liquefaction hazard iii Liquefaction hazard remediation methods b These restricted discretionary activities will be assessed against the following criteria: i Whether techniques proposed for remediation and mitigation of the effects of any liquefaction hazard identified are appropriate, including but not limited to: A Provision for ground-strengthening, foundation design, and provision of resilient services B Setbacks in relation to any waterway or waterbody, or any sharp change in ground elevation, sloping ground or free-face. Alternatively, whether ground-strengthening or other proposed engineering or geotechnical solutions are identified to address any identified potential for lateral spread. ii The extent to which the siting and layout of the proposal is appropriate, including the proposed location of buildings, earthworks, car-parking areas, servicing, access and building platforms in relation to the liquefaction hazards identified.

The Waimakiriri District Plan includes information about hazard mapping completed and being carried out by the Council. There is a single rule establishing a permitted activity status with one performance standard in the form of Liquefaction Mitigation Design Standards.

Example: Waimakiriri District Plan

Section 8 Natural hazards

Issue 8.3

Lack of recognition of the potential earthquake hazard and potential consequences of an earthquake.

Objective 8.3.1

Increase Council and community understanding of the earthquake risk and associated natural hazard.

Policy 8.3.1.1

Identify areas which are at risk from liquefaction, associated ground damage effects, and amplified ground shaking.

The Council has completed stage one of an Earthquake Hazard Analysis which focused on identifying historical seismicity and active faults (November 1995). This study identified liquefaction and its associated ground damage effects as a potential significant threat to the areas in the east of the District.

Stage two of the Analysis is intended to:

- assess the distribution of sediment susceptible to liquefaction
- identify earthquake intensities likely to promote liquefaction
- identify areas with the potential to liquefy under different intensity earthquakes
- help assess the risks of liquefaction to key lifelines such as water, sewerage, power, telephone, roads and bridges.

Lateral spreading affects areas next to streams, rivers, ponds and the coast where there is low lateral ground support. Surface structures can sink or tilt. Buried structures such as tanks and pipes can 'float' causing connections to break. Deep foundations such as bridge piers can tilt. The Canterbury Regional Council is also working to improve understanding of hazard events in Canterbury and is co-ordinating projects identified in their Regional Policy Statement.

27.1 Permitted activities

Any land use is a permitted activity if it:

i is not otherwise listed as a discretionary (restricted), discretionary or non-complying activity under this chapter

ii complies with the conditions under Rule 27.1.1

iii complies with all the conditions and provisions for permitted activities in all chapters.

27.1.1 Conditions

27.1.1.16 Within the Residential 6, 6A and Business 1 Zones at Pegasus any dwelling house shall be located, designed and constructed in a manner which achieves the standards set out in Table 27.2 below, having regard to the potential for earthquake induced liquefaction of the ground on which the dwellinghouse is to be located, and the potential effects of associated ground settlement and lateral spreading of the ground.

Table 27.2: Liquefaction mitigation design standards

MAXIMUM PERMANENT GROUND MOVEMENT		
Design earthquake return period	**Settlement**	**Lateral movement**
150 years	100 mm	250 mm

F3 Resource consent examples

There are limited examples of conditions from issued consents with detailed requirements relevant to liquefaction. In the box below are examples:

- from a consent issued by Waimakariri District Council for water infrastructure on a site
- for dwellings based on performance requirements that have been incorporated in the Waimakariri District Plan but that could be applied in other situations
- subdivision consent conditions issued by Christchurch City Council which refer to specific foundation design requirements. These conditions make links between geotechnical engineering reports and building consent processes and refer to the MBIE guideline requirements for Canterbury.

Consent issued by Waimakariri District

The water system shall be designed to incorporate resilience to earthquake events. Specifically, where PVC or other socket jointed pipes are used in TC2 equivalent land, then the water reticulation must meet the following requirements unless specifically authorised otherwise, in writing, by the 3 Water Manager of the Council:

a Maximum depth to pipe invert of 1.5 m.

b The water reticulation shall be designed and constructed to withstand an Ultimate Limit Scale (ULS) earthquake event with a Peak Ground Acceleration of 0.35 g with no more than 100 mm vertical deviation and 200 mm of horizontal deviation in any 50 m length of main.

c The water reticulation shall be resilient, and shall incorporate specific resilient design components, including ground improvement where necessary, and the use of non-liquefiable backfill such as compacted AP65 or similar.

d An engineering and geotechnical report shall be prepared and signed by a Chartered Professional Engineer, which shall certify that the design and construction shall achieve the criteria of condition 11.5. This report shall be prepared upon the completion of the works and submitted to Council prior to the issue of the Section 224 (c) certificate.

Example: Dwelling house condition

The dwelling house shall be located, designed and constructed in a manner which achieves the standards set out in the Table below, having regard to the potential for earthquake induced liquefaction of the ground on which the dwelling house is to be located, and the potential effects of associated ground settlement and lateral spreading of the ground.

Table: Liquefaction mitigation design standards

MAXIMUM PERMANENT GROUND MOVEMENT		
Design earthquake return period	**Settlement**	**Lateral movement**
150 years	100 mm	250 mm

Examples: Christchurch subdivision

Specific foundation design:

1 Any structures requiring a Building Consent in terms of Building Act provisions, proposed on Lot 17, Lot 18, Lot 22 to Lot 24, 32 and Lot 54, shall have specific foundation design with consideration given to the effects of lateral spreading.

2 Any structures requiring a Building Consent in terms of the Building Act provisions, proposed on Lots 12–16, 19–21 shall have specific foundation design by a suitably experienced Chartered Engineer or an appropriately qualified Geotechnical Engineer. The foundation design shall take into consideration the MBIE Guideline requirements for the Technical Classification which the final report has applied to the land.

APPENDIX G.
EXAMPLES OF RESILIENT INFRASTRUCTURE DESIGN DETAILS

G1 Modes of failure

The following examples are common observations, and differentiations between different systems.

- Gravity pipelines with shallow grade are vulnerable to development of dips associated with differential settlement that can affect network functionality even where structural damage does not occur.
- Pressurised pipe systems have reduced vulnerability to differential settlement, however exhibit significant reduction or total loss of functionality in the event of even a modest structural failure.
- Even though shallow pipes may be exposed to larger magnitude ground deformations than pipes installed at depth, generally shallow installation is preferential due to significantly improved ease of construction and repair, and associated lower cost.
- Discrete critical infrastructure components such as pump stations require higher levels of seismic performance than the wider distributed network. The importance of such assets can be determined though considering the number of users reliant upon operation of the asset, and the sensitivity of the users in the community (eg hospitals, schools, emergency services).
- Pipe and utility connections to below or above ground structures are vulnerable to damage. Frequently associated with differential vertical settlement, structure rotation, or lateral stretch of the ground. Improving flexibility and ductility of connection details and pipe materials can substantially reduce damage and improve post disaster functionality. In the event that ductile failure reduces the residual life of the connection of level of service is reduced, remediation can be programmed, facilitating a controlled post-disaster recovery.

Assessment of critical infrastructure resilience should consider all network components that influence the level of service experienced by the end user. This may require consideration of components of the wider network that may be owned and/or operated by another party, eg private wastewater laterals. Infrastructure design within multi-unit buildings should consider resilience as described for wider networks above. In addition, improving the ability to access and repair potential earthquake damage should be considered when determining the layout of the infrastructure both connecting to a building and within the structure.

G2 Resilience prioritisation method

The resilience prioritisation method can be summarised into the following key design components:

1. Determine appropriate level of resilience required for the overall asset, and for sub components.
2. Identify geotechnical hazards, infrastructure vulnerability and key failure mechanisms, considering influence on overall seismic performance and impact on post-disaster functionality.
3. Develop engineering solutions to mitigate or limit extent and severity of earthquake damage, commencing with reducing the highest priority risks and vulnerabilities.
4. Consider improvement in performance provided by each design solution and overall value provided. Initial design focus on low-cost/high-value solutions.
5. Check that the completed design satisfies project objectives and resilience requirements.

Gibson, Green, Holmes and Newby (2013) discuss and apply the resilience prioritisation method in designing earthquake resilience into pump station foundations, and demonstrate its application for design of a terminal wastewater pump station.

G3 Infrastructure design principles

Table G1 presents a summary of the design measures implemented by the SCIRT alliance in the repair and replacement of infrastructure damaged by the Canterbury earthquake sequence which would appear to have wider applicability for infrastructure in similarly vulnerable land.

Table G1: Summary of design measures implemented by SCIRT

ASSET TYPE	SUMMARY OF DESIGN EXAMPLES TO IMPROVE RESILIENCE
Wastewater, stormwater and water supply networks	– Standard design details must have an appropriate level of resilience suitable for the majority for the network. Vulnerabilities in standard details can have a cumulative impact over the wider network – Geotechnical hazards were considered when developing wider network strategy. Routes should be adjusted away from greatest geotechnical risks when feasible – Use of flexible and durable materials such as polyethylene – Steepen pipe grades and incorporate more lift stations or pump stations – Consideration of influence of lateral spread and channel heave at pressure main crossings beneath rivers, designing to limit influence of ground deformation – Consider pressure sewer and vacuum sewer wastewater systems which exhibit improved resilience to differential settlement, and the shallow pipes improve the ease of repair compared to the existing deep gravity network
Below ground chambers and pump stations	– Ground improvement or piles to mitigate effects of liquefaction – Resilient foundations to mitigate buoyant uplift and differential seismic settlements though; well graded backfill, extended foundation slab, piles, adding mass, permeable backfills to relieve excess pore pressures or ground improvement – Over-steepening the gravity inlet to accommodate differential settlement of the catchment relative to pump station settlement – Provide flexible pipe and service connections to accommodate differential settlements and ***Minor to Moderate*** lateral stretch – Locate pump stations away from free-faces prone to lateral spread – Uniformity in foundation level and limit eccentric loading – Structural and backfill design to accommodate anticipated soil loadings – Multiple smaller structures distributed in parallel throughout the at risk catchment area can reduce the consequence of failure and enable a faster recovery – Use of horizontal pumps allowed design of robust but lightweight shallow structures designed to maintain functionality with moderate lateral spread and differential settlements. Resilience associated with low cost and ease of repair
Bridges	– Ground improvement at abutments to limit deformation – Design of robust piles to resist lateral spread, accepting damage to approaches
Seawalls and retaining walls	– Use of flexible riprap seawalls to accommodate ***Moderate to Severe*** lateral spread deformation while maintaining coastal protection and low repair costs – New Zealand Building Code requirements controlled retaining wall design

APPENDIX H.
SCOPING AND PROCURING A LIQUEFACTION STUDY

H1 Introduction

The purpose of this appendix is to provide guidance to those who are considering commissioning a liquefaction assessment study. This guidance is primarily focused on the case of a territorial authority undertaking a large-scale liquefaction assessment, however it may also be relevant for other parties (eg those involved in land development).

Liquefaction assessment is a complex and highly specialised undertaking. It is important that the purpose of the work is clearly defined, that it is undertaken by a suitably experienced team, and that it is consistent with current industry practice.

While MBIE has developed guidance for categorising land performance and foundation requirements relating to liquefaction in the Canterbury earthquakes, this guidance is not directly applicable for other parts of New Zealand. Therefore a regional liquefaction assessment will need to consider the specific factors relevant in the local area, rather than simply adopting the Canterbury guidance.

H2 Defining the purpose of the liquefaction assessment

There are various reasons why a territorial authority may wish to undertake a regional liquefaction assessment, including:

- long-term strategic land use planning
- defining requirements for subdivision consent and building consent
- land development or building projects
- facilitating earthquake-prone building assessments
- improving infrastructure and lifeline resilience
- civil defence and emergency management planning
- insurance loss modelling.

It is essential that the practical purpose of the regional liquefaction assessment is clearly defined, as this will govern many aspects of the scope and detail of the technical work that needs to be undertaken. For example, a generic liquefaction hazard map or detailed geological model may be of limited practical use if it not developed with a clear purpose and understanding of how it will be applied.

The necessary level of detail and accuracy of the assessment should be considered. This should take into account how the findings will be used in practice, and the balance between upfront costs of more detailed work compared to longer term costs of a less detailed and potentially more conservative assessment. As part of defining the purpose of the work, the spatial extent of the area to be assessed should also be carefully delineated.

There may be more than one purpose for the liquefaction assessment – in some cases the work required for each purpose may be complementary, but in some cases it may be more effective to consider each as related but separate packages of work.

H3 Communications and stakeholder engagement

There can often be significant community interest in regional hazard studies, as a wide range of people and organisations may be affected by the findings. Stakeholders to consider include:

- residential and commercial property owners
- council consent officers and land use planners
- infrastructure owners
- land developers
- technical practitioners such as engineers, geologists, architects and builders
- insurance companies.

There are a number of project stages where engagement with stakeholders may be useful:

- defining and communicating the purpose of the liquefaction assessment
- agreeing the deliverables from the work and how they will be used in practice
- collating historic information (eg history of land development, observations from previous earthquakes, and existing geotechnical investigation data)
- communicating the findings of the assessment, what they mean for individual property owners, and how they will be implemented for future policy, planning and consenting.

H4 Selecting a project team

H4.1 Specialist expertise

Selecting the right team for a regional liquefaction assessment is vital. Specialist expertise is required in the fields of seismic hazard, geology, geohydrology and earthquake geotechnical engineering. This may dictate that a multi-disciplinary team is engaged under one lead consultant to deliver the services.

Natural hazard assessment can have a significant impact on many stakeholders, and may be subject to legal challenge when incorporated into planning or consenting rules. Therefore it is important to select a technically credible project team, and in many cases it can be beneficial for the team to include nationally or internationally recognised experts.

In many cases, depending on the purpose of the liquefaction assessment, specific analysis of liquefaction and its effect on buildings and infrastructure may be required. This is highly specialised engineering work, and should be carefully overseen by a Chartered Professional Engineer (CPEng.) with competence and proven track record in earthquake geotechnical engineering.

H4.2 Procurement

Many territorial authorities will follow a tendering process for service procurement. It may be beneficial to prequalify potential providers via an Expression of Interest (EIO) process. The response to the EOI would normally be a brief document (approximately 2–5 pages), sufficient to demonstrate the capability to carry out the work. Shortlisted teams would then prepare a full tender submission (approximately 3–15 pages) to provide detail on their proposed methodology and budget.

For very simple liquefaction assessments based on broad regional geology, a full EOI and tender process may not be necessary. For larger or more complex assessments, a rigorous tendering and review process may be essential to the success of the project. The cost of tender submission and evaluation is a significant industry and client overhead, so it is important that that the procurement process is appropriate to the level of the project.

H4.3 Team selection criteria and weightings

It is important that the scope of work or services included in the tender documents contains sufficient detail to support proper evaluation and pricing. The RFP must be clear on what criteria will be used to evaluate the tender. It is recommended that this include the following non price criteria:

- relevant expertise and competence (both of the lead consultant and any sub-consultants)
- methodology
- resources (including Intellectual Property)
- track record (relevant projects).

Optionally, price may be included as one of the criteria but it is recommended the weighting on the price component as low as practically possible, and ideally less than 20 percent. The nature of the work is very specialised, and great care is required to ensure that the assessment is technically robust and useful in practice. Selection based primarily on lowest consultant price may compromise the practical usefulness of the work, and result in delays and greater costs in the long-term.

Due to the specialist nature of the task it is recommended the tender evaluation panel include an expert in the field of liquefaction assessment where possible, to advise on the technical expertise and proposed scope of work of potential providers.

H4.4 Forms of contract

IPENZ has worked with other industry and government agencies to develop standard forms of contract for consultancy services – refer to http://www.ipenz.org.nz/IPENZ/Engineering_Practice/Conditions_of_Contract.cfm

For regional liquefaction assessment work it is recommended that the IPENZ standard 'Short Form Agreement' or 'Long Form Contract' (also known as CCCS) be used. These contracts have been developed specifically for technical consulting services – so they cover this type of work better than more general forms of contract that may be used for other types of procurement, are well understood and accepted by the industry, and have established legal precedent for this application. Use of non-standard forms of contract or excessive special conditions should be avoided, as these may affect the availability and cost of professional indemnity insurance and have other negative overall impacts on the project.

H4.5 Information provided by the client

The Request for Proposal (RFP) should provide details of relevant information held by the Territorial Authority that can be made available for the project. This could include:

- previous liquefaction or seismic hazard studies undertaken in the region
- groundwater level monitoring
- LiDAR ground elevation survey
- existing geotechnical investigation data
- information about damage caused by historic earthquakes in the region.

The RFP should include at least a broad indication of the client budget for the project, as this will help to ensure that the scope of work and client objectives are aligned with the financial constraints.

H4.6 Peer review and collaboration

Given the complexities and uncertainties inherent in liquefaction assessment, and the rapidly advancing state of scientific knowledge in this field, the involvement of independent peer reviewers is recommended.

Peer review is most useful as an ongoing collaborative process while the work is being scoped and undertaken, rather than simply a review of the final end product. As a minimum, collaboration with peer reviewers is recommended at the following stages of the project:

- defining the purpose of the regional liquefaction assessment
- finalising the agreed scope of work and deliverables for the project
- planning new ground investigations
- development of key findings from the liquefaction assessment
- final reporting.

Peer review requirements will vary depending on the scope and scale of the project – ranging from an individual reviewer with recognised liquefaction assessment expertise in the local area, to a review panel of several national or international experts covering a range of specialist fields. It will usually be most appropriate for peer reviewers to be engaged directly by the client.

H5 Determining the scope of technical work

H5.1 Items of work required

It is typically not necessary for the RFP to include a detailed scope of the technical work required. If the RFP outlines the purpose of the work, the information already available and gives a broad indication of available funding then prospective consultants will be able to draw on their experience to prepare a corresponding scope of technical work for their offer of service.

The following items of work will often be required as part of the technical scope, depending on the purpose of the regional liquefaction assessment:

- **Geology and geomorphology**
  This may include broad geological mapping and interpretation of air photos and LiDAR ground elevation survey, to understand the types of soil present and how they have been deposited.
- **Seismic hazard**
  For liquefaction assessment it is important to consider a range of earthquake return periods, and to determine representative combinations of earthquake magnitude and peak ground acceleration (PGA) for analysis.
- **Geotechnical investigations and laboratory testing**
  This may include collation of existing data, and new ground investigations targeted at the specific requirements of the project.
- **Groundwater levels**
  This information is very important for most types of regional liquefaction assessment studies, as soil will not liquefy unless it is saturated. In some cases it will be important to understand how groundwater levels fluctuate between seasons and from year to year.
- **Liquefaction susceptibility**
  This is a fundamental physical characteristic of the soil that describes how it responds to earthquake shaking. It is important to understand the basic susceptibility of the soil before undertaking more complex liquefaction analysis. Laboratory testing of soil samples is often necessary to assess liquefaction susceptibility.

- **Liquefaction triggering**
  This describes the strength of shaking required to liquefy susceptible soils. It is often assessed using ground investigation data such as CPT and SPT test results.
- **Liquefaction consequences and vulnerability**
  The triggering of liquefaction does not necessary result in damaging consequences, there are a range of factors that can influence how significant the effects are. In many situations, the most damaging effects of liquefaction relate to differential ground settlement and lateral spreading (horizontal stretching of the ground). Liquefaction vulnerability describes the severity or likelihood of damaging consequences resulting from liquefaction.

When scoping the project, it is important to keep the final purpose of the regional liquefaction assessment in mind. The effort expended on each item of work should be appropriate within the overall context and scale of the project, taking into account the level of detail and uncertainties in the other parts of the liquefaction assessment and how the results will be used in practice. For example, there may be little additional value in detailed analysis of the soil profile or the seismic hazard if there is only limited information about groundwater levels or liquefaction susceptibility (and vice-versa).

H5.2 New geotechnical investigations

The accuracy and detail it is possible to achieve in a liquefaction assessment will be partly dependent on the quality and spatial distribution of the available geotechnical investigation data. In cases where the intended purpose of the liquefaction assessment is to provide detailed or more accurate information on a specific area, it may be necessary to undertake new ground investigations to provide the required input data.

However, for broad-scale regional studies it may not be necessary or appropriate to undertake new geotechnical investigations, as basic geological mapping and 'ground-truthing' can provide much of the necessary information. Any decision to invest in new investigations should carefully balance the cost of the work with the practical benefits of the additional data, and be targeted to provide greatest value.

It is recommended that the cost of any new geotechnical investigations is kept separate from the consultant fees. In some cases, a separate workstream may be established to undertake these investigations. However, the scope of any new geotechnical investigations should be directed by the consultant team, with peer review input.

New geotechnical investigations should not commence until after the initial phases of the liquefaction assessment have been undertaken, as the findings of this early desktop work will help to define the locations where investigations are of greatest value, the information that needs to be collected in the field and any laboratory testing that may help refine the assessment.

It is crucial that geotechnical testing such as CPT, SPT and laboratory testing is undertaken in accordance with the relevant standards, with a focus on collecting quality information. NZGS (2016b) provides guidance on good practice when scoping and undertaking geotechnical investigations for earthquake engineering purposes.

H6 Deliverables

The proposed deliverables should be agreed at the start of the project, with peer review input.

Careful thought is required to ensure that the proposed deliverables will be effective for the desired purpose. It may be beneficial to consult with those who will be making use of the work or will be affected by the findings, as outlined in Section 18.3. There may also be value in liaising with other territorial authorities and nationwide organisations such as MBIE and the NZ Geotechnical Society, to provide consistency with work undertaken elsewhere across the country.

Depending on the purpose of the regional liquefaction assessment, some of the following deliverables may be required:

- geological or geomorphic maps – broad-scale mapping provides useful background information, however as liquefiable soils are typically highly variable, complex soil models (eg interpolated 3D models) are unlikely to be of significant practical value for practitioners undertaking site-specific liquefaction assessments
- recommended combinations of earthquake magnitude and PGA for liquefaction analysis
- geotechnical investigations and lab testing uploaded to the NZ Geotechnical Database
- maps of groundwater levels
- report detailing the assessment of liquefaction susceptibility, triggering, and consequences, plus assumptions made, sensitivity analyses undertaken and limitations of the study
- maps showing the liquefaction vulnerability categories assigned
- maps summarising the severity or likelihood of damaging consequences from liquefaction for various earthquake scenarios
- resources to assist in communicating the findings of the assessment to stakeholders and the public, such as simple non-technical factsheets and summary maps.

H7 Resources and contacts

The following resources may be of interest to those considering commissioning a regional liquefaction assessment study:

- MBIE guidance: *Repairing and rebuilding houses affected by the Canterbury earthquakes*
  http://www.building.govt.nz/guidance-on-repairs-after-earthquake
- Environment Canterbury – 'Liquefaction information'
  http://www.ecan.govt.nz/advice/emergencies-and-hazard/earthquakes/Pages/liquefaction-information.aspx
- NZGS/MBIE guideline on *Earthquake Geotechnical Engineering Practice – Module 3: Identification, assessment and mitigation of liquefaction hazards*
  http://www.nzgs.org/library/earthquake-geotechnical-engineering-module-3-liquefaction-hazards/
- US Geological Survey – 'About liquefaction'
  http://geomaps.wr.usgs.gov/sfgeo/liquefaction/aboutliq.html
- California Geological Survey – *Guidelines for evaluating and mitigating seismic hazards in California*
  http://www.conservation.ca.gov/cgs/shzp/webdocs/sp117.pdf

Regional liquefaction assessments are a specialised undertaking, and it can be challenging to determine the scope of work and assemble the project team. There are several organisations that may be able to provide guidance to territorial authorities embarking on this work:

- MBIE – Building Systems Performance Branch
  http://www.building.govt.nz/
  https://www.building.govt.nz/about-building-performance/contact-us/
- NZGS
  http://www.nzgs.org
- EQC – Research and Education Programmes
  http://www.eqc.govt.nz/what-we-do
  http://www.eqc.govt.nz/contact-us

APPENDIX I. EXAMPLE METHODOLOGY FOR QUANTITATIVE ESTIMATE OF LIQUEFACTION-INDUCED LAND DAMAGE

This appendix is currently under development, and will be issued as part of the finalised guidance document.

It will provide an example of using a liquefaction vulnerability parameter to estimate the likelihood of various degrees of land damage occurring at different levels of earthquake shaking. This example will use LSN, but similar approaches could be developed for other vulnerability parameters. It will consider the distributions of observed damage, and compare these to the target levels of certainty. It will identify LSN values which can be used to distinguish between ***None to Minor***, ***Minor to Moderate***, and ***Moderate to Severe*** damage when applying the performance criteria.

The team developing this guidance are interested in any technical feedback from the profession regarding liquefaction vulnerability calculation methodologies that are currently being applied in practice for categorisation of liquefaction-related risk to inform planning processes.

Please get in touch by email to engineering@mbie.govt.nz or contact the technical team directly (refer to inside cover for details).

APPENDIX J.
DETAILED ASSESSMENT OF GROUND DAMAGE RESPONSE IN PRACTICE

J1 Managing uncertainty in the liquefaction vulnerability categorisation

As with most fields of engineering, because of the significant uncertainties involved in predicting liquefaction-induced ground damage, a liquefaction assessment will sometimes over-predict or under-predict the true liquefaction vulnerability. It is important to understand the consequences of these mispredictions when setting the performance criteria for liquefaction categorisation.

Table J1 presents an indicative comparison of the relative costs of over-predicting and under-predicting liquefaction vulnerability for typical buildings and infrastructure. It also demonstrates that over-prediction costs are incurred up-front, while under-prediction costs are only incurred at some time in the future when sufficiently strong earthquake shaking occurs.

The consequences of mispredictions were taken into account when defining the performance criteria recommended in Section 4.5 to distinguish between liquefaction vulnerability categories.

Table J1: Indicative comparison of the relative costs of over-predicting and under-predicting liquefaction vulnerability for typical buildings and infrastructure

Predicted liquefaction vulnerability	Actual liquefaction vulnerability: Very Low	Low	Medium	High
Very Low	Correct prediction	No material change in damage	Major increase in damage if EQ occurs	Major increase in damage if EQ occurs
Low	No material change in costs	Correct prediction	Major increase in damage if EQ occurs	Major increase in damage if EQ occurs
Medium	Minor increase in up-front cost	Minor increase in up-front cost	Correct prediction	Slight increase in damage if EQ occurs
High	Major increase in up-front cost	Major increase in up-front cost	Major increase in up-front cost	Correct prediction

Under-prediction of vulnerability

Over-prediction of vulnerability

Note:
This table makes the following assumptions:

- There is a low incremental cost to upgrade from a low-resilience engineering solution to a moderate-resilience option (eg upgrading from a thin concrete slab foundation to a waffle-slab foundation).
- There is a high incremental cost to upgrade from a moderate-resilience engineering solution to a high-resilience option (eg upgrading from a waffle-slab foundation to a piled foundation, plus associated ground investigation and specific engineering design costs).
- A low-resilience engineering solution will usually perform poorly when subjected to ***Minor to Moderate*** liquefaction-induced ground damage, resulting in substantial damage.
- A moderate-resilience engineering solution will often provide reasonable performance even when subjected to ***Moderate to Severe*** liquefaction-induced ground damage, limiting the resulting damage.

When attempting to distinguish between ***Low*** and ***Medium*** liquefaction vulnerability:

- There is a low cost for over-prediction; a minor increase in up-front cost for moderate-resilience construction when low-resilience construction would have been sufficient.
- There is a high cost for under-prediction; a major increase in damage if liquefaction occurs and low-resilience construction was adopted when moderate-resilience was needed.
- Therefore in this situation it is likely to be preferable to err on the higher side when assigning the liquefaction vulnerability category. This is the reason that 85 percent confidence is specified in Table 4.4 for assigning a ***Low*** category.

When attempting to distinguish between ***Medium*** and ***High*** liquefaction vulnerability:

- There is a high cost for over-prediction; a major increase in up-front cost for ground investigations, specific engineering design and highly resilient construction, when moderate-resilience construction would have been sufficient.
- There is a low cost for under-prediction; a minor increase in damage if an earthquake occurs and moderate-resilience construction was adopted when high-resilience was needed.
- Therefore in this situation it is likely to be preferable to err on the lower side when assigning the liquefaction vulnerability category. This is the reason that 50 percent confidence is specified in Table 4.4 for assigning a ***Medium*** category.

J2 Use of less precise categories to represent uncertainty in the assessment

A guiding principle of this framework is that land should only be assigned one of the more precise liquefaction categories (ie ***Very Low***, ***Low***, ***Medium*** or ***High***) when there is sufficient certainty that it is the appropriate category (refer Table 4.4). If there is insufficient certainty it should be assigned one of the less precise categories (***Liquefaction Category is Undetermined***, ***Liquefaction Damage is Unlikely***, or ***Liquefaction Damage is Possible***), awaiting more detailed assessment and recategorisation in future if the need arises.

This may be different to the way that many engineers approach a liquefaction analysis. Engineers are typically most accustomed to working in a traditional design situation, where it is usually necessary to choose specific values for parameters to complete the work. If there is uncertainty, it is often necessary and appropriate to select conservative parameters (ie parameters that give a less favourable design outcome).

However, when undertaking a liquefaction assessment to inform planning processes, it is often not necessary to determine a specific liquefaction category. For many purposes, it will be sufficient to determine whether ***Liquefaction Damage is Unlikely*** (in which case one set of planning rules would apply) or ***Liquefaction Damage is Possible*** (in which case a different set of planning rules would apply). It is only necessary to determine a specific category when the intended purpose requires this higher level of detail (eg subdivision design or building design).

The purpose of the planning rules assigned in each case would be to direct that this more detailed assessment is undertaken when required, and any liquefaction issues identified are appropriately managed. Furthermore, assigning a less favourable category 'just to be safe' can be counterproductive. It can result in significant opportunity costs, and also undermine the scientific credibility of the assessment by appearing to over-extrapolate or misrepresent the technical information.

In summary, when undertaking a liquefaction assessment to inform planning, consenting and other decision-making, it is appropriate to take a suitably cautious approach when assigning liquefaction vulnerability categories. But this shouldn't mean simply assuming the worst when there is uncertainty. A more appropriate way to apply caution is for the assessment to acknowledge that the uncertainty exists and clearly communicate this, along with the potential consequences. The uncertainty can be communicated by using one of the less precise liquefaction categories, and by explaining the uncertainty in the liquefaction assessment report and in the metadata accompanying the liquefaction vulnerability category map (refer Appendix E). Planning rules can then be used to require that more detailed assessment is undertaken when necessary in future.

J3 Limited number of points on the response curve

In practice the extent to which it is possible to define a liquefaction-induced ground damage curve will depend on the level of detail in the information used for the assessment (refer Table 3.2).

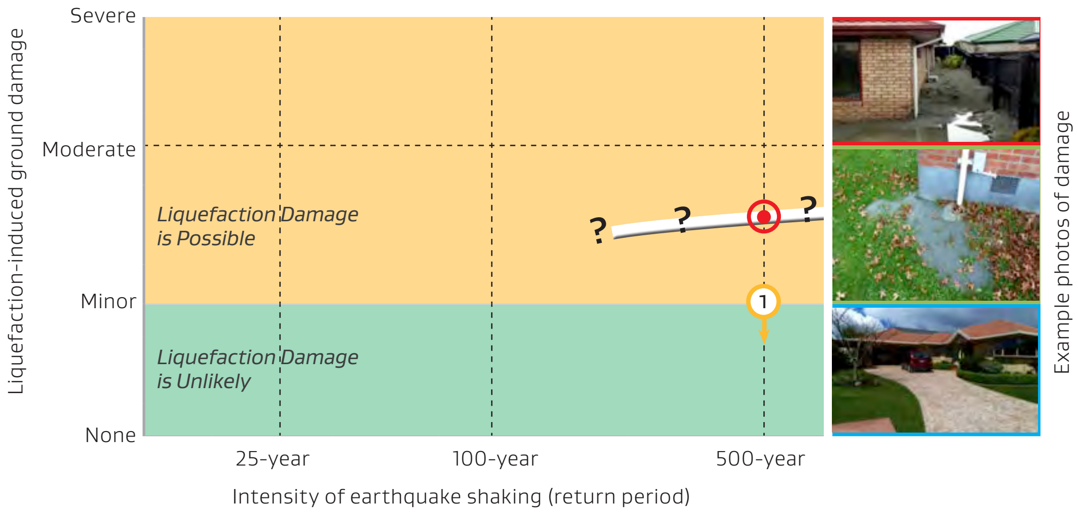
For a ***Basic Desktop Assessment*** (***Level A***) it is generally only possible to evaluate (in a simplified manner) whether or not liquefaction could be triggered in a large earthquake. The information used for the assessment is unlikely to allow prediction of the degree of ground damage if liquefaction were triggered, or the intensity of shaking required to trigger liquefaction. Therefore for ***Level A*** assessments it is generally only possible to evaluate the first of the three performance criteria identified in Figure 4.3 (ie whether less than ***Minor*** ground damage is expected at 500-year intensity of shaking). A similar limitation might also be encountered for a ***Calibrated Desktop Assessment*** (***Level B***), depending on the information available and the type of analysis undertaken for the calibration.

This situation is illustrated in Figure J1. In this example there is enough information to identify land where ***Liquefaction Damage is Unlikely*** in large earthquakes, and where ***Liquefaction Damage is Possible***. There is insufficient information about the degree of ground damage in smaller or larger earthquakes to allow a more precise liquefaction category to be assigned (eg to distinguish between ***Medium*** and ***High*** liquefaction vulnerability).

Nonetheless, in some situations it may be possible to assign one of the more precise liquefaction categories based on a ***Level A*** or ***Level B*** assessment, for example:

- In cases where the land is simply not susceptible to liquefaction (eg exposed bedrock) there may be sufficient certainty to categorise an area as ***Very Low***.
- In cases where severe damage is expected at 500-year intensity of shaking there may be sufficient certainty to categorise an area as ***High*** (eg a deep and loose estuarine deposit with high water table and potential for lateral spreading, in an area with high seismicity).

Figure J1: Conceptual example of partial ground damage response curve determined from a Level A assessment – in this example Liquefaction Damage is Possible



Performance criteria for liquefaction categorisation

1 If less than ***Minor*** ground damage at 500-year level of shaking then ***Liquefaction Damage is Unlikely***, otherwise, ***Liquefaction Damage is Possible***

Point on the response curve that would be identified from assessment of the minimum earthquake scenario (500-year)

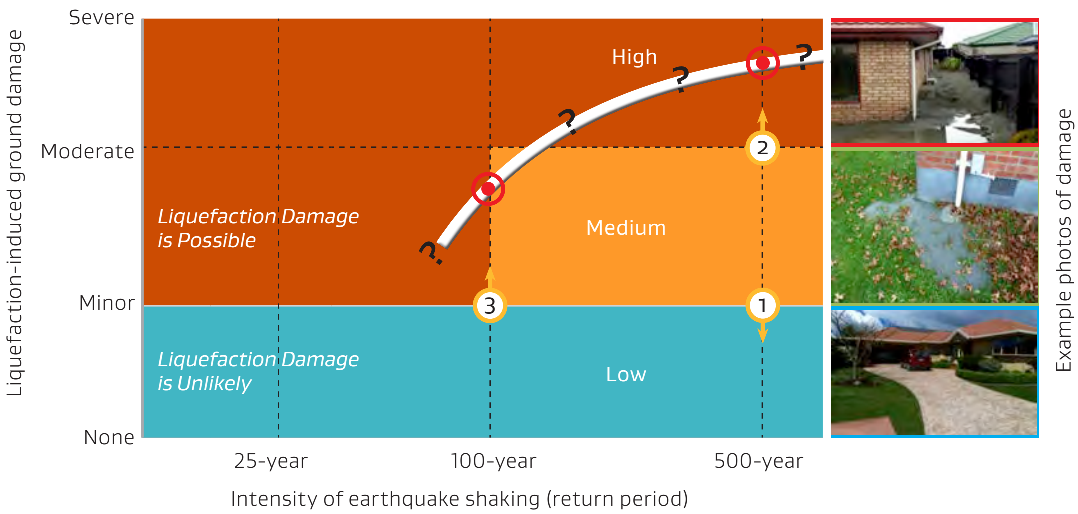
? Remainder of the response curve would often be unknown in practice

Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

For more detailed assessments (typically ***Level C*** and ***Level D***, but sometimes also ***Level B***) the inclusion of subsurface ground investigation information means that quantitative liquefaction vulnerability analysis can be undertaken. This allows assessment of the degree of liquefaction-induced ground damage and the intensity of earthquake shaking required to cause significant liquefaction damage, so it is now possible to evaluate all three of the performance criteria identified in Figure 4.3.

This situation is illustrated in Figure J2, demonstrating that there is now sufficient information about the ground damage response curve to distinguish between ***Low***, ***Medium*** and ***High*** categories.

Figure J2: Conceptual example of partial ground damage response curve determined from a Level C or Level D assessment, for high liquefaction vulnerability category



Performance criteria for liquefaction categorisation

Select the highest category from these three criteria, if none apply then the liquefaction vulnerability category is ***Medium***

1. If less than ***Minor*** ground damage at 500-year level of shaking then the liquefaction vulnerability category is ***Low***
2. If more than ***Moderate*** ground damage at 500-year level of shaking then the liquefaction vulnerability category is ***High***
3. If more than ***Minor*** ground damage at 100-year level of shaking then the liquefaction vulnerability category is ***High***

Point on the response curve that would be identified from assessment of the minimum earthquake scenarios (100-year and 500-year)

? Remainder of the response curve would often be unknown in practice

Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

J4 Variability in the response curves across a particular area of land

Soil deposits are naturally variable, particularly the alluvial soils common around New Zealand where liquefaction is of particular concern. Therefore there will be variations in the ground damage response even across short distances. This poses a challenge for liquefaction assessment, where a particular category needs to be assigned to some defined area of land based on subsurface data from a limited number of discrete point locations.

Figure J3 provides an example of what this might look like in practice for a ***Level C*** or ***Level D*** assessment, for 10 CPT tests distributed across a small area of similar geology and geomorphology. Unlike the simple conceptual examples provided above, these ground damage response curves do not all follow a single well-defined path. If the performance criteria in Figure 4.3 were used to categorise these 10 CPT tests:

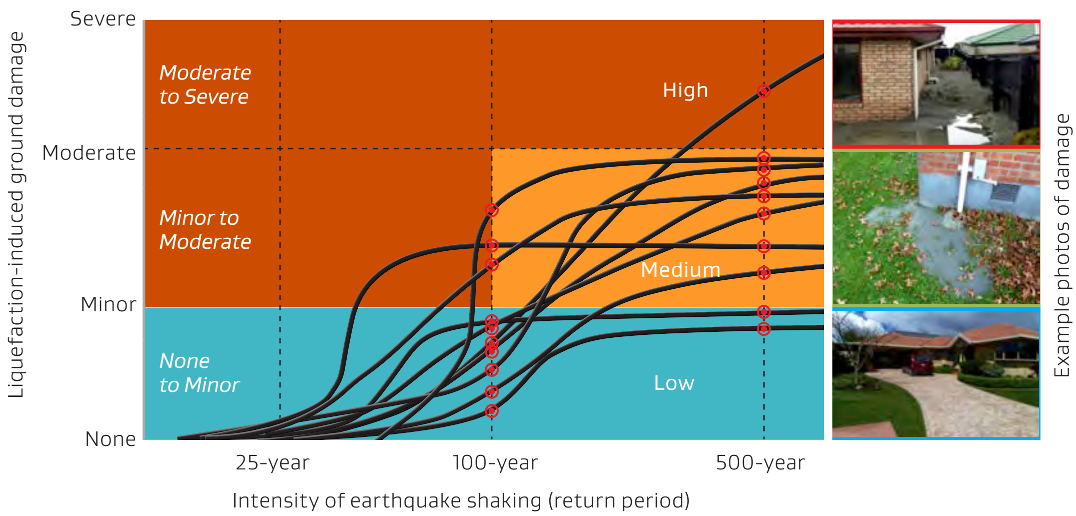
- four would be ***High***
- four would be ***Medium***
- two would be ***Low***.

To further complicate the assessment, the full response curves would not be known, only the points on the curve for the two earthquake scenarios analysed (100-year and 500-year).

In this situation further assessment may be required before specific liquefaction categories can be assigned to the area, such as:

- Subdividing the area into separate sub-areas with more similar responses, and assigning different liquefaction categories to each. This may require additional ground investigations to better define the boundaries between sub-areas.

Figure J3: Conceptual example of the range of ground damage response curves for a Level C or Level D assessment of 10 CPT tests distributed across a small area of similar geology and geomorphology



Points on the response curve that would be identified from assessment of the minimum earthquake scenarios (100-year and 500-year). The remainder of the response curves would often be unknown in practice.

Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

- Analysing additional earthquake scenarios for some or all of the CPT tests to better understand the shape of the ground damage response curve.
- Considering whether it would be appropriate to neglect outliers when assessing the data, such as by excluding specific data for a particular reason or taking an 85th percentile envelope of the response curves. Whether or not this will be appropriate will depend on many factors, such as the detail, scale and purpose of the assessment, the statistical basis of the liquefaction vulnerability analysis methodology used, or an understanding of the variability and uncertainties inherent in the ground conditions and analysis.
- Undertaking a comprehensive probabilistic assessment of the likelihood of different degrees of ground damage. For example by taking specific account of the uncertainty in key parameters (such as groundwater level, earthquake shaking, liquefaction triggering and damage correlations) to better understand the overall distribution of the resulting ground damage.
- Applying judgement, informed by both engineering and planning considerations, to determine whether it would be appropriate to 'lean one way or the other' given the specific details of the situation. This could include considerations such as the following:
  - The risks and uncertainties associated with the depositional processes in the area.
  - Evidence that the severity of land damage is often under or over-predicted for the particular ground conditions in the area.
  - The degree of uncertainty in the base information used for the assessment, and how this influences the distribution of uncertainty in the overall prediction of damage.
  - The purpose and level of detail of the liquefaction assessment.
  - Any proposed planning or consenting controls that might mitigate risks of incorrectly categorising the land.

As an alternative to undertaking further assessment, or if this further work is not conclusive, then the land could be categorised as ***Liquefaction Damage Is Possible***, awaiting more detailed assessment in future if the need arises.

J5 Uncertainty in predicting the degree of ground damage that could occur

All else being equal, the level of uncertainty associated with a liquefaction assessment should decrease as the amount of knowledge about the soil conditions, ground water conditions and intensity of earthquake shaking increase.

The intensity of ground shaking that occurs at a site during an earthquake is dependent on several factors (eg the travel path from the fault rupture and the cyclic response of the local soil profile) so will likely vary across a region. However, for typical design of structures and liquefaction assessment, it is common to assume that the intensity of shaking is constant across a relatively large area. The soil and groundwater conditions (ie geotechnical conditions) across that same area may vary widely, and such differences may have a significant impact on the liquefaction potential from one location to the next.

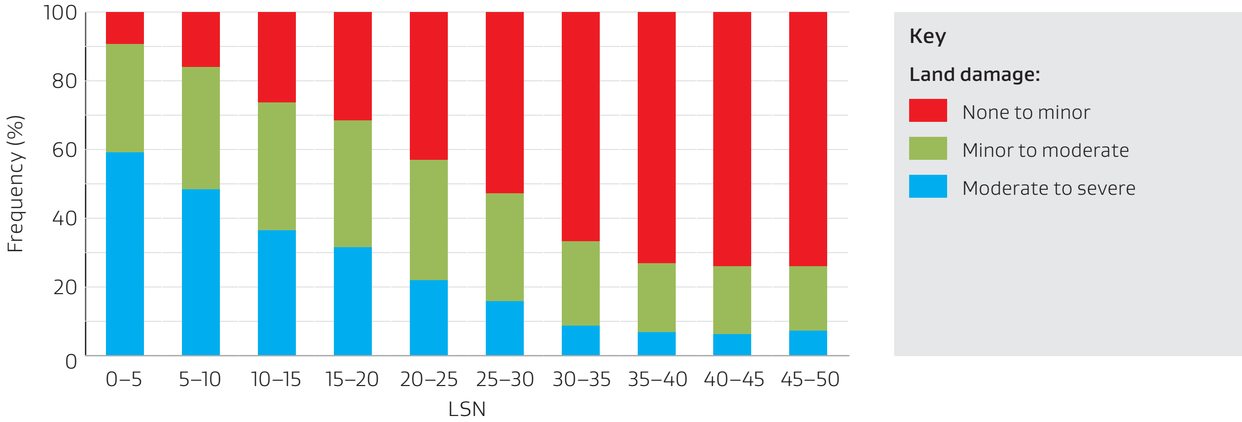
For a regional or city-wide liquefaction assessment where detailed geotechnical information across the entire area may not be available, the level of uncertainty associated with the assessment will likely be high. In this case, the land categorisation should acknowledge the uncertainty by incorporating an appropriate level of conservatism. Conversely, in areas where the geological and geotechnical conditions are well defined, the level of uncertainty will be lower and hence the level of conservatism in the land categorisation can be lower.

Figure J4 provides an example from the Canterbury earthquakes of the effect that these various uncertainties have on the ability to predict the degree of liquefaction-induced ground damage that could occur. In this example a particular calculated value for a liquefaction vulnerability parameter (LSN in this case) does not provide a unique correlation to a specific degree of land damage. Instead, as the LSN value increases the likelihood of a more severe degree of damage increases and the likelihood of a less severe degree of damage decreases.

Figure J5 provides a conceptual example of the effect of the uncertainties associated with a liquefaction assessment. Reducing uncertainty in the assessment results in a narrower distribution liquefaction-induced ground damage, so it is possible to predict the degree of damage with a higher level of confidence.

It is also important to understand how changes in uncertainty can affect threshold values used for evaluating the performance criteria for categorisation of land. In the example in Figure J5, part of the reduction in uncertainty was due to correction of a systematic under-prediction of ground damage for a particular soil type. This resulted in a shift to the right of the thresholds for distinguishing between ***Medium*** and ***High*** liquefaction categories (50 percent probability of ground damage being more than minor at 100-year or more than moderate at 500-year). This emphasises the need to recalibrate the correlations used as part of the liquefaction assessment whenever there is a significant change in the analysis methodology.

Figure J4: Frequency bar chart showing the likelihood of None to Minor, Minor to Moderate and Moderate to Severe land damage for different LSN bands based on correlated back calculated LSN values with the land damage observations from the September 2010, February 2011 and June 2011 earthquakes in Canterbury (Tonkin + Taylor, 2015)

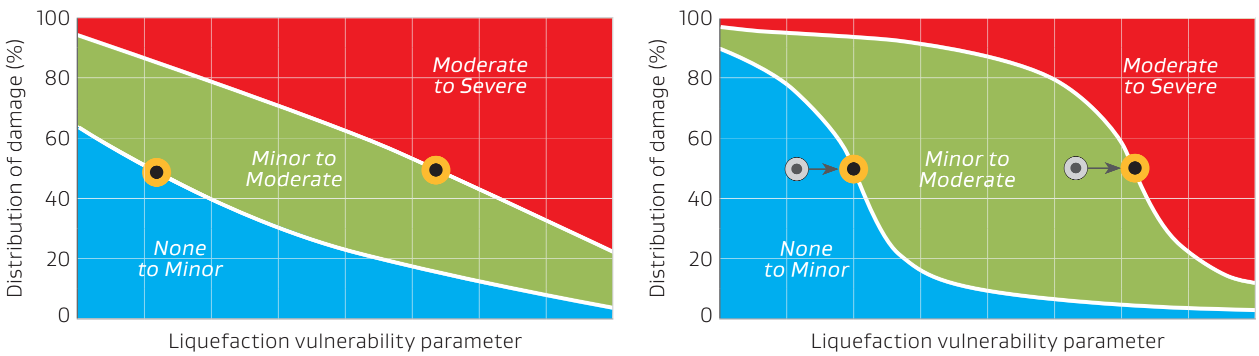


Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

Figure J5: Conceptual example demonstrating how reducing the uncertainties in a liquefaction assessment increases the level of confidence in predicting the degree of liquefaction-induced ground damage

a **Ground damage, with larger uncertainty** – thresholds distinguishing between ***Medium*** and ***High*** liquefaction categories (50 percent probability of ground damage being more than minor at 100-year or more than moderate at 500-year)

b **Ground damage, with smaller uncertainty** – resulting in a narrower distribution of damage and a shift of the threshold positions; threshold positions from the previous example



Refer to Section 2.5 for details about the different degrees of liquefaction-induced ground damage.

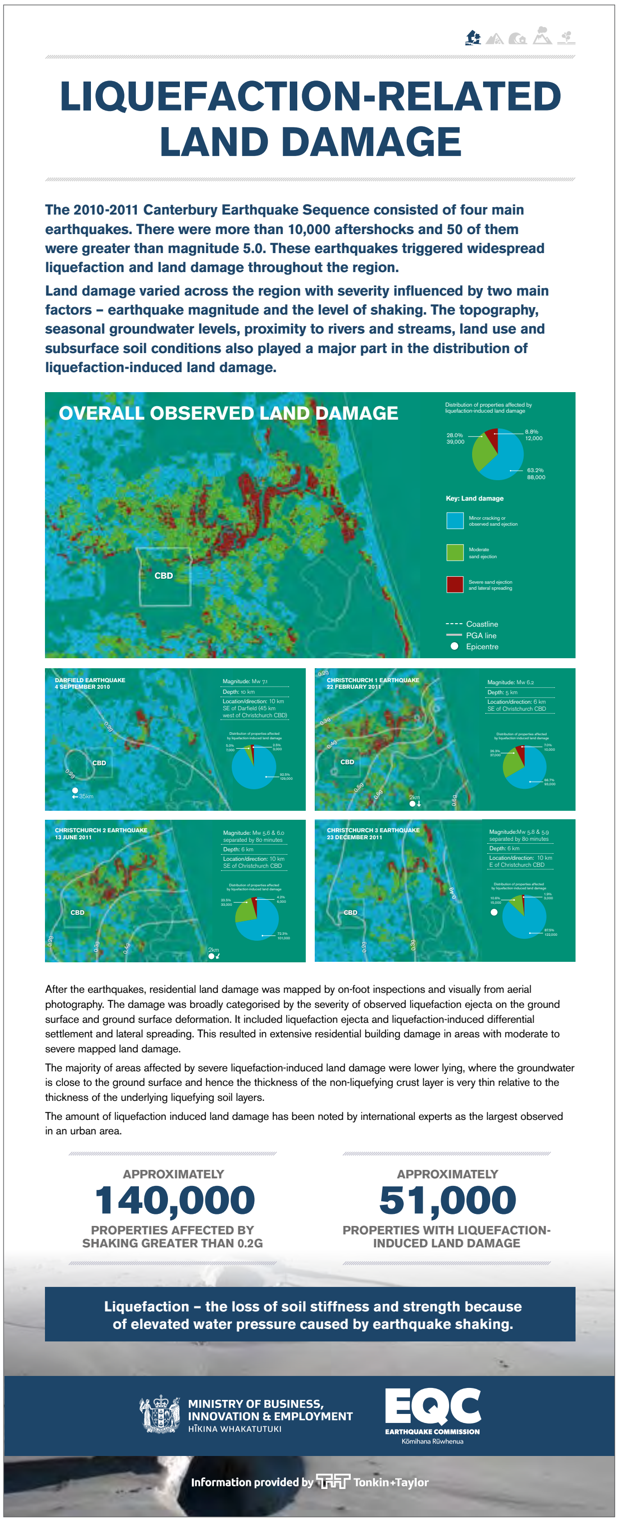
APPENDIX K. CASE STUDIES OF THE CONSEQUENCES OF LIQUEFACTION IN THE CANTERBURY EARTHQUAKES

When implementing a risk-based process to manage liquefaction-related risk it can be useful to refer to case studies of the consequences of liquefaction in previous earthquakes. This might be particularly relevant during the risk evaluation stage to develop an understanding of the consequences and the merits of various risk treatment options, and as part of communication and consultation.

The following pages present a series of posters jointly developed by EQC and MBIE to provide simple case studies of the consequences of liquefaction in the Canterbury earthquakes, and some of the initiatives that have been implemented to gather information about liquefaction.

These posters cover a range of topics:

- liquefaction-related land damage
- lateral spreading
- foundation damage
- localised ground surface changes
- ground surface subsidence
- rconomic impact of liquefaction
- a wealth of data
- the power of shared data
- paleoliquefaction.

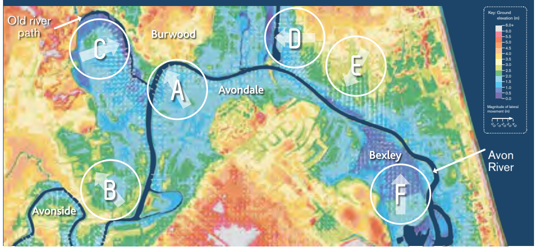


High-resolution versions of these posters are available at http://www.eqrecoverylearning.org/search/site?aut=Earthquake+Commission

LATERAL SPREADING

Horizontal ground movements related to liquefaction occurred across greater Christchurch following the 2010-2011 Canterbury Earthquake Sequence. Information including aerial LiDAR and aerial photograph imagery helped evaluate the extent and magnitude of horizontal movements caused by the earthquakes.

LATERAL SPREADING DIRECTION MAP



A EXPECTED OBSERVATIONS
Lateral spreading is movement towards a free face such as a river, stream, channel or dip where the land is not physically constrained. As the soils liquefy from earthquake shaking, tension cracks develop as the land moves towards the free face.

B COUNTER-INTUITIVE DIRECTION
Lateral spreading has occurred in a direction away from the free faces in some areas of Christchurch. Land moves in the direction of least resistance and this is not always obvious from ground cracking observations in the field. Thorough analysis of datasets must be undertaken before mitigation works are commenced.

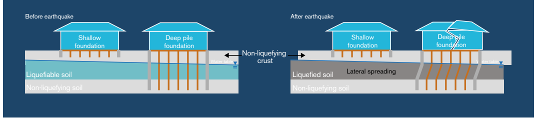
C DOWNSLOPE SLIDING OF LAND
Sliding deformation was observed where there are two free faces in an area but the ground does not displace towards the nearest free face. Instead the ground mainly displaces in a downslope direction.

D DRAINS
Horizontal land movement occurred towards drains that consequently exacerbated land and building damage on adjacent properties. These drains were constructed to manage stormwater runoff from new developments but as a result compromised the land integrity, which resulted in greater than predicted liquefaction damage.

E GENTLY-SLOPING LAND
Gently-sloping land can laterally spread. This type of lateral spreading in Canterbury caused only minor damage to properties, however this can have major consequences on some types of foundations and infrastructure networks.

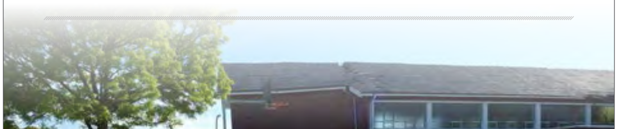
F ELEVATED LAND
Some recently developed suburbs were raised to manage the effects of sea level rise and flooding. This caused significant lateral spreading towards land that was not raised, increasing liquefaction related damage across communities.

FOUNDATIONS IN LATERAL SPREADING AREAS



Deep pile foundations are readily recommended in Canterbury because of their resilience to damage from liquefaction related subsidence, but may be unsuitable in regions susceptible to lateral spreading. In creating a built environment that interacts appropriately with the land consideration of planning, engineering, infrastructure and development solutions need to have an integrated approach to disaster risk management by matching residential building construction to all the likely hazards.

Integrated approach to risk management by matching building construction to all the likely hazards



MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

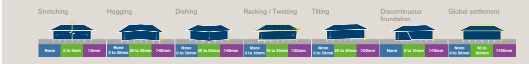
EQC
EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

Information provided by Tonkin+Taylor

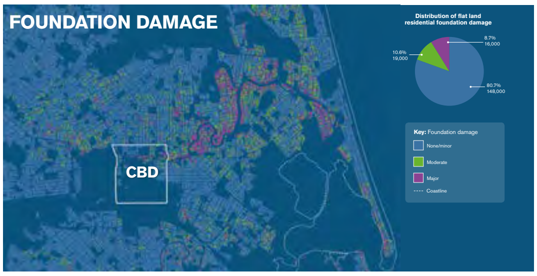
FOUNDATION DAMAGE

Geotechnical engineers have inspected more than 60,000 residential properties for possible liquefaction-induced land damage after the 2010-2011 Canterbury Earthquake Sequence. Visually observed liquefaction-induced damage to house foundations was recorded based on criteria reflecting the type of damage and its severity. Historical and modern construction practices were put to the test with some building foundations performing better than others. This foundation damage has been compiled into a database and the severity from seven modes of damage has been plotted.

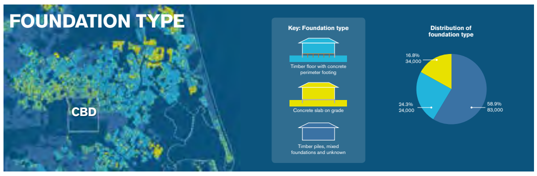
Seven modes of damage



FOUNDATION DAMAGE



FOUNDATION TYPE



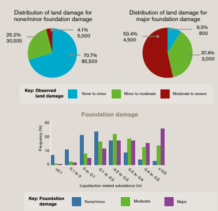
Concrete slab on grade is a more modern foundation system, but early versions of this design were not sufficiently reinforced or robust and lacked stiffness to withstand the differential ground surface deformation caused by liquefaction. This resulted in greater foundation and structural damage in areas where liquefaction-induced ground surface deformation occurred. Older foundation systems of timber floors, supported by a concrete perimeter footing and internal shallow timber piles, performed better.

LIQUEFACTION-INDUCED DAMAGE TO PROPERTIES

Major foundation damage generally coincided with areas of moderate to severe observed liquefaction land damage where large quantities of sand was ejected, there was differential settlement or severe lateral spreading occurred. By contrast, areas with a low concentration of foundation damage generally coincide in areas of none to minor observed land damage.

There is a strong correlation between land damage resulting from liquefaction and residential foundation damage which also extends to measured liquefaction-related subsidence.

Major foundation damage occured in areas with more liquefaction related subsidence.



APPROXIMATELY
60,000
PROPERTY INSPECTIONS

APPROXIMATELY
16,000
PROPERTIES WITH MAJOR FOUNDATION DAMAGE

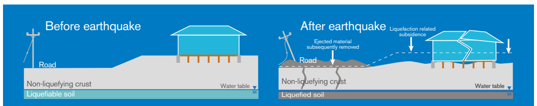
MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

EQC
EARTHQUAKE COMMISSION
Kōmihana Rūwhenua

Information provided by Tonkin+Taylor

LOCALISED GROUND SURFACE CHANGES

Liquefaction of underlying soil layers can cause slumping of elevated areas displacing the liquefied soils sideways. In addition to the liquefaction related subsidence, this slumping increases the risk of damage to the built environment.

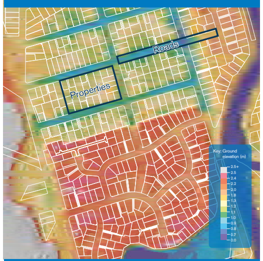


Elevated properties experience greater than expected subsidence resulting in increased property damage

As a result of the Canterbury Earthquake Sequence topographical relevelling occured. Even in areas where small height differences are present, such as between properties and roads, liquefaction related subsidence will be greater than that predicted by analysis tools, particularly in areas with a thin non-liquefying crust, relative to the thickness of the underlying liquefying soil layers.

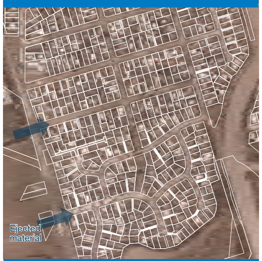
Residential properties are typically elevated above roads to allow stormwater runoff to be easily transported away from properties. The maps below represent this typical urban design methodology implemented in Canterbury, and images from the Canterbury Geotechnical Database illustrates the topographical relevelling that occured as a result of liquefaction related subsidence.

PRE-EARTHQUAKE GROUND SURFACE ELEVATION



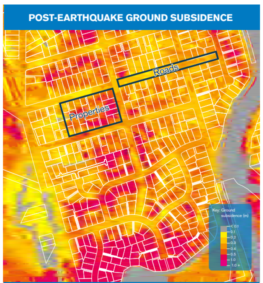
Property and road elevations are uneven. Roads (blue/green) are constructed lower than properties (yellow/light green).

AERIAL IMAGE FEBRUARY 2011



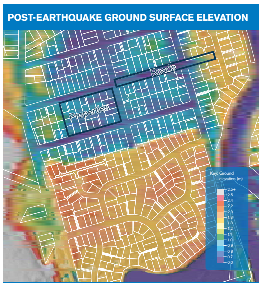
Liquefaction occurred and ejected material was observed on roads more than on the properties.

POST-EARTHQUAKE GROUND SUBSIDENCE



All land has subsided with properties showing more subsidence (0.5 - 1.0m) than the roads (0.1 - 0.4m).

POST-EARTHQUAKE GROUND SURFACE ELEVATION



Properties (now blue) have relevelled so they now have a similar elevation to the roads.

Analysis of ground elevation changes show properties have subsided more than the roads in areas where the properties were significantly elevated above the roads and where liquefaction occurred. In liquefaction vulnerable areas, elevated lightweight building solutions could be considered to reduce the consequences of future liquefaction damage.

Future subdivision planning with more uniform topographic designs could reduce the significant economic impacts of property subsidence.

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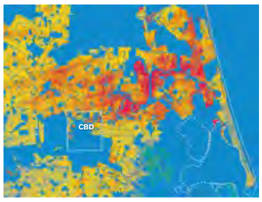
GROUND SURFACE SUBSIDENCE

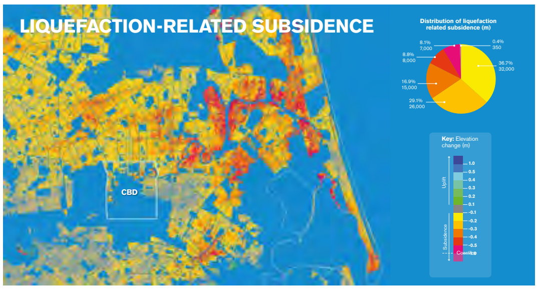
The 2010-2011 Canterbury Earthquake Sequence caused regional tectonic subsidence and uplift. The earthquakes also triggered widespread liquefaction, contributing to subsidence and localised lateral spreading.

Aerial LiDAR (light detection and ranging) surveys were used to quantify the changes in ground surface elevations across the region. Models were developed to estimate the vertical and horizontal tectonic movements. These tectonic movements were subtracted from the measured changes in ground surface elevation to determine the spatial distribution of liquefaction-related subsidence and ground surface deformation.

EARTHQUAKE-RELATED SUBSIDENCE

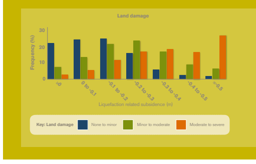


LIQUEFACTION-RELATED SUBSIDENCE



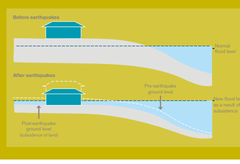
LIQUEFACTION-INDUCED DAMAGE TO PROPERTIES

Liquefaction-related subsidence was a major contributor to observed land damage. Properties with moderate to severe land damage subsided considerably more than properties with none to minor land damage.



FLOODING AND FUTURE LIQUEFACTION VULNERABILITY

Earthquake-related land changes have increased the flood risk in parts of Christchurch. Widespread tectonic and liquefaction-related subsidence along with alteration of waterways is a key factor. Future liquefaction vulnerability has also increased in parts of Christchurch as the ground surface is now closer to the groundwater level as a result of the subsidence.



EQUIVALENT TO SIGNIFICANT SEA-LEVEL RISE

Some Christchurch suburbs have experienced the equivalent of significant relative sea-level rise as a result of the Canterbury Earthquake Sequence. The observed effects of the subsidence caused by the earthquakes provides insight into the potential impact of sea-level rise in other coastal environments.

APPROXIMATELY
85%
OF CENTRAL AND EASTERN CHRISTCHURCH SUBSIDED

APPROXIMATELY
10,000-15,000
RESIDENTIAL PROPERTIES ARE MORE FLOOD PRONE

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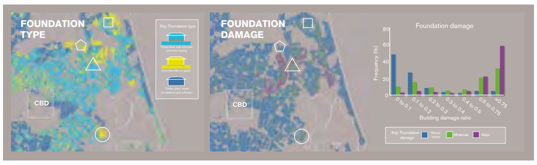
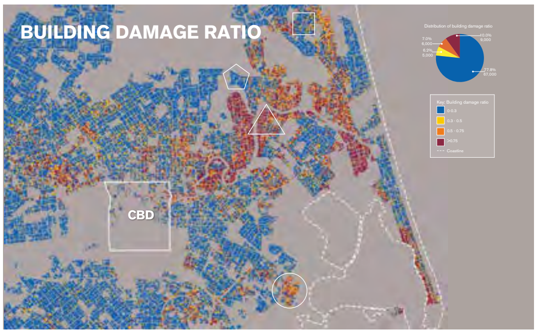
ECONOMIC IMPACT OF LIQUEFACTION

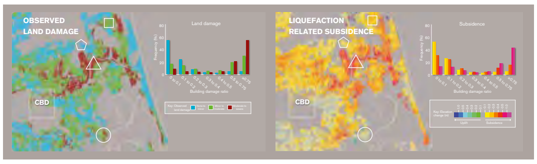
The 2010-2011 Canterbury Earthquake Sequence has had an enormous economic impact on Christchurch and New Zealand. Liquefaction-induced damage from the earthquakes has significantly exacerbated the economic impact. To better understand the reasons for the significant economic impact, the building damage repair costs for the residential housing portfolio have been normalised with respect to the value of each house. This is expressed as a Building Damage Ratio (BDR).

$$\text{Building Damage Ratio} = \text{The greater of} \left(\frac{\text{Repair cost}}{\text{House rebuild cost*}} \text{ OR } \frac{\text{Repair cost}}{\text{House valuation**}} \right)$$

* The rebuild rate has been assumed as $2,000/m²
** House valuation is based on the pre-CES 2007 Christchurch City Council valuations.







The maps show the building damage ratios for the residential housing portfolio. They show the strong spatial correlation between areas with high building damage ratio and areas where observed land damage was moderate to severe, measured liquefaction related subsidence is high (more than 0.5 metre) and where the observed foundation damage was moderate or major.

Conversely, the building damage ratio values are low in areas where land damage was none to minor and where little to no liquefaction-related subsidence occurred.

It is possible to predict the likely land damage and corresponding building damage on a portfolio basis using geotechnical data. Using this information, planners, decision-makers and engineers are able to better manage and reduce the economic and social impact of liquefaction-related damage.

To reduce economic losses from future earthquake events, land with expected poor performance (i.e. likely moderate to severe land damage) could be developed with implemented ground improvement measures or alternatively be avoided. Where there is expected to be minor to moderate land damage, building damage can be mitigated by using more resilient repairable foundation types (i.e. houses on stiffer and more robust foundations).

The wealth of data and lessons learned in recovery can be applied to communities throughout the world with similar tectonic and geological environments.

DISTRIBUTION OF BUILDING DAMAGE RATIO

△	When land performs poorly (i.e. moderate to severe land damage), the distribution of BDR values is typically high, irrespective of foundation types	○	When land performs with minor to moderate land damage where houses have concrete slab on grade floors, the distribution of BDR values are typically high
□	When land performs with minor to moderate land damage, where houses have timber floors with concrete perimeter footings, the distribution of BDR values are typically low to moderate	⬠	When land performs well (i.e. none to minor land damage), the distribution of BDR values is typically low, irrespective of foundation type (i.e. building damage is predominantly caused by shaking)

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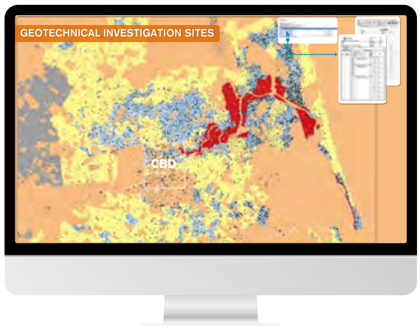
A WEALTH OF DATA

The Canterbury Geotechnical Database is an online database developed for the rebuild of Christchurch after the 2010-2011 Canterbury Earthquake Sequence. It was designed as a searchable repository for new and existing geotechnical, geological and groundwater information used for planning and building requirements. The database has been very successful due to the sharing of information between the private and public sectors.



Key: Geotechnical investigation sites
Coastline
Residential Red Zone
Foundation Technical Category 1
Foundation Technical Category 2
Foundation Technical Category 3
Borehole
Cone Penetrometer Test (CPT)
Piezometer

Since the Canterbury Geotechnical Database was created in 2012:

MORE THAN	MORE THAN	MORE THAN
3,000 users have joined	**40,000** uploads of information	**800,000** downloads of information

The data is primarily used in the design of foundations for rebuilding infrastructure and buildings in Canterbury. Strategic applications of this data enables more informed asset management planning; regulatory changes; catastrophe, loss and damage modelling; and assisting in future recovery and resilience.

Shared access to more geotechnical data enables professionals to focus on analysis and design, and to consider a wider area. This results in more robust project outcomes and cost savings (as at September 2015) of more than NZ$50 million.

The database is an efficient and cost-effective way to store, share and enable use of this geotechnical information.

This extensive post-disaster dataset is the first of its kind and has been essential to Canterbury's recovery, as well as driving research in liquefaction triggering and its consequences.

As a result of the success of the Canterbury model, a national geotechnical database is now being developed.

More than 20,000 CPTs pushed

More than 4,000 boreholes

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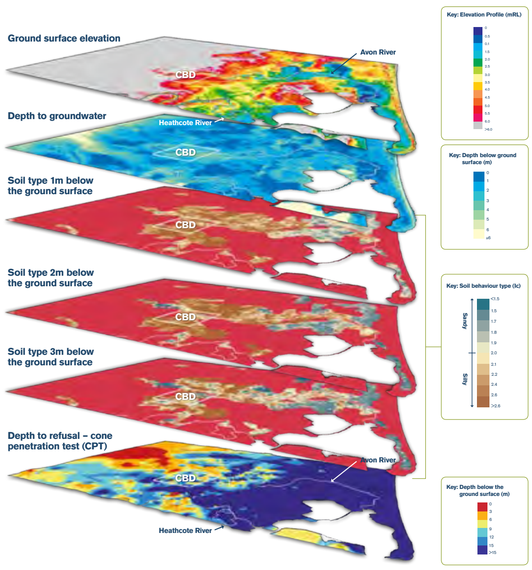
THE POWER OF SHARED DATA

The Canterbury Geotechnical Database harnesses the power of sharing geotechnical information between the public and private sectors to aid the recovery by significantly improving the understanding of the Canterbury-wide subsurface soil conditions.



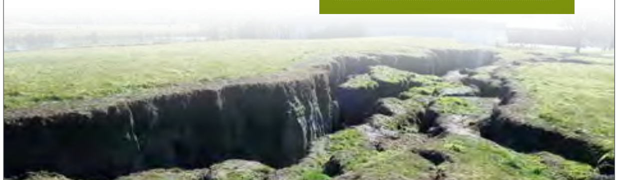
The sharing of information enables the rendering of raw data between investigation points, and the automatic update when an investigation is uploaded ensures that the database remains current.

As data intensity and richness increases at any particular location, professionals have better information underpinning decision-making. When this data is used with information from other regions, professionals can better inform asset management systems, land use and infrastructure planning. Existing schemes can also benefit by enhancement.

The sharing of data can lead to an improvement of community resilience to future natural hazards across New Zealand and the world.

Collaboration led to data intensity

Resilience and better decisions



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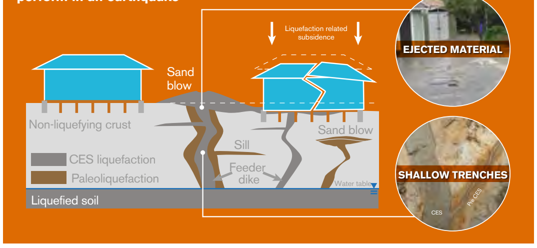
PALEOLIQUEFACTION

Paleoliquefaction is the preserved evidence of liquefaction in the soil profile attributed to seismic events occurring before earthquake records began.

Features in the land can significantly influence how buidlings perform in an earthquake



Following the 2010-2011 Canterbury Earthquake Sequence, paleoliquefaction evidence in shallow (1-2m depth) trenches was documented in several suburbs in eastern Christchurch. Observable features include liquefaction induced feeder dikes, sills, lateral spreading cracks and subsurface sand blows. These paleoliquefaction features are similar to those that have formed as a result of the Canterbury Earthquake Sequence. Paleoliquefaction features were present prior to the Canterbury Earthquake Sequence, however the origin of them was not widely recognised until after the earthquake sequence.

Paleoliquefaction features are typically observed to cut through recent soil profiles and are heavily mottled by weathering. This implies historical earthquakes have triggered liquefaction and the evidence has been preserved in the subsurface. In eastern Christchurch, the number of liquefaction features formed during the Canterbury Earthquake Sequence exceeded that of any identified paleoliquefaction features, suggesting that liquefaction and lateral spreading was the most severe event captured since deposition of the sediments in the last 1000 years.

The past is an important factor in predicting liquefaction in future earthquakes

Past liquefaction is an important factor in determining whether liquefaction is likely to occur following future earthquakes. Evidence of paleoliquefaction was present in the subsurface profile and hence the liquefaction vulnerability could have been identified. This evidence complements the liquefaction observations recorded in archives from the earthquakes in the 1800s throughout the Canterbury region.

More recent research strongly indicates that future urban planning developments in areas with high seismicity and potentially liquefaction prone soils should include a review of geomorphology along with targeted subsurface trenching to identify areas with paleoliquefaction features in the subsurface soils. These indicators can provide insights into where liquefaction damage has been more frequent in geological times. In conjunction with other geotechnical/geological studies, this will assist in identifying other areas potentially vulnerable to liquefaction in New Zealand. Future risk of extensive built environment damage can be managed through avoidance or mitigation in these areas to improve community resilience in future earthquakes.

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The paleoliquefaction work and images are provided courtesy of the University of Canterbury

NOTES