BUILDING PERFORMANCE

Regional liquefaction vulnerability assessment method statement

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

New Zealand Government

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Contents

1 Introduction

This method statement has been developed to provide an overview of the main steps associated with undertaking a liquefaction vulnerability study at a regional (or district) level in accordance with the Ministry of Building, Innovation and Employment (MBIE) and the Ministry for the Environment (MfE) Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE, 2017) (hereinafter referred to as the MBIE/MfE Guidance (2017)).

The main intended audiences for this method statement are local government agencies who are in the process of procuring one of these studies, and consultants who are preparing proposals for one of these studies.

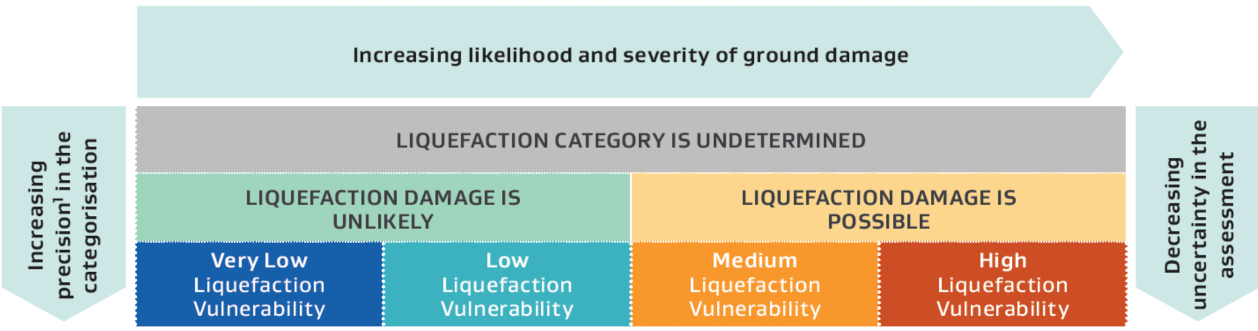
Note this method statement should be read in conjunction with the MBIE/MfE Guidance (2017) that provides a significant amount of detail about the assessment process. Furthermore, it is not intended to provide detailed technical guidance on liquefaction analysis or earthquake engineering. Detailed information about this topic can be found in the NZGS/MBIE Earthquake Geotechnical Engineering Practice series (NZGS/MBIE, 2016; NZGS/MBIE, 2017a – 2017f).

1.1 MBIE/MfE Guidance

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

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

The MBIE/MfE Guidance (2017) provides a performance-based framework for categorising the liquefaction vulnerability of land to inform planning and consenting processes. That framework is based on the severity of liquefaction-induced ground damage that is expected to occur at various intensities of earthquake shaking. Figure 1 shows the recommended liquefaction vulnerability categories for use in that performance-based framework.



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.

Figure 1: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes - from MBIE/MfE Guidance (2017)

1.1 MBIE/MfE Guidance cont...

The categorisation of the liquefaction vulnerability of the land within the study area into one of these seven categories is one of the key deliverables of a regional liquefaction vulnerability study. It is important to note that regional scale studies typically result in categorisation of the land into one of the top three vulnerability categories of "Liquefaction Category is Undetermined" or "Liquefaction Damage is Unlikely" or "Liquefaction Damage is Possible".

As shown in Figure 1, the liquefaction vulnerability categories established in the MBIE/MfE Guidance (2017) are a function of both the precision in the categorisation and the degree of uncertainty in the assessment. To provide guidance on how to manage these aspects, recommendations are provided in the MBIE/MfE Guidance (2017) for the minimum level of detail required in the liquefaction assessment for specific applications. Figure 2 shows the categories used to define the levels of detail for liquefaction vulnerability studies. Section 3.2 of the MBIE/MfE Guidance (2017) provides information about the key features of each level of detail.

Regional scale studies are typically undertaken to Level A or Level B level of detail and this method statement is written with this objective in mind. Level C and Level D studies are typically associated with site specific development to support subdivision and building consent applications. Section 3.5 of the MBIE/MfE Guidance (2017) provides information about the minimum levels of detail recommended to support different purposes and associated development scenarios.

The key feature defining each level of detail is the degree of "residual uncertainty" in the assessment, such that the residual uncertainty is reduced as the level of detail in the liquefaction assessment increases. It is likely that substantial residual uncertainty will remain in some locations, so this should be acknowledged, recorded and clearly conveyed as part of the reporting process.

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

Figure 2: Categories of level of detail used to define the levels of detail for liquefaction vulnerability studies - from MBIE/MfE Guidance (2017)

1.2 Objectives and purpose

The main objective of undertaking a regional liquefaction vulnerability study is to ensure that buildings are located and built with appropriate consideration of the land conditions.

The main purpose is to provide a regional or district wide map that can be utilised to inform policy, planning and consenting processes.

1.3 Main outputs

The main outputs required from a regional liquefaction vulnerability study in accordance with the MBIE/MfE guidance (2017) are:

- Categorisation of the land into the liquefaction vulnerability categories shown in Figure 1 and production of an associated map. This map should be provided in geospatial format and in accordance with the standard data format provided in Appendix E of the MBIE/MfE Guidance (2017).
- Preparation of a report to accompany the liquefaction vulnerability study. It is recommended that the accompanying report be structured in accordance with the key steps in the process (i.e. Establish the Context, Risk Identification and Risk Analysis). Section 2 of this method statement has been set out to provide an example of this recommended structure.

Other outputs may be required depending on the specific regulatory requirements and the overarching objectives of the agency procuring the study.

2 Methodology

The MBIE/MfE Guidance (2017) includes the overview of the recommended process for categorising the potential for liquefaction-induced ground damage shown in Figure 3. That figure shows the key steps in a liquefaction vulnerability study, namely Establish the Context, Risk Identification and Risk Analysis, broken down into high level tasks. The process outlined is consistent with the risk management process defined in ISO 31000:2018.

Note that the Monitoring and Review process is typically outside of the scope of a liquefaction vulnerability study and therefore it is not included in this method statement. For more information about the monitoring and review process refer to Section 8 of MBIE/MfE Guidance (2017).

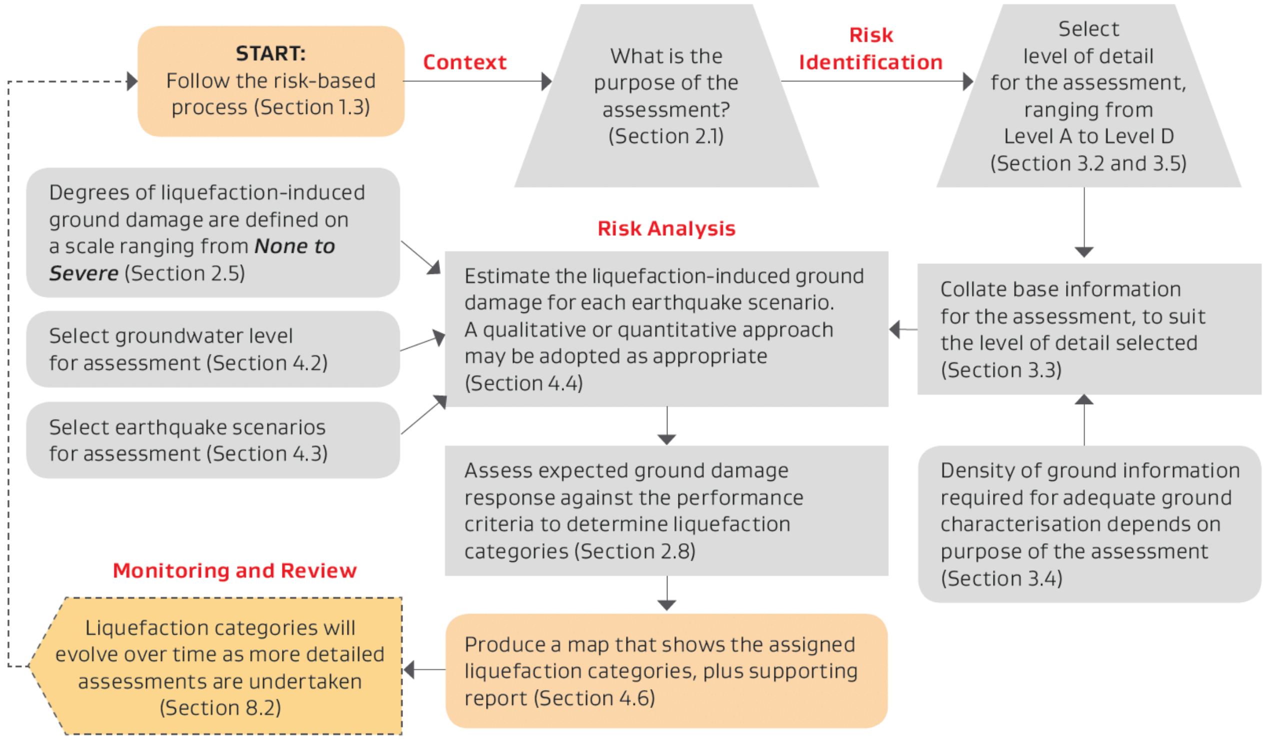


Figure 3: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage - from MBIE/MfE Guidance (2017)

TABLE 2.1 outlines the high-level steps and tasks associated with undertaking a regional liquefaction vulnerability study. The following sections provide further supporting detail associated with each of these steps and tasks.

Step	Task	Comments	Outputs
Context	Establish context and intended purposes	**Consultation with stakeholders is required to establish the following:** • Intended purposes and use for the liquefaction vulnerability study • Identify existing information about liquefaction • Identify areas where more detail is required • Identify and gather existing base information	• Summary of the established context
Risk identification	Determine target level of detail	**Typically, Level A and/or B for regional studies. This may require consideration of:** • The range of intended purposes • The availability of base information • Whether a better outcome can be achieved at a higher level of detail	• Summary of target level of detail • Map of target level of detail (mandatory)
	Base information review	**Information to be reviewed:** • Ground surface levels • Geology and geomorphology • Geotechnical investigations • Groundwater • Seismic hazard • Historic observations of liquefaction	• Summary of each source of base information • Maps of base information (where applicable)
	Uncertainty assessment	**Uncertainty assessment to cover:** • Base information • Interpretation of the base information to: – Estimate the expected degree of liquefaction-induced ground damage – Assess the liquefaction vulnerability category against performance criteria Needs to note how these uncertainties will be managed.	• Summary of each uncertainty assessed • Maps of uncertainty assessment (where applicable)
	Level of detail supported by the available information	**Evaluate the level of detail supported by the available base information. Key sources of uncertainty are likely to be:** • Spatial density of available geotechnical investigations • The quantity and quality of groundwater data • Seismic hazard information	• Summary of level of detail supported by the available information • Map of level of detail supported (mandatory)
Risk analysis	Groundwater levels for analysis	Typically, groundwater is assessed qualitatively and using geomorphic terrains and topography groupings. However, regional groundwater models should be utilised where available. Coastal low-lying areas should include consideration of potential effects of sea level rise.	• Summary of groundwater levels for analysis
	Earthquake scenarios for analysis	**Typical seismic hazard scenarios adopted for Level A and B studies include:** • 500-year return period • Extreme scenario (150% of PGA of 500-year return period)	• Summary of earthquake scenarios adopted for analysis
	Sub areas of similar expected performance	**Sub areas are typically developed from:** • Geomorphic terrains (as a representation of the likely soil conditions) • Topographic screening (as a proxy for groundwater) • Lateral spread screening	• Summary of sub areas of similar expected performance
	Liquefaction vulnerability category assessed against performance criteria	**For Level A and B studies, liquefaction vulnerability will typically be categorised into:** • Liquefaction damage category is undetermined (insufficient information to support categorisation) • Liquefaction damage is possible (susceptible landforms) • Liquefaction damage is unlikely (non-susceptible landforms) Include discussion about how to refine the classification of land where liquefaction damage category is undetermined for each geomorphic terrain	• Summary of liquefaction vulnerability categorisation for each geomorphic terrain • Map of liquefaction vulnerability categorisation (mandatory)
Conclusion and recommendations	Summarise conclusions and provide recommendations	List key findings of the liquefaction vulnerability study and provide recommendations for next steps to refine the liquefaction vulnerability assessment process.	• Summary of conclusions and recommendations

2.1 Context

To establish the context for a regional liquefaction vulnerability assessment it is important to engage with key stakeholders in this focus area. Section 2 of the MBIE/MfE Guidance (2017) provides useful background information to engage with these stakeholders. The recommended method of engagement is to undertake a workshop with representatives from the following groups:

- The consultants undertaking the assessment (typically geo-professionals who specialise in the assessment of liquefaction hazards) and in most cases they will facilitate the workshop
- Staff responsible for the management of natural hazards (typically Natural Hazard specialists)
- Staff responsible for the implementation of the RMA (typically RMA planners)
- Staff responsible for the implementation of the Building Act (typically building consent/control officers)

Note there may be other relevant staff who can make a relevant contribution to this workshop (such as Asset Managers and Council Engineers) and their inclusion in the process should be considered on a case by case basis.

The main objectives of a context setting workshop are to establish the following:

1. **Intended purposes of the liquefaction vulnerability study.** It is recommended that other intended uses outside of informing RMA and Building Act processes be documented, and it is important to establish what the outputs of the study will (and will not) be suitable for.
2. **Identify existing information about liquefaction.** Typically, this focusses on regional scale liquefaction hazard assessments that may have been undertaken prior to the release of the MBIE/MfE Guidance (2017). It may also be useful to identify select geotechnical reports prepared for large sub-divisions and significant infrastructure projects as applicable.
3. **Identify areas where more detail in the liquefaction assessment is required.** Typically, these are existing residential areas or proposed urban growth areas. In some cases, areas that support commercial activities (such as ports) will also be identified.
4. **Identify and gather existing base information to inform the liquefaction vulnerability study.** The relevant base information includes ground surface levels, geology and geomorphology, geotechnical investigations, groundwater, seismic hazard, and observations of liquefaction from historic events.

The key findings of the workshop should be documented within the Context section of the report. In that section it is important to clearly establish the intended purposes of the liquefaction vulnerability study (objective 1), and to summarise any review of the existing information about liquefaction (objective 2).

2.2 Risk identification

In the context of liquefaction-related risk, the aim of the risk identification process is to identify land where there is the potential for liquefaction-induced ground damage to occur (or just as importantly, identify areas where it is unlikely so no further assessment is required). This involves the following key tasks:

- Establish the target level of detail
- Review the available base information
- Assess the uncertainty associated with the available information
- Evaluate the level of detail supported by the available information

Each of these key tasks is discussed in further detail as follows and further information is provided in Section 3 of the MBIE/MfE Guidance (2017).

2.2.1 Target level of detail

The level of detail required for intended purposes (Target Level of Detail) is evaluated based on information obtained during the context setting workshop. Key things to consider when establishing the Target Level of Detail are as follows:

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

A summary of the rationale applied and accompanying maps of the study area showing the Target Level of Detail should be included in the report. It is also useful to include a digital copy of the Target Level of Detail in geospatial format because this information can be used to inform future studies should the Target Level of Detail not be achieved in the current study.

2.2.2 Base information review

The objective of this task is to collate and document the base information available in the assessment. While the specific details of the base information will vary depending on the specific location, the key sources of base information can typically be grouped under the following sub-headings.

2.2.2.1 Ground surface levels

Ground surface levels for regional liquefaction vulnerability studies are typically characterised using 3D computer graphics representations of elevation data known as Digital Elevation Models (DEM). A national 8m DEM is available for download from LINZ Data Service however this DEM was derived from interpolation of 20m contours. Therefore, it is only considered suitable for cartographic visualisation and to make general observations about differences in elevation across the region. It is not considered to be of sufficient accuracy to support detailed analysis.

A regional liquefaction study typically utilises DEM's derived from LiDAR (or Light Detecting and Ranging). LiDAR is an aerial survey method using laser scanning technology that can collect millions of elevation points across a surveyed area. LiDAR derived DEM's are available in most large towns and cities in New Zealand and some (although not all) of this data is publicly accessible through Land Information New Zealand's (LINZ) Data Service (LINZ, 2020). Figure 4 shows the extent of LiDAR derived DEM available from LINZ Data Service as of 14 October 2020.

LiDAR derived DEM can be utilised for a number of different applications in a liquefaction vulnerability study including the development of geomorphic terrain models and depth to groundwater surface models. Prior to undertaking detailed analysis it is important to understand what information the DEM presents because some, typically known as Digital Surface Models (DSM), represent all reflective surfaces captured in the LiDAR survey (including buildings, trees, bridges etc.). Whereas others are post-processed to remove some features and are a representation of the surface of the earth only, typically known as bare earth DEM.

A summary of the available ground surface information for the study area should be included in the report. Where LiDAR derived DEM are available this summary should include basic information about the survey such as the agency who commissioned the survey, the year of acquisition, the company that undertook the survey, the resolution of the DEM and the extent of area covered by the DEM. A brief summary of the variability in ground surface elevation across the region including identification of key topographic features and an associated map are also useful.

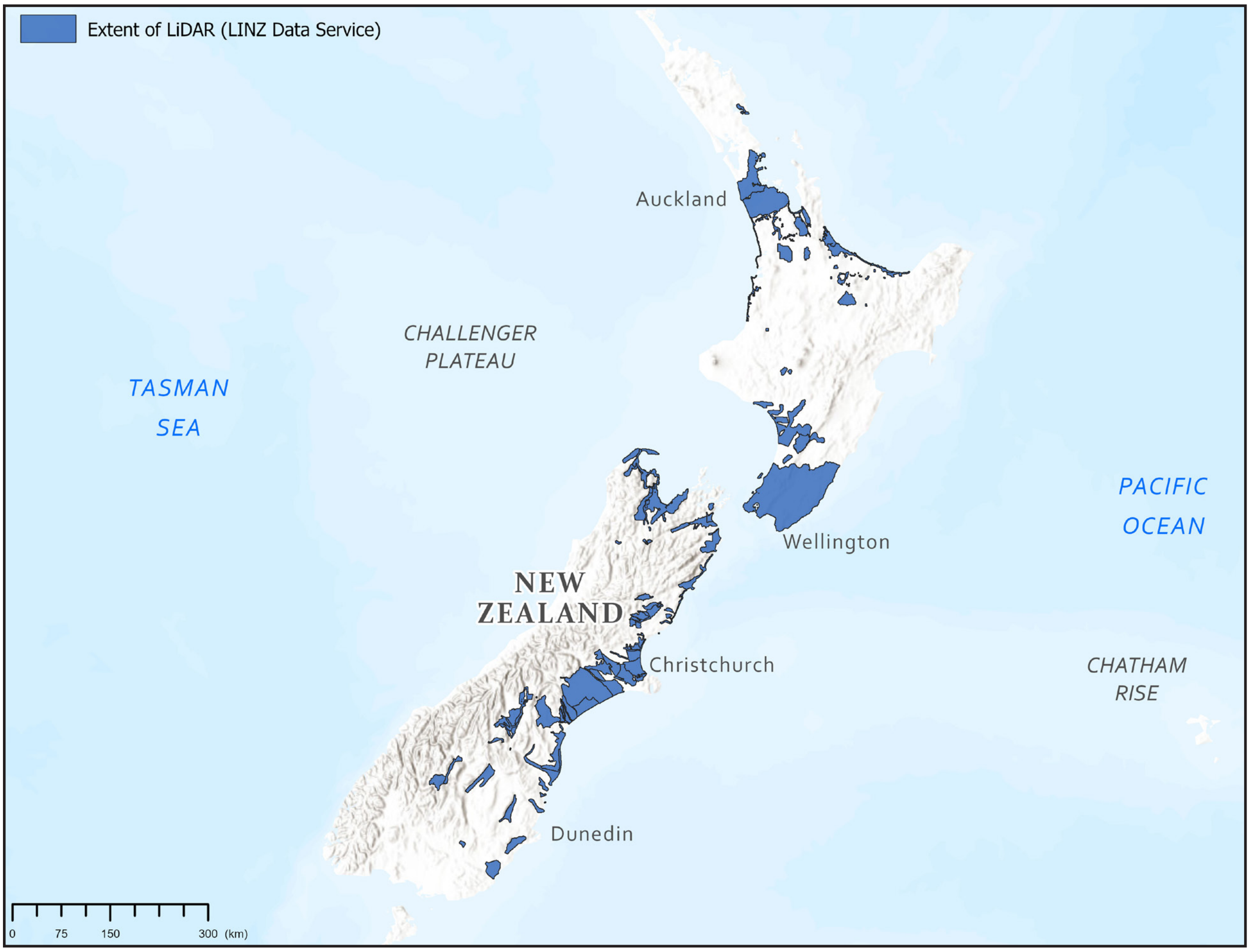


Figure 4: Extent of LiDAR derived DEM available from LINZ Data Service as at 14 October 2020

2.2.2.2 Geology and geomorphology

Information about geology and geomorphology is useful because it can be used to group geotechnical investigation data and infer the likely performance under seismic shaking.

Landforms that are commonly susceptible to liquefaction include:

- Estuaries and swamps
- Reclamation fills and tailings dams
- Coastal margins
- Uncontrolled or poorly compacted fill
- Flood plains
- Along rivers, streams and lakes

Note this list is not exhaustive, liquefaction is still able to occur in other types of landforms.

A 1:250,000 scale geological map of New Zealand known as QMAP is available from GNS Science in both hardcopy and digital versions. The accompanying texts provide a valuable source of information about regional geology including descriptions of each area's geomorphology, stratigraphy, tectonic history, geological hazards and engineering geology. In total there are 21 QMAP's across New Zealand and each one of these maps was typically compiled from a number of smaller local geological maps of varying scales. In some locations, these local geological maps are of higher resolution and may provide more detailed geological information. Figure 6 shows the extent of the 21 QMAP series geological maps and a simplified representation of the geological map of New Zealand.

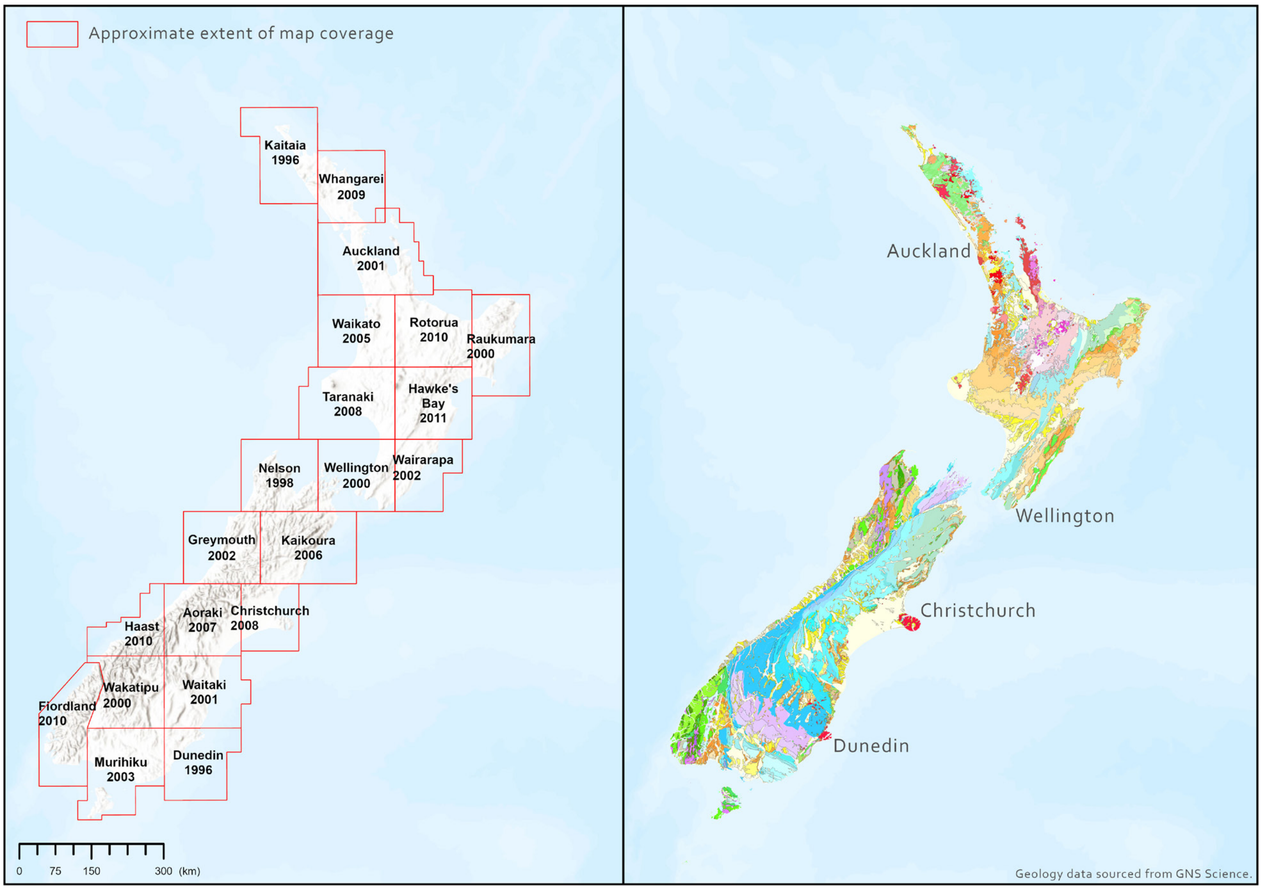


Figure 6: Approximate Extent of the 21 QMAP series geological maps and a simplified representation of the geological map of New Zealand – geology data sourced from GNS Science

2.2.2.2 Geology and geomorphology cont...

A summary of the available geological information that is utilised for the study should be included in the report. It is also useful to include a high-level description of the geological terrains that comprise the study area including information about the age of the terrains and the geological processes that shaped them.

In some locations geomorphic maps are also available and these maps can provide important information about the processes that shaped the topography and the nature of the underlying soil conditions. Geomorphic mapping will typically identify where these landforms are present, although for a regional scale exercise some smaller areas may not be identified and this should be considered in the uncertainty assessment (refer Section 2.2.3).

More often however geomorphic maps are not available, and it may be necessary to develop these from existing information such as ground surface information, geological maps and historic aerial imagery. Typically, a geomorphic map developed for a regional liquefaction vulnerability study should target a scale of approximately 1:25,000. General guidance on the likely requirements for liquefaction assessments is included in Table 3.4 of the MBIE/MfE Guidance (2017). Figure 7 shows an example geomorphic map for reference.

A summary of the available geomorphic information that has been utilised for the study should be included in the report. It is useful for this to include a map of the different geomorphic terrains in the region, in particular if this is utilised as the primary basis of characterising the likely soil conditions when defining sub-areas of similar expected performance (discussed further in Section 2.3.3 below). If the geomorphic map has been developed as part of the regional liquefaction vulnerability study then a brief summary of the methodology used to develop the map should also be included.

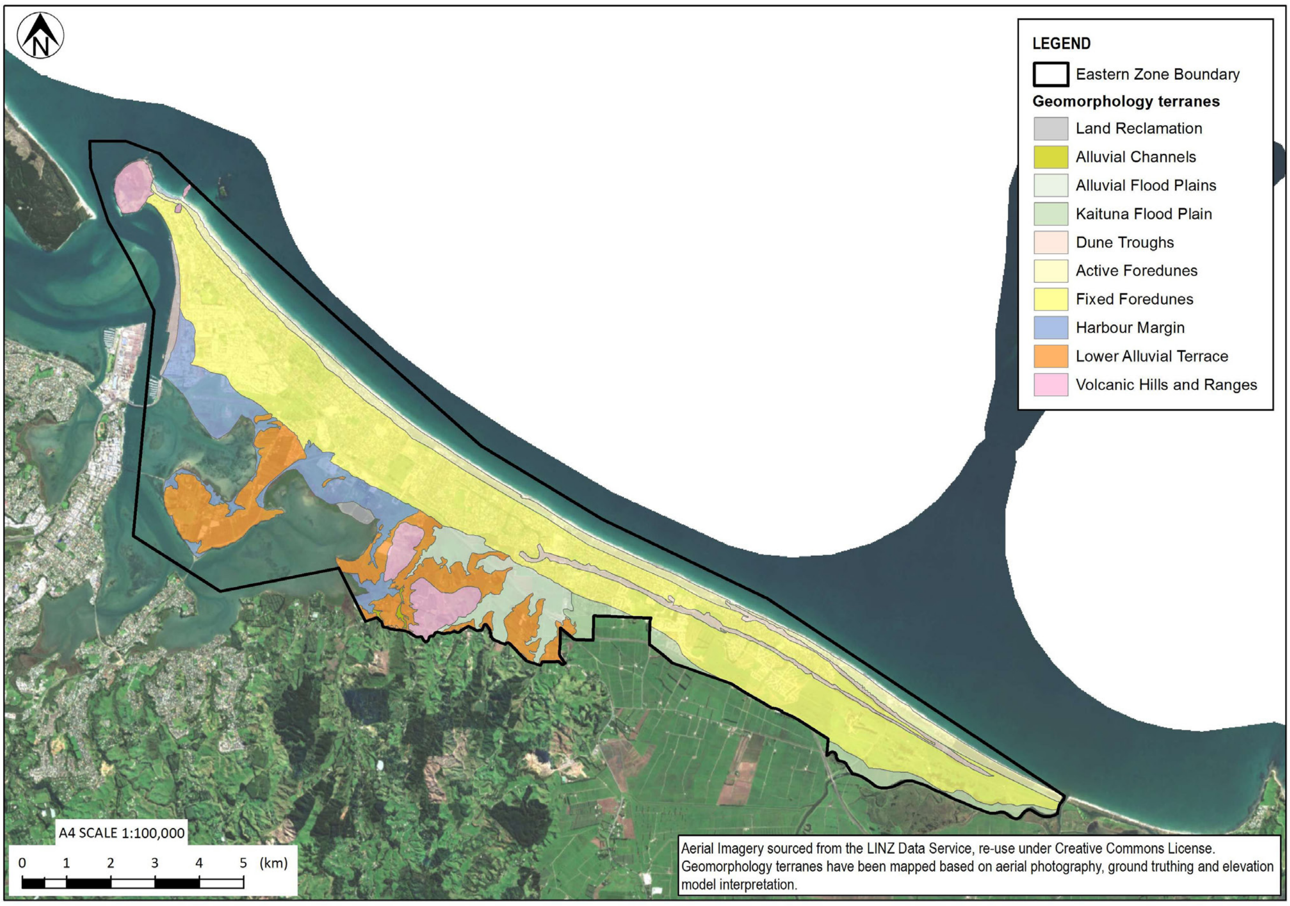


Figure 7: Example geomorphic map reproduced from T+T (2020)

2.2.2.3 Geotechnical investigations

Geotechnical investigations provide a valuable data source for regional liquefaction vulnerability studies. For Level A studies they are useful for qualitative assessment of the likely underlying ground conditions within each terrain that is being assessed. For Level B studies they enable high level calibration (both qualitative and potentially quantitative) of the ground conditions. This may indicate the ground performance within a broad area is likely to fall within a particular range.

A significant number of geotechnical investigations that have been approved for public access are available on the New Zealand Geotechnical Database (NZGD). The number of geotechnical investigations on the NZGD varies from region to region and is more likely to include investigations undertaken since 2017 when the nationwide database was established. Typically, investigations are clustered around areas of residential, commercial and infrastructure development with the highest density of investigations being found in larger cities.

The geotechnical data on the NZGD includes, but is not limited to, boreholes, Cone Penetration Tests (CPT), hand augers, test pits, laboratory tests and piezometers. Boreholes and CPT are typically the most useful deep investigation methods for assessing liquefaction. For residential and light commercial development, the MBIE/MfE Guidance (2017) recommends that these be undertaken to a depth of at least 10–15 m below ground level or at least 20–25 m for heavier structures or critical facilities. In some circumstances test pits and hand augers can be utilised to help understand the shallow sub-surface profile but they are not considered to be an appropriate tool when more detailed analysis is required.

The investigations on the NZGD may also be supplemented with data from other sources. For example:

- Historic projects often have associated geotechnical reports that contain geotechnical investigations that predate the development of the NZGD.
- Geotechnical practitioners who undertake work in the region may maintain their own database of geotechnical investigations from work undertaken for their clients.

Prior to procuring a regional liquefaction vulnerability study a useful first step is to identify and upload historic geotechnical investigations to the NZGD. Note a list of data owners who have given preapproval for their data to be uploaded is maintained under the Help & Support tab on the NZGD website. If in particular areas it is known that Level B or higher detail will be required, procuring suitable geotechnical investigations in conjunction with or prior to procuring the liquefaction vulnerability study is also likely to provide significant benefit.

A summary of the available geotechnical investigation data that has been utilised for the study should be included in the report. It is useful for this to include a map showing the spatial distribution of the geotechnical investigations and to categorise the geotechnical investigations by the geomorphic or geological terrains they are situated in. Undertaking such classification provides an indication of how well the ground conditions can be characterised using the available geotechnical investigations. Figure 8 shows an example geotechnical investigation map for reference.

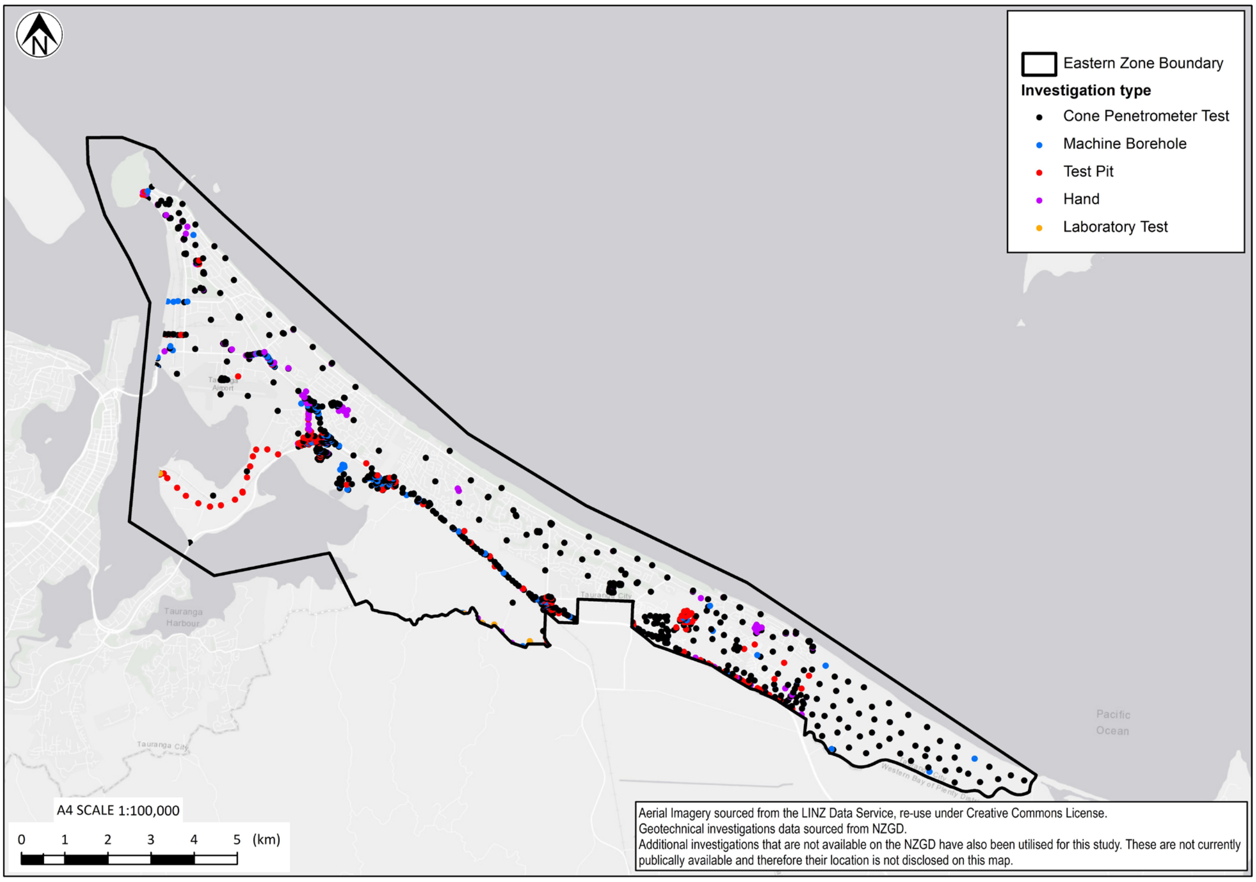


Figure 8: Example geotechnical investigation map reproduced from T+T (2020)

2.2.2.4 Groundwater

For liquefaction to occur the soils must be saturated (i.e. below the groundwater table), therefore it is important to gather information about groundwater to inform regional liquefaction vulnerability studies. Typically, information about groundwater comes in two main forms:

1 Groundwater measurements – raw data records of the depth to groundwater in a specific location

2 Groundwater studies – analysis of groundwater records (and other information) to develop an understanding of groundwater characteristics across an area

Groundwater measurements are typically in the form of a single reading of groundwater depth, or an ongoing record of groundwater level over time. Single readings of groundwater depth are typically the most numerous records within a region and are commonly associated with drillers logs from bores used for water supply, or geotechnical investigations (such as boreholes and CPT). Ongoing records of groundwater level over time are typically less numerous and are associated with established groundwater monitoring locations known as piezometers.

The number of groundwater measurements available varies from region to region. Those associated with geotechnical investigations tend to be clustered around areas of residential, commercial and infrastructure development. Those associated with bores used for water supply tend to be in rural areas where reticulated water systems are not available, and often measure deep artesian aquifers rather than the near-surface shallow groundwater table which is more relevant for liquefaction assessment. Ongoing records can be associated with both a) areas of residential, commercial and infrastructure development, and b) rural areas depending on the intended use of the data. These groundwater measurements can also be supplemented with geospatial information about the location of surface waterbodies and coastal margins as these are locations where it can sometimes be assumed that the shallow groundwater table intercepts with the ground surface.

Groundwater studies to evaluate the sustainability of rates of extraction from aquifers are often available in areas where groundwater resources are utilised for water supply. These can provide a useful source of information for understanding the general characteristics of groundwater in a region. However, that information is not typically sufficient to infer the depth to the near-surface shallow groundwater table.

Less commonly available are groundwater surface models and these are developed for a range of applications including the assessment of liquefaction vulnerability. Groundwater surface models should ideally include data from ongoing groundwater monitoring records that span at least one year such that seasonal fluctuations can be understood. They are not typically used to inform level A studies and are only seldom available for Level B studies. However, when they are available or there is sufficient ongoing ground water monitoring data for one to be developed as part of the study, they provide a very useful tool to support the risk analysis and reduce residual uncertainty.

Prior to procuring a liquefaction vulnerability study another useful first step is to install a network of piezometers to record ongoing groundwater measurements and develop a groundwater surface model. If this option is preferred, this should occur with sufficient time to record at least one year of groundwater measurements and to develop the groundwater surface model. Note that this groundwater information is likely to be of significant benefit to other applications including the development of water balance models, infrastructure operations and maintenance, and estimating the potential effects of sea level rise on the groundwater surface.

A summary of the available groundwater information that has been utilised for the study should be included in the report. It is useful for this to include a map or a series of maps showing the location of available groundwater measurements, surface waterbodies, and the extent of groundwater models (where available).

2.2.2.5 Seismic hazard

Soils that are susceptible to liquefaction require a particular level of earthquake shaking (duration and intensity) to cause them to liquefy and seismic hazard is one of the most significant sources of uncertainty in the assessment of liquefaction vulnerability. Therefore, it is important to clearly review and communicate the regional seismic hazard context.

Records of historic seismic activity can be accessed on the Geonet New Zealand earthquake database (GNS, 2020) and this can be used to develop a summary of notable historic earthquakes in the region. The Atlas of Isoseismal Maps of New Zealand Earthquakes contains estimated felt intensity distributions of 123 earthquakes felt in New Zealand with records from 1848 to 1990. It is important to identify mapped active faults within the region and these can be accessed on the New Zealand Active Faults database (GNS Science, 2020). The information from these sources should also be supplemented with information from reports about historical events and the regional seismic hazard when available.

A key input into the analysis of liquefaction is the intensity of shaking that is expected to occur at a particular location in future earthquake events and the 500-year return period is the recommended minimum earthquake scenario for Level A and B studies. However, it is useful to calculate the intensity of seismic shaking across a range of return period events so the sensitivity to any uncertainty in seismic hazard can be explored. The earthquake scenarios used for the analysis are discussed further in Section 2.3.2.

The NZTA Bridge Manual methodology (NZTA, 2018) is the commonly accepted method for the determination of seismic shaking intensity for use in liquefaction assessment for routine engineering projects (NZGS/MBIE, 2016). It provides a simple method that can be utilised to derive seismic hazard parameters for a range of different return period intervals for any site in New Zealand. However, issues have been identified with this approach and these are discussed further in Section 2.2.3.5.

The seismic hazard parameters derived using the NZTA Bridge Manual approach can be cross checked against the findings of site-specific seismic hazard assessment if such studies are available. In doing so, it is important to consider that any site-specific seismic hazard assessment will have been developed for the specific ground conditions encountered at the site and it is likely that the ground conditions across the region will vary significantly.

A regional seismic hazard study will make allowance for such variability in ground conditions and this information should be reviewed if available. However, commissioning a regional seismic hazard study may not be warranted for a regional liquefaction vulnerability study because significant residual uncertainty will still remain from other sources. Deciding whether or not to commission such a study will be dependent on a number of factors such as the seismic hazard context in the region and whether the information will be utilised for other purposes (e.g. higher level of detail studies, earthquake-prone building assessment or infrastructure resilience strategy).

A summary of the seismic hazard information that has been utilised for the study should be included in the report. It is also useful to include supporting geospatial information such as mapped active faults in the region, the location of notable historic earthquake events, and information used to characterise the impact of ground conditions on site response (if available).

2.2.2.6 Observations of liquefaction from historic events

Observations of liquefaction from historic earthquake events provide an extremely valuable record. Observations of where liquefaction has and has not occurred following an earthquake are both useful for the evaluation of liquefaction susceptibility and triggering.

Such information can often be sourced from review of case study information and Fairless and Berrill (1984) provides a collection of observations from previous earthquake events. Mapped liquefaction observations from some historic events have been compiled by researchers at the NZ Centre for Earthquake Resilience (QuakeCoRE) and this information is available for visualisation and download via a web based portal (QuakeCoRE, 2020).

While very valuable, this information must be treated with caution because there are potential sources of uncertainty associated with this data including observer error and variation in physical conditions. The key sources of uncertainty associated with this information are discussed further in Section 2.2.3.

Where available, a summary of any observations of liquefaction in the region under consideration should be included in the report. It is useful for this to include a map showing the location of these observations with measurements and/or estimates of earthquake shaking intensity from the earthquake that triggered the liquefaction overlaid. If no observations of liquefaction are available in the region this should also be documented in this section of the report

2.2.3 Uncertainty assessment

The objective of this task is to evaluate the uncertainty in the assessment. This evaluation should focus on both the base information available and the methods applied to the base information to support the risk analysis.

A summary of the assessment of uncertainty should be included in the report. Where feasible it is useful to use maps to convey uncertainty. While the specific details of the uncertainty assessment will vary depending on the level of detail and the methods adopted, the following sections provide typical key sources of uncertainty for regional liquefaction vulnerability studies.

2.2.3.1 Ground surface levels

Accuracy of the national 8m DEM (if LiDAR derived DEM is not available)

As discussed in Section 2.2.2 this DEM was derived from interpolation of 20m contours. Therefore, it is only considered suitable for cartographic visualisation and to make general observations about differences in elevation across the region. This may be sufficient to support a Level A study however where the definition of boundaries between different sub areas of similar expected performance relies on this elevation data, appropriate allowances for this source of uncertainty will be required.

Temporal changes in ground surface elevation

To a greater or lesser extent, any ground surface will be undergoing some degree of change in elevation. These changes may be attributable to natural processes (e.g. earthquake induced ground deformation) or anthropogenic (man-made) changes (e.g. land development activities). These temporal changes may be identified by comparison of aerial imagery or DEM of the same area at different times.

Accuracy of LiDAR derived DEM (if available)

LiDAR derived DEM is relatively high resolution and considered suitable for use in a regional liquefaction vulnerability study. However, there are limitations with such data and if utilised the following issues should also be acknowledged and allowed for:

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

Note these issues are particularly relevant for the assessment of the heights of free faces to support the assessment of lateral spreading potential.

2.2.3.2 Geology and geomorphology

Precision of mapping and accuracy of boundaries between terrains

This can result in the incorrect categorisation of the land (if placed into the wrong geomorphology type) and hence incorrect estimation of ground performance. The scale of the mapping undertaken provides an indication of the degree of uncertainty and areas where there is more uncertainty associated with the location of the boundary should be identified.

Anthropogenic landform changes

Some anthropogenic landform changes, in particular those associated with large infrastructure or land development projects, can result in changes to the severity of liquefaction related land damage under seismic loading. In some cases these changes will result in an improvement of liquefaction performance (e.g. ground improvements such as dynamic compaction or stone columns) or in some instances there will be a degradation in liquefaction performance (e.g. reduction of the ground surface elevation resulting in a reduced depth to ground water, or new free faces allowing lateral spreading to occur). Historical aerial imagery can provide a useful source of information to identify areas where anthropogenic changes may have occurred.

2.2.3.3 Geotechnical investigations

Geotechnical investigation data quality

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

Variability in ground conditions within geomorphic terrains

Within each geomorphic terrain there is a degree of natural variability in ground conditions that results in a degree of variability in expected liquefaction related performance. Some geomorphic terrains, such as the beach and dunes, are likely to have a low degree of variability and this would be reflected in a relatively uniform estimate of liquefaction related performance for a constant depth to groundwater. Other geomorphic terrains, such as the reclamation fill and the alluvial terrains, are much more variable in the soil conditions encountered and this would be reflected in a relatively variable estimate of liquefaction related performance for a constant depth to groundwater.

To understand the potential variability in ground conditions it is useful to group CPT according to their geomorphic terrain and produce plots of CPT data outputs vs. depth. Such plots will enable a geo-professional experienced in liquefaction analysis to make a qualitative assessment of the variability in ground conditions and the likely performance of the soils under earthquake shaking.

Such analysis is typically only warranted in areas with sufficient CPT data to support a level B or higher liquefaction vulnerability study.

Spatial distribution and density of geotechnical investigations

Section 3.4 of the MBIE/MfE Guidance (2017) provides guidance about the required spatial density of ground information. It emphasises 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, not simply the investigation density. Specifically, it states that:

"The key requirement is that the investigations should be sufficient for adequate ground characterisation for the specific purpose of the assessment and ground conditions encountered."

With that noted it provides indicative spatial densities of deep ground investigations for adequate ground characterisation for liquefaction assessments. This includes typical average spacings between investigations for each level of detail. Using GIS analytics, maps of the study area showing the distance to the nearest investigation can be produced. This can provide an indication of the level of detail supported by the available geotechnical investigations. Such analysis is typically only warranted in areas with sufficient CPT data to support a Level B or higher liquefaction vulnerability study. Figure 9 provides an example of geospatial analysis showing distance to the nearest CPT within the same geomorphic terrain for reference.

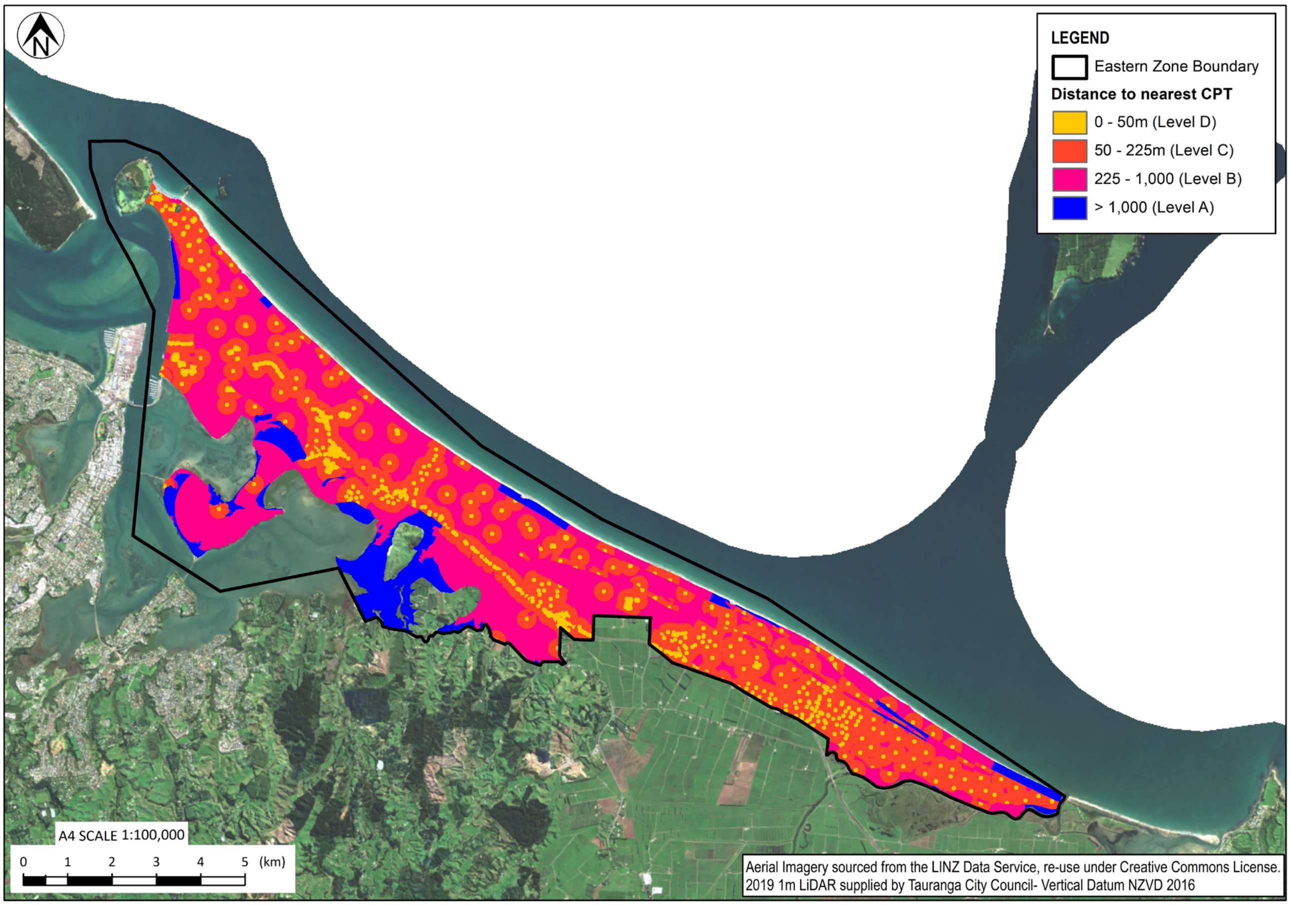


Figure 9: Example of geospatial analysis showing distance to the nearest CPT within the same geomorphic terrain reproduced from T+T (2020)

2.2.3.4 Groundwater

Spatial distribution and length of groundwater measurements (where available)

The distance between available measurements of groundwater records will govern how meaningful the interpolation of the depth to groundwater between these points is. Even in areas where the groundwater measurement network is expected to characterise the average large-scale patterns of groundwater level reasonably well, it may not capture localised small-scale variations. These localised variations could exist for various reasons, such as:

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

Similar maps to those showing the distance to the nearest geotechnical investigation can be produced for groundwater measurements. These can provide an indication of the level of detail supported by the available groundwater data. However, there is currently no specific guidance about typical average spacings between each measurement location for each level of detail. Figure 10 shows an example of a groundwater confidence index value map for reference.

As discussed in Section 2.2.2, it is also important to consider the length of groundwater measurements available because records that span at least one year are typically required to understand the potential seasonal fluctuations. While not critical for the areas where Level A detail is targeted, this information becomes increasingly important at higher levels of detail because it provides valuable information about the variability in groundwater levels.

Potential effects of climate change

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

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

It is very challenging to accurately predict changes in the distribution of rainfall at a future date. However, broad categorisations of areas where the depth to groundwater is likely to be reduced due to the effects of SLR can be made based on the proximity to coastal and harbour margins and the elevation above sea level.

The uncertainty associated with the available groundwater data does not contribute significantly to the uncertainty in areas where a Level A level of detail is targeted. However, it does represent a significant source of uncertainty in areas where a Level B (or higher) is targeted.

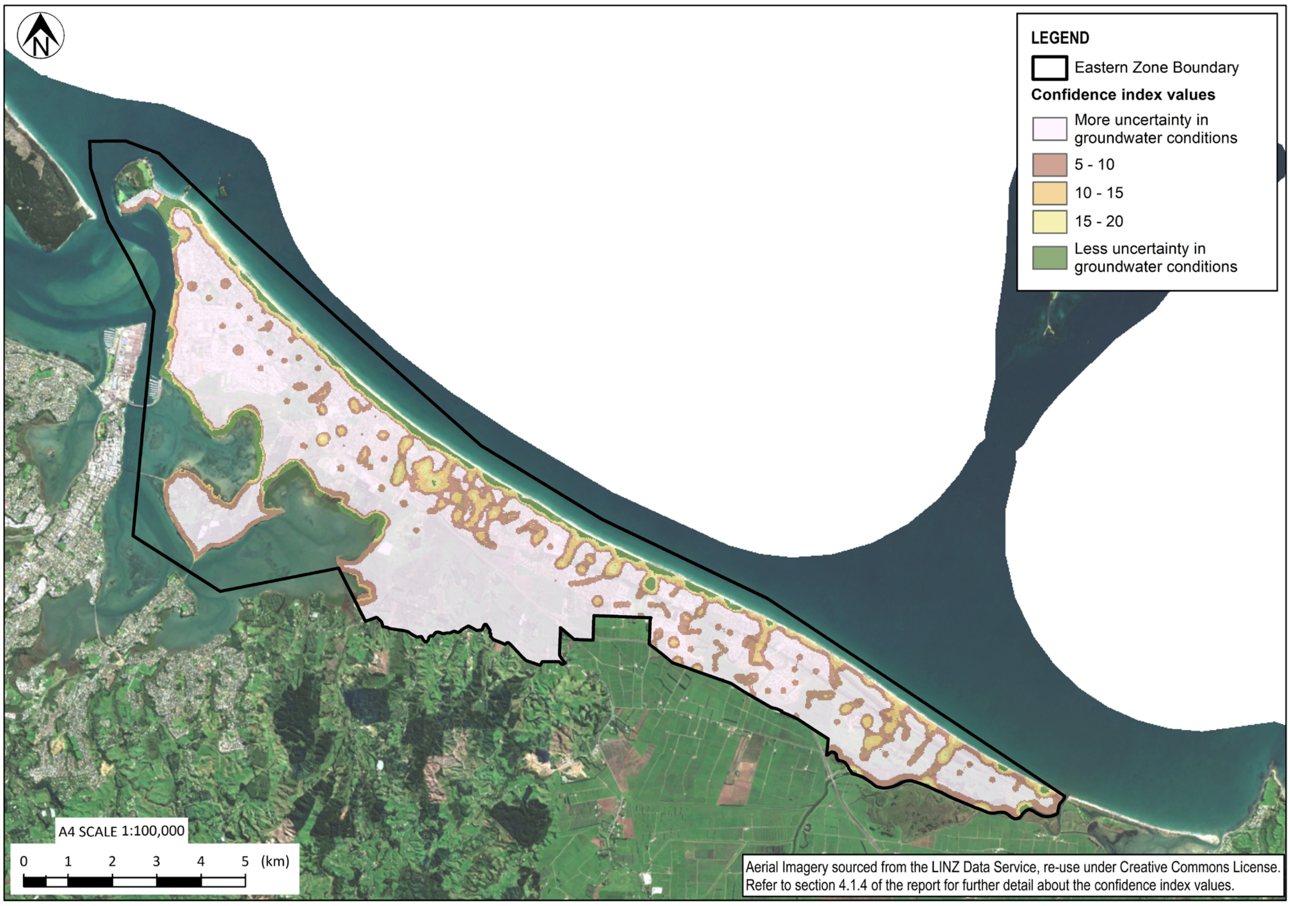


Figure 10: Example groundwater confidence index value map reproduced from T+T (2020)

2.2.3.5 Seismic hazard

NZTA Bridge Manual approach

Module 1 of the NZGS Earthquake Geotechnical Engineering Practice Guidelines (NZGS/MBIE, 2016) notes the following issues have been identified with the NZTA Bridge Manual approach:

1 Compatibility issues between the magnitude weighting factors embedded in the hazard evaluation and the magnitude scaling factors in the liquefaction evaluation procedures adopted in that guideline series

2 The use of an "effective earthquake magnitude"

3 The need to incorporate updates in the NSHM

A Level A study primarily involves the use of qualitative methods that do not rely heavily on the precise seismic hazard parameters adopted. Therefore, in areas where Level A is targeted, the uncertainty associated with the methods used to calculate seismic hazard parameters are unlikely to contribute significantly to the residual uncertainty in the assessment. Similarly, for areas where Level B detail is targeted this uncertainty in seismic hazard can typically be managed with sensitivity testing of any quantitative liquefaction analysis undertaken.

Regional or site-specific seismic hazard assessment (if available)

If a regional or site-specific seismic hazard assessment has been produced by a suitably competent practitioner, this will typically provide a significant improvement in the understanding of seismic hazard and a corresponding reduction in the associated residual uncertainty. However, even with these methods a degree of residual uncertainty will remain in the assessment.

Similar to the NZTA Bridge Manual approach, for a Level A study, the uncertainty associated with the methods used to calculate seismic hazard parameters are unlikely to contribute significantly to the residual uncertainty in the assessment. However, where quantitative liquefaction analysis is proposed (i.e. Level B or higher) more detailed assessment of uncertainty may be warranted.

Two key sources of uncertainty associated with regional and site-specific hazard assessments include:

- The methodology applied to develop the seismic hazard curves proposed in the assessment – typically this requires expert judgement, and evaluation of these uncertainties may be a role best suited to an independent peer reviewer if such expertise is not available within the consultancy commissioned to undertake the study.
- The information used to characterise the impact of ground conditions on site response. The nature of the uncertainty assessment required typically varies as follows depending on whether the study is a regional or site-specific:
  - For a regional study, such evaluation may be undertaken using a combination of geospatial analytics and sensitivity testing of the quantitative liquefaction analysis methods to be used in the assessment. These are core skills required in a consultancy undertaking regional liquefaction vulnerability studies in accordance with the MBIE/MfE Guidance (2017).
  - For a site-specific study this requires expert judgement, and this may also be a role best suited to an independent peer reviewer if such expertise is not available within the consultancy commissioned to undertake the study.

To manage seismic hazard uncertainty the MBIE/MfE Guidance (2017) recommends the consideration of a series of simple earthquake scenarios with an assessment of what the consequences could be before progressing into detailed analysis - for example small, moderate and extreme (low probability) events. Specifically, the MBIE/MfE Guidance (2017) notes that:

"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."

2.2.3.6 Observations of liquefaction from historic events

For a regional liquefaction vulnerability study, observations of liquefaction are a clear indication that the soil is susceptible to liquefaction. In this case the primary issue to consider in the assessment of uncertainty is whether observer error resulted in land damage being incorrectly attributed to liquefaction.

Similarly, 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 the future. However, there are some complexities associated with this and the MBIE/MfE Guidance (2017) provides the following examples:

- It is possible that the soil is susceptible to liquefaction, but the intensity and/or duration of shaking was not sufficient to trigger liquefaction
- It is possible that liquefaction was triggered at depth in the soil but there was no surface evidence of liquefaction, and greater intensity and/or duration of shaking may be required to induce liquefaction damage at the ground surface
- There may have been surface evidence of liquefaction occurring, but the observation was not recorded or was attributed to some other cause such as flooding.

2.2.3.7 Expected degree of liquefaction-induced ground damage

Qualitative assessment methodss

For a regional Level A liquefaction vulnerability study the uncertainty associated with the estimation of liquefaction-induced ground damage will largely relate to matters of engineering judgement. The impact of this uncertainty will likely be most significant where there is yet to be clear consensus of expert judgement or zones of transition between areas of similar expected performance.

In such cases it is important to remember that the main objective of a Level A study is to identify land where there is a high degree of certainty that Liquefaction Damage is Unlikely. This means that in areas where there is yet to be clear consensus of expert judgement, the pragmatic approach will likely be classify the land as “Liquefaction Vulnerability Category is Undetermined” until more information or improved understanding becomes available in future. This is particularly relevant for areas where there is no immediate need to classify the liquefaction vulnerability more precisely (e.g. in a remote rural area where there is little new land development occurring).

Quantitative assessment methods

For a regional Level B liquefaction vulnerability study qualitative engineering judgement is likely to be supported by quantitative liquefaction analysis. In these cases, the uncertainty associated with the estimation of liquefaction-induced ground damage will also be influenced by the inherent limitations associated with quantitative methods adopted.

While the specific details of the uncertainty will relate to the method applied, it is useful to consider the uncertainties as they relate to the following key steps in the application of quantitative methods:

1 Evaluate whether the soil is susceptible to liquefaction

2 Estimate the earthquake shaking level required to trigger liquefaction for soils that are susceptible to liquefaction

3 Estimate the likely consequences of liquefaction triggering within the soil profile.

By evaluating the uncertainty associated with each of these steps and communicating these issues to the reader a clearer picture of the overall uncertainty in the method adopted can be conveyed.

2.2.3.8 Liquefaction vulnerability category assessed against performance criteria

The MBIE/MfE Guidance (2017) provides the performance criteria shown in Figure 11 to determine the liquefaction vulnerability category for a particular area of land.

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

For Level A/B liquefaction vulnerability studies the level of confidence will ultimately be evaluated qualitatively with these indicative probabilities used as guidance. With any qualitative assessment, it will be necessary to apply a degree of judgement to determine the liquefaction vulnerability category for each area of land and there is inherent uncertainty associated with this subjective process.

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

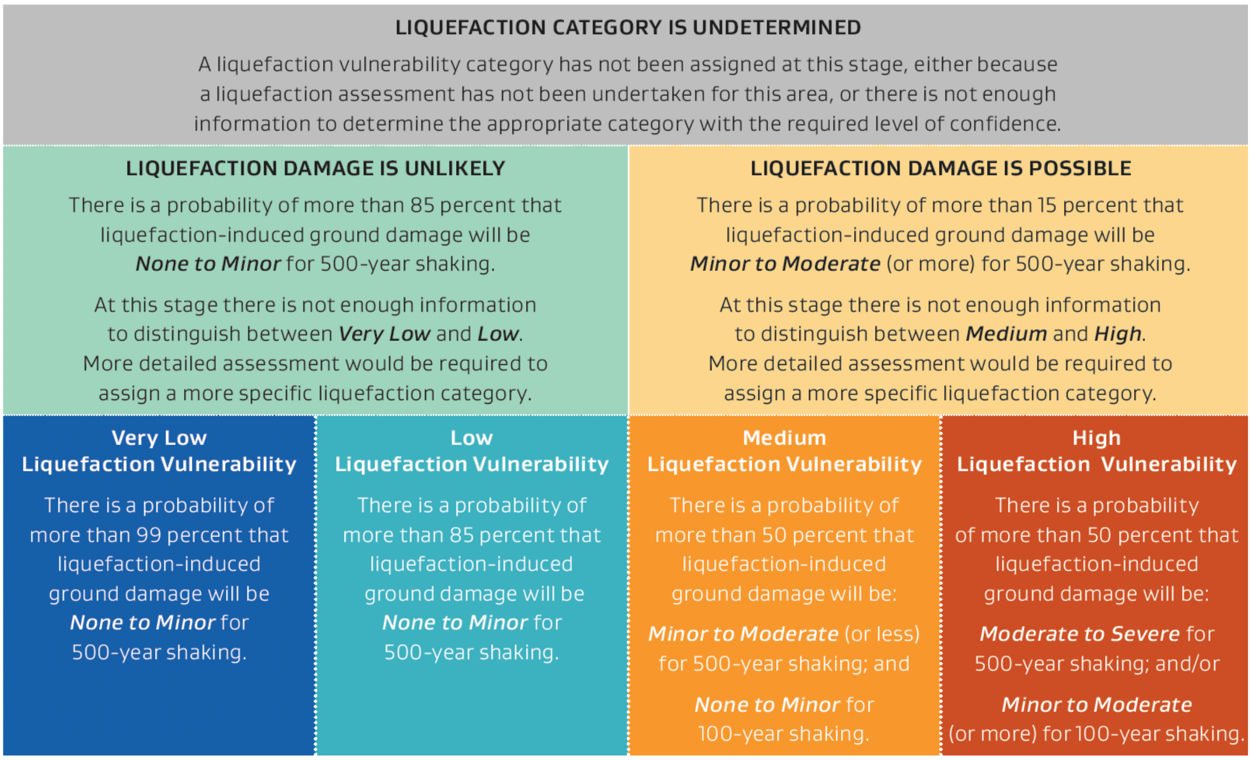


Figure 11: Performance criteria for determining the liquefaction vulnerability category – reproduced from MBIE/MfE Guidance (2017)

2.2.4 Level of detail supported by the available information

The uncertainty assessment is a key input in the evaluation of the level of detail supported by the currently available information (Level of Detail Supported). The key input into the Level of Detail Supported is the overall degree of residual uncertainty associated with the assessment. Table 3.1 of the MBIE/MfE Guidance (2017) summarises the degree of residual uncertainty associated Level A and Level B studies as follows:

- **Level A residual uncertainty –** the primary focus is identifying land where there is a High degree of uncertainty that Liquefaction Damage is Unlikely (so that 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 residual uncertainty –** due to 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.

A summary of the rationale applied and accompanying map of the region showing the Level of Detail Supported should be included in the report. This map should be provided in geospatial format and in accordance with the standard data format provided in Appendix E of the MBIE/MfE Guidance (2017). Figure 12 shows an example map showing the level of detail supported by the available base information.

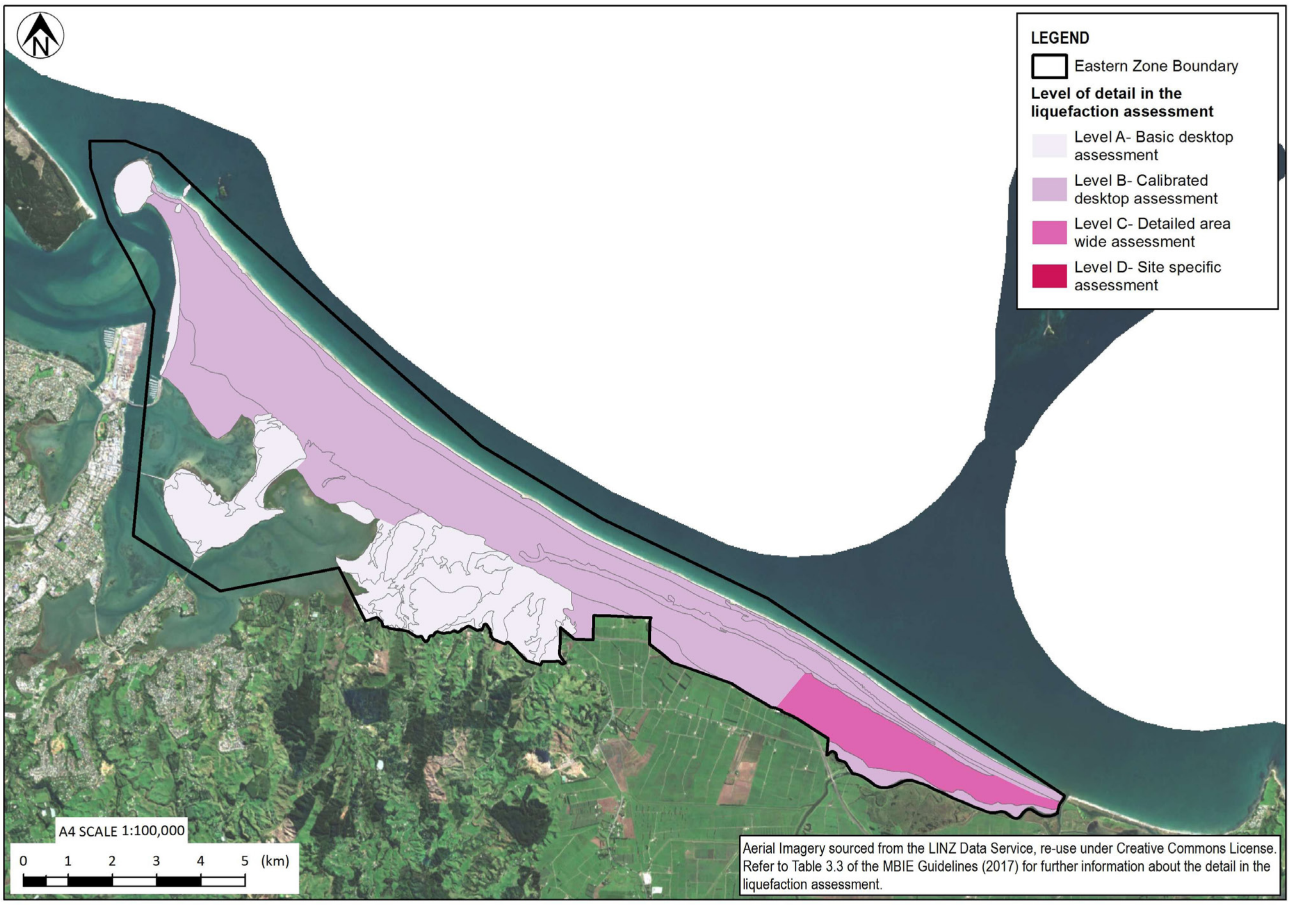


Figure 12: Example map showing the level of detail supported by the available base information. Reproduced from T+T (2020)

2.3 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 land damage. The key tasks in this step involve the following:

- Choosing groundwater levels to support the analysis
- Choosing earthquake scenarios to support the analysis
- Identifying sub-areas of similar expected performance
- Evaluating the expected degree of liquefaction-induced ground damage
- Assessing the liquefaction vulnerability category against the performance criteria

Each of these key tasks is discussed in further detail in the following sections and further information is provided in Section 4 of the MBIE/MfE Guidance (2017).

2.3.1 Groundwater levels for analysis

As described in Section 4.2.3 of the MBIE/MfE Guidance (2017) it is recommended that the average (median) groundwater level be adopted for the assessment of liquefaction vulnerability. The rationale for adopting the average groundwater level is to avoid issues of compounding conservatism associated with assuming a low probability earthquake event (e.g. 1 in 500-year return period) would occur at the same time as the seasonally high groundwater level. Once the average condition is understood, the effects of seasonally low and high groundwater conditions or climate change and sea level rise can be understood with sensitivity analysis.

For areas where a Level A study is supported by the available base information, it is likely that only qualitative statements about the likely groundwater conditions will be able to be made and a high degree of residual uncertainty about groundwater conditions will remain. In such cases it is useful to assume a typical depth to groundwater across a broad area (such as geomorphic terrains). Similar qualitative assumptions about the areas where there is the potential for sea level rise to influence groundwater depth (e.g. low elevation coastal margins where liquefiable soils are likely to be present) should also be made as part of this assessment. However, care should be taken in relying too heavily on these qualitative assumptions for the final assessment of liquefaction vulnerability as the true depth to groundwater may vary significantly across such a broad area.

The qualitative groundwater assessment does provide important (and useful) information to the reader about the potential next steps for higher level of detail studies within each broad area. For example, if the Level A study indicates that a relatively deep depth to groundwater (e.g. >8m) is likely to be present within a geomorphic terrain and groundwater is not expected to be influenced by sea level rise, a logical first step is to test this assumption with simple site specific geotechnical investigations such as hand auger boreholes. If the assumption is demonstrated to be true, subject to the ground conditions encountered at the site, it may be possible to categorise the land as Liquefaction Damage is Unlikely. If the assumption is demonstrated to be false, further work may be warranted to assess the liquefaction vulnerability at the site.

In areas where ongoing groundwater measurements of at least one calendar year are available numerical calculation of the median groundwater level is recommended and it may be warranted to develop depth to groundwater models. As noted previously such detailed groundwater information is not a requirement for regional liquefaction vulnerability studies but they do provide valuable screening tools when available.

This improved precision in groundwater information does not remove the need to consider the residual uncertainty associated with the groundwater model and sensitivity testing of any quantitative liquefaction analysis is still recommended. Like the qualitative assessment, an assessment of the potential effects of climate change and sea level rise will be required and Section 4.2.4 of the MBIE/MfE Guidance (2017) provides recommendations for undertaking such assessments.

A summary of the groundwater scenarios adopted for the assessment should be provided in the report. It is not expected that any additional geospatial maps would be required to support this summary as these should be provided as part of the risk identification process.

2.3.2 Earthquake scenarios for analysis

As discussed in the MBIE/MfE Guidance (2017), the minimum recommended earthquake scenario for regional liquefaction vulnerability studies is the 500-year return period and this should be the primary scenario used to assess the liquefaction vulnerability category against the performance criteria.

For Level A studies it is also useful to consider an Extreme (low probability) earthquake scenario as a sensitivity test for the liquefaction vulnerability classification. It is calculated by multiplying the 500-year return period PGA by 150 percent as recommended in Section 4.3 of the MBIE/MfE Guidance (2017). This sensitivity test is intended to be used to provide additional background information (e.g. "what if" questions) to help guide development of natural hazard management strategies.

This approach is also particularly useful for managing any residual uncertainty in the seismic hazard information. If the extreme scenario results in a large step-change worsening of land performance compared to the 500-year scenario (e.g. 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.

If quantitative liquefaction analysis is included as part of the assessment (Level B or higher studies), the following additional scenarios may also be considered as part of a regional study:

- **25-year earthquake scenario –** for most buildings in New Zealand this is the earthquake scenario specified by NZS 1170.0:2002 for the Serviceability Limit State design case. Proactive consideration of this earthquake scenario at a regional level can be useful to confirm the land performance will be suitable for building purposes.
- **100-year earthquake scenario** – this earthquake scenario will be required for the assessment of Level C/D studies. Similar to the 25-year scenario, proactive consideration at a regional level can be useful to guide the requirements of any more detailed site-specific studies and understand whether there are any areas with higher or lower likelihood of liquefaction induced ground damage occurring.

A summary of the earthquake scenarios adopted for the assessment should be provided in the report. It is not expected that any additional geospatial maps would be required to support this summary as these should be provided as part of the risk identification process.

2.3.3 Sub areas of similar expected performance

For a regional liquefaction vulnerability study, sub-areas of similar expected performance can be created by grouping areas of land according to the following characteristics:

- **Geomorphic sub-areas** – geomorphic maps are recommended as the primary basis to evaluate the likely soil conditions within each sub-area of similar expected performance. Geological maps can be used but this should be undertaken with caution because in some instances these provide more information about the underlying lithology rather than the surficial soils.
- **Topographic sub-areas** – elevation data can be utilised to divide the into broad topographic categories such as hilltops, ridges and elevated land, sloping land and flat lowland areas. This is a useful means of subcategorization because it allows further refinement of the qualitative assessment of groundwater depth.

  This topographic screening approach should only be applied when there is a reasonable degree of certainty associated with the accuracy of the elevation data available. For example, it is more likely to be suitable in areas where LiDAR derived DEM's are available. Post processing of the available DEM using GIS analytics can help improve the efficiency and accuracy of such an approach, however careful manual review of the outputs would be required to evaluate the accuracy of the method applied.
- **Lateral spread sub-areas** – a high level screening of areas where lateral spreading is more likely to be possible can be provided by applying an appropriate buffer distance to mapped waterbodies. The MBIE/MfE Guidance (2017) notes that attention should be given to liquefaction susceptible land within 200 m of a free face greater than 2 m high. This 200 m buffer is recommended as a simplified screening tool for regional liquefaction vulnerability studies.

  Note that it is possible that areas outside of this buffer zone could also be subjected to lateral spreading damage and it is recommended that this be considered as part of the overall liquefaction vulnerability assessment. It is also important to evaluate the accuracy of any mapping of water bodies – in some instances there is significant discrepancy between the mapped and actual location of the water bodies on publicly available sources.

A summary of the sub-areas of expected performance utilised for the study should be included in the report. To illustrate the process, it may be useful to include maps showing how the various sources of information used to define these sub-areas overlap.

2.3.4 Expected degree of liquefaction-induced ground damage

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

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

Detailed descriptions of each of the three land damage categories, including photographic examples from the Canterbury earthquakes, are provided in Section 2.5 and Appendix A of the MBIE/MfE Guidance (2017).

Section 4.4 of the MBIE/MfE Guidance provides a range of methods that can be used to determine the expected degree of liquefaction induced ground damage in accordance with the descriptions above. For a regional liquefaction vulnerability study predominantly qualitative assessment and semi-quantitative assessment methods should be utilised. The quantitative methods provided are typically only suitable for Level C and D studies where sufficient information is available to support these more complex analytical methods.

A summary of the methods used to estimate the expected degree of liquefaction-induced ground damage should be included in the report. It may be useful to include maps and summary plots to illustrate the methods adopted, in particular when quantitative calibration methods are used.

2.3.5 Liquefaction vulnerability category assessed against performance criteria

The final step in the process is to assess the liquefaction vulnerability of each sub area against the performance criteria. The end result of that assessment is a map showing the assigned liquefaction vulnerability categories in Figure 9. As discussed in Section 1.1, regional scale studies typically result in categorisation of the land into one of the top three vulnerability categories of "Liquefaction Category is Undetermined" or "Liquefaction Damage is Unlikely" or "Liquefaction Damage is Possible".

A copy of the map in geospatial format is a necessary output of the liquefaction vulnerability study. This should be provided in accordance with the standard data format provided in Appendix E of the MBIE/MfE Guidance (2017). Figure 13 shows an example liquefaction vulnerability category map.

The map itself should be relatively self-explanatory, however it can be useful to include a summary of the assessment undertaken within specific areas to illustrate the process applied and provide information to guide potential next steps in the liquefaction vulnerability assessment process. For a regional liquefaction vulnerability study, it is logical that this summary be based on the broad sub-areas of similar expected performance, such as geomorphic terrains.

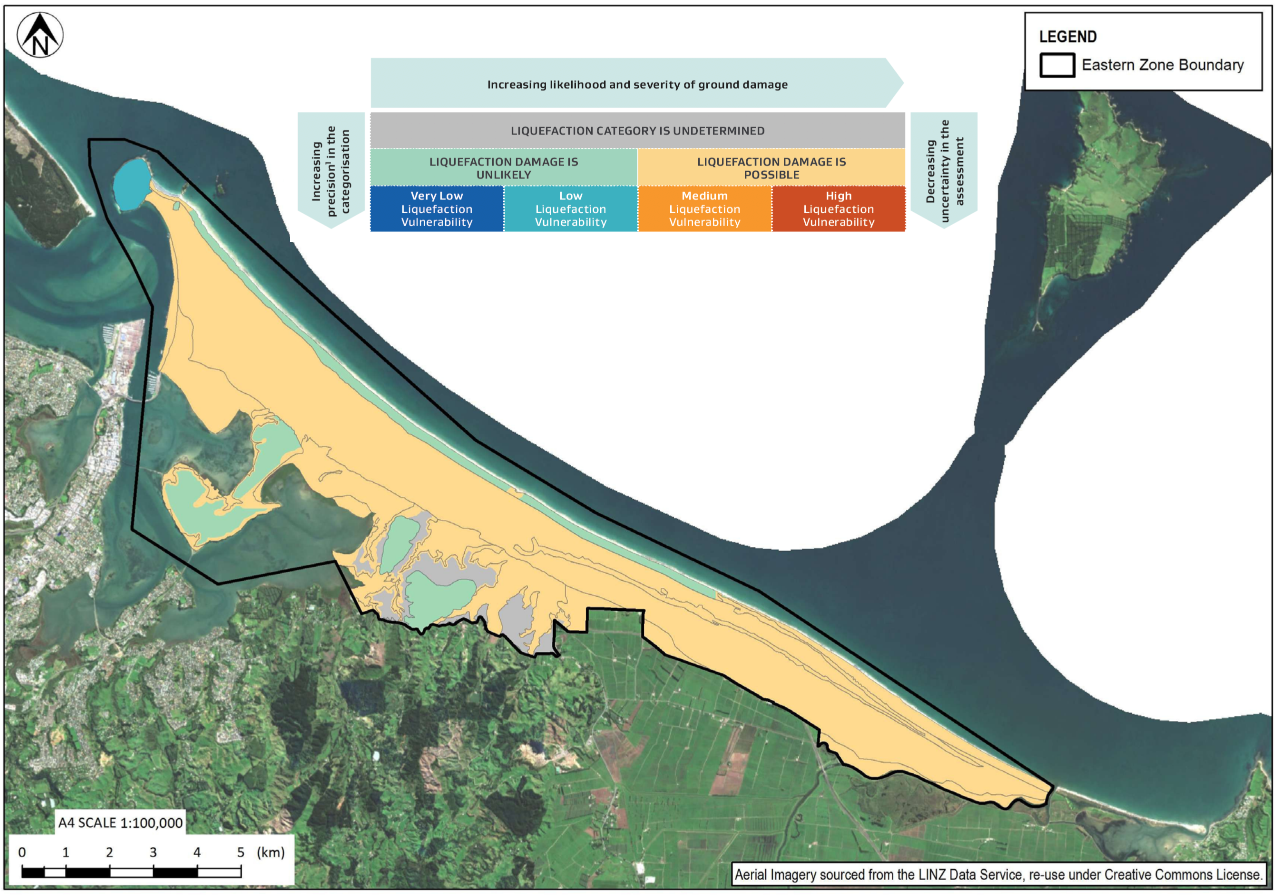


Figure 13: Example liquefaction vulnerability category map reproduced from T+T (2020)

2.4 Conclusions and recommendations

This section of the report should highlight the key sources of uncertainty in the assessment and provide recommendations for potential next steps. They key sources of uncertainty for a regional liquefaction vulnerability study and the associated recommendations are likely to include:

- **The availability of geotechnical investigations –** to help facilitate the collection of more geotechnical investigations the following recommendations can be made:
  - Identify geotechnical investigations from historic projects within the region and upload these onto the NZGD
  - Encourage the uploading of supporting geotechnical investigations onto the NZGD as part of the process of evaluating resource and building consents
  - Engage suitably competent geo-professionals to undertake geotechnical investigations within the study area where more information about the ground conditions is required (e.g. areas where Level B detail is targeted)
- **The availability of groundwater data –** installing a network of piezometers to monitor groundwater level fluctuations over time and developing depth to groundwater surface models from this data can help reduce this potential source of uncertainty.
- **The available seismic hazard information –** Providing a recommendation to commission a regional seismic hazard assessment will be dependent on a number of factors such as the seismic hazard context in the region and whether the information will be utilised for other purposes (e.g. higher level of detail studies, earthquake-prone building assessment or infrastructure resilience strategy).

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