Tonkin+Taylor

Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology

Prepared for
Chapman Tripp acting on behalf of the Earthquake Commission (EQC)

Prepared by
Tonkin & Taylor Ltd

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Exceptional thinking together

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Executive Summary

I. About this Report

This report sets out the methodology used by Tonkin & Taylor Ltd (**T+T**) to assess the land damage known as "Increased Liquefaction Vulnerability" which resulted from the 2010-2011 Canterbury Earthquake Sequence (**CES**). This type of damage to residential land is covered by statutory insurance under the Earthquake Commission Act 1993 (**EQC Act**).

The report is prepared for Chapman Tripp, Solicitors, acting on behalf of the Earthquake Commission (**EQC**).

The report has been peer reviewed by an expert review panel, comprising world-leading liquefaction researchers from several universities – Canterbury; California, Berkeley; California, Davis; and Cornell.

II. Some Key Terms

The methodology discussed in this report is for assessing Increased Liquefaction Vulnerability (or **ILV**). The report differentiates between the following key terms:

- **Liquefaction** – this is the process by which earthquake shaking increases the water pressure in the ground in sandy and silty soil layers resulting in temporary loss of soil strength. Liquefaction can give rise to significant land and building damage, for example through the ejection of sediment to the ground surface, differential settlement of the ground due to volume loss in liquefied soil and horizontal movement of the ground;
- **Liquefaction Vulnerability** – this refers to the vulnerability of land to liquefaction-related land and building damage in future earthquakes;
- **Increased Liquefaction Vulnerability** – this refers to the physical change to land as a result of ground subsidence from an earthquake which *materially increases* the vulnerability of that land to liquefaction damage in future earthquakes.

The methodology set out in this report is designed to assess Increased Liquefaction Vulnerability (as opposed to Liquefaction or Liquefaction Vulnerability by themselves).

III. Increased Liquefaction Vulnerability (ILV)

Engineering Criteria

EQC has determined that, in assessing whether residential land has sustained ILV damage, the following two engineering criteria must be met:

- **Criterion 1** – the residential land has a *material* vulnerability to liquefaction damage after the CES; and
- **Criterion 2** – the vulnerability to liquefaction damage of the residential land in future earthquakes has *materially increased* as a result of ground surface subsidence of the land caused by the CES.

The material vulnerability under Criterion 1, and the material increase in vulnerability under Criterion 2, are each measured at up to 100 year return period levels of earthquake shaking.

Assessing what is "Material" Under the Engineering Criteria

These engineering criteria require an assessment of what level of liquefaction vulnerability (and what level of *change* in liquefaction vulnerability) can properly be regarded as "material". This assessment is described at Section 4.2.5 of the report. The assessment takes into account:

- That predictions of liquefaction vulnerability at the individual property level will sometimes not be precise;
- That some changes in liquefaction vulnerability are likely to impact the suitability of the land for use as a residential building platform and for other related purposes.

Valuation Criteria

Identifying ILV also involves a valuation assessment. This assessment is addressed in a separate report by EQC's valuers.

IV. Framework for the ILV Assessment Methodology

The methodology described in this report (**ILV Assessment Methodology**) has been developed iteratively over the last four years. Substantial amounts of new information, which have become available during this time, have been taken into account.

In the development process, T+T has focused on the objectives of the methodology, identified important principles that must be applied consistently, and formulated the assumptions that underpin the methodology.

Objectives of the Methodology

The general objectives of the ILV Assessment Methodology are to:

- Provide a basis for the settlement of claims involving ILV land damage. This basis has to be consistent with EQC's obligations under the EQC Act, and be in accordance with the best available scientific understanding of ILV and the information available to EQC; and
- Provide a consistent treatment of the issues associated with ILV land damage, given the large number of properties affected by ILV land damage as a result of the CES.

In accordance with the requirements stated in the High Court judgement in *Earthquake Commission v Insurance Council of New Zealand* (the **Land Declaratory Judgement**), the ILV Assessment Methodology is designed to ensure that:

- It can be applied in good faith;
- It is not applied mechanically; and
- It does not exclude consideration of factors that are relevant to any particular case.

Important Principles Applied in the Methodology

The ILV Assessment Methodology:

- Enables assessment of whether a property meets the engineering criteria for ILV on the balance of probabilities;
- Takes into account relevant publicly available information. However, as part of a separate review process, any claimant is entitled to provide further information (or an alternative interpretation of existing information) regarding whether their particular property has ILV land damage;
- Considers the change to liquefaction vulnerability across the entire CES. A separate process then considers which individual earthquakes are likely to have contributed to that change. There are practical reasons for this approach (see Section 2.7.3 of the report).

Information used in the Methodology

The sources of information used in the ILV assessment methodology include:

- Geological and soil maps;

- Ground surface levels derived from LiDAR surveys;
- Groundwater levels throughout Christchurch, which have been the subject of ongoing monitoring;
- Soil composition data obtained from extensive geotechnical investigations, including Cone Penetrometer Tests (**CPT**), subsurface drilling, and laboratory tests;
- Aerial photographs taken after each of the main earthquakes in the CES;
- Land performance observations in the CES relative to the estimated levels of shaking in each of the earthquakes.

Most of this information is on the Canterbury Geotechnical Database (**CGD**). This database is publically available to a range of organisations, including EQC, insurers, local authorities, and professional engineering companies involved in the Canterbury recovery. The only information not sourced from the CGD is the EQC Land Damage Assessment (**LDAT**) Reports, which were prepared by T+T following the inspection of each property.

Assumptions Underpinning the Methodology

The ILV Assessment Methodology is underpinned by some key assumptions, including the following:

- *Vulnerability is based on an up to 100 year return period level of shaking* – Section 6.3.1 of the Report explains why the selection of this up to 1 in 100 year return period level provides a reasonable basis on which to assess liquefaction vulnerability, and is consistent with the assessment of other natural land hazards;
- *Loss of land crust integrity as a result of cracking is not taken into account* – It is assumed that compensation paid by EQC for such cracking is used to repair the cracks. On that basis, the repaired cracks will not provide a pathway for the ejection of liquefied soil, and accordingly will not contribute to increased liquefaction vulnerability.

The detailed reasons for these and other assumptions are set out at Section 6 of the report.

V. Process for the ILV Assessment Methodology

The ILV Assessment Methodology process is outlined in Figure i below.

To summarise the key phases of the methodology:

- **Phase 1** – involves determining which parts of the Christchurch area need to be assessed for ILV. It was decided that all TC1, TC2, and TC3 and flat land Red Zone residential properties would go through to the Phase 2 assessment. The remaining properties (Port Hills, rural, and commercial) have not been assessed. They will only be assessed on a case by case basis as required;
- **Phase 2** – asks the question “is there sufficient information to do the ILV assessment?” If there is not, more information is obtained about the property. This is mainly geotechnical information and includes CPT data, borehole logs, laboratory testing data and groundwater information;

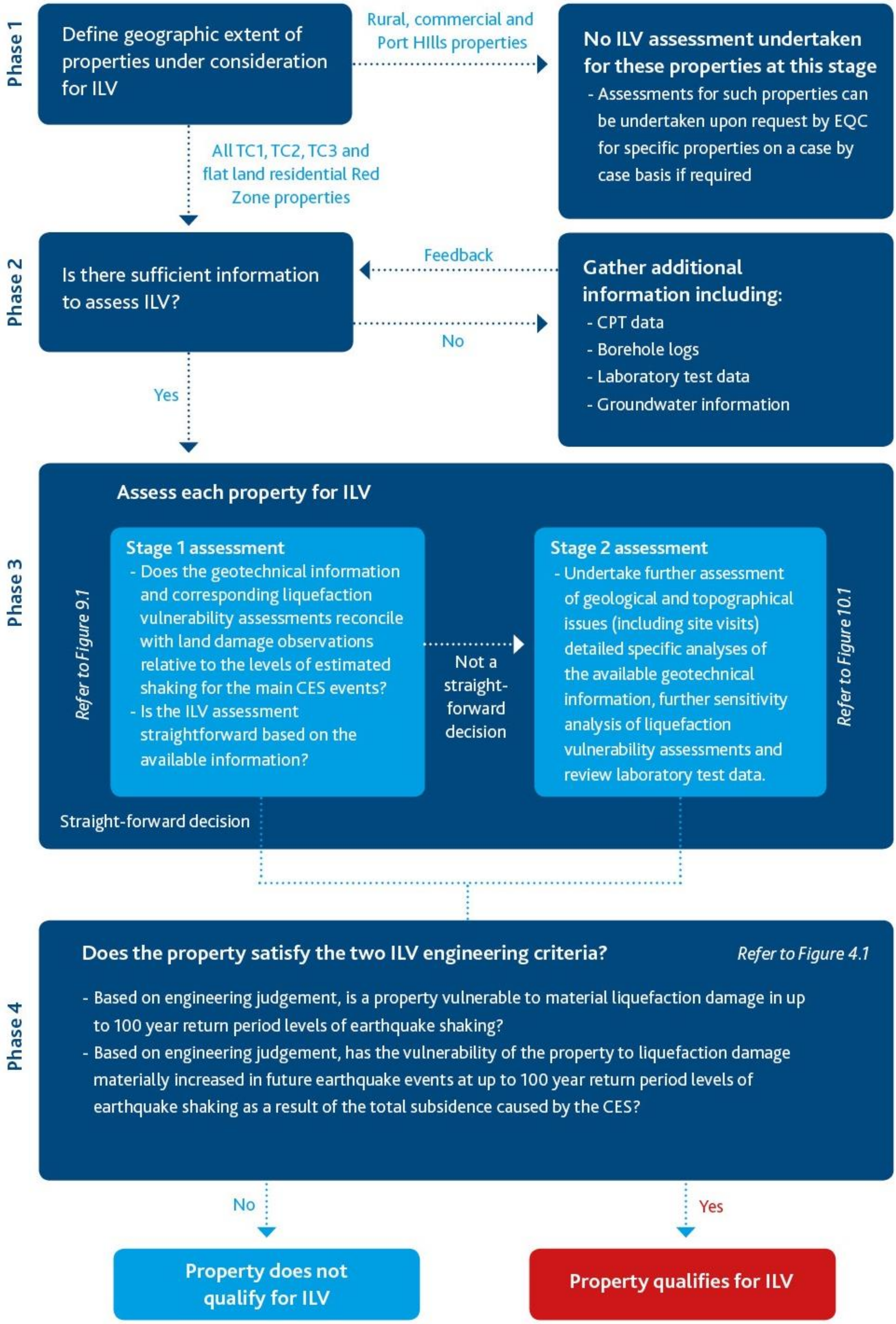

Figure i– Process for ILV Assessment Methodology

- **Phases 3 and 4** – ask whether the residential land meets the two engineering criteria (described under iii. above). Phase 3 involves two assessment stages which feed into the decision making process of Phase 4:
  - **Stage 1** – At this stage, the question is broadly whether the geotechnical information reconciles with land damage observations for the main CES earthquakes. If the information and the observations do reconcile and the ILV assessment decision is straightforward for a property, then the result will either be a 'yes' or 'no' for the engineering criteria for ILV land damage. Over 133,000 properties have been resolved at Stage 1. If the decision is not straightforward, then there is a more detailed assessment under Stage 2;
  - **Stage 2** – This stage involves a further assessment of geological and topographic matters (including in some cases, site visits); more detailed analysis of the available geotechnical information; a sensitivity analysis of liquefaction vulnerability assessments; and the review of laboratory test data. Based on this assessment, a final decision is made. The result for the 6,000 to 7,000 remaining properties is either 'yes' or 'no' for the engineering criteria for ILV land damage.

VI. Automated ILV Model and Manual Assessments

The ILV Assessment Methodology in both Stages 1 and 2 uses:

- An automated ILV model, based on LSN parameters (described below); and
- A manual ILV assessment which uses all publicly available data and considers the results of the automated ILV model.

Liquefaction Severity Number (LSN) Parameter

The ILV Assessment Methodology uses a liquefaction vulnerability parameter called the Liquefaction Severity Number (**LSN**). This parameter is estimated from the CPT test results. The LSN indicates the vulnerability of land to liquefaction-related damage at a particular level of shaking. Importantly however, the LSN parameter is just one of several tools available for the engineering assessment of ILV. Each ILV assessment has involved the reconciliation of the LSN parameter with the other tools and information.

To illustrate the use of the LSN in relation to the two engineering criteria (see iii. above):

- The LSN value of 16 has been chosen as an indicator of material liquefaction vulnerability for the purpose of engineering Criterion 1;
- A difference of 5 LSN units between the LSNs before and after the CES has been chosen as an indicator of the level of material change in vulnerability under engineering Criterion 2.

The reasons for the use of the LSN in this way are set out in detail at Section 7 of the report. Notably:

- The LSN value of 16 is considered to be generally representative of the transition between land which is materially vulnerable to liquefaction and land which is not. The selection of the LSN value of 16 as an indicator has been informed by land and building performance across the CES; and
- The difference of 5 LSN units is considered the minimum practical value for the assessment of ILV to enable confidence that, on the balance of probabilities:
  - A material change in vulnerability has occurred; and
  - The change is material having regard to the use of the land for a residential building platform or other related purpose.

Automated ILV Model

An automated ILV model was developed using the estimated LSN values and change in LSN values, which were derived from the CPT tests. This model was used to:

- Indicate on a regional basis where the residential properties are likely to qualify for ILV; and
- Assist with the manual ILV assessment for the 139,390 urban residential properties in Christchurch (see below).

However, while the automated model is useful to assist the manual process, it had two key limitations:

- The automated model does not account for differences in soil profiles, or topographic transitions (for example, changing ground conditions due to old silted-up river channels), which may occur between the CPT data points;
- The modelling of LSN and hence the automated ILV model is subject to a range of uncertainties. The only way to overcome these is to use engineering judgement to manually review the liquefaction vulnerability results of the automated model.

Manual ILV Assessment

The manual assessment for determining ILV qualification is divided into several tasks. First, regional level data are considered. Then local data packs comprising a number of neighbouring properties (typically 20 for areas of reasonable complexity) are analysed. The qualification status for each property is then reviewed by a senior engineer to ensure an appropriate and consistent outcome. The results are then entered into a database for a final review by the senior technical review team and the project director.

This manual process is the same for both the Stage 1 and Stage 2 assessments. However, the more complex Stage 2 assessments require more detailed analysis.

VII. ILV Assessment Methodology Results

The ILV Assessment Methodology has generated results about the location of properties with ILV land damage. Those results are consistent with the areas where ILV land damage was expected, given the typical characteristics of land with such damage.

The results are shown in Figure ii below. This figure shows areas where properties satisfy the engineering criteria for ILV (red); which have material liquefaction vulnerability (but not ILV) (purple); and which do not have material liquefaction vulnerability (blue).

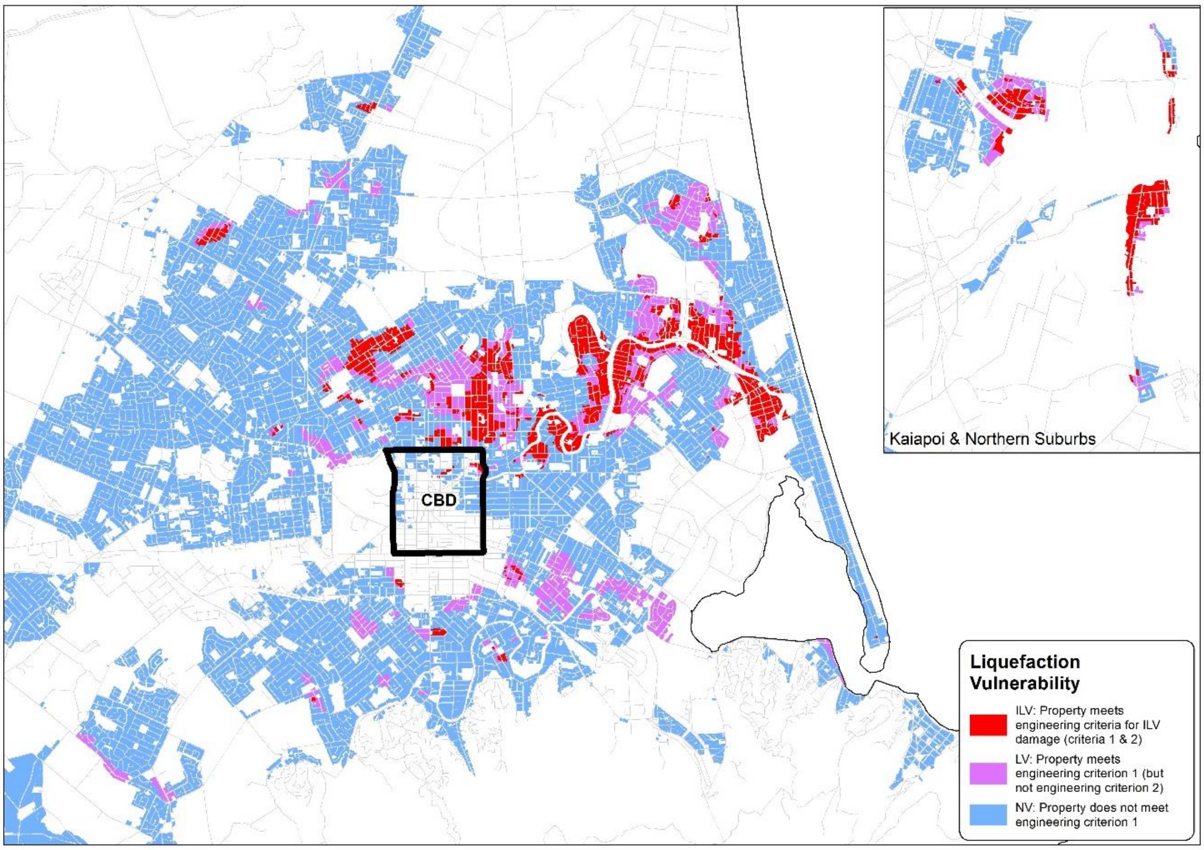

Figure ii: ILV assessment results after the completion of the Stage 2 assessment. The map also shows the properties with material liquefaction vulnerability and properties without it. The white areas on the map represent the non-urban and non-residential land in Christchurch.

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… nature oftentimes breaks forth

In strange eruptions; oft the teeming earth

Is with a kind of colic pinched and vexed …

Henry IV, Part 1, Act III, Scene 1

1 Introduction

This report is prepared for Chapman Tripp (**CT**) on behalf of the Earthquake Commission (**EQC**) and sets out the methodological approach (the **ILV Assessment Methodology**) used by Tonkin & Taylor Ltd (**T+T**) to assess the adverse change in vulnerability to liquefaction damage of residential land due to ground surface subsidence caused by the 2010 to 2011 Canterbury Earthquake Sequence (**CES**). Where an adverse change in liquefaction vulnerability affects the uses and amenities of residential land, EQC proposes to recognise the ground surface subsidence as a type of land damage to which the statutory insurance provided by the Earthquake Commission Act 1993 (the **EQC Act**) responds.

This land damage type is referred to as '*Increased Liquefaction Vulnerability*' (**ILV**) by EQC and is referred to as such in this report.

Increased Liquefaction Vulnerability (or **ILV**) is a physical change to residential land as a result of ground surface subsidence from the CES which adversely affects the uses and amenities that would otherwise be associated with the land by materially increasing the vulnerability of that land to liquefaction damage in future earthquakes.

The methodology for the engineering assessment of ILV has been decided by EQC based on the requirements of the EQC Act, legal advice, policy and engineering considerations.

1.1 Structure

This report is organised into the following sections:

- **Section 2** describes the legal and analytical framework and objectives of the ILV Assessment Methodology. In particular, this section sets out:
  - The definition of liquefaction vulnerability;
  - How the CES has caused an increase in liquefaction vulnerability for some properties;
  - The recognition of ILV as a form of natural disaster damage to which the EQC Act applies, and the reasons for this recognition;
  - The legal principles which the assessment methodology is required to satisfy (in accordance with EQC's instructions); and
  - The objectives of the ILV Assessment Methodology.
- **Section 3** provides background to the CES and basic liquefaction science and practice, against which the ILV Assessment Methodology was developed. In particular, this section describes:
  - Liquefaction and the mechanism by which liquefaction occurs;
  - The concepts of liquefaction susceptibility, triggering and vulnerability;
  - The features of the Christchurch geology that creates a vulnerability to liquefaction in earthquake events;
  - The shaking characteristics of, and the land and building damage caused by, the CES;
  - The changes to residential land caused by the CES that have led to an increase in vulnerability to liquefaction in future earthquake events; and
  - Some of the regulatory responses to rebuilding in Christchurch following the CES.
- **Section 4** provides an overview of the ILV Assessment Methodology;
- **Sections 5 to 10** describe and explain the methodology in more detail. In particular:
  - Section 5 describes the information used in the ILV Assessment Methodology;
  - Section 6 describes the assumptions used in the ILV Assessment Methodology;

- Section 7 describes the indicators that have been used to assess liquefaction vulnerability and the change in liquefaction vulnerability. This section also describes what levels of liquefaction vulnerability and change in liquefaction vulnerability are regarded as material using these liquefaction vulnerability indicators, having regard to both the uncertainty in the available information and the impacts of vulnerability on the use and amenity of land;
- Section 8 describes the detailed considerations and analysis that are undertaken as part of the ILV assessment process;
- Section 9 describes the Stage 1 ILV assessment process for the residential properties in Christchurch;
- Section 10 describes the Stage 2 ILV assessment process for the residential properties in Christchurch where the ILV status could not be determined in the Stage 1 ILV assessment process;

- **Section 11** describes the results of the application of the assessment methodology to Christchurch residential properties, and reviews the results for sensibleness against the objectives of the methodology described in Section 2; and
- **Section 12** sets out the main conclusions of this Report.

Additional information and detail on some aspects of the methodology are provided in the Appendices to this report. These include:

- **Appendix A** includes a report on the assessment of liquefaction vulnerability in Christchurch, summarising Christchurch specific studies and papers undertaken on liquefaction susceptibility, triggering and vulnerability including the development of a new liquefaction vulnerability parameter called the Liquefaction Severity Number (**LSN**);
- **Appendix B** provides detail about the forms of land damage covered by EQC on the flat land in Christchurch and includes photos of the typical land damage representing the different categories of land damage;
- **Appendix C** discusses the evolution of the ILV Assessment Methodology and the complexity of the geology within the Christchurch area;
- **Appendix D** includes a report from Bradley Seismic Ltd on the probabilistic seismic hazard analysis for Christchurch soil sites, relevant to the selection of ground motions for the ILV assessment process;
- **Appendix E** includes comparison of Cone Penetration Test (**CPT**) results which were undertaken before the earthquakes and pushed again in a nearby location after the earthquakes to examine whether the earthquakes have affected the soil strength;
- **Appendix F** includes a discussion on lateral spreading vulnerability and that the potential for it to occur has not increased as a result of the physical changes to the land as a result of the CES.
- **Appendix G** includes a technical note on the accuracy and limitations of the LiDAR survey data. The LiDAR survey data was used to determine both the depth to groundwater for liquefaction vulnerability assessment purposes as well as estimating the ground surface subsidence caused by the CES;
- **Appendix H** includes a technical note on the assessment of the median and mean liquefaction vulnerability LSN parameter;
- **Appendix I** provides a technical note on the estimation and interpolation of LSN values from the CPT locations to determine LSN values for each residential property based on an automated model;
- **Appendix J** includes liquefaction vulnerability parameter sensitivity analysis summary sheets for typical CPT traces in Christchurch;

- **Appendix K** provides the regional maps used in the Stage 2 ILV assessment process;
- **Appendix L** provides a summary of a Stage 2 worked example which demonstrates how the ILV methodology is applied to an area with variable ground conditions; and
- **Appendix M** describes the process used to classify the properties that did not qualify for ILV into properties which have material liquefaction vulnerability (but not ILV) and properties which do not have material liquefaction vulnerability.

1.2 How to Read this Report

The ILV Assessment Methodology is a complex process involving the application of engineering judgement to a considerable volume of information to provide individual property assessments. This report is intended to provide both an overview of the essential features of the methodology as well as a detailed description of the methodology for professional engineers who may be advising claimants and other interested parties.

Readers interested in the background and an overview of the methodology should read Sections 1 to 4, as well as the overview of the results of the ILV assessments described in Section 11.

Details of the information sources used and the descriptions of the essential assumptions and reasons for those assumptions are provided in Sections 5 and 6.

Sections 7 to 10 describe the methodology in further detail and are primarily aimed at engineering advisors wishing to understand and be able to replicate the results of the ILV Assessment Methodology

The scope of work for the assessment of ILV was limited to residential land on the relatively flat parts of the Christchurch area. Therefore the data discussed and presented in this Report is restricted to this land. It is important to note that there is land in the Christchurch area that was damaged in the CES on non-residential and sloping land that is not discussed or presented in this report.

Note that the figures showing regional views of the Christchurch area in the body of the text are small because they are intended to provide readers with a high level overview of regional trends. Where appropriate, enlarged versions of these figures have been provided in **Appendix K**.

1.3 Iterative Development of the ILV Assessment Methodology

The ILV Assessment Methodology described in this report has been developed iteratively over the last four years. Considerable amounts of new information has become available during this time which has been taken into account. In some cases, this led to properties being re-assessed for ILV. The ILV Assessment Methodology in this report describes the assessment approach that has been applied to all residential properties in the Christchurch area.

An account of the recognition of increased liquefaction vulnerability and the evolution of the ILV Assessment Methodology since 2012 is given in **Appendix C**.

1.4 Role of Other Parties in the Development of the ILV Assessment Methodology

This iterative development of the ILV Assessment Methodology has occurred in collaboration with, or taking into account the views of a number of, other parties with an interest in the ground surface subsidence caused by the CES. These other parties include:

- An international expert review panel, comprising world-leading liquefaction researchers from University of California at Berkeley, University of California at Davis, University of Canterbury and Cornell University;
- Local and international engineering practitioners and researchers, with engagement via well-attended Technical Clearinghouse briefing sessions, conferences and liquefaction workshops;
- The Ministry of Business Innovation and Employment (**MBIE**) Engineering Advisory Group (**EAG**), who provide technical guidance to industry regarding repair and rebuilding of land vulnerable to liquefaction in Canterbury; and
- Engineering consultants engaged by private insurance companies and their project management offices. The Technical Advisory Group (**TAG**) was formed, for technical discussion and feedback regarding the ILV assessment framework and implementation.

Where the issues raised by the TAG were technically valid and supported by the scientific evidence from the information gathered, T+T have worked to improve the ILV assessment process in line with their suggestions. However, the TAG group suggestions which were not supported by scientific evidence from the information gathered, have not been adopted.

2 Purpose of the ILV Assessment Methodology

2.1 Purpose and Outline

This section of the report describes the legal and analytical framework and objectives of the ILV Assessment Methodology. In particular, this section sets out:

- The definition of liquefaction vulnerability;
- How the CES has caused an increase in liquefaction vulnerability for some properties;
- The recognition of ILV as a form of natural disaster damage to which the EQC Act applies, and the reasons for this recognition;
- The legal principles which the assessment methodology is required to satisfy (in accordance with EQC's instructions); and
- The objectives of the ILV Assessment Methodology.

2.2 Definition of Liquefaction Vulnerability

Liquefaction is the process by which earthquake shaking increases the water pressure in the ground in sandy and silty soil layers resulting in temporary loss of soil strength. Liquefaction can give rise to significant ground and building damage, for example through the ejection of sediment to the ground surface, settlement of the ground due to volume loss in liquefied soil and horizontal movement of the ground.

Liquefaction Vulnerability is used in this report to refer to the vulnerability of residential land to liquefaction related land and building damage in a future earthquake event.

2.3 The Canterbury Earthquake Sequence has caused an Increase in Liquefaction Vulnerability to some Properties

The Canterbury area has been affected by a large number of earthquake events following the main earthquake on 4 September 2010. In this report, these earthquake events are described as the *2010-2011 Canterbury Earthquake Sequence* or *CES.*

There were four main earthquakes in the CES which caused widespread land and building damage around Christchurch, including the manifestation of liquefaction, lateral spreading, widespread land subsidence and differential foundation settlement of residential buildings. These earthquakes, each of which caused material ground surface subsidence of some properties in the Christchurch area, occurred on:

- 4 September 2010;
- 22 February 2011;
- 13 June 2011; and
- 23 December 2011.

Following the CES, it was identified that the ground surface subsidence as a result of the CES for a large number of properties has increased the vulnerability of the land to liquefaction damage in future earthquakes (Russell, et al., 2015).

In areas where the depth to the groundwater is shallow, ground surface subsidence caused by these earthquakes has reduced the thickness of the non-liquefying crust. As a result, in future earthquakes the consequences of liquefaction at the site are likely to be more severe. There is broad consensus in the scientific literature that ground surface subsidence, with the resulting shallower depth to groundwater, may result in a thinner non-liquefying crust, resulting in increased liquefaction vulnerability. The more difficult question is to identify, on an individual property basis, whether the scale of the reduction has been sufficient to say that there has been a resulting material increase in liquefaction vulnerability.

2.4 ILV is a form of Natural Disaster Damage

EQC provides insurance for "*natural disaster damage*" to residential land. "*Natural disaster damage*" is defined in the EQC Act as:

a *Any **physical loss or damage** to the property occurring as the direct result of a natural disaster; or*

b *Any **physical loss or damage** to the property occurring (whether accidentally or not) as a direct result of measures taken under proper authority to avoid the spreading of, or otherwise to mitigate the consequences of, any natural disaster, but does not include any physical loss or damage to the property for which compensation is payable under any other enactment.*

EQC has advised that legally the phrase "*physical loss or damage*" has two elements to it. There must be:

- A physical change to the residential land as a direct result of a natural disaster, such as an earthquake; and
- A loss of use or amenity to the residential land as a result of that physical change.

These two elements are substantiated by the findings of the full bench of the High Court in *Earthquake Commission v Insurance Council of New Zealand* (the **Land Declaratory Judgement**). In that case the High Court considered whether ILV was a form of "*natural disaster damage*" for the purposes of the Act. The Court concluded that:

> *Residential land that is materially more prone to liquefaction damage in a future earthquake because of changes to its physical state as the direct result of one or more of the earthquakes in the CES, has sustained natural disaster damage in terms of the Act. Those physical changes have reduced the use and amenity of the land such that it is now less suitable for use as a building platform and for other purposes usually associated with residential land.*

A loss of use or amenity can be assessed by reference to whether the market value of the property in question has reduced. The identification of ILV therefore involves a combination of engineering and valuation assessments. Consistent with the Land Declaratory Judgement, EQC has determined that it will apply three criteria in assessing whether residential land has sustained ILV:

- The residential land has a material vulnerability to liquefaction damage after the CES at 100 year return period levels of earthquake shaking (***Criterion 1***);[1]
- The vulnerability to liquefaction damage of the residential land in future earthquakes has materially increased at up to 100 year return period levels of earthquake shaking[1] as a result of ground surface subsidence of the land caused by the CES (***Criterion 2***); and
- The increase in vulnerability to liquefaction damage of the residential land has caused the value of the property (the residential land and associated buildings combined) to decrease. (***Criterion 3***)

Criterion 3 is addressed in a separate report by EQC's valuers. However the valuers will use information from the ILV Assessment Methodology and other relevant information in determining the extent of any loss in value.

[1] An event that is expected to occur once in every 100 year period, which is defined as (Magnitude (M_W) = 6.0 and Peak Ground Accelerations (PGA) = 0.3g consistent with the Ministry of Building Innovation and Employment (MBIE) 2015 guideline specified design levels of earthquake shaking (these parameters are discussed in detail in Section 6.2 and 6.3).

2.5 An Engineering Assessment of ILV is Required

The purpose of this engineering assessment methodology is to identify properties which satisfy the first two criteria (the ***engineering criteria***), that is:

- The residential land has a material vulnerability to liquefaction damage after the CES at 100 year return period levels of earthquake shaking; and
- The vulnerability to liquefaction damage of the residential land in future earthquakes has materially increased at up to 100 year return period levels of earthquake shaking as a result of ground surface subsidence of the land caused by the CES.

Both *engineering criteria* must be satisfied in order for a property to qualify as having ILV. In other words, land that is not materially vulnerable to liquefaction damage after the CES does not have ILV because by definition it cannot have increased in vulnerability in a material way.

The *engineering criteria* are concerned with assessing whether residential land is materially more prone to liquefaction damage in future earthquakes because of changes to its physical state.

In evaluating what level of liquefaction vulnerability and what changes in liquefaction vulnerability are material, consideration has been given to the limitations in the precision of the predictions of liquefaction vulnerability at the individual property level. Changes that are likely to impact on uses and amenities of the land with respect to how those changes reduce its suitability as a residential building platform and for other purposes have also been taken into account.

2.6 Objectives of the ILV Assessment Methodology

Given the large number of urban residential properties in Christchurch which may have sustained potential ILV damage, EQC has instructed T+T to develop a methodology which enables the *engineering criteria* for ILV damage to be assessed in a robust and consistent manner (the **ILV Assessment Methodology**).

The general objectives of the ILV Assessment Methodology are to:

- Provide a basis for settlement of claims involving ILV land damage, consistent with EQC's obligations under the EQC Act, in accordance with the best available scientific understanding of ILV and the information available to EQC; and
- Provide a consistent treatment of the issues associated with ILV land damage, given the large number of properties affected by ILV land damage as a result of the CES.

In accordance with the requirements stated in the Land Declaratory Judgement, EQC has also instructed T+T to ensure that the ILV Assessment Methodology:

- Can be applied in good faith;
- Is not applied mechanically; and
- Does not exclude consideration of factors that are relevant to any particular case.

These considerations have been taken into account in developing the ILV Assessment Methodology and the methodology that has been developed satisfies each of these standards. Certain simplifying assumptions, which are not material to the outcome of the assessments, have been made. However, these assumptions do not preclude any individual requesting EQC to consider further information in any particular case.

Other important principles which are applied in the ILV Assessment Methodology are set out below.

2.7 Important Principles in the ILV Assessment Methodology

2.7.1 Assessment is on the Balance of Probabilities

EQC have advised T+T that, in the Land Declaratory Judgement, the High Court held that EQC's policy for assessing claims for damage to residential land claims must not produce "wrong answers" in the sense that it leads to rejection of claims which are on the balance of probabilities well-founded.

Accordingly, the ILV Assessment Methodology has been developed in a manner that is consistently reinforced by engineering judgement to enable assessment of whether a property has potential ILV on the balance of probabilities.

2.7.2 Relevant Publicly Available Information is taken into Account

Relevant publicly available information has been taken into account in designing this methodology for undertaking an ILV assessment on every urban residential property in Christchurch.

Significant work has been undertaken on behalf of EQC to commission Light Detection And Ranging (**LiDAR**) survey information, geotechnical investigation and laboratory testing (see Section 5 of this report). This data has been analysed as well as the other publicly available data on the Canterbury Geotechnical Database (**CGD**) relevant to the assessment of ILV land damage.

It is acknowledged that any claimant is entitled to provide further information (or an alternative interpretation of existing information) and ask EQC to reconsider its decisions regarding whether the land on the property has ILV land damage. In such cases, EQC may request that T+T consider any further information the claimant provides. This process will be discussed in a separate report.

2.7.3 Assessment of ILV is made Across the CES

The EQC Act requires EQC to determine whether an insured property has sustained natural disaster damage in each natural disaster event. EQC must therefore be satisfied that a physical change has occurred resulting in a material increase in vulnerability to liquefaction that has affected the amenity and value of the insured property in one or more of the main earthquake events.

However, for the following reasons, the ILV assessment methodology developed for the CES can only practically be undertaken by considering ground surface subsidence-induced changes to liquefaction vulnerability across the CES, and then considering which individual events are likely to have contributed to that change. These reasons can be summarised as follows:

- The ILV Assessment Methodology incorporates a manual assessment for each property using engineering judgement. It is not technically feasible to undertake a single event assessment using this manual assessment process. The engineering judgement is underpinned by a complex process, requiring the assessment and consideration of a large amount of information. While it is technically feasible to undertake a single event assessment of ILV using an automated process, the automated process requires simplifying assumptions that mean that particular issues relevant to individual properties may not be adequately identified and addressed. Accordingly, a manual process for determining whether a property has sustained ILV is both more accurate and reliable and best meets the objectives of the ILV Assessment Methodology; and
- The LiDAR survey data itself does not have appropriate levels of accuracy to justify undertaking a detailed manual ILV assessment process for each event (refer to **Appendix G**). The detailed manual ILV assessment process for each property can only be justified over the CES, because the limitations of the LiDAR survey accuracy become smaller relative to the total ground surface subsidence estimated over the CES (i.e. the absolute error in estimated ground

surface subsidence is the same, but the percentage error in estimated ground surface subsidence becomes smaller for the larger cumulative CES ground surface subsidence).

Even if an individual assessment were possible, it would also be necessary and appropriate to undertake a review of the change across the CES. This is for the following reasons:

- There are advantages in undertaking the manual assessment process across the CES, as described above;
- Ground levels in the Christchurch area have not uniformly subsided as a result of the earthquake sequence. In some cases LiDAR survey data suggests that residential land has subsided in the September 2010 earthquake and then risen in a subsequent earthquake. This apparent reversal of subsidence in some areas (predominately south eastern), is attributable to tectonic uplift. In other areas it is attributable to LiDAR survey errors and limitations in the conversion of this data into ground surface elevation models (refer to **Appendix G**);

  In any case where any increased vulnerability to liquefaction temporarily caused by subsidence in an earlier event is eliminated by ground movement in a subsequent event, the insured has suffered no loss. EQC therefore needs to consider the physical change across the sequence to ensure that claimants are compensated only for actual loss; and
- EQC's valuers have advised that assessment of loss of value and amenity is most reliably assessed by considering the change in ground level, and thus the change in vulnerability to liquefaction, across the CES. This is because, in general, the change across the sequence is likely to be larger, and the loss of value therefore more confidently and accurately identified. Accordingly, the assessment of whether a physical change has resulted in a loss of value is best conducted across the change caused by the full sequence.

In contrast, in almost all cases, there would be no additional benefit to customers in trying to undertake ILV assessment manually for each individual earthquake event. If a property is identified as having sustained ILV land damage across the sequence, it is likely, that ILV has been caused by one or more earthquakes. Equally, if a property is identified as not having sustained ILV land damage across the sequence, it is likely that no earthquake within the sequence has caused ILV.

Once it is satisfied, based on the ILV Assessment Methodology, that ILV has been caused across the CES, a separate process is undertaken to allocate that damage to the main individual CES events. The purpose of this allocation is to attribute the ILV damage to the earthquake events that, on the balance of probabilities, have contributed to the ILV damage. The detail of how this has been assessed is beyond the scope of this report and will be covered in a separate report. However, for most properties qualifying for ILV outside the residential Red Zone,[2] the material increase in liquefaction vulnerability is likely to have occurred in a single event.

[2] The residential Red Zone in Christchurch is explained in Section 3.8 of this report.

3 Background to Liquefaction, the CES and ILV

3.1 Purpose and Outline

This section of the report provides background information and context on:

- Basic principles of liquefaction science and techniques; and
- The Canterbury geology and the CES;

to readers who may be less familiar with either or both of these topics.

In particular, this section of the report describes:

- Liquefaction and the mechanism by which liquefaction occurs;
- The concepts of liquefaction susceptibility, triggering and vulnerability;
- The features of the Christchurch geology that creates a vulnerability to liquefaction in earthquake events;
- The shaking characteristics of, and the land and building damage caused by, the CES;
- The changes to residential land caused by the CES that have led to an increase in vulnerability to liquefaction damage in future earthquake events; and
- Some of the regulatory responses to rebuilding in Christchurch following the CES (which are referred to in subsequent sections of this report).

3.2 The Liquefaction Process

It can be readily observed that dry, loose sands and silts contract in volume if shaken. However, if the loose sand is saturated, the soil's tendency to contract causes the pressure in the water between the sand grains (known as "pore water") to increase. The increase in pore water pressure causes the soil's effective grain-to-grain contact stress (known as "effective stress") to decrease. The soil softens and loses strength as this effective stress is reduced. This process is known as liquefaction.

The elevation in pore water pressure can result in the flow of water in the liquefied soil. This water can collect under a lower permeability soil layer and if this capping layer cracks, rush to the surface bringing sediment with it. This process causes ground failure and with the removal of water and soil, a reduction in volume and hence subsidence of the ground surface.

The surface manifestation of the liquefaction process is the water, sand and silt ejecta that can be seen flowing up to 2 hours following an earthquake. The path for the ejecta can be a geological discontinuity or a man-made penetration, such as a fence post, which extends down to the liquefying layer to provide a preferential path for the pressurised water. The sand often forms a cone around the ejecta hole. With the dissipation of the excess pore-water pressure, the liquefied soil regains its pre-earthquake strength and stiffness (discussed further in Section 6.5).

The surface expression of liquefaction, water and sand depends on a number of characteristics of the soil and the geological profile. If there is a thick crust of non-liquefiable soil such as a clay, or sand that is too dense to liquefy during the particular level of shaking of the earthquake, then water fountains and sand ejecta may not be seen on the surface. The amount of ground surface subsidence is generally dependent on the density of the sand layers as well how close the liquefying layers are to the surface. Ground surface subsidence increases with increasing looseness in the soil packing. Figure 3.1 summarises the process of liquefaction with a schematic representation.

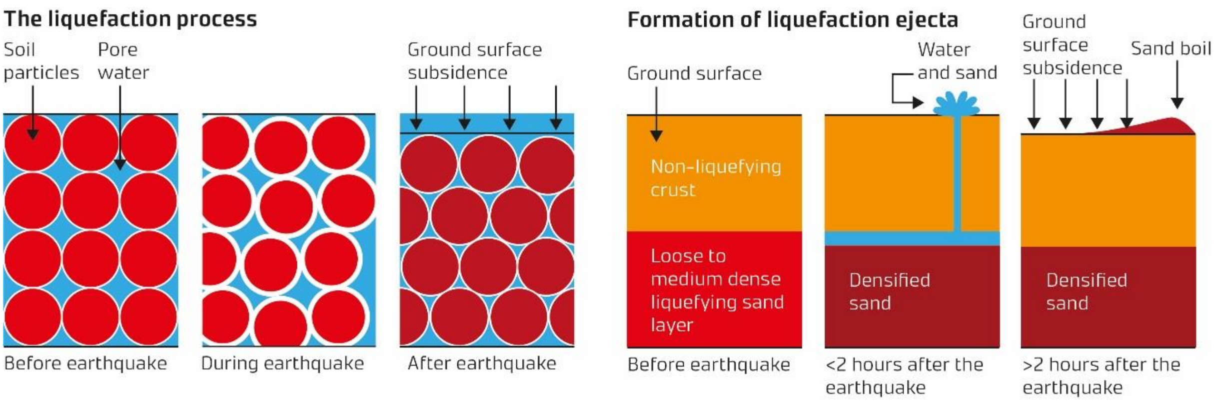


Figure 3.1: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta.

3.3 Susceptibility of Soils to Liquefaction

The susceptibility of a soil to liquefaction depends on its compositional characteristics and state in the ground. Factors affecting this include history or age and geologic environment (Idriss & Boulanger, 2008). Soils that are cohesive in nature such as clays with high plasticity are not susceptible to liquefaction. The susceptibility of soils to liquefaction can be assessed based on the plasticity of fine grained clay particles. These are combined to define a "cutoff" between soils that are, and are not, susceptible to liquefaction.

The soil behaviour Index **(I_c)** as determined from Cone Penetration Tests (**CPTs**) is used as a screen to identify soils that are likely to be susceptible to liquefaction. The I_c value is calibrated to laboratory test results that are carried out on soil samples obtained from drilling adjacent to the CPT locations. A further process of screening susceptible soils is based on plasticity of the soils, as described in terms of a soil's plasticity index (determined from the Atterberg limits) and water contents obtained from laboratory testing (Bray & Sancio, 2006).

An I_c value of 2.6 is typically indicative of soils that are not susceptible to liquefaction (Robertson & Wride, 1998). Another study by Lees et al (2015) found that an I_c cutoff of 2.6 is appropriate for assessing liquefaction susceptibility in Christchurch based on an extensive set of laboratory test results paired with adjacent CPT data in Christchurch. For all liquefaction analyses discussed throughout this report an I_c cutoff of 2.6 has been assumed unless otherwise stated. Further discussion regarding I_c and its correlation to the Christchurch soils is provided in **Appendix A**.

3.4 Liquefaction Triggering

Liquefaction is triggered in a susceptible soil if the level of shaking (usually due to an earthquake) is sufficiently large enough to overcome the soil's resistance to liquefaction. This is based mainly on the soil's density, the behaviour of fine grained soil components and groundwater levels.

The extent of liquefaction within a soil profile is typically assessed by analysing CPT test results. This assessment uses a recognised triggering method to obtain a continuous evaluation over the full depth profile of which layers are likely to liquefy, and which are not likely, for a given level of shaking.

The main published liquefaction triggering methodologies used in practice are Robertson and Wride (1998), Moss et al. (2006) and Idriss and Boulanger (2008). Extensive studies were undertaken to determine which liquefaction triggering methodologies best fitted the CES observations. The results from these studies showed that the Idriss and Boulanger (2008) liquefaction triggering method produced a slightly better fit compared to the other methods.

The Idriss and Boulanger (2008) methodology for predicting liquefaction triggering was updated in 2014 (Boulanger & Idriss, 2014). The methodology is based in part on an expanded international liquefaction case history database incorporating 50 case histories from the CES. This updated method provides a better correlation to the observed land damage from the CES than previous methods. For all liquefaction triggering analysis discussed and presented throughout this report, the Boulanger and Idriss (2014) method has been used unless otherwise stated (summarised in **Appendix A**).

The spatial distribution of where liquefaction is estimated as triggering in small, medium and large earthquakes is shown in Figure 3.2. It is noted that prediction of liquefaction triggering could only be made in the areas where a sufficient density of CPT data are available (i.e. the red and blue areas). The maps indicate that liquefaction is predicted to be triggered somewhere in the soil profile over a large proportion of Christchurch even at a small level of shaking. For a large level of shaking (similar to the level of shaking which was experienced in much of the centre and south of the city in the February 2011 event), soil layers are predicted to liquefy virtually over the whole of the Christchurch area.

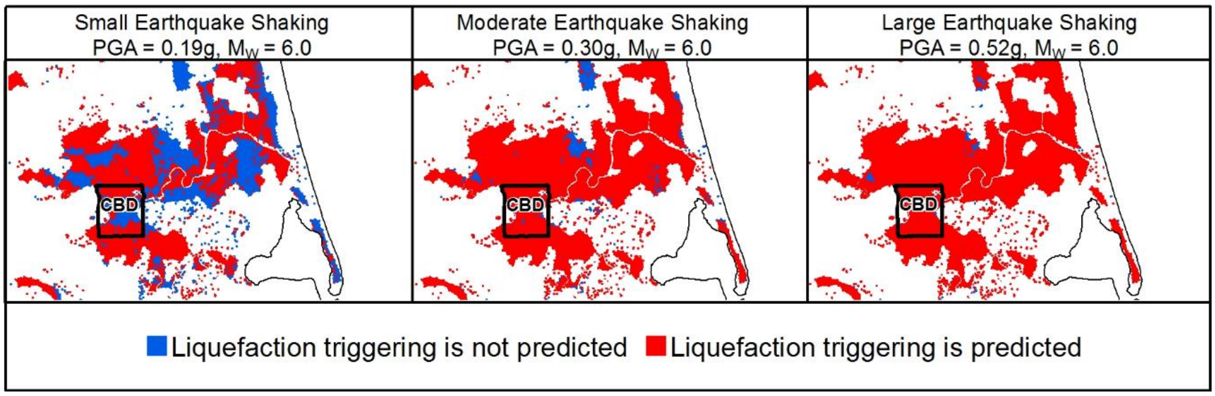


Figure 3.2: Maps showing areas where liquefaction triggering is predicted for small, medium and large levels of earthquake shaking. White areas on the map indicate areas where there is insufficient density of geotechnical investigation data available to assess liquefaction triggering.

In order to use the Boulanger and Idriss (2014) liquefaction triggering procedure certain input parameters must be assumed. Unless otherwise stated, for all liquefaction triggering analyses discussed and presented in this report the following input parameters have been assumed for the reasons provided:

- **Site specific fines content estimation calibration parameter (C_{FC}) = 0** – In the Boulanger and Idriss (2014) liquefaction triggering methodology, Fines Content (FC) can be directly obtained from laboratory testing of recovered soil samples from adjacent boreholes in regular depth intervals (which is not practical in Christchurch) or alternatively approximated from I_c. To make this approximation site specific calibration using the C_{FC} parameter is recommended. Lees et. al. (2015) found that adopting the default C_{FC} of 0 provided an appropriate upper estimate for the prediction of FC from I_c for the assessment of liquefaction triggering in the Christchurch area.
- **Probability of liquefaction triggering (P_L) = 15%** - There is uncertainty in the liquefaction triggering assessment methodology. Adopting a P_L factor of 15% indicates that a soil layer assessed as not liquefying for a given level of earthquake shaking has a 85% likelihood of no liquefaction being triggered and a 15% likelihood of liquefaction being triggered. This value has been adopted because it provides an appropriate level of conservatism for application to Christchurch residential properties.

- **Unit weight of soil (γ) = 18 kN/m^3** – A unit weight of soil of 18 kN/m^3 has been adopted because it is generally representative of soils in the Christchurch area. It is useful to note that the Boulanger and Idriss (2014) liquefaction triggering methodology is not particularly sensitive to changes in this parameter.

Further detail about the input parameters used for the assessment of liquefaction triggering is provided in **Appendix A**.

3.5 Liquefaction Vulnerability

Land is vulnerable to liquefaction damage when it is exposed to risk of land damage due to the effects of liquefaction in soil layers below the ground surface.

The effects of liquefaction may include ground surface subsidence, ejecta, ground cracking, loss of strength and lateral spreading, all typically resulting in differential ground surface subsidence. The extent and severity of the effects is dependent on the depth of the liquefying soil layers, their thickness and triggering shaking level, and the proximity to river banks, old river terraces and slopes and the corresponding height of these features. These effects may result in consequential land damage which in turn may result in damage to residential buildings situated on top of such land.

The severity of the consequential land damage depends in part on the thickness of the overlying non-liquefying soils which act as a protective raft over the liquefied soils. The greater the depth to liquefying soils, the lesser the effects observed at the surface. The amount of the consequential land damage is also dependent on the thickness of the liquefying layers and the relative density of the liquefying layers. Looser liquefying soils and thicker liquefying layers are likely to have a more adverse effect at the ground surface compared to denser liquefying layers, and liquefying layers that are deeper below the ground surface. Also, the land in close proximity to river banks, old river terraces and slopes has a greater potential for lateral spreading damage to occur. This greater potential is dependent on the depth, thickness and relative density of the underlying liquefiable soil layers. The greater the height of these features the greater the potential for this damage to occur.

Extensive studies have been undertaken on assessing the vulnerability of land to liquefaction damage on the flat land (summarised in **Appendix A**) and lateral spreading damage (summarised in **Appendix F**). These liquefaction vulnerability studies show that liquefaction triggering of soil layers more than 10m below the ground surface provides a negligible contribution to liquefaction damage at the ground surface. Therefore, all liquefaction consequence analyses presented in this report are for the upper 10m of the soil profile unless otherwise stated.

Figure 3.3 presents a sequence of maps showing the pre-CES liquefaction vulnerability for small, moderate and large levels of ground shaking. The difference between liquefaction triggering and liquefaction vulnerability can be observed when comparing Figure 3.2 and Figure 3.3 which show liquefaction triggering and liquefaction vulnerability for the same levels of earthquake shaking. This difference is most evident when comparing the estimated liquefaction vulnerability with liquefaction triggering at moderate levels of earthquake shaking (i.e. the middle columns in Figure 3.2 and Figure 3.3). White areas on the maps indicate land areas where there is insufficient density of CPTs data to estimate the vulnerability of the land to liquefaction damage.

Liquefaction is predicted to be triggered in at least some of the soil profile over most of the area in Christchurch where geotechnical investigations have been undertaken (refer to Figure 3.2). However a far lesser extent of land is assessed to be vulnerable to liquefaction damage at the land surface at the same level of shaking.

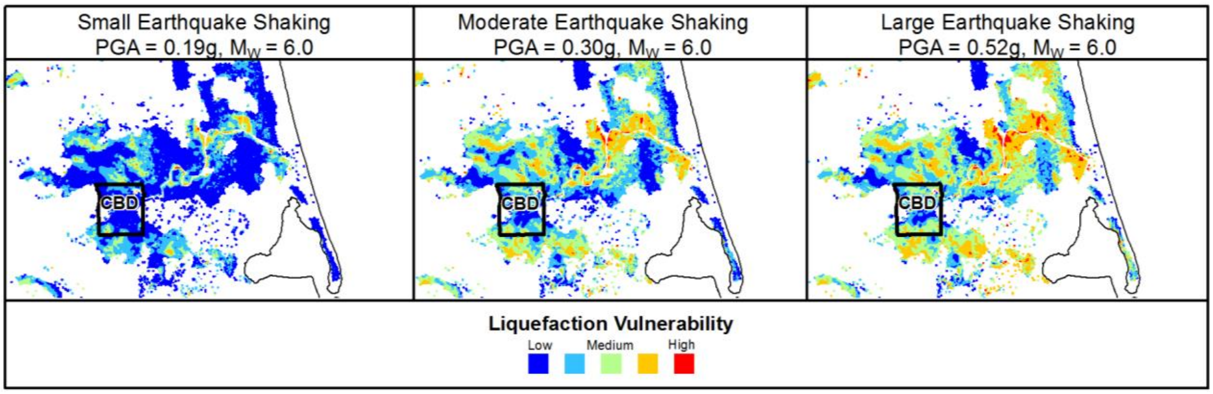


Figure 3.3: Maps showing the pre-CES liquefaction vulnerability for a small, moderate and large levels of ground shaking. White areas on the map indicate areas where there is insufficient density of geotechnical investigation data available to assess liquefaction triggering.

There are a number of different CPT-based indices that can be used to estimate liquefaction vulnerability (Iwasaki, Arakawa, & Tokida, 1982; Zhang, Robertson, & Brachman, 2002; Tonkin & Taylor, 2013; Maurer, Green, & Taylor, 2014a). The applicability of these various indices to the soils found in Christchurch is discussed in **Appendix A** and their use in the ILV Assessment Methodology is discussed in Sections 7 to 10.

3.6 The Canterbury Geology and the Development of Christchurch

3.6.1 Geological Setting of Christchurch

The *Geology of Christchurch Urban Area* by Brown & Weeber (1992) provides a very good description of the local geology and geological history. A 1:250,000 scale geological plan extracted from this publication is presented in Figure 3.4 with a simplified cross-section from this map presented in Figure 3.5.

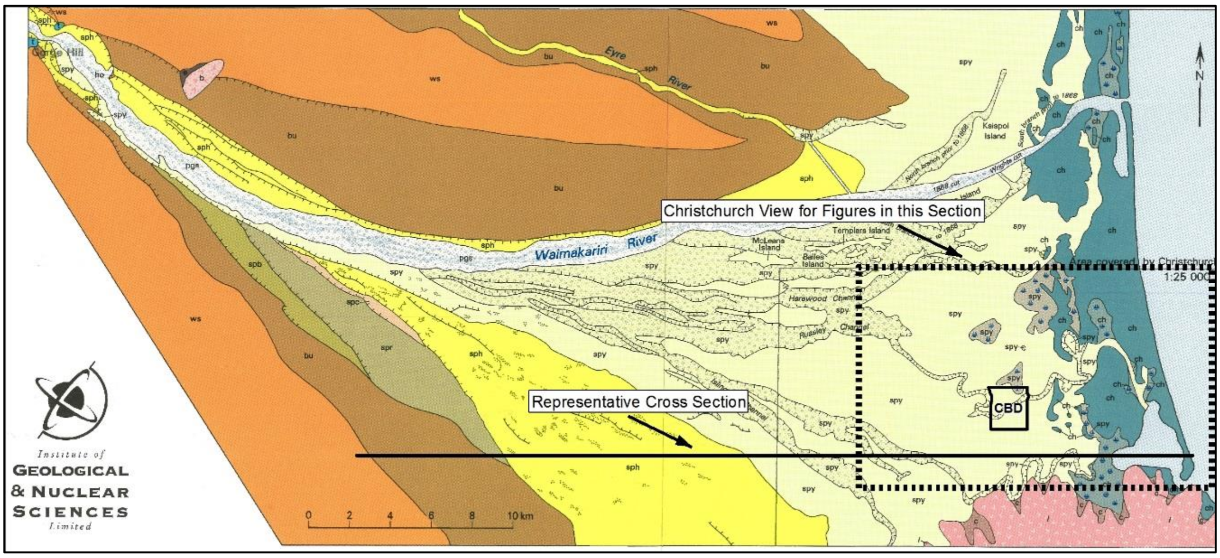


Figure 3.4: Geological map of the Canterbury area - for the legend to this map refer to Brown and Weeber (1992).

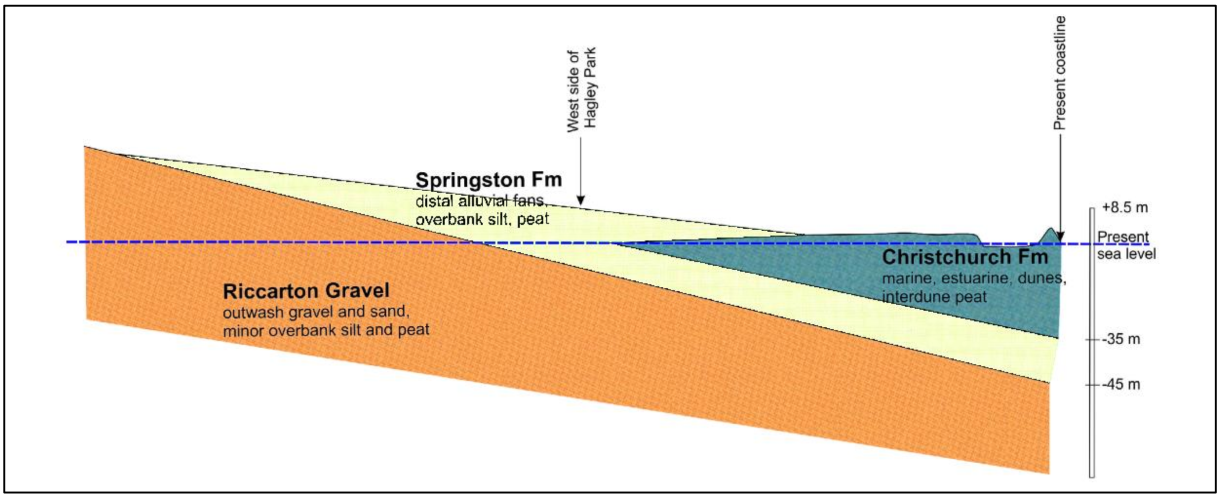


Figure 3.5: Simplified cross-section from Figure 3.4.

A summary of the geological units found in Christchurch is presented in Table C2.1 in **Appendix C**. This summary is based on information contained in Brown & Weeber (1992). As a result of the geologic complexity, the geologic units shown in Figure 3.4 and listed in Table C2.1 are not all shown in the simplified cross section (Figure 3.5).

The geological processes that have formed the soils on the Canterbury plains are complex. The formation of these soils is dependent upon a number of interacting processes including:

- Continuous changes in the direction and size of the braided river systems in the area (primarily the Waimakariri river);
- Progressive sea level raising and lowering;
- Tectonic uplift of the Southern Alps; and
- Climatic changes and influences.

The interaction of these processes over time has resulted in the formation of a complex geological soil profile which creates challenges for the prediction of liquefaction vulnerability, in particular by providing a high level of spatial variation of geological features as well as variability within geologic units in the Canterbury region.

3.6.2 Geological Setting of Canterbury in the Context of Natural Hazards

The post glacial geological history, within the past 10,000 years is significant to the Christchurch areas exposure to natural hazards and future engineering approaches for development. The key aspects include:

- Sea level rise to form a coastline at Riccarton some 6,500 years ago;
- Pro-gradation of the coast line eastward to New Brighton by build-up of sand and silt deposits on a very flat coastal plain (1 in 1,500 slope);
- Advancement of the fan of the Waimakariri River over the top of the coastal plain, generally depositing gravels to the west and sands and silts to the east. Major flooding and flood deposition ceased with the construction of flood protection works in the late 1800s;
- Near surface loose sand and silt deposited by alluvial and estuarine activity have a generally high potential for liquefaction. Many of the areas of Christchurch which experienced severe liquefaction related damage due to the CES experienced lateral spreading towards the semi-tidal Avon River. Point bar deposits are well developed on the insides of major bends in the meandering river;

- The potential for liquefaction can result in differential surface damage and consequential land and building damage due to the generally shallow depth of groundwater on the flat coastal plain; and
- Relatively subtle changes in topography due to depositional environment can reflect significant changes to observed liquefaction damage, due to changes in soil type, soil layering and depth to groundwater.

It is noted that Christchurch is a region of low-to-moderate seismicity where earthquake design ground motions are about a half of those for other New Zealand cities such as Wellington in the main earthquake zone.

3.6.3 Earthquakes in Christchurch Prior to the CES

Christchurch has experienced at least five earthquakes causing isolated chimney damage and minor building damage along with significant contents damage (Modified Mercalli Intensity (MMI) >6) since European settlement in 1850 and prior to the CES (Downes & Yetton, 2012). There are no reports of liquefaction during these events in eastern Christchurch, however liquefaction was reported in Kaiapoi and Belfast following the 1901 M_W 6.8 Cheviot earthquake (Berrill et al., 1994). The 1869 Christchurch earthquake caused widespread building and chimney damage (MMI 7) within the Central Business District (**CBD**) and surrounding suburbs including Avonside. No liquefaction or ground deformation was reported in these events. However it was observed that the tide ran higher up the Heathcote River than prior to the 1869 Christchurch earthquake. This is consistent with subsidence within the estuary indicating liquefaction may have occurred in this area at this time (Downes & Yetton, 2012).

Extensive and recurrent liquefaction observations triggered by the main CES events as well as some of the smaller aftershocks were used to characterise site-specific threshold triggering in Avonside, eastern Christchurch (Quigley et al., 2013). Of the historic events known to have caused damage within Avonside, only the 1869 Christchurch earthquake is likely to have generated levels of earthquake shaking at or above the site specific liquefaction triggering threshold. Therefore, it can be inferred that liquefaction triggering occurred in the most vulnerable areas, such as Avonside, during the 1869 Christchurch earthquake (Quigley et al., 2013). The estimated Peak Ground Acceleration (**PGA**) for the 1869 event is consistent with reports of widespread contents damage and chimney collapse within Avonside (Downes & Yetton, 2012).

3.7 The Canterbury Earthquake Sequence

3.7.1 The Main Earthquake Events

The Canterbury area has been affected by a large number of earthquake events following the earthquake on 4 September 2010. There have been more than 50 earthquakes having a magnitude of 5 or greater. There have been 16 events which are reported to have caused either land, dwelling and/or contents damage resulting in lodgement of claims with EQC.

There were four main earthquakes in the sequence which caused widespread building damage and land damage around Christchurch, including the manifestation of liquefaction, lateral spreading and widespread land subsidence. These earthquakes, each of which caused material ground surface subsidence of some properties in the Christchurch area, occurred on:

- 4 September 2010 (M_W 7.1);
- 22 February 2011 (M_W 6.2);
- 13 June 2011 (M_W 5.6 foreshock followed 80 minutes later by a M_W 6.0 aftershock); and
- 23 December 2011 (M_W 5.8 foreshock followed 80 minutes later by a M_W 5.9 aftershock).

As a result of the CES, EQC have received more than 460,000 claims for damage, with a substantial number of these claims involving land damage.

3.7.2 Levels of Earthquake Shaking

The PGA contour models from Bradley and Hughes (2012) for each of the four main earthquakes are shown in Figure 3.6. These PGA estimates are useful for comparing the return period levels of earthquake shaking that were experienced in different parts of Christchurch during the main CES events with the MBIE (2012) guideline values specified in Section 6.2.

During the September 2010 earthquake (Figure 3.6a), most of urban Christchurch experienced approximately 100 year return period levels of earthquake shaking. The exception to this was the south-western suburbs (i.e. Halswell, Hornby and Oaklands) which experienced higher return period levels of earthquake shaking.

During the February 2011 earthquake (Figure 3.6b), most of urban Christchurch experienced approximately 500 year return period levels of earthquake shaking. The exceptions are:

- The north-western suburbs (i.e. Avonhead, Bishopdale, Brooklands, Bryndur, Burnside, Casebrook, Ilam, Northcote Spencerville and Upper Riccarton) which experienced approximately 100 year return period levels of earthquake shaking; and
- The northern suburbs (including Belfast, Kaiapoi and Styx) which experienced approximately 25 year return period levels of earthquake shaking.

During the main June 2011 earthquake (Figure 3.6c), the spatial distribution of the level of earthquake shaking throughout the Christchurch area was as follows:

- The south-eastern suburbs of Christchurch (generally south of the Avon River) experienced approximately 500 year return period levels of earthquake shaking;
- The central and eastern suburbs in the Avon River catchment experienced approximately 100 year return period levels of earthquake shaking; and
- The north-western and western areas (west of Hagley Park) experienced approximately 25 year return period levels of earthquake shaking.

During the main December 2011 earthquake (Figure 3.6d), the spatial distribution of the level of earthquake shaking throughout the Christchurch area was as follows:

- The eastern suburbs of Christchurch (i.e. Aranui, Avondale, Bexley, Burwood, New Brighton, North New Brighton, Parklands, Queenspark, Southshore, South New Brighton, Travis and Waimairi Beach) experienced approximately 500 year return period levels of earthquake shaking;
- The central suburbs experienced approximately 100 year return period levels of earthquake shaking; and
- The western areas (west of Hagley Park) of experienced approximately 25 year return period levels of earthquake shaking.

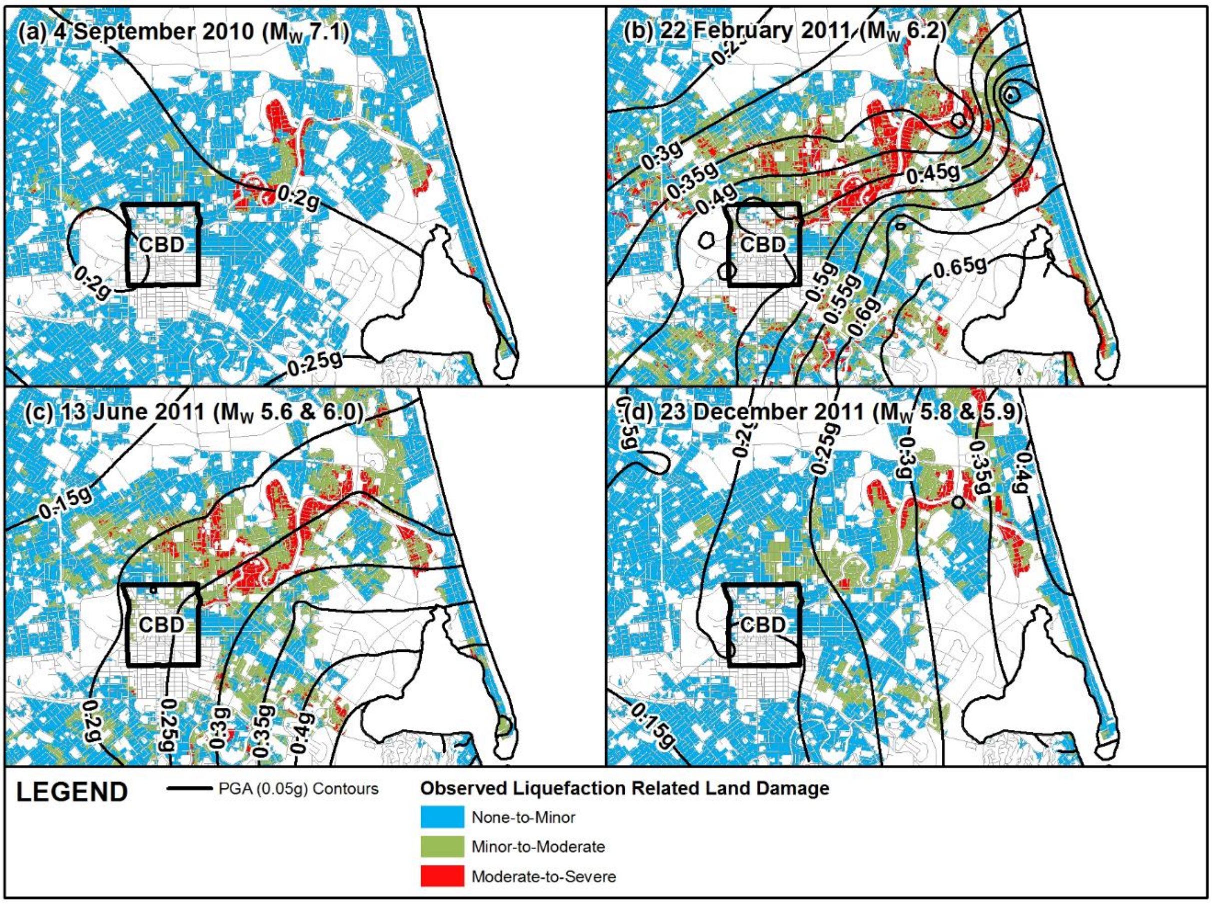


Figure 3.6: Map showing the inferred levels of earthquake shaking and the observed land damage for urban residential properties in Christchurch after the (a) 4 September 2010, (b) 22 February 2011, (c) 13 June 2011 and (d) 23 December 2011 earthquakes.

In Figure 3.6 the contour lines for the June 2011 and December 2011 are the estimated PGA contour lines for the main earthquake events on those dates. These do not capture the influence of the PGAs associated with the foreshocks of these events which are relevant to the liquefaction related damage observed. This is discussed in more detail in Section 3.7.3.

Overall, throughout the CES most of urban Christchurch has experienced approximately 500 year return period levels of earthquake shaking for one or more of the four main earthquakes. The exceptions to this are the north-western suburbs (i.e. Avonhead, Belfast, Bishopdale, Brooklands, Bryndur, Burnside, Casebrook, Ilam, Kaiapoi, Northcote Spencerville, Styx and Upper Riccarton) which experienced approximately 100 year return period levels of earthquake shaking.

3.7.3 Mapped Liquefaction Related Land Damage

As a result of the earthquakes and lodged insurance claims for land damage with EQC, extensive land damage evaluations were undertaken by teams of geotechnical engineers and engineering geologists. These evaluations characterised the extent and severity of liquefaction related land damage after each of the main earthquakes.

Liquefaction related land damage mapping of residential properties was carried out immediately after the September 2010, February 2011, and June 2011 earthquakes to assess the extent and severity of the surface effects of liquefaction. The mapping was supplemented by interpretation of aerial photography after each of the four main earthquakes to identify areas where liquefaction ejecta occurred, but which may have been cleaned up by the time the ground teams arrived to map the areas. For the December 2011 earthquake events, the land damage maps were derived primarily from manual review of the aerial photography and limited ground based observations.

These ground and aerial land damage observations, as well as information collected during subsequent detailed property assessments, were combined to produce standardised land damage observation maps after each of the four main earthquakes. These maps categorised the observed land damage into three categories:

- **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; and
- **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 are provided in **Appendix B**. Some example photos of land with moderate-to-severe liquefaction related land damage are shown in Figure 3.7. Photos of the other land damage categories are provided in **Appendix B**.

Figure 3.7: Observed liquefaction related land damage and residential house damage in Christchurch following the CES – reproduced from van Ballegooy et al. (2014b).

The liquefaction related land damage maps for each of the four main earthquakes are presented in Figure 3.6. A lot of Christchurch properties have soil layers within the soil profile which are susceptible to liquefaction, and hence widespread triggering of liquefaction is believed to have occurred in each of the main earthquakes (that is, the earthquakes caused soil layers to liquefy). But the triggered liquefaction only had damaging consequences for a narrower range of properties. In some suburbs the liquefaction damage had little to no consequence to the built environment and may therefore have not been visually evident at the ground surface.

The maps presented in Figure 3.6 are based on the observation of the surface expression of liquefaction (sand ejecta) and visible liquefaction related differential ground surface settlement. Most of the ejecta was removed and major ground cracks filled (but not repaired) between each of the four main earthquakes. The qualitative land damage mapping therefore generally recorded the incremental effects of each earthquake. However, there are likely to be some effects from previous earthquakes that influenced the land damage observed after later earthquakes. These effects included the influence of unrepaired cracks on the integrity of the non-liquefied crust.

The severity of the liquefaction related damage was primarily influenced by the earthquake motions (i.e. M_W and PGA), subsurface soil conditions and seasonal groundwater levels. Topography, proximity to rivers and streams and land use also played a big part in the distribution of liquefaction related land damage.

The spatial distribution of mapped land damage is explained below:

- **September 2010 earthquake** (Figure 3.6a) – The minor-to-moderate and moderate-to-severe land damage after the September 2010 earthquake is generally clustered in small localised areas. This land damage is indicative of locations where the land at pre-CES ground surface levels was already vulnerable to liquefaction related damage at approximately post-CES 100 year return period levels of shaking.

  There were less than 10,000 residential properties which had minor-to-moderate and moderate-to-severe liquefaction related land damage after the September 2010 earthquake. This number represents less than 10% of urban residential properties in Christchurch. These clusters of properties with minor-to-moderate and moderate-to-severe mapped land damage correlated closely with the locations with high concentrations of land damage insurance claims.

- **February 2011 earthquake** (Figure 3.6b) – The spatial distribution of land damage after the February 2011 earthquake shows a more extensive pattern of liquefaction related damage. Approximately 37,000 residential properties had minor–to-moderate liquefaction damage and just under 10,000 residential properties had moderate-to-severe liquefaction damage. Approximately 5,000 of the residential properties with the most severe liquefaction damage were within the residential Red Zone. It is noted that the Technical Category (TC) 2 land typically had none-to-minor land damage with a clear demarcation in eastern Christchurch between TC2 and TC3 areas.[3]

  It can be inferred from this data set that almost all residential Red Zoned land and most of the TC3 land had liquefaction related damage at approximately 500 year return period levels of earthquake shaking.

  The TC2 land in southern, central and eastern Christchurch does not appear to be vulnerable to moderate-to-severe liquefaction related damage at approximately 500 year return period levels of shaking. In the north-west of the city the February 2011 earthquake only caused approximately 100 year return period levels of shaking. Therefore the same conclusions about liquefaction performance of the TC2 land at 500 year return period levels of shaking cannot be extended to this area of the city. These areas may therefore be vulnerable to liquefaction related land damage at 500 year return period levels of earthquake shaking.

- **June 2011 earthquake** (Figure 3.6c) – The spatial patterns of mapped land damage after the June 2011 earthquake are similar in extent, but were less severe, compared to spatial patterns from the February 2011 earthquake. This is attributable to the lower levels of shaking.

- **December 2011 earthquake** (Figure 3.6d) – With the exception of the suburbs of Parklands and Queenspark, the spatial pattern of observed land damage after the December 2011 earthquakes shows a pattern to the land damage more extensive than after the September 2010 earthquake but less extensive and severe compared to the June 2011 earthquake. Like the September 2010 earthquake, the spatial distribution of land damage in the December

[3] The Technical Category TC1, TC2 and TC3 areas are described in Section 3.8

2011 earthquake is indicative of locations where the land is vulnerable to liquefaction damage at approximately 100 year return period levels of shaking.

The experienced levels of shaking in the suburbs of Parklands and Queenspark (north of the Avon River) after the December 2011 earthquake are comparable to, or greater than, the levels of shaking observed in the February 2011 earthquake. Therefore, the liquefaction damage from the December 2011 earthquake was more pronounced in Parklands and Queenspark relative to the February 2011 earthquake.

Comparison of the mapped land damage for the June 2011 and December 2011 events (Figures 3.6c and 3.6d) shows that the mapped land damage was generally more severe and more extensive for the June 2011 event. This is despite the estimated levels of ground shaking being similar or in some areas higher in the December 2011 event. The main exception is the Parklands area as noted above. These apparently counterintuitive results highlight both the complexity of the conditions and the uncertainty associated with the estimated levels of seismic demand for each area.

It is noted that the June 2011 and December 2011 earthquakes were both accompanied by significant foreshocks approximately 80 minutes prior to the main events. Both of the foreshocks had sufficient shaking intensity to trigger liquefaction in some of the looser less dense soil layers (Quigley, 2015) and would have increased the propensity for liquefaction to occur during the main earthquake events. In addition, seasonal variation in groundwater levels is one of many important contributing factors that help explain some of the observed land damage patterns. In some parts of Christchurch the groundwater was seasonally elevated in June 2011 relative to December 2011 and partially explains the different extent and severity of the land damage.

While some of the differences in observed land performance can be explained by the influencing factors from the foreshocks and the seasonal variations in the groundwater levels, it is not possible to account for all of these differences. The differences in earthquake shaking characteristics (such as time domain characteristics and the length in the time period between significant events) are also important and are not fully captured by the simple parameters of PGA and M_W. There is also natural variability in the phenomenon of liquefaction and its manifestation at the ground surface.

Based on liquefaction vulnerability assessment studies undertaken by Lacrosse et al. (2015), the variation in liquefaction related damage following the June 2011 and December 2011 fits within the envelope of predicted outcomes for similar levels of earthquake shaking (i.e. the modelled vulnerability ranging from low values at P_L=85% to high values at P_L=15%). Refer to **Appendix A** for more information about P_L.

3.7.4 Ground Surface Subsidence

Before the CES LiDAR surveys were flown by the local territorial authorities, primarily for storm water modelling and flood assessment purposes. LiDAR surveys were flown after each of the main earthquake events in the CES for the purpose of assessing the ground surface subsidence caused by each main earthquake event. The LiDAR surveys were typically acquired a month after each main earthquake (apart from the LiDAR survey after the September 2010 earthquake), providing time for ejected sand and silt to be removed from most of the land, so the survey measurements recorded the ground surface level.

A suite of Digital Elevation Models (**DEM**s) of the ground surface were developed from position data points collected during the LiDAR surveys that were flown before and after each of the main earthquake events. The substantial amount of position data points collected during each LiDAR survey were acquired as a LiDAR survey point cloud (referred to herein as LiDAR points). The LiDAR points were classified as either ground classified points or non-ground (i.e. LiDAR points reflected off vegetation and structures) classified points. While all LiDAR points may be used in the development of DEM, only ground classified points were used in the development of the bare earth DEMs (referred to herein as DEM).

To estimate the change in vertical ground surface elevation due the CES, difference DEMs were obtained by subtracting the later in time DEM from the earlier DEM. Figure 3.8a shows the cumulative vertical differences between the pre-CES and post-CES DEMs. These differences show that the CES caused widespread ground surface subsidence in central and eastern Christchurch and uplift in the south-eastern part of Christchurch.

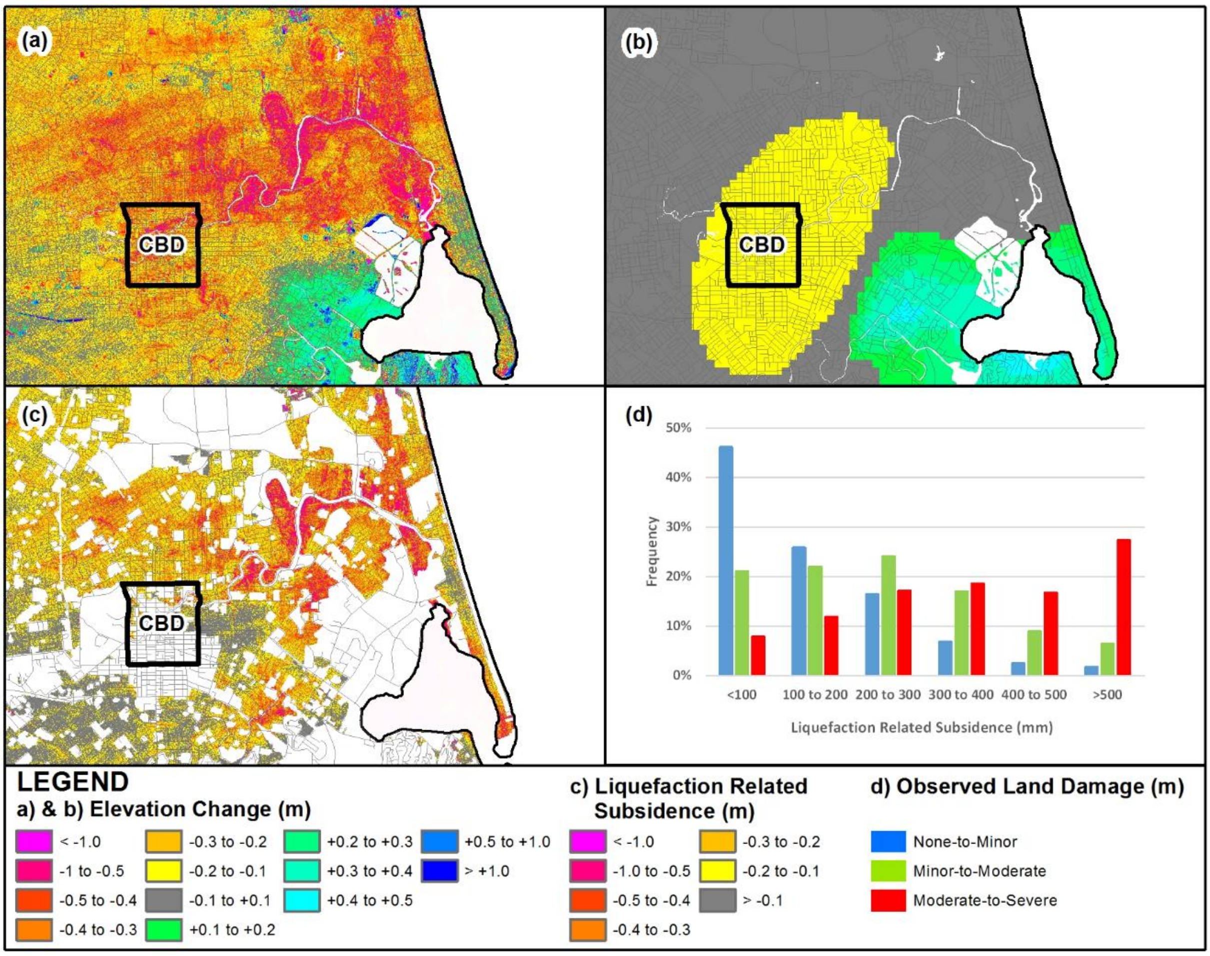


Figure 3.8: (a) Estimated total vertical ground movement caused by the CES. (b) Estimated vertical tectonic movement from the CES. (c) Estimated liquefaction related subsidence for urban residential properties in Christchurch as a result of the CES. (d) Frequency histogram of the estimated liquefaction related subsidence on the urban residential properties in Christchurch grouped by the worst observed liquefaction related land damage observation categories over the CES.

This difference DEM indicates that 85% of the urban residential properties in Christchurch have subsided as a result of the CES and approximately 60,000 residential properties have subsided by more than 0.2m. The most severe subsidence occurred in the suburbs adjacent to the Avon River. The changes in ground surface elevation can be mainly attributed to:

- Vertical tectonic movement;
- Liquefaction related volumetric densification;
- Surface ejection of liquefied soil material;
- Topographic re-levelling; and;
- Lateral spreading.

Not all ground surface elevation changes in Figure 3.8a can be attributed to the CES. In particular:

- There are areas where construction fill has been placed at some stage between the initial LiDAR surveys in 2003 and 2008 and the post-CES LiDAR surveys; and
- Some of the vertical differences are due to the limits of the measurement accuracy of the LiDAR point elevations, as well as the limitations of the DEMs to represent the ground surface elevation and difference DEMs to estimate the change in ground surface elevation. For example, in the western part of Christchurch a series of “error bands” can be seen as yellow bands running in a west-south-west to east-north-east direction, which corresponds to the flight paths of the aircraft during the base 2003 LiDAR survey. Similarly, in densely vegetated parts of Christchurch there are very few measured ground surface LiDAR points resulting in interpolation error of the DEMs.

Further discussion relating to these LiDAR surveys and their artefacts is provided in **Appendix G**.

Figure 3.8b shows the vertical tectonic movement estimate as a result of the CES. This estimate is derived from models of the tectonic slip distributions and fault locations for the CES which were developed by Beavan et al. (2012). These models were based on Global Positioning System data and synthetic aperture radar data collected before and after each of the four main earthquakes. These models were used to develop a three dimensional tectonic deformation estimate throughout the Canterbury region due to each earthquake.

It should be noted that the models were not fully developed at the time of the primary author’s death, and thus, there are limitations that have not been fully documented. Therefore, some caution is required when using the models and it should be recognised that the results are approximate.

Figure 3.8c shows the estimated liquefaction related ground surface subsidence as a result of the CES (i.e. the total estimated vertical ground surface movement with the estimated vertical tectonic component subtracted). This map suggests that:

- The CES caused widespread liquefaction related ground surface subsidence in central and eastern Christchurch;
- Approximately 40,000 residential properties have subsided by more than 0.2m due to liquefaction related effects; and
- The most severe subsidence occurred in the suburbs adjacent to the Avon River and the residential properties adjacent to the Avon-Heathcote estuary.

There is a strong correlation between the amount of estimated liquefaction related ground surface subsidence and the observed liquefaction related land damage as shown in the histograms in Figure 3.8d. Approximately 85% of the residential properties where the estimated liquefaction related ground surface subsidence was less than 0.3m, had none-to-minor observed liquefaction damage. Conversely, approximately 70% of the residential properties where the estimated liquefaction related ground surface subsidence was greater than 0.3m, had minor-to-moderate and moderate-to-severe observed liquefaction related land damage.

3.7.5 Urban Residential Foundation Deformation

The liquefaction of near surface soil layers (mainly in the upper 10m of the soil profile) had the following effects:

- Volumetric densification;
- Sand and water ejecta;
- Topographic re-levelling; and
- Lateral spreading.

All of these effects resulted in differential ground surface subsidence. When this differential ground surface subsidence occurred beneath residential buildings founded on shallow foundation systems, it resulted in differential settlement of the foundations (Chapman, et al., 2015).

Figure 3.9a shows the estimated differential foundation settlement of residential dwellings in Christchurch based on 60,000 visual inspections. This information was collected as part of a detailed inspection of liquefaction related land damage for EQC land damage claim assessment purposes. The inspections were carried out by the Land Damage Assessment Team (**LDAT**) which included approximately 400 geotechnical engineers and engineering geologists. The inspections were predominantly focused in the areas affected by liquefaction land damage.

The visual estimate of differential settlement to residential building foundations was recorded based on criteria reflecting its severity. The data for each residential house was collected to identify three categories of differential settlement, which were described on the assessment forms as:

- **None/minor** - less than 20 mm;
- **Moderate** - 20 to 50 mm; and
- **Major** - greater than 50 mm.

16,000 residential buildings were assessed as having major (> 50mm) differential settlement. Comparison of Figure 3.9 with Figure 3.6 shows that this assessment is closely spatially correlated with the properties that have moderate-to-severe mapped land damage. Comparison with Figure 3.8c shows that these properties also spatially correlate with properties which are estimated to have subsided by more than 0.3m due to liquefaction related effects.

It is important to note that, because these estimates of differential foundation settlement were based on visual inspection, the magnitudes of recorded differential settlement are approximate. Therefore, the three categories of differential foundation settlement are not as reliable as the three categories of liquefaction related land damage or the ground surface subsidence derived from the high resolution LiDAR surveys. Correlations between liquefaction indicators and differential foundation settlement are not likely to be as robust or consistent as those using liquefaction-related land damage and the LiDAR derived ground surface subsidence.

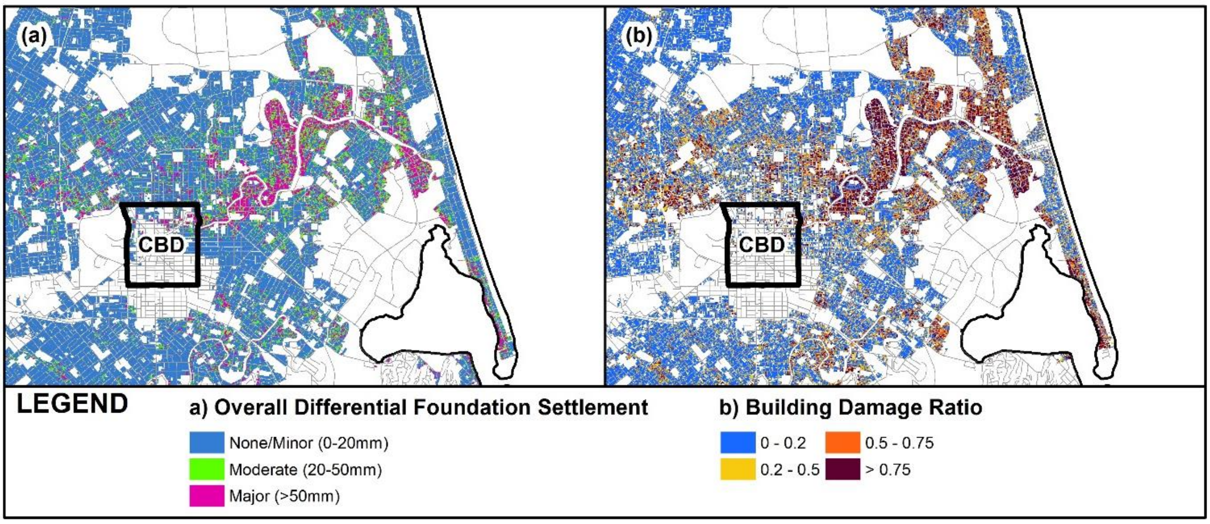


Figure 3.9: (a) Estimated differential foundation settlement from visual inspections of the urban residential buildings in Christchurch as a result of the CES; (b) the estimated BDR of the urban residential buildings in Christchurch as a result of the CES.

Figure 3.9b shows the Building Damage Ratio (**BDR**) values of the portfolio of residential buildings in the Christchurch area. The BDR is estimated by dividing the cost to repair earthquake related damage to a residential building by the greater of the replacement value or valuation of that building. The building damage repair costs were assessed by a separate independent team to the LDAT assessment team.

When the BDR of a residential building is greater than 0.5, the damage to that building is typically significant. This damage often results from liquefaction related foundation deformation which is impractical to repair. In many cases this results in the building being demolished and rebuilt because the cost of repair exceeds the cost of rebuilding.

BDR values between 0.2 and 0.5 typically represent practical repairable damage such as cosmetic repairs and minor structural repairs. Often this also includes minor foundation re-levelling of the building.

BDR values of less than 0.2 generally comprise only non-structural damage such as repairing cracks in the internal wall plaster lining and repainting the house. Typically this does not involve foundation repair works.

Comparison with Figure 3.6 shows that properties with BDR of greater than 0.5 is closely correlated with the properties that have moderate-to-severe mapped land damage. Comparison Figure 3.8c shows that these properties also spatially correlate with properties which are estimated to have subsided by more than 0.3m due to liquefaction related effects.

Figure 3.10 shows histograms which correlate BDR with observed land damage, liquefaction related subsidence and differential foundation settlement.

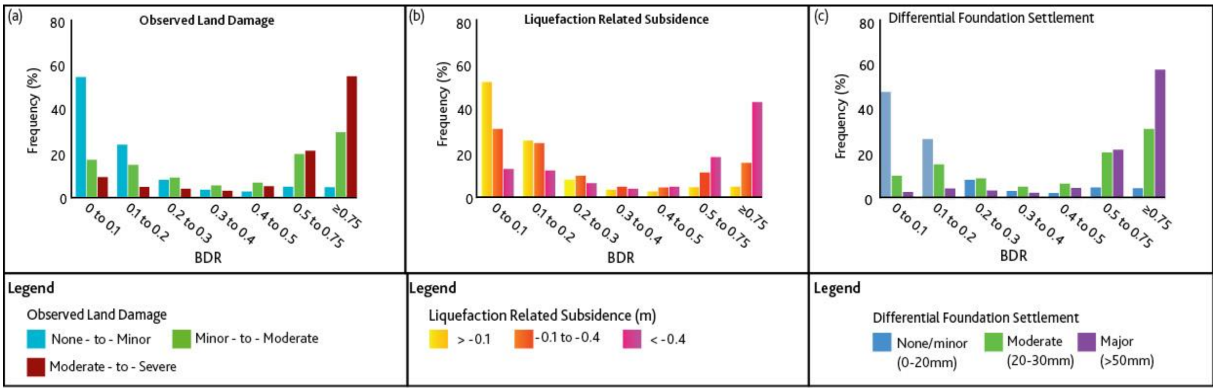


Figure 3.10: Histograms showing BDR correlations with (a) observed land damage, (b) liquefaction related subsidence and (c) differential foundation settlement.

Figure 3.10a shows that there are strong correlations between the properties with high BDR and the properties where the observed liquefaction related land damage was moderate-to-severe.

Figure 3.10b shows that there are strong correlations between the properties with high BDR and the properties where the estimated liquefaction related subsidence is high (i.e. greater than 0.3m).

Figure 3.10c shows that there are strong correlations between the properties with high BDR and the properties where observed foundation differential settlement was moderate or major.

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

3.7.6 Ground Surface Subsidence and Increased Liquefaction Vulnerability

Over the course of the CES, it was observed that in some areas where the ground had subsided significantly, the land performance was becoming worse relative to the levels of earthquake shaking in subsequent events. Each of the main aftershocks was causing proportionally more severe liquefaction-related damage than the previous larger earthquakes. This increase in damage was inferred to be due to a change in the land as a result of the earthquakes. The damage comprised greater volumes of ejected liquefied soil, greater ground surface subsidence and undulation and greater settlement of building foundations into the ground.

The groundwater elevation across Christchurch has not substantially changed through the CES (van Ballegooy, et al., 2014a). As a result of the subsidence caused by the CES, the groundwater surface is now shallower and closer to the ground surface. In turn, a number of residential properties are now more vulnerable to moderate-to-severe liquefaction damage in future moderate-to-strong earthquakes (Russell, et al., 2015). The balance of this report discusses the extent to which these changes that have occurred have made the land more vulnerable to liquefaction damage in future earthquake events.

Throughout the Christchurch area, the vulnerability of the land to lateral spreading is judged to have not increased. In most cases it very likely has remained the same or slightly decreased (refer to **Appendix F**). Only forms of liquefaction damage that have the potential to increase the future vulnerability of the land to liquefaction damage have been considered in the *Criterion 1* assessment (i.e. the types of liquefaction damage that could result in land damage that could satisfy *Criterion 2*). For this reason vulnerability of land to lateral spreading has not been included.

3.8 Land Classifications and Foundation Guidance for Rebuilding in Christchurch

As a result of the CES, the Canterbury Earthquake Authority (**CERA**) and MBIE have made a number of classifications of different areas of Christchurch which are referred to in this report.

Following the second main CES earthquake (in February 2011), the Government established CERA under the Canterbury Earthquake Recovery Act 2011 to lead the recovery planning for the Canterbury region. CERA's role has included undertaking assessments of the areas most affected by the CES and providing recommendations to Government about the suitability of the land for residential occupation in the short to medium term. Based on these recommendations, Government made decisions about short to medium term usability of land, represented by the residential red and green zone classifications (shown in Figure 3.11 below):

- **Red zone**: The land is unlikely to be able to be rebuilt on for a prolonged period because it has been so badly damaged by the earthquakes; and
- **Green zone**: The land is suitable for residential occupation, though some land may require geotechnical investigation and/or particular types of foundations to minimise any future liquefaction damage.

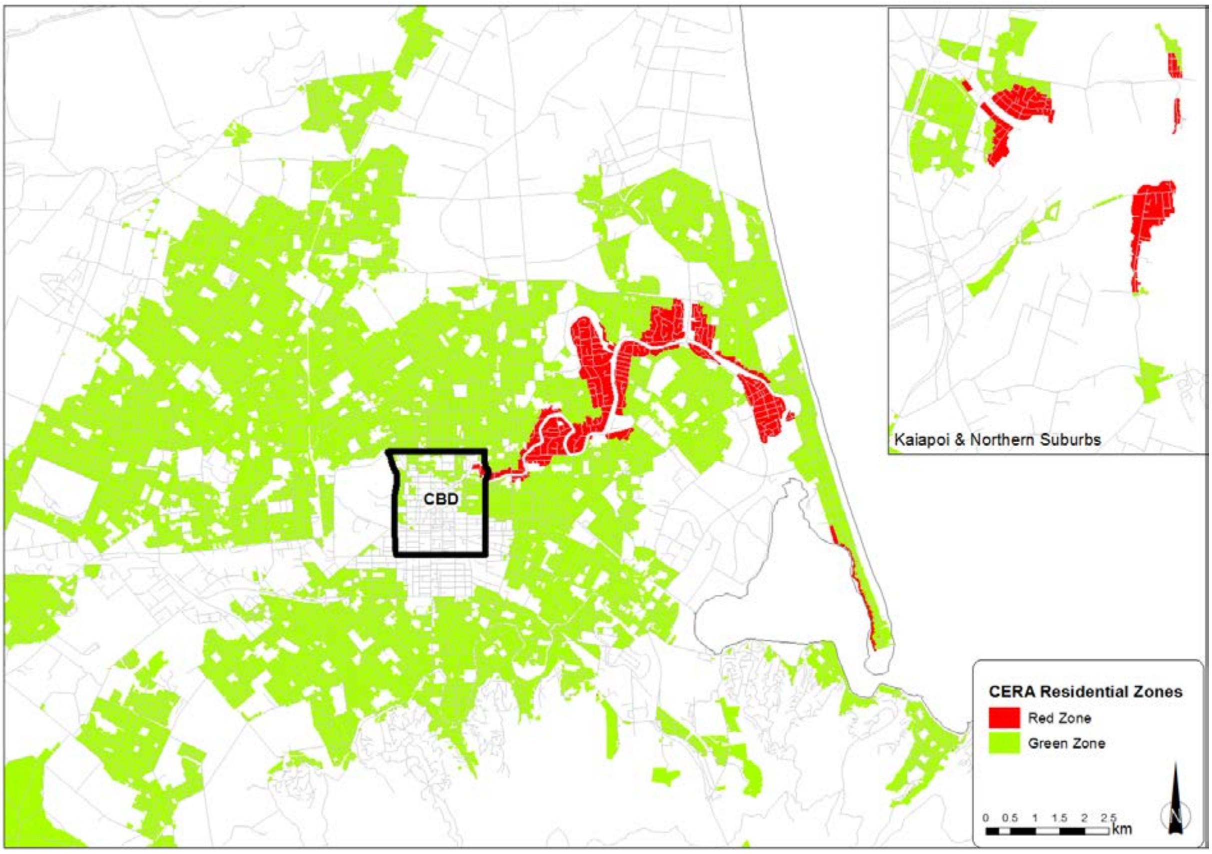


Figure 3.11: Map of the CERA residential red and green zones on the flat land for the urban residential properties.

MBIE is a Government Department which integrates the functions of the (former) Department of Building and Housing. MBIE has:

- Provided guidance on suitable foundations for different areas in the residential green zone in order to reduce damage from liquefaction in future earthquakes;
- Published the classification of green zone land in Canterbury in three Technical Categories (TC) on 28 October 2011. The spatial location of the three residential TC areas is shown in Figure 3.12 below;
- Subsequently issued guidance on repairing and rebuilding buildings affected by the CES (the **MBIE Guidelines**). These guidelines have been updated through the CES with the latest update occurring in April 2015.

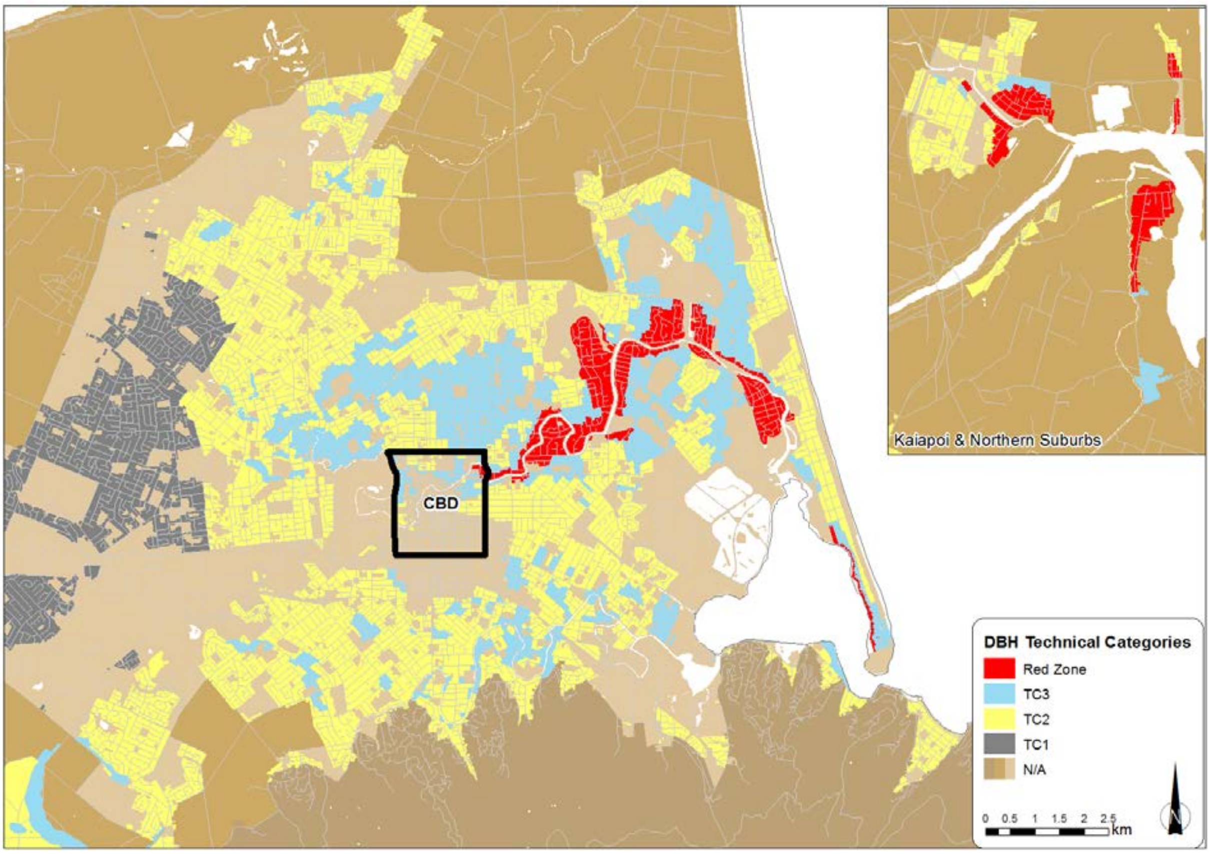


Figure 3.12: Map of the MBIE residential TC areas in Christchurch on flat land for the urban residential buildings in Christchurch

Section 1.4.3 of the MBIE (2012) guidelines defines the Technical Categories as follows:

- **TC1** - Liquefaction damage is unlikely in future large earthquakes. Standard residential foundation assessment and construction is appropriate;
- **TC2** - Liquefaction damage is possible in future large earthquakes. Standard enhanced foundation repair and rebuild options in accordance with MBIE Guidance are suitable to mitigate against this possibility; and;
- **TC3** - Liquefaction damage is possible in future large earthquakes. Individual engineering assessment is required to select the appropriate foundation repair or rebuild option.

The term “standard enhanced” in the definition of TC2 above should be interpreted in context. It is good engineering practice to specify “standard enhanced” foundation systems (such as those recommended in the MBIE guidelines) for residential dwellings constructed on soils throughout New Zealand that are susceptible to liquefaction. This is because there are a number of benefits to these foundation systems for only moderate additional cost over and above the cost of the standard foundation systems. In most cases it is cheaper to incur that additional cost than it is to undertake deep geotechnical investigations and have a liquefaction assessment report prepared by a geotechnical engineer. Hereinafter “standard enhanced” foundation systems will be referred to as TC2 foundation systems.

The additional benefits of the TC2 foundation systems include:

- Significantly more strength and stiffness than the standard residential foundation system;
- Flood protection due to the increased thickness of the concrete slab resulting in additional floor height from the ground surface; and

- Enhanced capacity to resist differential settlement due to other soil conditions (e.g. movement of the ground surface due to seasonal groundwater table fluctuation, consolidation of peat and weak cohesive soils, etc).

Non-residential properties in urban areas, properties in rural areas or beyond the extent of land damage mapping, and properties in parts of the Port Hills and Banks Peninsula have not been given a TC (i.e. the technical category is not applicable).

Section 3.1 of the MBIE (2012) guidelines outlines that the TC1, TC2 and TC3 areas were established as a recovery measure following the CES. The TC1, TC2 and TC3 areas are intended to facilitate the recovery by providing an indication of what geotechnical assessments are required, and therefore directing scarce engineering resources appropriately. The TC1, TC2 and TC3 areas provide guidance on foundation solutions appropriate to both the ground on which the residential buildings are situated and the level of damage sustained by the existing buildings and land.

A number of TC2 foundation solutions are presented in the MBIE guidelines that can be applied for rebuilding buildings on TC1 and TC2 land. Generally, these solutions only require shallow subsurface investigations to be carried out.

However, for rebuilding on TC3 land, the foundation requirements could vary significantly depending on the specific details of the proposed residential building and the ground conditions at the site. Therefore, site specific geotechnical investigations and subsequent analysis are required to determine the appropriate foundation type.

Since 2012, EQC and the private sector have undertaken a large amount of geotechnical investigations in the TC3 area to better understand ground conditions and inform foundation design. At the end of 2014, approximately 18,000 CPTs and 4,000 boreholes, 1,000 groundwater monitoring wells and 6,000 laboratory tests from recovered soil samples have been undertaken mainly in the TC3 area (Scott, et al., 2015a & 2015b). The spatial location of these investigations are shown in the regional maps in **Appendix K.**

Analysis of the CPT data in accordance with the procedures and criteria set out in the MBIE (2012) guidelines shows that approximately 55% of the properties in TC3 can utilise TC2 foundations (the green area in Figure 3.13). 45% of the properties in TC3 require some form of more enhanced structural foundation system or ground improvement in conjunction with a TC2 foundation system to reduce the liquefaction related damage to the buildings in future design levels of earthquake shaking.

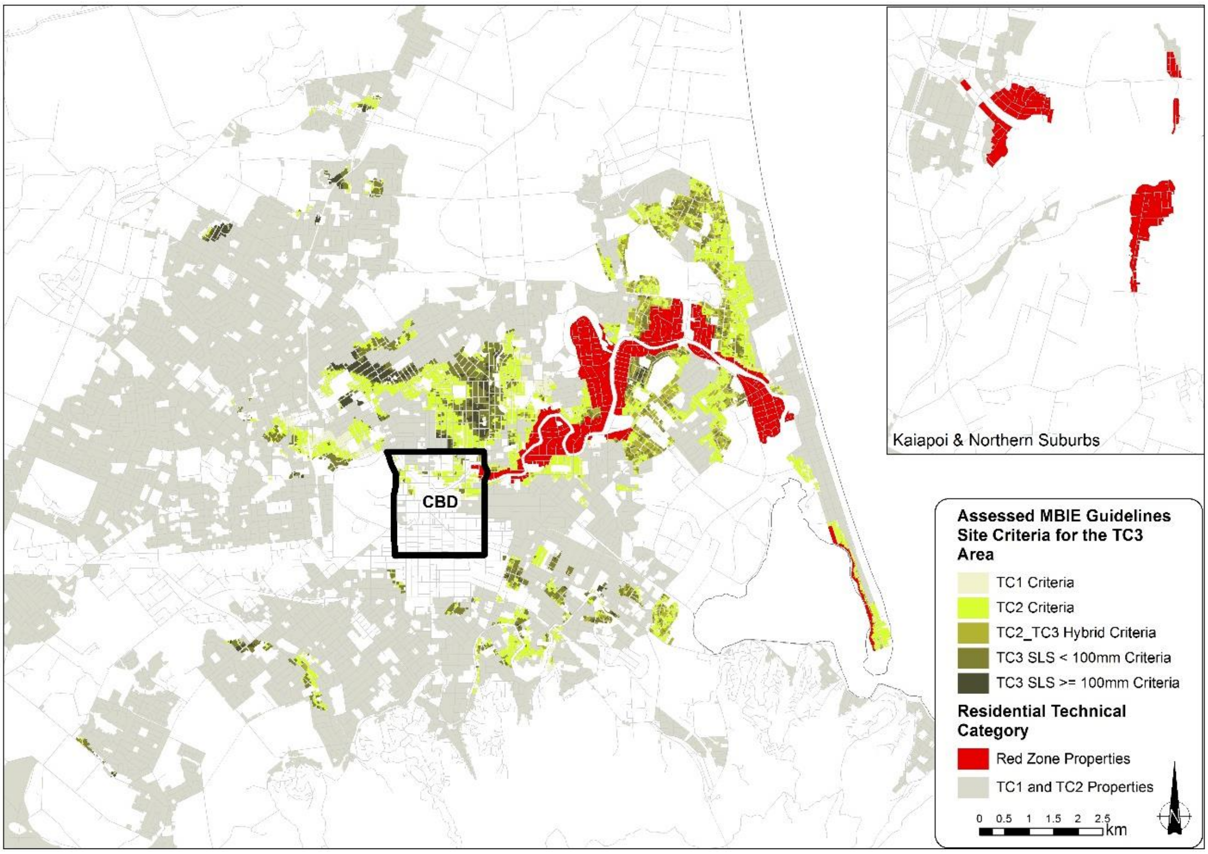


Figure 3.13: Map showing the assessed MBIE (2012) guidelines site criteria for the TC3 land using the CPT test results. This map indicates geospatially which foundation systems can be used throughout the TC3 area. White areas on the map represent the Port Hills, urban non-residential, rural and unmapped land. Grey areas indicate the TC1 and TC2 areas, on which residential buildings can be built with TC2 foundation solutions without specific deep geotechnical investigation analysis.

4 Assessment Methodology Overview

4.1 Purpose and Outline

This section of the report provides an overview of the ILV Assessment Methodology, including:

- The framework for the assessment methodology, including how the *engineering criteria* have been interpreted, in particular in relation to the question of what level of liquefaction vulnerability, and change in vulnerability, should be regarded as material as a matter of engineering judgement;
- The typical attributes of properties that would qualify for ILV, and the typical attributes of properties that would not qualify for ILV; and
- The process used to assess properties for ILV qualification, and to enable the appropriate level of scrutiny to be applied in different areas of Christchurch having regard to the complexity of the assessment required.

Further details on important elements of the ILV Assessment Methodology are then provided in the subsequent sections of this report.

4.2 ILV Assessment Methodology Framework

4.2.1 The *Engineering Criteria*

The ILV Assessment Methodology is designed to consider whether, on the balance of probabilities, the *engineering criteria* are satisfied in the case of a particular property. The *engineering criteria* (as described in more detail in Section 2.4) are as follows:

- ***Criterion 1***: The residential land has a material vulnerability to liquefaction damage after the CES at 100 year return period levels of earthquake shaking.
- ***Criterion 2***: The vulnerability to liquefaction damage of the residential land in future earthquakes has materially increased at up to 100 year return period levels of earthquake shaking as a result of ground surface subsidence of the land caused by the CES.

In all cases, the objectives are those set out in Section 2.6 of this report. These objectives include providing a consistent treatment of the issues associated with ILV land damage.

4.2.2 Information Taken into Account

The information for the assessment of ILV was predominantly sourced from the CGD**.** This database is publicly available to professional engineering companies involved with Canterbury recovery, the New Zealand Government, scientific and academic institutions, EQC, local authorities and insurers.

The sources of information used for the ILV assessments included:

- Geological maps, soil maps and other historical land use and drainage maps;
- Ground surface levels, relative to sea level, estimated using DEMs. These models were derived from LiDAR surveys of the Christchurch region undertaken in 2003 and after each of the main earthquakes in the CES;
- Soil composition data obtained mainly from extensive post-CES geotechnical investigations, including CPTs, subsurface drilling, and laboratory tests;
- Groundwater levels throughout Christchurch, which have been the subject of ongoing monitoring;
- Models estimating PGA in each of the main events in the CES;

- Aerial photography after each of the main earthquakes in the CES;
- Observed performance of land, including liquefaction, in the CES, relative to the estimated levels of earthquake shaking;
- Mapping of lateral spread caused by the CES; and
- Consequential building damage.

These information sources are described in Section 5 of this report.

This information provides a high quality dataset for the assessment of ILV in the Christchurch area. Without this dataset it would be impossible to undertake this assessment. However, there are limitations associated with this dataset which must be accounted for both in the development of the ILV Assessment Methodology and in the assessment of specific locations. These limitations are discussed in Sections 5 to 10.

4.2.3 Assessment Assumptions

The assessment is undertaken on the basis of certain assumptions, designed to ensure that the assessment of potential ILV is consistent with the requirements of the EQC Act.

The assessment of ILV is based on:

- The vulnerability of the residential land to liquefaction in up to a 1 in 100 year return period levels of earthquake shaking (that is, the levels of shaking which on average is expected to occur once in every 100 year period);
- A current level of seismicity of a 1 in 100 year return period levels of shaking that is consistent with the values specified by the MBIE Guidelines (2012; 2014);
- The mean and median liquefaction vulnerability, having regard to seasonal groundwater level variation based on the 15th percentile, median and 85th percentile groundwater surfaces included in the GNS groundwater report (van Ballegooy, et al., 2014a);
- The assumption that the soil behaviour characteristics (i.e. the resistance to liquefaction triggering) are unchanged as a result of the CES;
- The assumption that the lateral spreading vulnerability has not increased as a result of the physical changes to the land caused by the CES;
- The assumption that the cracking of the land caused by the CES, where EQC has or will pay the cost of repairing that damage, should effectively remove the effect of cracking on liquefaction vulnerability; and
- Long access ways are not considered in the assessment of ILV.

These assumptions, and the reasons for them, are described in Section 6 of this report, apart from the mean and median liquefaction vulnerability consideration which is described in Section 7.5 and **Appendix H**.

4.2.4 Assessment Tools

To assess individual properties against the *engineering criteria* using the publicly available dataset and assessment assumptions, engineering judgement has been used, informed by the following indicators:

- The observed performance of land in the CES relative to the estimated levels of earthquake shaking;
- Estimating predicted liquefaction vulnerability based on geotechnical investigation data, such as CPTs and borehole drilling results;

- Estimates of ground-surface subsidence; and
- The other publicly available relevant information described in Section 5.

To estimate predicted liquefaction vulnerability in a future earthquake event from the geotechnical investigation data, a new liquefaction vulnerability parameter, known as the Liquefaction Severity Number (**LSN**) was developed. LSN is estimated using the results of CPTs, borehole drilling, and depth to groundwater models.

The LSN parameter was developed to provide an indicator of liquefaction vulnerability that is better attuned to the ground conditions in Christchurch and is consistent with the engineering and scientific principles governing liquefaction. Existing liquefaction vulnerability parameters are not suitable because they:

- Are not practical to apply in the complex interlayered Christchurch soil profiles beneath the residential properties (as discussed in Sections 3.6 and 7.2); or
- Do not appropriately capture the mechanisms causing the land damage and hence do not correlate with the observed damage patterns in the CES (discussed in Sections 3.7.3, 7.2 and **Appendix A**).

LSN better captures the mechanisms causing the liquefaction related land damage in Christchurch, and as a result correlates better with the observed land damage patterns from the main CES events. The studies which discuss the development of LSN are summarised in **Appendix A**. How the LSN parameter is applied in the ILV Assessment Methodology in conjunction with engineering judgement is discussed in Sections 7 to 10 of this report.

4.2.5 Interpretation of Materiality Requirements

Both *engineering criteria* require an assessment of what level of vulnerability to liquefaction, and what level of change in vulnerability to liquefaction, can properly be regarded as material from an engineering perspective.

Land can be considered materially vulnerable to liquefaction where:

- The land is more likely to suffer moderate-to-severe liquefaction related land damage than none-to-minor liquefaction related land damage at up to 100 year return period levels of earthquake shaking; and
- The vulnerability of the land to liquefaction means that based on specific engineering assessment of geotechnical investigation data an enhanced building foundation (over and above a TC2 foundation) is likely to be required when applying the objectives set out in MBIE (2012) Guidelines. This requirement is dependent on the liquefaction vulnerability at 25 year return period levels of earthquake shaking.

Land can be considered to have materially increased liquefaction vulnerability where:

- The observed and measured changes are such that, having regard to uncertainty associated with the liquefaction analysis, it is more likely than not that a change in vulnerability has occurred; and
- The measured change is such that, from an engineering perspective, the use and amenities of the land as a building platform and other related purposes, can be said to have changed. In practice, a 5 to 10% increase in the likelihood of moderate-to-severe liquefaction related land damage is considered material.

To enable the LSN parameter to be used to as a tool in the assessment of the materiality requirement within the *engineering criteria*, it was necessary to determine the value of the LSN parameter which indicates this level of material vulnerability, and the change in the LSN parameter which indicates a material change in vulnerability. Based on comparison of estimated LSN values to the corresponding observed land performance in the CES, the following values were selected as indicators of the *engineering criteria* being satisfied:

- Land is materially vulnerable to liquefaction damage where the land performance is equivalent to LSN 16 or greater; and
- Land has experienced a material increase in vulnerability where the change in land performance is equivalent to a change of ΔLSN of 5 or greater. This indicator reflects both an assessment of what change can be regarded as materially affecting land performance as a matter of engineering judgement, and the uncertainty in assessing whether a change has in fact occurred.

The materiality assessments of LSN and ΔLSN, and the reasons for this, are described in detail in Sections 7.3 and 7.4 respectively. It is noted that the LSN parameter and the associated indicator values of LSN of 16 and ΔLSN of 5, like any other available liquefaction vulnerability assessment tool, are only an indicator of the likelihood of particular levels of liquefaction related damage occurring in a future earthquake. Liquefaction analysis cannot provide a precise prediction of the exact level of land damage that will occur. Hence, the application of engineering judgement is required when considering estimated LSN values against the indicator values as part of a liquefaction vulnerability assessment.

4.3 Typical Attributes of Properties with and without ILV

The primary considerations taken into account in the assessment of each of the *engineering criteria* are set out in Figure 4.1. This figure shows that in order to qualify for ILV the property under consideration must satisfy both of the *engineering criteria*.

The assessment of ILV is a complex process, requiring the assessment and consideration of a large amount of information. These considerations do not constitute a complete check list for ILV.

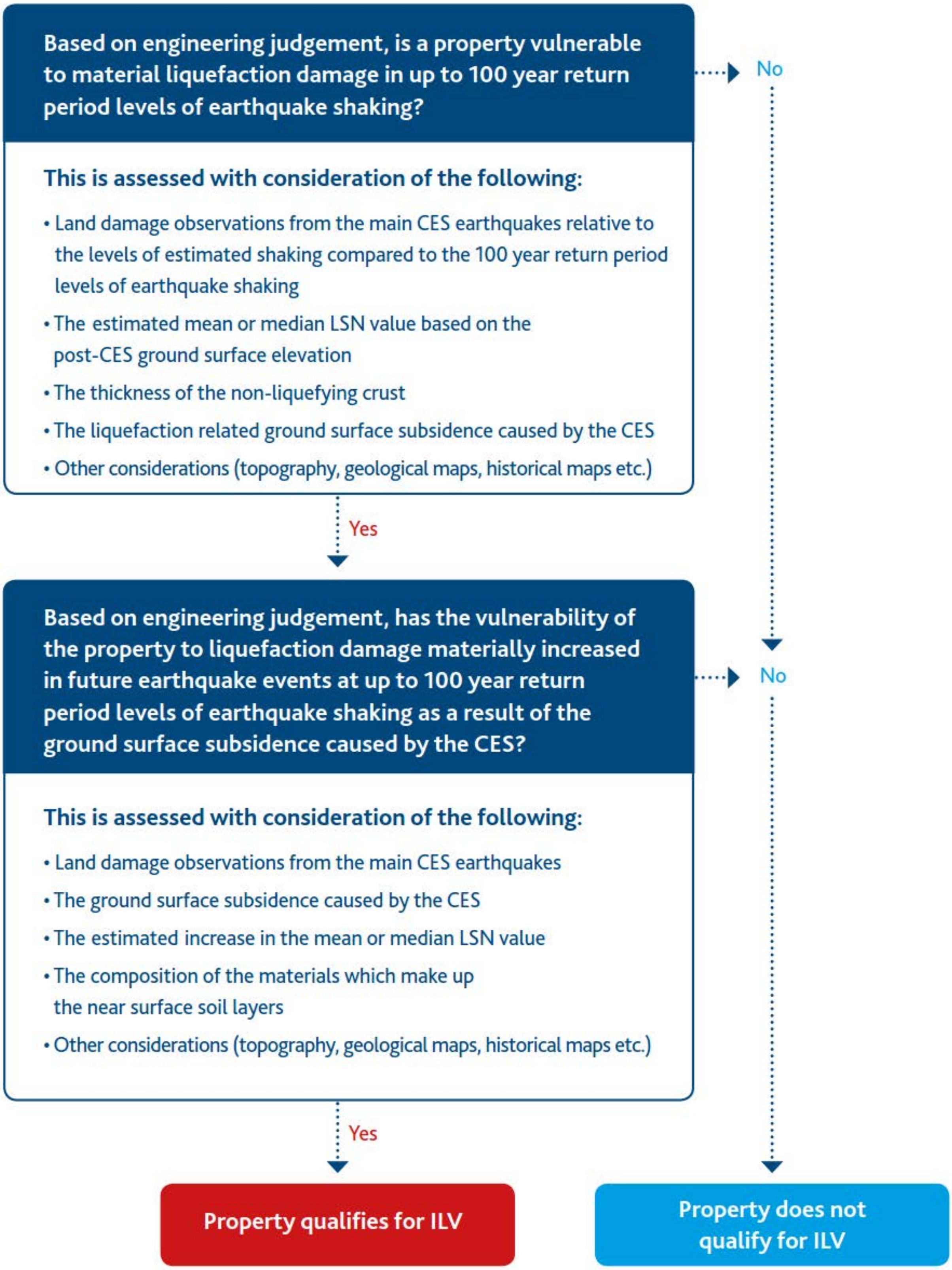


Figure 4.1: Typical property attribute considerations incorporated in the ILV Assessment Methodology.

4.3.1 Typical Attributes of a Property that would Qualify for ILV

Attributes relevant to Criterion 1: Material vulnerability

The typical attributes of a property which is materially vulnerable to liquefaction damage at up to 100 year return period levels of earthquake shaking are described below:

- Moderate-to-severe liquefaction related land damage in the area surrounding the property in events with estimated levels of ground shaking close to or less than 100 year return period levels of earthquake shaking indicates vulnerability to material liquefaction damage;
- An estimated mean or median LSN value of greater than 16 based on the post-CES ground surface elevation indicates potential vulnerability to material liquefaction damage (refer to Section 7.3);
- If the thickness of the non-liquefying crust is less than 3m this potentially indicates vulnerability to material liquefaction damage; and
- Relatively high estimated *liquefaction related* ground surface subsidence over the CES (refer to Section 3.7.4) in the area surrounding the property (where the maximum estimated levels of shaking through the CES are close to or less than 100 year return period levels of earthquake shaking). This suggests a high likelihood of material vulnerability to liquefaction damage.

Attributes relevant to Criterion 2: Material change in vulnerability

For those properties which are materially vulnerable to liquefaction in events up to a 100 year return period, the typical attributes of a property which has materially increased vulnerability to liquefaction in future earthquake events at up to 100 year return period levels of earthquake shaking as a result of the total subsidence caused by the CES are described below:

- An increase in severity of land damage observations during subsequent events with comparable levels of earthquake shaking;
- Relatively high levels of estimated ground surface subsidence across the CES. Note the total ground surface subsidence incorporates both the liquefaction related subsidence and the tectonic component;
- An estimated change in mean or median LSN of greater than 5 over the CES (refer to Section 7.4); and
- Sandier and looser materials in the near surface soils below the groundwater surface are more likely to liquefy.

4.3.2 Typical Attributes of a Property that would not Qualify for ILV

Attributes relevant to Criterion 1: Material vulnerability

The typical attributes of a property which is **not** vulnerable to material liquefaction damage at up to 100 year return period levels of earthquake shaking and therefore would **not** qualify for ILV are described below:

- None-to-minor liquefaction related land damage in the area surrounding the property in earthquakes with estimated levels of ground shaking greater than 100 year return period levels;
- An estimated mean or median LSN value of less than 16 based on the post-CES ground surface elevation (refer to Section 7.3);
- If the thickness of the non-liquefying crust is greater than 3m; and
- Relatively low estimated *liquefaction related* ground surface subsidence over the CES (refer to Section 3.7.4) in the area surrounding the property (where the maximum estimated levels of shaking through the CES are greater than 100 year return period levels of earthquake shaking). This suggests a low likelihood of material vulnerability to liquefaction damage.

Attributes relevant to Criterion 2: Material change in vulnerability

For those properties which are materially vulnerable to liquefaction in up to a 100 year return period levels of earthquake shaking, the typical attributes of a property which has **not** had its vulnerability to liquefaction damage materially increased in up to 100 year return period levels of earthquake shaking as a result of the total subsidence caused by the CES are described below:

- No increase in severity of land damage observations during events with comparable levels of earthquake shaking;
- Relatively low levels of *total* estimated ground surface subsidence across the CES. Note the total ground surface subsidence incorporates both the liquefaction related subsidence and the tectonic component;
- An estimated change in mean or median LSN of less than 5 over the CES (refer to Section 7.4); and
- Siltier or gravel or denser soil materials in the near surface soil layers below the groundwater surface are less likely to liquefy.

4.3.3 Marginal and Complex Cases

Although many properties either clearly qualify, or do not qualify, for ILV, a significant minority of the ILV assessments are either marginal or complex.

Marginal cases occur when all the available information reconciles (i.e. land damage observations and geotechnical information) but the property is on the margin of satisfying *Criterion 1* and /or *Criterion 2*. In marginal cases it is possible to justify the decision going either way. Complex cases occur when one or more of the typical attributes of properties with or without ILV is either missing or indicates that an alternate ILV decision from the other attributes is appropriate, or where the observations and assessments fall on the margins (boundaries) of the materiality assessments.

Such cases have been resolved by the application of engineering judgement in accordance with the criteria, objectives and processes described in this report.

4.4 Process for ILV Assessment

The process for the assessment of urban residential properties in Christchurch for ILV is summarised in Figure 4.2. All approximately 140,000 urban residential properties were assessed using this process.

This process has enabled these assessments to be completed in a consistent and reasonable manner. The process was designed to ensure an appropriate level of resources was used to assess different residential suburbs in Christchurch, depending on the complexity of the engineering assessments required.

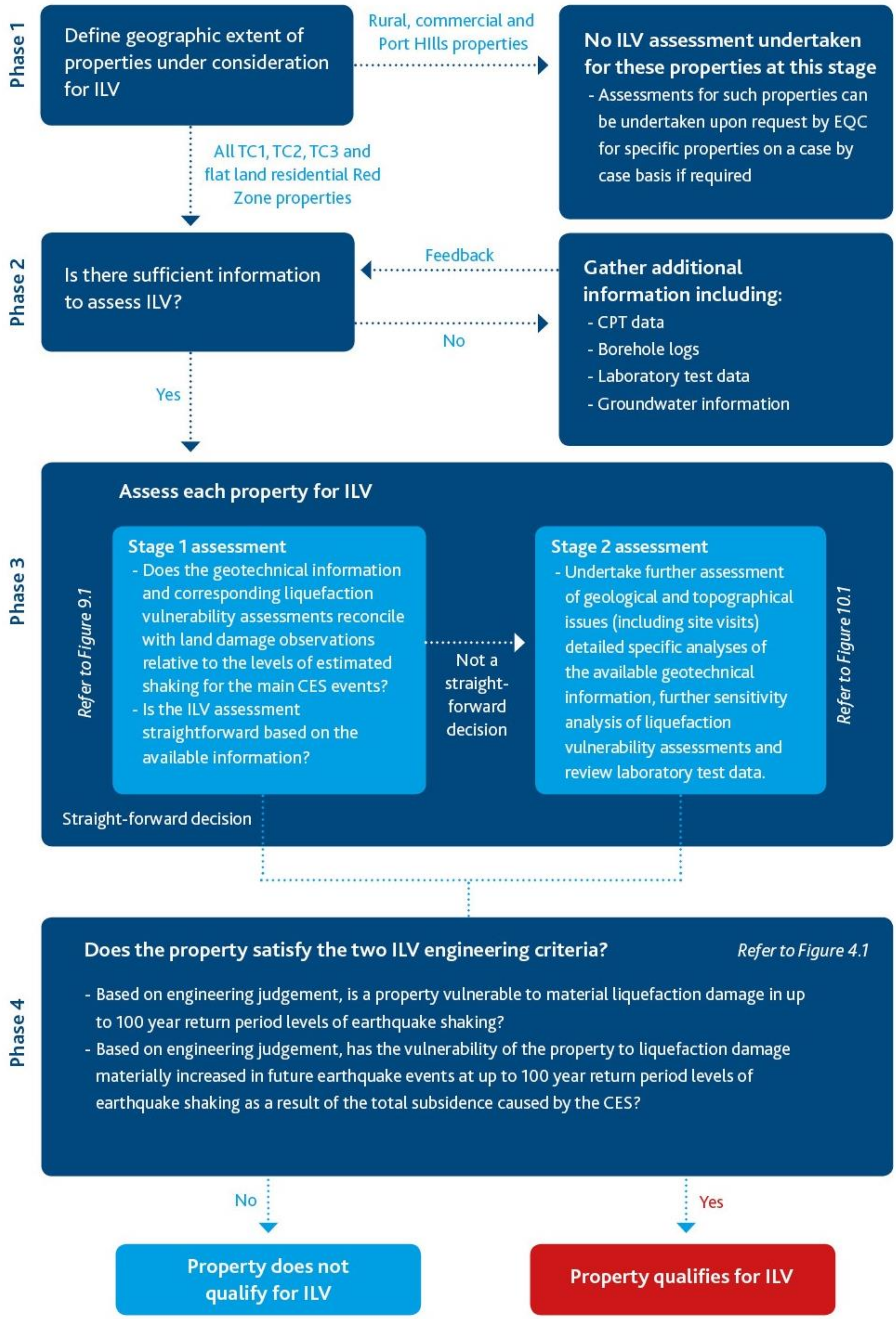


Figure 4.2: Process for ILV Assessment.

4.4.1 Phase 1: Definition of Geographic Extent

Phase 1 of the process defined the geographic extent of properties to be assessed for ILV as being all TC1, TC2, TC3 and flat land residential Red Zone properties. This covered the majority of residential properties which were affected by liquefaction related damage and ground surface subsidence from the CES. Rural, commercial zoned or Port Hills properties for which EQC requires an ILV assessment will be undertaken on a case by case basis.

4.4.2 Phase 2: Collation of Information for Spatial Assessment of Geographic Regions

The next step, **Phase 2** in Figure 4.2, was to determine whether or not there was sufficient geotechnical information to assess ILV for the property.

Properties were grouped together in geographic areas, taking account of the relevant information available to assess those properties. This approach involved mapping of an appropriate number of properties and collating the following information listed below (where available). Typically the clusters of properties varied between 10 to 20 in areas of reasonable geological complexity and poor land performance through the CES, but up to hundreds or thousands in areas of less complexity (for liquefaction vulnerability assessment purposes) and good observed land performance throughout the CES (such as in the TC1 area). The collated information includes:

- Geological and soil maps;
- Post-CES ground surface elevations represented by the post-CES LiDAR DEM;
- Groundwater surface elevation maps;
- High resolution aerial photography;
- Observed land damage mapped across the area for each of the main CES events relative to the estimated levels of earthquake shaking;
- Estimated vertical change in elevation over the CES represented by the pre- to post-CES LiDAR difference DEM;
- The results of automated ILV assessment based on the available CPT data taking into account the groundwater levels, post-CES ground surface elevations and estimated changes in elevation over the CES; and
- Detailed liquefaction assessment of the results of all available ground investigation data (CPTs, boreholes and laboratory testing) in the geographic area.

The above information was collated into hard copy information packages or “packs” for each of these geographical groupings (described in Section 9.2.2 and Section 10.2.2).

The objective of assessing this information across appropriate geographical groupings of individual properties was to ensure that patterns in the information could be identified and linked, where possible, to understandings of the likely causes of liquefaction vulnerability and changes in liquefaction vulnerability due to ground surface subsidence as a result of the CES.

If there was insufficient information to assess ILV in a particular location, additional geotechnical data (in the form of CPTs, borehole logs, laboratory test data and groundwater information) was collected and fed back into the approach as indicated in Figure 4.2.

Additional geotechnical information was not sought where sufficient information already existed to conclude that, on the balance of probabilities, no ILV damage had occurred. This occurred in two main areas:

- **Areas where land performance in CES demonstrates that the land is not vulnerable (*Criterion 1*):** The consideration of liquefaction related land damage and liquefaction related ground surface subsidence caused by the CES has meant large areas of properties in TC1 and

TC2 have been assessed as not qualifying for ILV with little to no geotechnical investigation data being required. This is because if:

– No liquefaction related land damage observations were made for any of the CES earthquakes with at least one or more of the main earthquakes with estimated levels of shaking greater than 100 year return period levels of earthquake shaking; and

– Very little liquefaction related subsidence was estimated over the CES represented by the pre- to post-CES LiDAR difference DEM,

then the earthquakes have demonstrated that such land is very unlikely to be vulnerable to liquefaction damage at 100 year return period levels of earthquake shaking. Therefore, properties in these areas would not satisfy *Criterion 1* and would not qualify for ILV land damage.

- **Areas which have not subsided as a result of the CES (*Criterion 2*):** There are areas in Christchurch where there has been little to no ground surface subsidence through the CES. There are also areas where liquefaction related land damage was observed and liquefaction related ground surface subsidence was estimated, but as a result of tectonic uplift, the post-CES ground surface elevation of some areas is at or above the pre-CES ground surface elevation. In these areas because the groundwater elevation has remained unchanged there will not have been an increase in liquefaction vulnerability. As a result, this has enabled properties in such areas to be assessed as not qualifying for ILV with little to no geotechnical investigations being required.

4.4.3 Phases 3 and 4: Spatial Assessment of Liquefaction Vulnerability

Once any further information was obtained, **Phases 3 and 4** involved reviewing and considering the information for each geographical grouping of properties for ILV assessment and determining the ILV qualification status for each property.

The assessment of liquefaction vulnerability involved:

- The use of the automated ILV model, based on estimated LSN parameters for each CPT which are spatially interpolated to provide estimated LSN and ∆LSN assessments for each urban residential property. This is described in more detail in Section 8.2; and
- The manual review of the publically available CPTs and borehole data, including liquefaction vulnerability sensitivity analyses for each CPT within the area of the properties being assessed in the packs. This is described in more detail in Section 8.3.

While the automated ILV model is a useful tool for the manual assessment process, it has limitations both in relation to its exclusive reliance on LSN (which has known limitations in predicting liquefaction vulnerability in certain soil conditions) and simple linear interpolation of LSN results between known CPT points with no regard to the regional geologic features as well as the spatial variability of the soils. As a result, a manual process is required to ensure that results are reliable and appropriately account for regional geological features and the spatial variability of the soils.

The manual qualification process is based on the information contained in the packs generated in Phase 2. It involves consideration of:

- Regional level data to identify relevant geological features and geospatial trends in land damage patterns and estimated LSN values;
- Local data packs comprising neighbouring properties; and
- As appropriate, specific analysis for groups of properties with similar ground conditions and similar observed performance through the CES.

The manual assessment process was undertaken in two stages, which ensured that the greatest resource and consideration was brought to bear on the most difficult properties.

Stage 1 Assessments

All of the 139,390 properties[4] in TC1, TC2, TC3 and residential Red Zone areas were assessed in the Stage 1 process.

The key question under consideration is whether or not the geotechnical information and corresponding liquefaction vulnerability and change in liquefaction vulnerability assessments reconciled with land damage observations, relative to the levels of estimated shaking for the main CES earthquakes, as well as the estimated ground surface subsidence over the CES (for the pre- to post CES LiDAR difference DEM). If these did reconcile and the ILV assessment decision was relatively straightforward for a property it was qualified as either yes or no for ILV. If the decision was not straightforward the ILV decision for the property was deferred and reassessed using the subsequent Stage 2 process.

The ILV status of approximately 132,690 properties were resolved at Stage 1 of the process. Of these properties 8,366 classified as yes, and 124,324 classified as no. A further 6,700 properties required assessment using the Stage 2 process.

Stage 2 Assessments

The remaining 6,700 properties where then assessed using the Stage 2 process.

The Stage 2 process involved further assessment of geological and topographic issues (including site visits), detailed specific analysis of the available geotechnical information, sensitivity analysis of liquefaction vulnerability assessments and review of laboratory test data. Based on the subsequent Stage 2 ILV assessment, the remaining properties were qualified as either yes or no for ILV.

At the completion of the Stage 2 process in total, 9,917 properties were classified as yes and 129,473 were classified as no.

The qualification status for every property was technically reviewed by senior engineers to ensure an appropriate, fair and consistent outcome was reached for all 139,390 urban residential properties in Christchurch. The results were then entered into a database before the final review by the senior technical review team and the project director.

Further detail about both the Stage 1 and Stage 2 processes are provided in Sections 9 and 10 of this Report respectively, and the results of the ILV assessment process is provided in Section 11.

[4] The property counts are based on the QPID database (maintained by Quotable Value Ltd) which existed at the time of the CES. The number of properties/QPIDs does not necessarily represent the number of claims.

5 Information used for the ILV Assessment

5.1 Purpose and Outline

In this section of the report the sources of information used in the ILV Assessment Methodology are described.

The sources of information relied upon for the ILV assessments included:

- Geological maps, soil maps and other historical land use and drainage maps;
- Ground surface elevations, relative to sea level, estimated using DEMs. These models were derived from LiDAR surveys of the Christchurch region undertaken in 2003 and after each of the main earthquakes in the CES;
- Groundwater levels throughout Christchurch, which have been the subject of ongoing monitoring;
- Soil composition data obtained from extensive geotechnical investigations, including CPTs, subsurface drilling, and laboratory tests;
- Models estimating PGA in each of the main events in the CES;
- Aerial photography after each of the main earthquakes in the CES;
- Observed performance of land, including liquefaction, in the CES, relative to the estimated levels of earthquake shaking;
- Mapping of lateral spread caused by the CES; and
- Consequential building damage.

For the ILV Assessments this information was collected and collated into "packs" of information relating to geographic groupings of properties. The compilation of these packs is described in Sections 9.2.2 and 10.2.2. This process enabled the information to be considered on a holistic and spatial basis.

The information for the assessment of ILV was predominantly sourced from the CGD. This database is publicly available to professional engineering companies involved with Canterbury recovery, the New Zealand Government, scientific and academic institutions, EQC, local authorities and insurers.

The only information that was not sourced from the CGD is the EQC LDAT property inspection reports. The LDAT reports for individual properties are available from EQC at the request of the property owner.

5.2 Geological Maps, Soil Maps and other Historical Land Use and Drainage Maps

A range of regional and detailed geological maps is available on the CGD.

The main geological resource used in the assessment of ILV is the Geological and Nuclear Sciences (**GNS**) geology of the Christchurch Urban Area Map (Brown & Weeber, 1992). Additional resources available on the CGD include:

- the GNS 1:250,000 Geological Map 16 of Christchurch (Forsyth, et al., 2008);
- the GNS Christchurch Geoserver layers of geological units QMAP, faults, folds and boundaries;
- the GNS QMAPs for Aorangi, Kaikoura, Greymouth, Inactive Faults, and All New Zealand;
- Historical land use maps; and
- Historical drainage maps.

A selection of geotechnical and geological maps from the Archives NZ and Christchurch City Council are included as layers on the CGD. These maps have been referred to for additional historic information particularly regarding old swamps.

5.3 Ground Surface Elevations

Ground surface elevation DEMs derived from LiDAR surveys have been used for the assessment of ILV, both in terms of the pre- and post-CES ground surface elevations and the change in ground surface elevations. The ground return LiDAR survey points have been used to develop 'bare earth' DEMs of the pre-CES ground surface and after each of the four main CES earthquakes. Bare earth DEMs are models of the ground surface with vegetation and structures removed. For ILV assessment purposes, the DEMs were resolved to the following grids:

- **25m x 25m grid** to estimate the LSN values at each CPT location and to estimate the LSN value for each property for the automated ILV model (refer to Section 8.2); and
- **5m x 5m grid** to estimate the ΔLSN values for each property (refer to Section 8.2).

The accuracy of the LiDAR point elevations was evaluated by comparing them to elevations published by Land Information New Zealand (**LINZ**) from surveys of an extensive set of survey benchmarks within the Christchurch region (LINZ, 2013) before, between and after the earthquakes. 80% of the LiDAR point elevations were within ±0.07m of the surveyed elevations. The exception was the 2003 survey, where 80% were within ±0.15m. Further discussion about the LiDAR survey and accuracy is provided in **Appendix G**.

LiDAR surveys were acquired by Australian Aerial Mapping (**AAM**) and New Zealand Aerial Mapping (**NZAM**) following each of the main CES earthquakes. The LiDAR survey sources and commissioning agencies are tabulated in Table 5.1. The extents of the LiDAR survey are shown on maps in **Appendix G** and the accuracy and limitations of the LiDAR survey data, the DEMs and the difference DEMs are also discussed in **Appendix G**.

Table 5.1: LiDAR survey information

DEM	Source LiDAR	Commissioning Agencies
Pre-September 2010	AAM, 6-9 Jul 2003	Christchurch City Council
	AAM, 21-24 Jul 2005	Environment Canterbury and Waimakariri District Council
	AAM, 6-11 February 2008	Environment Canterbury and Selwyn District Council
Post-September 2010	NZAM, 5 September 2010	Ministry of Civil Defence and Emergency Management
Post-February 2011	NZAM, 8-10 Mar 2011	Ministry of Civil Defence and Emergency Management
	AAM, 20-30 May 2011	Christchurch City Council
Post-June 2011	NZAM, 18 & 20 Jul, 11 Aug, 25-27 Aug, and 2-3 September 2011	Earthquake Commission
Post-December 2011	NZAM 17-18 Feb, 2012	Earthquake Commission

5.4 Groundwater Surface Levels

Groundwater data used for ILV assessment was obtained from EQC monitoring wells, Environment Canterbury monitoring well records and Christchurch City Council monitoring wells. All of this data are available on the CGD (MBIE, 2012).

Data from approximately 1,000 shallow groundwater monitoring wells has been analysed. The monitoring wells are typically less than 10m deep and are therefore representative of the groundwater conditions in the upper soil layers.

These groundwater monitoring well records were used to develop four groundwater surface levels. The levels selected were the 15th, 50th and 85th percentile and the surrogate median groundwater surfaces. The 15th, 50th and 85th percentile groundwater surfaces include only groundwater monitoring wells with long term records (i.e. more than 12 months of data). The surrogate median groundwater surface includes groundwater monitoring wells with both short term (i.e. 12 months or less) and long term data. Further detail about the development of these models is provided in van Ballegooy et al. (2014a).

The 15th, 50th and 85th percentile groundwater surfaces were used to estimate mean LSN values. The surrogate median was used to estimate median LSN values. The use of these LSN estimations is discussed in more detail in Sections 7, 8.2 and 8.3.

5.5 Geotechnical Investigation Data

The CGD (MBIE, 2012) is a geotechnical data repository used by (among others) professional geotechnical engineers in Christchurch. This database holds a collection of geotechnical investigation information uploaded by EQC, private insurers and others. As at the end of 2014, information was available from the CGD regarding approximately 18,000 CPTs, 4,000 boreholes, 1,000 groundwater monitoring wells and 6,000 laboratory tests from recovered soil samples located around the Christchurch area. The investigations available in the CGD are primarily sourced from post-CES testing and have been used in the detailed assessment of ILV, including sensitivity analyses for liquefaction susceptibility and liquefaction triggering assessments.

Only the geotechnical data publicly available from the CGD, at the time each information pack (used to assess ILV) was compiled, has been used. These packs (for Stage 1 and Stage 2 assessments) are described in more detail in Sections 9.2.2 and 10.2.2 of this report.

The number of geotechnical investigations available in the CGD continues to increase as more investigation data collected by private insurers and private property owners is uploaded to the CGD. Therefore, any geotechnical information that has become publicly available subsequent to the compilation of an ILV assessment information pack will not have been considered as part of the ILV assessment process.

It is acknowledged that in some limited cases the consideration of the additional geotechnical information (which has become available subsequent to the compilation of the ILV assessment information pack) could change the ILV assessment outcome. A review process has therefore been adopted through which EQC customers can request that the additional geotechnical investigation data be considered as part of their ILV assessment.

5.6 PGA Models of the Main CES Earthquakes

Conditional PGA contours developed for liquefaction assessment by Bradley Seismic and the University of Canterbury (referred to as the **University of Canterbury model**) are provided on the CGD (Bradley and Hughes, 2012). For the University of Canterbury model, PGA at each location was estimated by combining the prediction from the empirical ground motion model of the fault rupture with the PGAs recorded at any adjacent strong motion recording stations.

The PGA contours developed by O'Rourke et al. (2012) as an interpolated geometric mean from recording stations (the **Cornell University model**) are also provided on the CGD. These were examined where significant differences were evident between the two PGA models.

The key difference between these two PGA models is that:

- The University of Canterbury model accounts for the ground motion attenuation physics, incorporating the location and magnitude of each of the main CES earthquake events;
- The Cornell University model in contrast, is a surface fitted interpolation over the geometric mean PGA values obtained from each recording station.

These two PGA models have been used for back analyses of the CPT-based liquefaction consequence parameters (in particular the LSN parameter) to compare the estimated LSN values with the observed land performance as part of the liquefaction vulnerability assessment (discussed in Sections 7 to 10).

Where the two models provide similar PGA estimates there is a higher level of confidence in the PGA estimate for a given property. Conversely, where the two models provide significantly different PGA estimates, then there is a lower level of confidence in the PGA estimate for a given property. However, the corresponding recorded land and building damage for an event also provides a good indication of which model provides the best estimate of PGA for that area.

5.7 Aerial Imagery

High resolution aerial photographs of areas of Christchurch affected by liquefaction have been used for the assessment of ILV. The images were primarily used to confirm the extent of any liquefaction ejecta (Section 5.8), assess the extent of landform changes due to human development and understand the influence of dense vegetation on LiDAR survey data (Section 5.3).

The aerial photographs were acquired on 5 September 2010, 24 February 2011, 14 – 15 June 2011, 16 June 2011 and 24 December 2011 by NZ Aerial Mapping. The acquisition dates and commissioning agencies for each photograph set are shown in Table 5.2.

Table 5.2: Acquisition dates and commissioning agencies for each set of aerial photographs

Photograph Set	Acquisition Date(s)	Commissioning Agencies
Post-September 2010	5 September 2010	Ministry of Civil Defence and Emergency Management
Post-February 2011	24 February 2011	Ministry of Civil Defence and Emergency Management
Post-June 2011	14-15 June 2011	The Earthquake Commission
	16 June 2011	The Earthquake Commission
Post-December 2011	24 December 2011	The Earthquake Commission

The images were acquired as soon as possible after each of the main CES earthquakes. The post-September 2010 and post-June aerial photography was obtained in light intensity conditions that were not ideal for aerial photography, but nevertheless the data are still useful records of where liquefaction ejecta occurred.

5.8 Land Damage Observations

Land damage mapping was undertaken following the September 2010, February 2011, June 2011 and December 2011 events through observational mapping, aerial photography and aerial LiDAR. The following information is available on the CGD:

- *Aerial Photography*: as discussed in Section 5.7;
- *Rapid inspections*: On foot rapid inspections were undertaken of liquefaction and lateral spreading in areas with significant damage following each earthquake. These have been collated into layer maps on the CGD for the September 2010 (property observations), February 2011 (road and property observations), June 2011 (road observations) and December 2011 (limited road and property observations as well as aerial surveys) events; and
- *Ground Cracking*: Ground cracks were mapped post the September 2010 and February 2011 events. Crack mapping was limited in the September event where mapping was generally undertaken on specific properties for insurance claims. Ground crack mapping following the February event was carried out at 1:10,000 to 1:2,000 in various areas. Horizontal ground movement was also derived from the LiDAR surveys and checked against ground surveys.

For the purpose of simplicity the land damage observation maps presented in this report have been provided as three colour maps representing the broad land damage categories of none-to-minor, minor-to-moderate and moderate-to-severe defined in Section 3.7.3 and **Appendix B**. However, six colour versions that provide more granularity for the same data set have been used in the ILV Assessment Methodology. Examples of these maps are provided in the regional maps in **Appendix K**. The relationship between the simplified three colour land damage maps and the more granular six colour land damage maps is shown in Table B1.1 in **Appendix B**.

In addition to the aerial and ground based land damage maps available on the CGD, the individual property LDAT inspection reports undertaken for approximately 60,000 properties in the areas affected by liquefaction land damage have also been used. These reports contain detailed qualitative and quantitative observations and locations of land damage including observed ejecta (including under timber floors), ground cracking, ground undulations, ground surface subsidence, lateral spreading and building damage. These reports are accompanied with photographs taken at the time of inspection.

5.9 Lateral Spread Mapping

The total horizontal movement of the ground surface between each of the main CES earthquakes and over the CES has been derived from a correlation process between respective LiDAR survey data sets. By subtracting the associated horizontal tectonic component, a map layer was developed giving an approximation of the magnitude and direction of the horizontal movement due to liquefaction related effects on the flat land across Christchurch. The estimated horizontal movements of the land around the lower reaches of the Avon River are given in **Appendix F**. The map showing the estimated horizontal movements over the wider Christchurch area is available on the CGD.

The horizontal movement mapping is used in the ILV assessment process to assist in the identification of properties where the observed damage may be in whole or in part the result of lateral spreading. For further detail on the development of these horizontal movement maps refer to Bevan et al (2012).

6 ILV Assessment Assumptions

6.1 Purpose and Outline

In undertaking this engineering assessment it has been necessary to make a number of assumptions. This section of the report explains those assumptions as they relate to:

- Earthquake seismicity (Section 6.2);
- Return period levels of earthquake shaking (Section 6.3);
- Anthropogenic and climate change influences on groundwater levels (Section 6.4);
- Changes in soil behaviour (Section 6.5);
- Vulnerability to lateral spreading (Section 6.6);
- Impact from other forms of land damage (Section 6.7); and
- Long access ways are not considered in the assessment of ILV (Section 6.8).

6.2 Earthquake Seismicity

Changes in seismicity (the level of shaking expected in an earthquake of a given return period) have occurred in the Christchurch area as a result of the rupturing of the Darfield fault in the September 2010 earthquake. As a result of these changes in regional seismicity, properties that may not have been materially vulnerable to liquefaction for a given return period level of ground shaking prior to the CES, may now be materially vulnerable to liquefaction for the same return period level of ground shaking because the level of shaking for that return period has increased.

EQC is only entitled to compensate for loss arising from physical changes to insured residential land. EQC has advised T+T that, for something to be considered a 'physical change' a change to the structure or materials of the residential land is required. While the seismicity of Christchurch as a whole has increased as a result of the CES, this results from large scale effects on faults rather than changes to the structure or materials of specific residential land. As a result, any increase in vulnerability due to changes in seismicity does not result from a physical change to the land which is covered by the EQC Act 1993.

To avoid taking into account increases in liquefaction vulnerability resulting from changes to seismicity which are unrelated to a physical change to the insured land, the ILV Assessment Methodology assumes a consistent level of seismicity both before and after the CES.

EQC has asked T+T to assess ILV based on the post-CES level of seismicity. This enables consideration of the current (post-earthquake) level of vulnerability of the land with the current seismic hazard. It is noted that had the ILV assessments been conducted on the basis of the pre-CES level of seismicity, less vulnerability and less change in vulnerability would have been estimated. As a result, fewer properties would have satisfied both *engineering criteria* and therefore fewer properties would have been eligible for ILV.

Prior to the CES the design 25, 100 and 500 year return period levels of earthquake shaking in Christchurch were PGAs of 0.06g, 0.12g and 0.25g, respectively, for a M_W 7.5 earthquake based on the New Zealand Loadings Code (NZS1170.5).

In Christchurch, the seismic hazard is now higher than it was before the CES (McVerry, et al., 2012). This is because the stress relief from the rupture of the various faults has been transferred to adjacent faults in the Canterbury region which, as a result of this transfer, now have a higher probability of rupturing. The currently elevated seismic hazard is expected to reduce with time provided that no major earthquakes occur. If one does occur, then the seismic hazard would again be expected to re-set to a higher value.

The MBIE (2012) guidelines specify the post-CES 25 and 500 year return period levels of earthquake shaking for liquefaction assessment as a PGA of 0.13g and 0.35g, respectively, paired with a M_W 7.5 earthquake (which incorporates the elevated seismicity post-CES). These PGA values are intended by MBIE to be used as interim values as part of the foundation design of residential buildings as part of the recovery from the CES while the seismicity is elevated. The 100 year return period level of earthquake shaking (derived from interpolation between the MBIE 25 and 500 year return period levels of earthquake shaking) is estimated to be 0.2g paired with a M_W 7.5 earthquake.

As the seismicity is expected to decrease over time (in the absence of a further significant earthquake event) these ground motions are an upper bound estimate of the expected levels of earthquake shaking over the next 50 to 100 year period.

The increased levels of seismicity mean that a large number of properties which were not materially vulnerable to liquefaction damage at 25, 100 and 500 year return period levels of earthquake shaking prior to the CES are now vulnerable at the same respective return period levels of earthquake shaking. However, the faults contributing to the seismicity in Christchurch are spatially distributed throughout the Canterbury region and most of the contribution to seismicity comes from faults which are of regional significance and are mainly located beyond the urban residential areas of Christchurch. This is discussed further in **Appendix D**.

6.3 Return Period Levels of Earthquake Shaking for ILV Assessment

In order to assess the two *engineering criteria*, a return period level of shaking and corresponding ground motions needs to be assumed. EQC has asked T+T to assess vulnerability based on an up to 100 year return period level of shaking and the associated ground motion values of M_W = 6.0 and PGA = 0.3g (here on referred to as M6 0.3g).

That request is based on engineering advice discussed briefly below.

6.3.1 Rationale for Adopting the 100 Year Return Period Level of Shaking Scenario

To assess liquefaction vulnerability (as well as change in liquefaction vulnerability), it is necessary to first select the return period level of earthquake shaking that is to be considered.

Based on engineering advice from T+T EQC has asked T+T to assess ILV at up to a 100 year return period level of earthquake shaking. If, based on the post-CES ground levels, a property is expected to experience material damage from liquefaction at a 100-year return period level of shaking or less, then it is considered to be materially vulnerable (*Criterion 1*).

Land is not separately insured outside of New Zealand. As a result, there is no significant international practice in relation to recognition of liquefaction vulnerability that can be drawn on for the purposes of selecting a return period level of shaking.

Accordingly, the selection of the up to 100 year return period level of earthquake shaking was based on the following engineering considerations:

- Design parameters for land hazard identification in New Zealand; and
- Design parameters for buildings in New Zealand.

Design parameters for land hazard identification in New Zealand

The approach taken for the assessment of natural hazards for the development of land in New Zealand has been considered. Section 106 of the Resource Management Act (1991) and Section 71 of the Building Act (2004) include a test of whether land is likely to be subject to damage from a natural hazard. For this application, "likely" has been determined to be a 1 in 100 year return period event (DBH, 2008), rather than an extreme event with a low probability of occurrence.

Liquefaction is not currently a hazard listed in either the Resource Management Act 1991 or the Building Act 2004. However, adopting an up to 1 in 100 year return period is consistent with the approach taken for other natural hazards which relate to land in both of these Acts. This also applies to other district and regional planning documents around the country.

While these assessment periods have generally been applied to other forms of natural disasters (flood, land slippage and coastal erosion), there is no reason that a similar period should not be adopted for liquefaction.

In addition, when requested for geotechnical advice by developers or a person seeking to obtain a resource consent to subdivide the land, it is best practice for an engineer to examine the property with regards to liquefaction vulnerability for a 100 year return period level of earthquake shaking to assess its suitability for residential purposes.

Design parameters for buildings in New Zealand

The approach taken for the design of residential buildings in the New Zealand Building Code has also been considered. The New Zealand Building Code is performance based. That is, the expected performance of buildings is prescribed at 25 year and 500 year return period levels of earthquake shaking. At 25 year return period levels of earthquake shaking the performance expectation is that building damage should only be minor and non-structural. At 500 year return period levels of earthquake shaking the performance expectation is that buildings should not collapse, thereby preventing loss of life. However, the building is expected to sustain structural damage. Engineers can utilise any design that meets these performance expectations.

In eastern Christchurch, where the estimated ground motions were greater than 500 year return period levels of earthquake shaking for some of the main CES earthquakes (described in Section 3.7.2), the performance of both the land and the buildings showed that no residential buildings on TC1, TC2 and TC3 land collapsed due to liquefaction related land damage. Accordingly, despite widespread triggering of liquefaction at the 500 year return period levels of earthquake shaking, the TC1, TC2 and TC3 land performance was demonstrated to achieve the residential building performance expectations to a satisfactory level.

This is consistent with international experience that liquefaction damage for single and two storey light weight residential structures is not a life risk. As a result, it is it is unlikely that liquefaction vulnerability at the 500 year return period levels of earthquake shaking would govern the foundation design of single storey or two storey residential buildings.

With the exception of some of the residential Red Zone areas, in areas where ground motions were around 25 year return period levels of earthquake shaking levels of shaking, there was no evidence to suggest that liquefaction triggering caused any structural damage to residential buildings (Rogers, et al., 2015; van Ballegooy, et al., 2015d). Hence the land performance at the 25 year return period levels of earthquake shaking also satisfactorily achieved the building performance expectations.

Therefore, in evaluating appropriate return period levels of earthquake shaking for the assessment of liquefaction vulnerability for land, neither the 25 nor the 500 year return period levels of shaking assist in that assessment. This is because the land in Christchurch has demonstrated that it has already adequately supported the residential buildings and achieved the New Zealand Building Code performance expectations. Accordingly, a return period somewhere between the 25 and 500 year return period level of earthquake shaking is appropriate to assess material liquefaction vulnerability.

Based on a consideration of the above factors, the selection of a 1 in 100 year return period levels of shaking provides an appropriate basis on which to assess liquefaction vulnerability.

6.3.2 Rationale for Assuming Ground Motion of M6 0.3g

As discussed above, the MBIE guidelines (2012) specify post-CES 25 and 500 year return period levels of earthquake shaking for liquefaction assessment as part of foundation design residential buildings as a PGA of 0.13g and 0.35g, respectively, paired with a M_W 7.5 earthquake. The 100 year return period level of earthquake shaking (estimated from interpolation between the MBIE 25 and 500 year return period levels of earthquake shaking) is 0.2g paired with a M_W 7.5 earthquake.

However, the critical 100 year return period level of earthquake shaking for evaluating liquefaction vulnerability for the Boulanger and Idriss (2014) liquefaction triggering assessment method is for lower magnitude higher PGA ground motions (as discussed and summarised in **Appendix A**). Therefore an appropriate equivalent 100 year return period lower magnitude, higher PGA case is required for undertaking ILV land damage assessment.

A site specific Probabilistic Seismic Hazard Analysis (**PSHA**) for Christchurch soil sites was undertaken by Bradley Seismic Ltd (refer to **Appendix D**). This analysis indicates a mean 100 year return period M_W value of 5.8 based on the modified seismic activity in the immediate vicinity of Christchurch. This was rounded to 6.0 and has been adopted as the M_W value for the ILV land damage assessment process.

Magnitude scaling is the most common approach to finding an equivalent PGA value for different magnitude events, but the Magnitude Scaling Factor (**MSF**) in the Boulanger and Idriss (2014) liquefaction triggering assessment method is a function of both the normalised CPT tip resistance (**q_{c1n}**) and M_W.

The difficulty with scaling the 0.2g at M_W 7.5 level of shaking to an equivalent PGA at M_W 6.0 value (using the Boulanger & Idriss (2014) MSF) is that, due to spatially differing soil characteristics, different scaling factors would be required for virtually every site and every soil layer throughout Christchurch. For the loose to medium dense soils with lower q_c values (i.e. the soils in Christchurch which have the greatest liquefaction potential), the Idriss and Boulanger (2008) MSF equations result in significantly higher MSF values when compared to the Boulanger and Idriss (2014) MSF equations.

This is demonstrated by applying the Idriss and Boulanger (2008) and Boulanger and Idriss (2014) MSF equations for a M_W 6.0 earthquake for a number of selected CPTs from the TC2, TC3 and residential Red Zone areas shown in Figure 6.1. The CPT q_c and I_c traces are shown in the first two left hand columns of Figure 6.2 and the estimated MSF traces are shown in the third column from the left. The coloured traces in the graphs on the two right hand columns represent the estimated MSF values using the Boulanger and Idriss (2014) method. The black dashed lines represent the Idriss and Boulanger (2008) MSF which is a constant value (i.e. independent of soil properties).

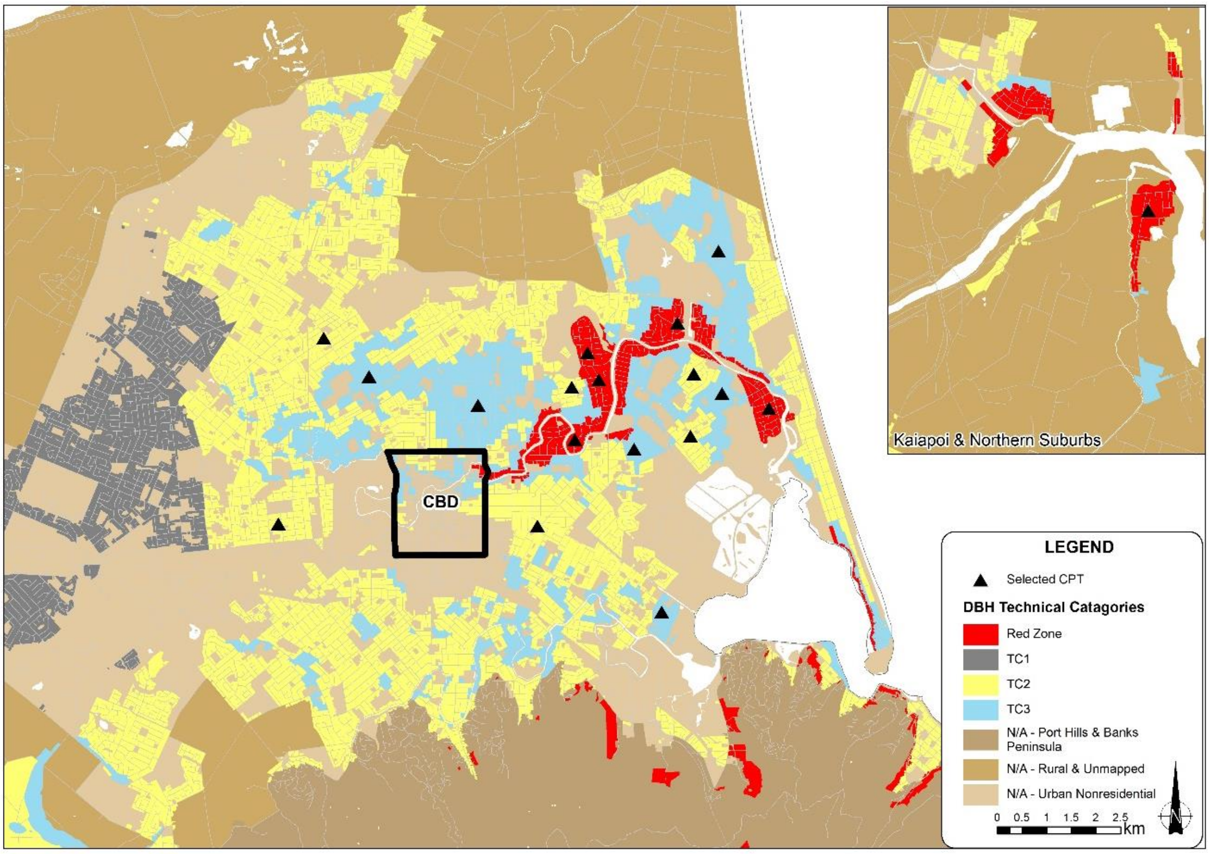


Figure 6.1: Location of the selected CPTs in the TC2, TC3 and residential Red Zone areas of Christchurch for the MSF assessment shown in Figure 6.2.

Comparison of the MSF traces in Figure 6.2 for the M_W 6.0 earthquake show that the Boulanger and Idriss (2014) estimated values for some soil layers are higher than the Idriss and Boulanger (2008) values. For other soil layers the opposite is true. Closer inspection of the MSF traces shows that, where the Boulanger and Idriss (2014) estimated values for some soil layers are higher than the Idriss and Boulanger (2008) values, the corresponding CPT q_c values are higher and are unlikely to liquefy for the ranges of ground motion values of relevance for residential design purposes. Therefore, estimated MSF values for the soil layers which have an assessed liquefaction triggering factor of safety greater than 1.5, based on the MBIE specified 500 year return period levels of earthquake shaking, using the Boulanger and Idriss (2014) liquefaction triggering methodology, have been filtered out so that the soil layers of greatest interest could be further examined.

The filtered MSF traces are shown in the right hand column of Figure 6.2. The filtered results show that the Boulanger and Idriss (2008) MSF is generally an upper bound for loose to medium-dense soils and is likely to overestimate the equivalent PGA value for the soil layers of interest when compared to the Boulanger and Idriss (2014) MSF.

In order to avoid these scaling issues, Bradley Seismic Ltd undertook a PSHA for Christchurch soil sites (refer to **Appendix D**). Based on the post-CES seismic activity in the immediate vicinity of Christchurch, the mean M_W values and associated PGA values for the 100 year return period level of earthquake shaking have been estimated as an M_W 5.8 and PGA of 0.19g. However this is significantly lower than the scaled MBIE guideline (2012) 25 year return period design value.

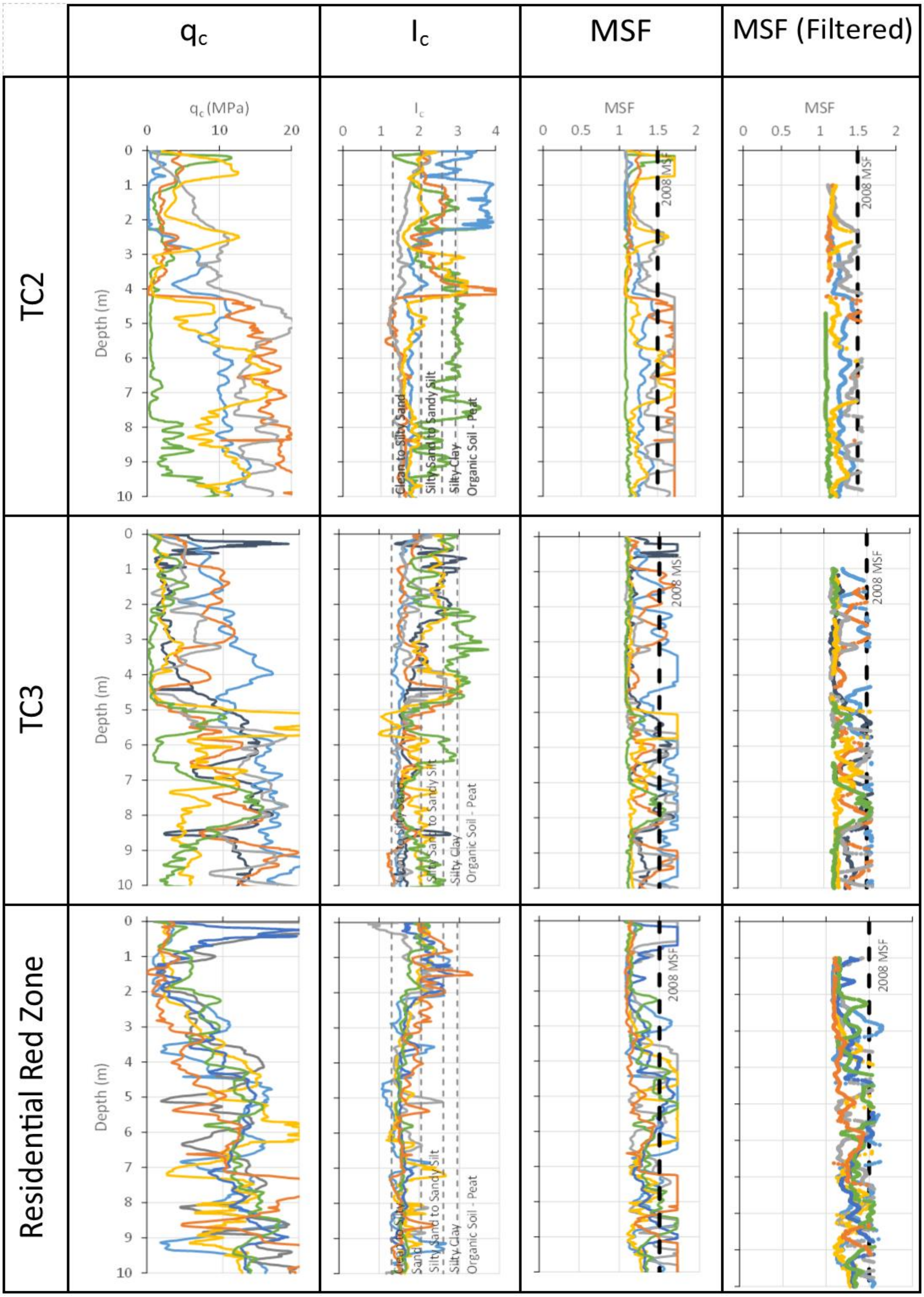


Figure 6.2: Estimated MSF values for a M_W 6.0 earthquake based on the Idriss and Boulanger (2008) and Boulanger and Idriss (2014) equations for selected CPT profiles (from locations shown in Figure 6.1) from the TC2, TC3 and residential Red Zone areas in Christchurch.

The MBIE guidelines are the industry standard with respect to the assessment of seismic hazard for single storey residential buildings in Christchurch. Typically a PSHA is only undertaken for structures of significance such as hospitals and other large buildings. Therefore, to avoid inconsistency between ILV land damage assessments and the MBIE guidance (2012) on assessment of liquefaction vulnerability, the Idriss and Boulanger (2008) MSF relationship has been applied to the M7.5 0.2g case. This gives an equivalent value of M6 0.3g.

It is recognised that this is a conservative assessment resulting in an upper estimate of the most likely 100 year return period levels of earthquake shaking for Christchurch based on the most recent scientific analysis.

6.4 Anthropogenic and Climate Change Influences on Groundwater Levels

Anthropogenic (man-made) influences and climate change induced sea level rise and climate change in future weather patterns will influence future groundwater levels and as a result will influence future liquefaction vulnerability (Russell, et al., 2015; Quilter, et al., 2015). However these changes in liquefaction vulnerability are not related to any physical change to the land as a result of the CES.

In order to assess the two *engineering criteria*, a groundwater level needs to be assumed. EQC has asked T+T to use the current groundwater levels (i.e. 15th, 50th and 85th percentile regional groundwater surfaces) for the assessment of ILV and that the assessment should not take into account any future changes in groundwater levels as result of anthropogenic influences, climate change and sea level rise.

The engineering basis for EQC's decision is set out briefly below.

6.4.1 Rationale for Assuming Groundwater Levels Excluding an Allowance for Future Anthropogenic Influences to Groundwater Levels

Anthropogenic changes to groundwater levels can be caused by:

- Changes in groundwater extraction patterns - either by pumping to lower groundwater levels in low lying areas or for extraction purposes for urban and rural use;
- Changes to drainage networks in low lying areas;
- Further land development increasing stormwater runoff and decreasing stormwater infiltration; and
- Changing stormwater management approaches such as construction or removal of soakage pits and ponds.

It is uncertain what anthropogenic influences will occur in the future development of Christchurch and how these will affect the groundwater levels. These changes do not form part of any physical change to the land occurring as a result of the CES. Therefore such potential effects have not been taken into account when determining appropriate groundwater levels for the assessment of ILV.

6.4.2 Rationale for Assuming Groundwater Levels Excluding an Allowance for the Effect of Climate Change on Sea Level Rise

Sea level rise will result in an increase to the groundwater levels in the low lying areas of eastern Christchurch. Studies undertaken by Quilter et al. (2015), based on a simplified modelling approach, indicate that the groundwater level is controlled by sea level up to the eastern side of the CBD (i.e. approximately from Fitzgerald Ave eastwards). Sea level rise is likely to affect groundwater levels in this area. If sea level rise was taken into account and applied to both pre-CES and post-CES ground surface levels more properties would qualify with *Criterion 1* and therefore the potential pool of properties that could then be considered by *Criterion 2* would increase. Ultimately this would affect the number of properties eligible for ILV.

A problem with using an elevated groundwater surface to take into account sea level rise is that a timeframe would also need to be defined. While there is consensus within the scientific community that sea level rise will occur, the rate at which it will occur is less certain. In the near term, effects are likely to be gradual, involving changes of an order of magnitude within the next 20 years that are within the range of uncertainty of the ILV assessments.

Rising sea levels and corresponding rise in groundwater levels are also likely to result in anthropogenic intervention in low lying areas (e.g. more drainage and pumping in low lying areas). These anthropogenic changes to groundwater levels due to sea level rise would result in additional uncertainty in selecting appropriate groundwater levels.

Given this uncertainty these potential effects have not been taken into account when determining appropriate groundwater levels for assessment of ILV.

6.4.3 Rationale for Assuming Groundwater Levels Excluding an Allowance for the Effect of Climate Change on Future Weather Patterns

It is unknown how the influence of climate change on future weather patterns will affect groundwater levels in Christchurch outside of those areas that are controlled by sea level or over what timeframe this will occur.

If climate change results in a decrease in the annual rainfall in the Canterbury region and Southern Alps, then the median groundwater level may decrease and thus liquefaction vulnerability might decrease. If climate change results in an increase in the annual rainfall in the Canterbury region and the Southern Alps, the groundwater level is likely to be higher and thus liquefaction vulnerability is likely to increase. Which of these two scenarios will occur is unclear.

In addition, weather related climate change is likely to result in anthropogenic intervention (e.g. more groundwater extraction) if the climate change results in prolonged periods without rainfall. These anthropogenic changes to groundwater levels due to climate change effects would result in further uncertainty in selecting an appropriate groundwater level. At this point in time, there is no way of reliably predicting what (if any) intervention will occur.

Given the slow and gradual nature of any changes and this uncertainty, these potential effects have not been taken into account when determining appropriate groundwater levels for assessment of ILV.

6.5 Change in Soil Behaviour

Almost all of the geotechnical investigation data available in the CGD, which has been used for ILV assessment purposes, was obtained following the 22 February 2011 earthquake and is therefore considered to be representative of the post-CES soil strength and stiffness characteristics.

For the liquefaction vulnerability assessments, it has been assumed that the estimated resistance of soil to liquefaction, often described as the Cyclic Resistance Ratio (**CRR**) was the same pre-CES as it has been estimated post-CES.

This assumption is necessary given the limited availability of geotechnical investigation data prior to the CES. This assumption is reasonable based on the current state of practice with respect to the assessment of liquefaction triggering and estimation of the CRR in soil deposits, and the likelihood that any change in CRR will not be material to the ILV assessments.

However, there are three hypotheses within the literature that are potentially at odds with this assumption. These hypotheses are:

- Liquefaction of soils can result in an increase in density of the soil which increases the CRR of the soil from the pre-earthquake condition in a process known as Densification; and
- Liquefaction of soils results in new soil fabric resulting from reconsolidation after liquefaction. This new soil fabric is known to have a very low resistance to liquefaction. Soil ageing (discussed in the next point) is related to micro changes in the soil fabric.
- Liquefaction of soils results in a breaking of mechanical and chemical bonds between the soil particles which decreases the CRR of the soil from the pre-earthquake condition. Over time these mechanical and chemical bonds reform resulting in an increase in CRR of the soil in a process known as Soil Ageing.

The purpose of this section is to address each of these hypotheses with comparison to the data available on the CGD and demonstrate that it is reasonable to assume that the pre and post-CES CRRs are the same.

6.5.1 The Densification of Soil due to Ground Shaking

Each time a soil has liquefied from an earthquake, it may reconsolidate which can result in some minor volumetric densification (i.e. it becomes slightly denser) and accompanying ground surface subsidence as seen in the liquefaction related subsidence maps shown in Figure 3.8c. As a result, the post-CES CRR of some liquefied soil layers may be greater than the pre-CES CRR. This is potentially more likely to occur in the deeper soil layers where there is greater confinement and is less likely to occur in the upper soil layers where there is less confinement.

At present, there is no practical and reliable way of quantifying this increase in CRR. Nor is it considered possible to determine the boundary between liquefying soil layers, which have subsequently had an increase in CRR, and liquefying soil layers, which have not had an increase in CRR.

To test the effects of these influences, CPTs that were pushed in Christchurch in close proximity to one another pre and post-CES have been analysed. There are 25 locations in Christchurch where CPTs were performed after the CES which are within 10m of CPTs that were performed before the CES. This set of adjacent pairs of pre-CES and post-CES CPT profiles enables one to examine if the CPT results were altered significantly by the CES. The locations of these 25 CPT sets are shown as blue and green circles on Figure 6.3. Additionally, CPTs were undertaken at 8 locations in the eastern suburbs of Christchurch following the September 2010 earthquake, and additional CPTs were pushed again at these 8 locations at various times (from 3 to 6 times) following later main earthquake events. The locations of these 8 CPT pairs are shown as purple circles in Figure 6.3.

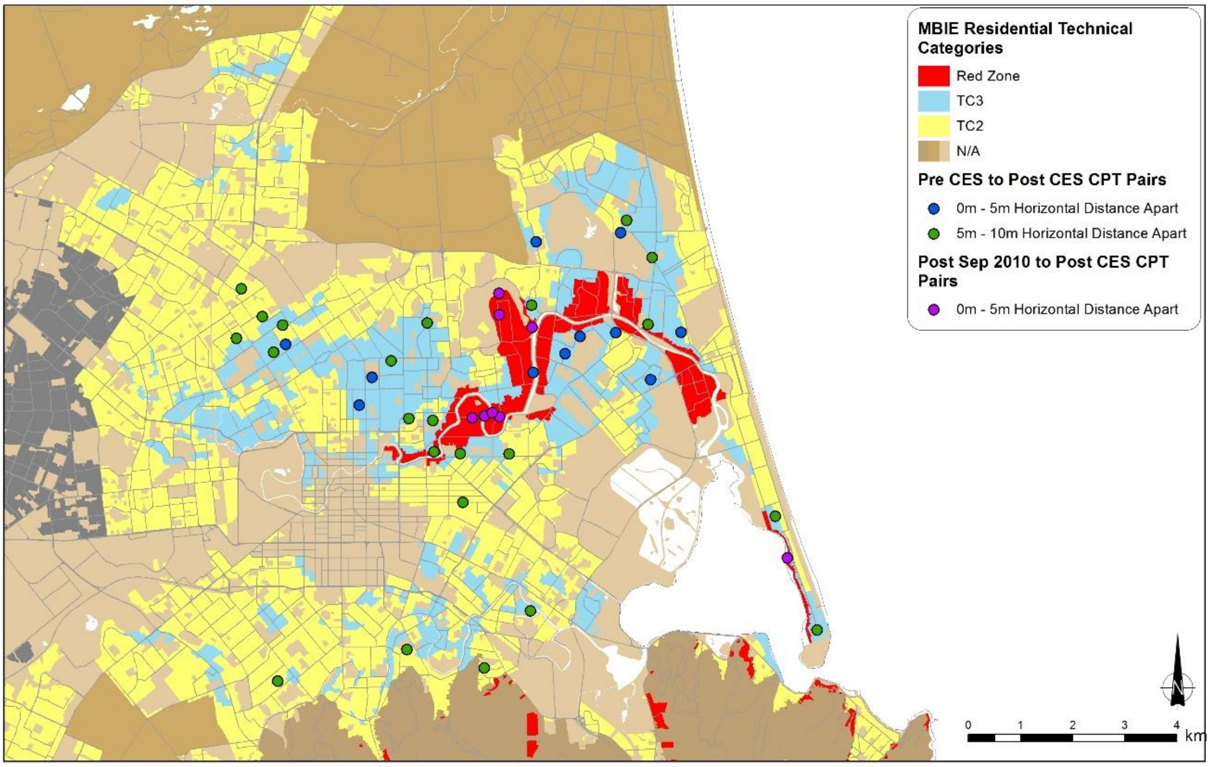


Figure 6.3: Locations where repeat CPTs have been undertaken.

Comparison of adjacent CPT traces at each location are shown in **Appendix E**. Inspection of each CPT pair and CPT set shows that while there are minor variations between the CPT traces at each location there is no inherent bias towards either an increase or a decrease in q_c with time. The minor variations in q_c between the pre- and post-CES values between adjacent CPTs is typically due to spatial variability in ground conditions over short distances (consistent with the expected natural soil variability discussed in Section 3.6). This variability in ground conditions is reflected in the corresponding I_c traces in **Appendix E**.

Based on these CPTs it is not possible to conclude that there has been a change in q_c as a result of the CES. To examine further whether the CES has changed soil properties, pre and post-CES q_c values for all the CPT pairs and CPT sets (where the corresponding I_c value is less than 2.6) have been plotted as cumulative frequency graphs for 0 to 5m and 5 to 10m as shown in Figures 6.4 and 6.5, respectively.

Figure 6.4 shows the cumulative frequency graphs for 0 to 5m and 5 to 10m horizontal distance corresponding to pre and post-CES CPT q_c values for the 25 locations in Christchurch described above (i.e. CPT pairs A to AH in **Appendix E**). There is little difference between the cumulative distributions for the pre and post-CES values and insufficient difference to substantiate a change in soil properties.

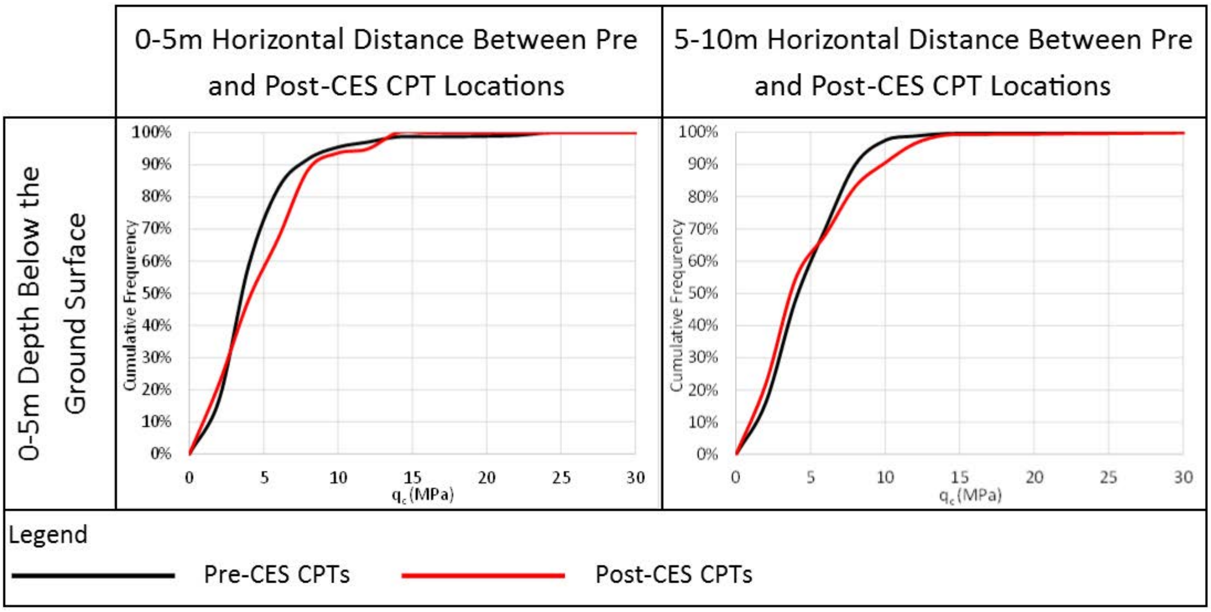


Figure 6.4: Pre and post CES cumulative frequency graphs of q_c for varying depths from CPT locations in Figure 6.3 filtered for soil layers with I_c < 2.6.

Figure 6.5 shows the cumulative frequency graphs for 0 to 5m and 5 to 10m depth below ground surface corresponding to post-September 2010, post-February 2011, post-June 2011, and post-December 2011 CPT q_c values for the 8 locations in Christchurch described above (i.e. CPT sets AI to AP in **Appendix E**). Note that due to spatially variable ground conditions some filtering of the data presented in Figure 6.5 has been undertaken. The full details of this are discussed in **Appendix E.**

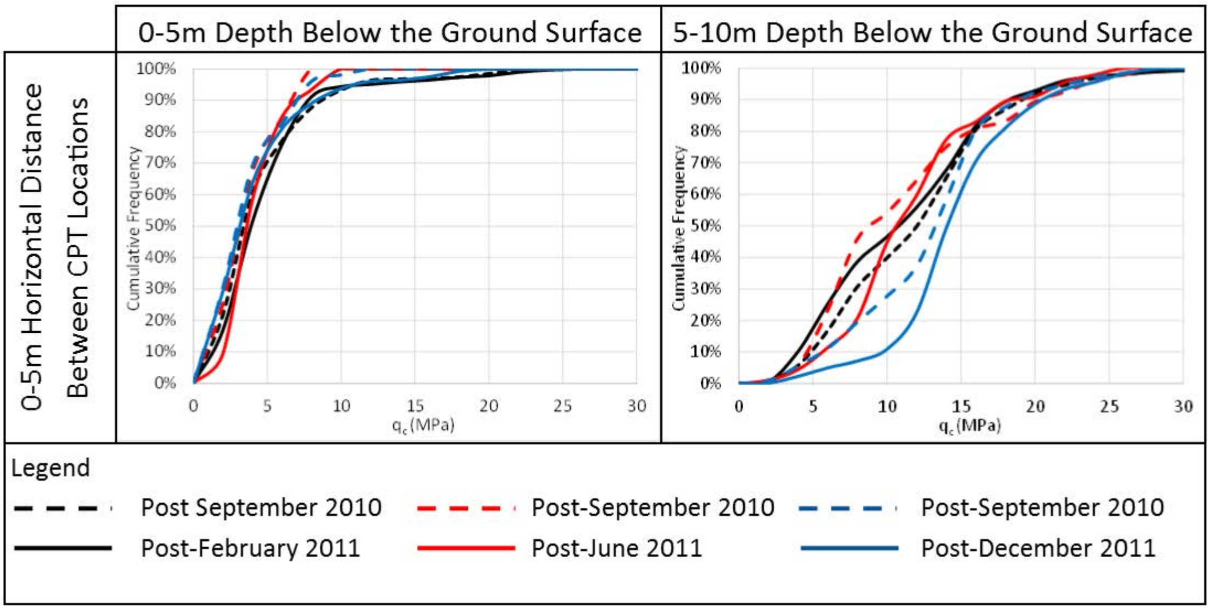


Figure 6.5: Post-September 2010, post-February 2011, post-June 2011 and post-CES cumulative frequency graphs of q_c for varying depths from CPT locations in Figure 6.3 filtered for soil layers with I_c < 2.6.

The resulting cumulative distribution plots show little difference for depths of 0 to 5m below ground surface. This is the depth range of soil deposits that tend to have the largest effect on potentially damaging ground deformations. Greater variability in the cumulative distributions is apparent for the 5 to 10m depth, reflecting a more rapid change in subsurface conditions for the deeper deposits at the locations of the 8 sets of CPT traces.

Note that there are three different cumulative frequency curves for the post-September 2010 data in Figure 6.5, because the CPTs that were used with each corresponding post-February, post-June or post-December 2011 CPTs were different for each event. Therefore, three slightly different post-September 2010 cumulative frequency curves were generated for comparison with the post-February, post-June, and post-December 2011 cumulative frequency curves.

There is little difference between the cumulative distributions for the post-September 2010, post-February 2011, post-June 2011 and post-December 2011 values, and insufficient difference to substantiate a change in soil properties.

Collectively, these figures demonstrate that there is a lack of systemic bias in the pre-CES values being higher or lower than the post-CES values. This supports the assumption that the CES has not changed the resistance of soil to liquefaction in the Christchurch area.

6.5.2 The Effects of Soil Ageing

There is ongoing research in the area of 'soil ageing', which suggests that mechanical and chemical processes that take place following the sedimentation of sand deposits results in an increase in the soil strength and therefore CRR over time (Leon, et al., 2006; Green, et al., 2008; Hayati & Andrus, 2009). The published literature suggests that liquefaction triggering resets the soil ageing clock back to zero in the liquefied soil layers (Green, et al., 2008; Maurer, et al., 2014b) . The current levels of scientific understanding of soil ageing and its effect on the soil strength and CRR are still in early development. Proposed methods to account for this, such as strength gain factors (often annotated as K_{DR}), are not widely accepted in engineering practice.

Published studies have typically considered very old (Pleistocene age) sand deposits (Lewis, et al., 1999; Arango & Migues, 1996) or a limited number of laboratory tests and undisturbed samples of recent Holocene deposits (Seed, 1979). Two published studies (Hayati & Andrus, 2009; Robertson, 2000) have considered both undisturbed samples from naturally deposited soils and reconstituted samples for laboratory tests ranging in age from <1 year to 35 million years to investigate the increase in soil strength and CRR over time.

A plot of strength gain factors versus time from recently published research papers is shown in Figure 6.6.

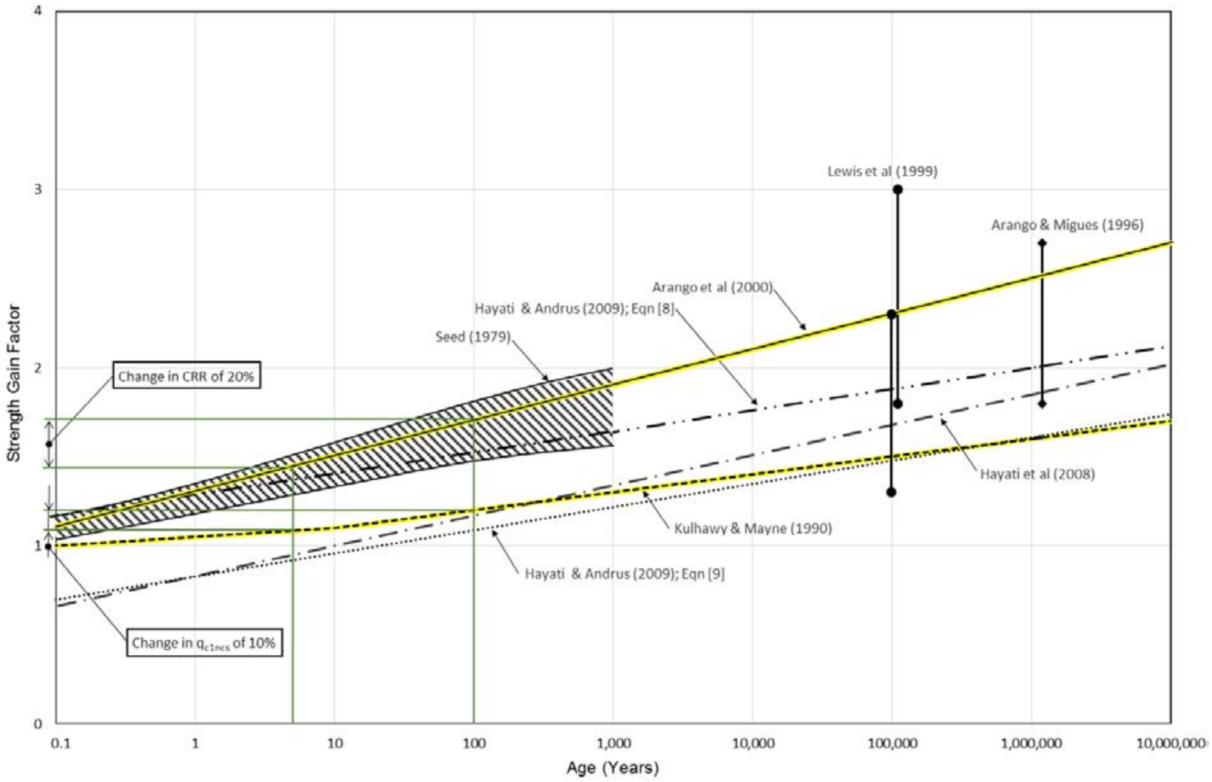


Figure 6.6: Time dependant strength gain factors for the various published studies on soil ageing.

While all published studies show an increase in the strength gain factor over time, the rate of increase and the reference age for naturally deposited or liquefied soils varies between all studies. These differences are likely due to the natural variability of the materials studied as well as different methods of preparation and testing used by the various researchers. Given the variability of the studies the selection of an appropriate strength gain factor for Christchurch soils is challenging.

Furthermore, as stated above the results in Figure 6.4 and Figure 6.5 show that there is no systematic bias in pre-CES q_c values being lower than the post-CES q_c values. Therefore, the underlying premise of an initial loss of soil strength has not been demonstrated with this data.

Given that:

- Strength gain factors are not currently widely used in engineering practice;
- Studies used to estimate strength gain due to soil ageing provide a wide range of estimates to adopt; and
- Investigation into the CGD CPT dataset has not demonstrated a loss of soil strength following the CES;

it is reasonable not to account for the effects of soil ageing in the ILV Assessment Methodology.

6.6 Vulnerability to Lateral Spreading has not Increased

The potential for lateral spreading from future earthquake shaking has been judged to have not increased as a result of the physical changes to the land caused by the CES. Therefore, when assessing *Criterion 1*, it has been assumed that lateral spreading vulnerability does not need to be considered when determining whether a property is materially vulnerable to liquefaction damage. That is, only vulnerability to “free field” liquefaction damage (that is, liquefaction damage unrelated to lateral spreading) is assessed in Criterion 1.

While the prediction of lateral spreading vulnerability is highly complex, the models recommended for use in engineering practice all generally predict an inverse relationship between lateral spreading vulnerability and the elevation between the ground surface and the base of adjacent river channels and old river terraces, all other factors being held constant.

As a result of the lateral spreading and ground surface subsidence caused by the CES, the elevation difference between the ground surface and the base of adjacent river channels and old river terraces remained the same or reduced (refer to **Appendix F**). Therefore, given that the elevation difference has not increased (and in most instances has decreased) and that the soil properties have not changed (refer to Section 6.5), the potential for lateral spreading has not increased and in most instances has decreased as a result of the changes to the land caused by the CES (refer to **Appendix F** for further analyses).

This assumption is supported by the liquefaction related horizontal movement measurements from the LiDAR surveys, satellite imagery, GPS based benchmark surveys, ground crack observation surveys, land damage observations and river channel profile surveys following each of the four main CES earthquakes. Analyses presented in **Appendix F** show that the horizontal movements indicate a reduction in the amount of lateral spreading for each of the three main earthquakes subsequent to the September 2010 event relative to the seismic demand of each earthquake.

6.7 Impacts of Other Forms of Land Damage

In addition to ILV damage, the CES caused other forms of land damage in Christchurch. These are described in **Appendix B** of this report.

Some of these other forms of land damage may also increase the vulnerability of land to liquefaction if unrepaired. In particular, crust disturbance, such as cracking, could provide a path for the ejection of liquefied soil and thereby increase the land vulnerability to liquefaction damage.

However, observable damage is compensated for separately by EQC by paying the cost of repairing the cracks in accordance with approved repair methodologies. Once the cracks are repaired in accordance with the repair methods listed in the Guide to the Settlement of Canterbury Flat Land Claims (EQC, 2013) then the crust integrity will be essentially reinstated back to the pre-CES crust integrity and hence pre-CES liquefaction vulnerability.

As a result, the loss of crust integrity as a result of cracking has not been taken into account as part of the ILV assessment process. This is because it has been assumed that the compensation provided for ground cracking will be used to re-instate the crust to its pre-CES integrity.

6.8 Long Access Ways are not Considered in the Assessment of ILV

The ILV engineering assessment documented in this Report was undertaken over the residential land comprising:

- The land under the main residential building (the building footprint); and
- The land in an area up to 8 m, in a horizontal line, of the main residential building, within the property boundary.

For most properties in urban residential Christchurch, this area of residential land covers all of the land holding, including any driveway and land around appurtenant structures (such as the garage and sheds). An example of this is presented in Figure 6.7a.

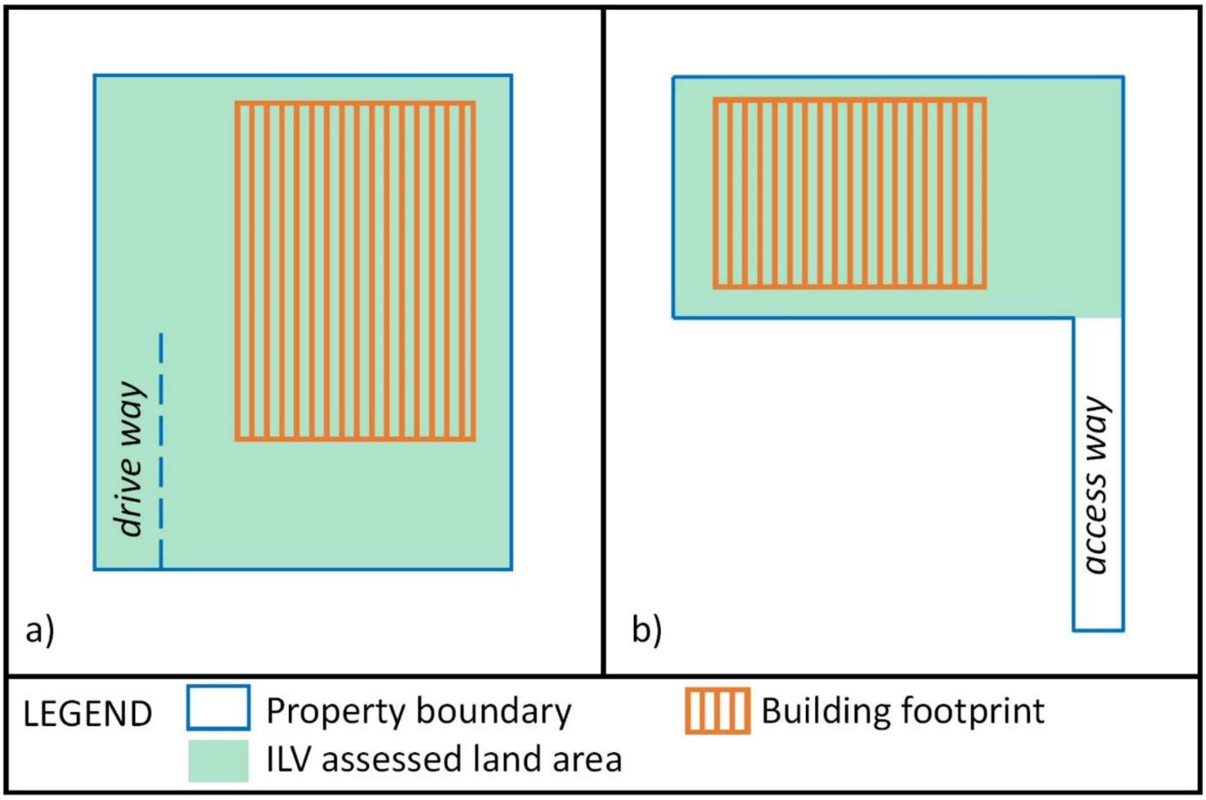


Figure 6.7: Schematic diagram showing the assessment area for ILV

The ILV assessment and, in particular, analysis of whether liquefaction vulnerability or a change in liquefaction vulnerability was material (as discussed in Sections 7.3 and 7.4) were determined in relation to the use and amenity of this land as a platform for a residential building.

All outcomes of the ILV assessment methodology recorded in this report, including the maps and statistics presented in Section 11, relate solely to the assessments carried out in relation to the above areas.

It is acknowledged that the "residential land" insured by the EQC Act may also include areas of land which are not otherwise included in the area of land that constitutes the building footprint and land within 8 m, in a horizontal line, of the main residential building. These additional areas may include, for example, the main access way within 60 m, in a horizontal line, of the residential building, and land up to 8 m, in a horizontal line, around appurtenant structures. An example of this situation in relation to a long access way is presented in Figure 6.7b.

It is possible that, in a limited number of cases, additional areas, such as a long access way, may experience a change in vulnerability to liquefaction damage when the building platform and area around the residential building does not. Where, on the balance of probabilities, it can be concluded that a change has occurred to such an additional area (and the land holding does not otherwise satisfy the Engineering Criteria), the additional area will be separately assessed against the Engineering Criteria and Criterion 3.

The assessment of these additional areas against the Engineering Criteria and Criterion 3 will take account that, unlike the building footprint and area surrounding the residential building, these areas generally cannot be used as a platform for a residential building. Accordingly, a change in liquefaction vulnerability may not be material for land that can only be used as an access way, even though that change may be material for land that can be used to support a residential building.

7 Estimating Liquefaction Vulnerability and Assessing Criterion 1 and Criterion 2

7.1 Purpose and Outline

To undertake an assessment of ILV within the Christchurch area it was necessary to develop a methodology that could use the extensive CPT and borehole data gathered following the CES, together with LiDAR DEMs obtained both before and after the CES, to estimate liquefaction vulnerability and change in liquefaction vulnerability due to ground surface subsidence as a result of the CES in conjunction with land damage observations and other information to undertake ILV assessments.

It was also necessary to determine what level of liquefaction vulnerability, and change in vulnerability, should be regarded as material for the purposes of assessing each of the *engineering criteria*.

This section of the report describes:

- The estimation of liquefaction vulnerability including the development of the CPT-based LSN parameter and why it is the preferred tool for estimating liquefaction vulnerability;
- The approach taken to define a material liquefaction vulnerability (that is, *Criterion 1* of the *engineering criteria*), and why the performance of land with LSN value of 16 or greater was chosen as an indicator of this level of vulnerability;
- The approach taken to define a material change in liquefaction vulnerability caused by the CES (that is, *Criterion 2* of the *engineering criteria*), and why a difference in performance of land implied by a difference of 5 LSN units or greater between the pre-CES and post-CES LSNs (**ΔLSN**) was chosen as an indicator of this level of change in vulnerability; and
- The concepts of the median and mean LSN parameters and why EQC has asked T+T to assess ILV considering both of these parameters for the purposes of assessing material liquefaction vulnerability and material change in liquefaction vulnerability.

7.2 Estimating Liquefaction Vulnerability

Following the CES there were a number of different tools available for the estimation of liquefaction vulnerability in the Christchurch area, including:

- Land damage observations (from aerial imagery, land damage mapping and LDAT property inspection reports);
- CPT-based liquefaction vulnerability parameters;
- Composition of near surface soils; and
- Liquefaction related ground surface subsidence.

Of these tools land damage observations provide the best evidence of liquefaction vulnerability. However, land damage observations only reflect the liquefaction vulnerability of a particular property under event specific conditions. These event specific conditions include the level of estimated ground shaking, the estimated groundwater level at the time of the earthquake event and the estimated ground surface elevation to estimate the groundwater depth.

For example, while ILV is assessed at up to 100 year return period levels of ground shaking, most of eastern Christchurch experienced ground shaking levels considerably in excess of the 100 year return period levels of ground shaking. In such areas, liquefaction related damage does not necessarily mean that the land is vulnerable in a lower level event.

Given that:

- The ILV Assessment Methodology requires specific assumptions for each of these conditions (refer to Section 6); and
- The observed land damage in many instances resulted from levels of ground shaking significantly above the M6 0.3g ILV assessment level;

it was necessary to consider additional tools to estimate liquefaction vulnerability.

The most widely used means of assessing liquefaction vulnerability are CPT-based liquefaction vulnerability parameters. This section summarises the development of the CPT-based LSN parameter and describes why it is the preferred tool for estimating liquefaction vulnerability at the M6 0.3g level of earthquake shaking.

It is important to reiterate that the LSN parameter is one of several tools available for the assessment of liquefaction vulnerability. Each ILV assessment has involved the reconciliation of the LSN parameter with the other liquefaction vulnerability tools. In particular this process of reconciliation has focussed on land damage observations. Sections 8.3, 9 and 10 describe this reconciliation process in detail.

7.2.1 The LSN Parameter

As discussed in Section 6, to provide detailed understanding of the observed liquefaction in Christchurch and to predict potential liquefaction vulnerability of future earthquakes, EQC commissioned and collated one of the most extensive databases of geotechnical investigation information and land and dwelling performance observations ever assembled. Subsequent to the EQC's collation of this database, private insurers and engineers have also contributed a large amount of geotechnical investigation information. A critical component of this dataset was the set of more than 18,000 CPTs (as at the end of 2014) in urban Christchurch.

A process involving detailed literature review, expert engagement and expert review was undertaken to select an analysis tool which was suitable to assess liquefaction vulnerability using information contained in the CPT dataset in Christchurch. The following range of existing numerical tools were reviewed:

- The Ishihara (1985) criteria;
- The estimated one dimensional volumetric densification settlement ($\mathbf{S_{V1D}}$) using the empirical equations developed by Zhang et al. (2002); and
- The Liquefaction Potential Index (**LPI**) parameter developed by Iwasaki et al. (1982).

Each of these parameters were assessed to have particular advantages and disadvantages for application in the Christchurch area.

The Ishihara (1985) criteria are internationally recognised and widely used in engineering practice to assess the potential for liquefaction damage at the ground surface due to liquefaction of underlying soil layers. However, it assumes a simple 2-layer soil model of a non-liquefying crust overlying a liquefying soil layer. This means it is difficult to apply to the complex layered soils (i.e. multiple interbedded layers of liquefying and non-liquefying soils) found in Christchurch. Nevertheless, the Ishihara (1985) criteria are useful for understanding the influence of the non-liquefying crust thickness on liquefaction vulnerability.

While it is recognised that the Ishihara (1985) criteria are based on a limited number of case studies, it is one of the standard assessment tools for liquefaction vulnerability. In the case of the CES, the Ishihara (1985) criteria has proved robust in predicting where liquefaction damage will and will not manifest at the ground surface in the limited situations where it has been able to be applied.

Results from CPT-based liquefaction vulnerability parameters (i.e. S_{V1D} and LPI) were compared to observed damage in each of the earthquakes to assess how well they predicted liquefaction vulnerability in Christchurch. As a result of these detailed studies (summarised in **Appendix A**) it was recognised that none of the existing CPT-based liquefaction vulnerability assessment tools were appropriate for assessing ILV in Christchurch and hence a new liquefaction vulnerability parameter was required that was specifically validated for Christchurch ground conditions.

The liquefaction vulnerability parameter developed is called the Liquefaction Severity Number (**LSN**). LSN is an estimated parameter that expresses in a numerical index the vulnerability of land to liquefaction related damage at a particular level of shaking. The higher the LSN, the greater the vulnerability of land to liquefaction-related damage. For example, an LSN of 20 predicts a greater probability of liquefaction related damage occurring than an LSN of 15, for the same level of shaking.

LSN combines many of the advantages of the other tools while reducing many of the disadvantages. The key advantages of the LSN liquefaction vulnerability parameter for application of assessing ILV in Christchurch, compared to the alternative parameters are:

- It is better able to analyse the complex layered soil profiles typical across Christchurch (described in Section 3.6);
- It incorporates both the CPT q_c and corresponding CRR of the soil and how severely the soil reacts (i.e. the expected volumetric densification) once it becomes liquefied;
- It applies greater weighting to the liquefaction of soil layers closer to the ground surface compared to the liquefaction of soil layers at greater depths, consistent with damage observations in Christchurch; and
- It factors in the non-liquefying crust thickness and the thickness and severity of the underlying liquefying soil layers, thereby providing a more consistent result across a wide range of soil profiles and ground conditions.

Further detail comparing the suitability of the different available numerical tools for assessing liquefaction vulnerability and the development of the LSN parameter is provided in **Appendix A**.

7.2.2 Uncertainties in CPT-based Liquefaction Vulnerability

While the LSN parameter has been adopted as the preferred tool for CPT-based liquefaction vulnerability assessment for ILV purposes, it is subject to a range of uncertainties. These uncertainties include:

- Earthquake motion characteristics;
- Geological spatial variability;
- Soil profile complexities;
- Groundwater pressure and saturation complexities; and
- Soil behaviour characteristics.

These uncertainties and complexities cannot be perfectly captured by current investigation and analysis tools.

For this reason, liquefaction analysis in engineering practice is based on correlations that aim to err on the side of conservatism. That is, the analysis over-predicts liquefaction triggering more often than it under-predicts. The analysis used to estimate the LSN value faces these same challenges, so it cannot fully predict the liquefaction vulnerability of a property in an earthquake.

The result of this uncertainty is that the LSN value does not predict a particular liquefaction consequence in a specified event. Instead, it represents a prediction of a range of possible consequences in a specified event.

If a group of 100 properties were considered that all had estimated LSN values of exactly 20 and they were all subjected to identical earthquake shaking, it is unlikely that the performance of all 100 properties would be identical. It is likely that a range of liquefaction damage would be observed with a few properties with none-to-minor land damage, the majority with minor-to-moderate land damage and some with moderate-to-severe land damage.

If a group of 100 properties with LSN of 40 were considered, it is likely that a greater number of properties would have moderate-to-severe liquefaction related land damage and very few would have none-to-minor liquefaction related land damage when compared to the group with lower estimated LSN values.

As such the LSN parameter, like any other available liquefaction vulnerability assessment tool, should be considered as an indicator of the likelihood of particular levels of liquefaction related damage occurring. Liquefaction analysis cannot provide a precise prediction of the exact level of land damage that will occur. This demonstrates the importance of the application of engineering judgement when considering estimated LSN values as part of a liquefaction vulnerability assessment.

7.3 Material Liquefaction Vulnerability (*Criterion 1*)

In order to assess whether or not a property is vulnerable to material liquefaction damage (*Criterion 1* in Section 2.4) it was necessary to determine what level of vulnerability to liquefaction represents the difference between land which is not materially vulnerable to liquefaction damage (i.e. the land is unlikely to suffer material liquefaction related land damage) and land which is materially vulnerable to liquefaction damage (i.e. the land is likely to suffer material liquefaction related land damage).

Figure 3.2 indicates that at M6 0.3g levels of ground shaking, liquefaction triggering is predicted to occur in almost all TC3 and residential Red Zone areas (note no inferences can be made regarding the TC2 areas because there is insufficient CPT data available). Therefore, all of this land has some degree of liquefaction vulnerability (because the estimated LSN will not be 0 if liquefaction triggering is predicted to occur). However, not all of this liquefaction vulnerability is material.

The level of vulnerability which can regarded as material, from an engineering perspective, is related to the use and amenities of the land as a building platform and for other related purposes.

Having considered a range of factors, land can be considered materially vulnerable to liquefaction where:

- The land is more likely to suffer moderate-to-severe liquefaction related land damage than none-to-moderate liquefaction related land damage at up to 100 year return period levels of ground shaking; and
- The vulnerability of the land to liquefaction means that based on specific engineering assessment of geotechnical investigation data an enhanced building foundation (over and above a TC2 foundation) is likely be required when applying the objectives set out in MBIE (2012) Guidelines. This requirement is dependant on the liquefaction vulnerability at 25 year return period levels of earthquake shaking.

Below these levels of liquefaction vulnerability, enhanced TC3 foundation systems would not be required and TC2 foundation systems would be sufficient. That is, any limited liquefaction vulnerability would be adequately addressed by standard engineering solutions (including TC2 foundations).

In addition, in order to use the LSN parameter to assess whether or not a property is vulnerable to material liquefaction damage (*Criterion 1* in Section 2.4) it was necessary to determine the value of the LSN parameter which represents this level of vulnerability.

For the purposes of the ILV assessment an LSN value of 16 is considered to be generally representative of the transition between land which is materially vulnerable and land which is not materially vulnerable to liquefaction damage. To determine the LSN value representative of this level of vulnerability, the following have been considered:

- Land and residential building performance across the CES;
- International literature on liquefaction vulnerability; and
- The MBIE (2012) guidelines for rebuilding on liquefaction susceptible soils in Christchurch.

Due to the inherent limitations of the LSN parameter (discussed in Section 7.2.2 and **Appendix A**) the LSN value of 16 is one of several indicators, rather than a strict threshold value, in the determination of whether or not a property is considered vulnerable to a material level of liquefaction damage (*Criterion 1*).

7.3.1 Land and Residential Building Performance

From an engineering perspective, material liquefaction vulnerability is best assessed by considering:

- The likelihood of moderate-to-severe liquefaction related land damage; and
- The likelihood of significant liquefaction related building damage.

Vulnerability to none-to-minor and minor-to-moderate land damage can be accommodated by conventional engineering techniques (i.e. a TC2 foundation), and is within an allowable level of risk for land at the 100 year return period level of shaking. Increases in the risk of damage being sustained should therefore not alter the practical advice that would be given by an engineer in relation to the uses of the land, in particular as a platform to support a residential building.

Vulnerability to significant liquefaction related building damage is more difficult to predict, as the performance of the building in an event causing moderate-to-severe land damage will depend on a number of factors that are independent from the vulnerability of the land to liquefaction. These include foundation design, building shape and building weight. However, as described in Section 3.7.5, data sets are available for the CES that provide some indication, in the Christchurch area, what level of liquefaction vulnerability gave rise to significant building damage across the portfolio of residential buildings in the CES, and therefore could be expected to perform similarly in future up to 100 year levels of earthquake shaking.

To assess the value of LSN for which moderate-to-severe land damage is more likely to occur than none-to-minor and minor-to-moderate land damage, the predicted land performance based on the CES earthquakes was considered. This was achieved by estimating event specific LSN values for each property using the estimated PGA and groundwater levels for the September 2010, February 2011 and June 2011 earthquake events. These LSN values were estimated in the TC3 and residential Red Zone areas because there was sufficient density of CPTs to estimate LSN values for each residential property. The LSN value for each property was then correlated with the corresponding observed land damage for each respective event (Tonkin & Taylor (2013) and van Ballegooy et al., (2014b; 2015c) describe how this was done).

The correlations showed that the frequency distribution of calculated LSN for each land damage observation grouping was relatively consistent with the correlations for each of the three earthquake events. These datasets were combined and box plots and histograms of the data are shown in Figure 7.1.

The plots in Figure 7.1 show that an LSN value of less than 16 characterises properties with none-to-minor liquefaction related land damage and approximately half of the properties with minor-to-moderate liquefaction related land damage. Whereas an LSN value of greater than 16 characterises properties with moderate-to-severe liquefaction related land damage and approximately half of the properties with minor-to-moderate liquefaction related land damage.

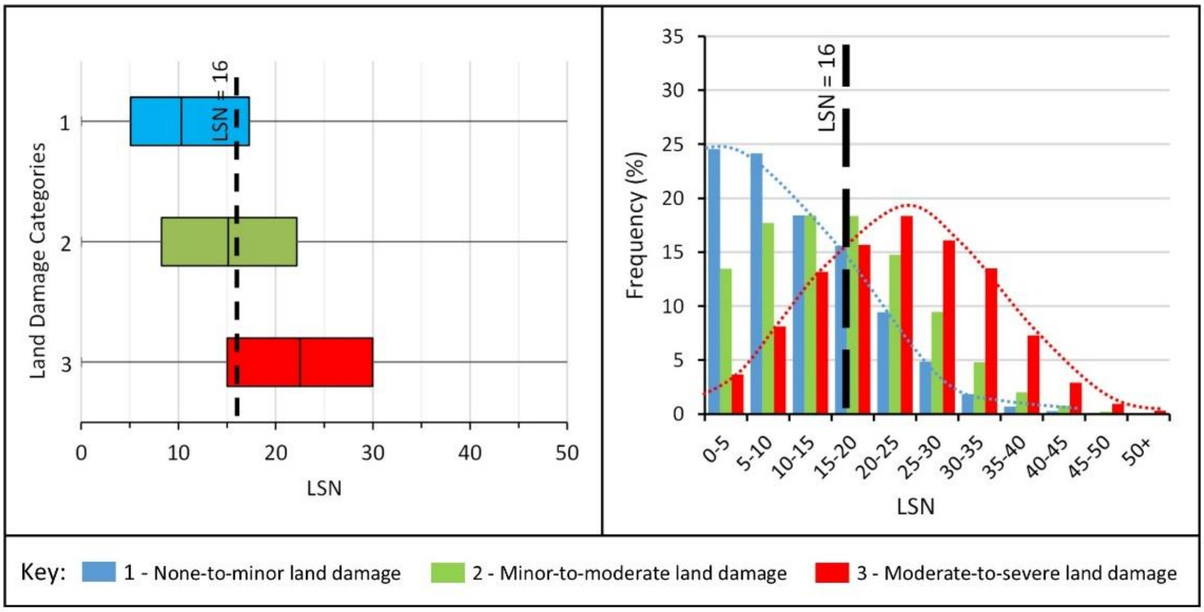


Figure 7.1: (a) Box and whisker plot[5] showing the distribution of land damage observations correlated against LSN for the September 2010, February 2011 and June 2011 earthquake events (b) histogram showing the distribution of land damage observations correlated against LSN.

These analyses were not undertaken for the December 2011 event. This is because, at the time these analyses were originally prepared for publication, the aerial photography for the December 2011 event had not been analysed in sufficient detail to develop the land damage map shown in Figure 3.6d. Review of the subsequent observed land damage and estimated PGA values for the December 2011 event indicates that there is no reason to believe that the incorporation of the December 2011 event analyses would result in a different distribution that would alter the LSN indicator values.

The moderate-to-severe land damage observation classification includes land also affected by lateral spreading damage. The LSN parameter is not intended to incorporate the potential for lateral spreading damage. It should only be used as an index to estimate free-field liquefaction vulnerability. However the inclusion of the lateral spreading damage in the moderate-to-severe land damage category for the back analysis shown in Figure 7.1 is unlikely to bias materially the distribution of observed land performance at different LSN values, and this will not change the LSN indicator value of 16. This is because:

- A very small proportion of properties have sustained lateral spreading damage without also sustaining free field liquefaction damage; and
- The majority of properties which have sustained significant lateral spreading damage, do not have a competent non-liquefying crust and, in the absence of a free face or slope, would be likely to sustain moderate-to-severe free-field liquefaction damage.

To assess the LSN value for which more significant liquefaction related building damage is likely to occur similar analyses were undertaken for the residential buildings in the TC3 and residential Red Zone areas for three groups of BDR (less than 0.3, between 0.3 and 0.5 and greater than 0.5). The

[5] The box and whisker plots and what they represent are defined in the glossary.

BDR dataset is discussed in Section 3.7.5 with the spatial distribution of BDR shown in Figure 3.9. The results from these analyses are shown in Figure 7.2.

It is important to note that the likelihood of significant liquefaction related building damage is not as reliable an indicator of material vulnerability to liquefaction as the land damage indicator. This is because the performance of the building in an earthquake event that results in liquefaction consequences is dependent on a number of factors that are independent of the vulnerability of the land to liquefaction. These factors include foundation design, building shape and building weight. Notwithstanding these limitations, the available BDR data and land damage observations indicate a spatial correlation between BDR and land damage. Therefore there is merit in also considering this dataset for the establishment of LSN indicator values.

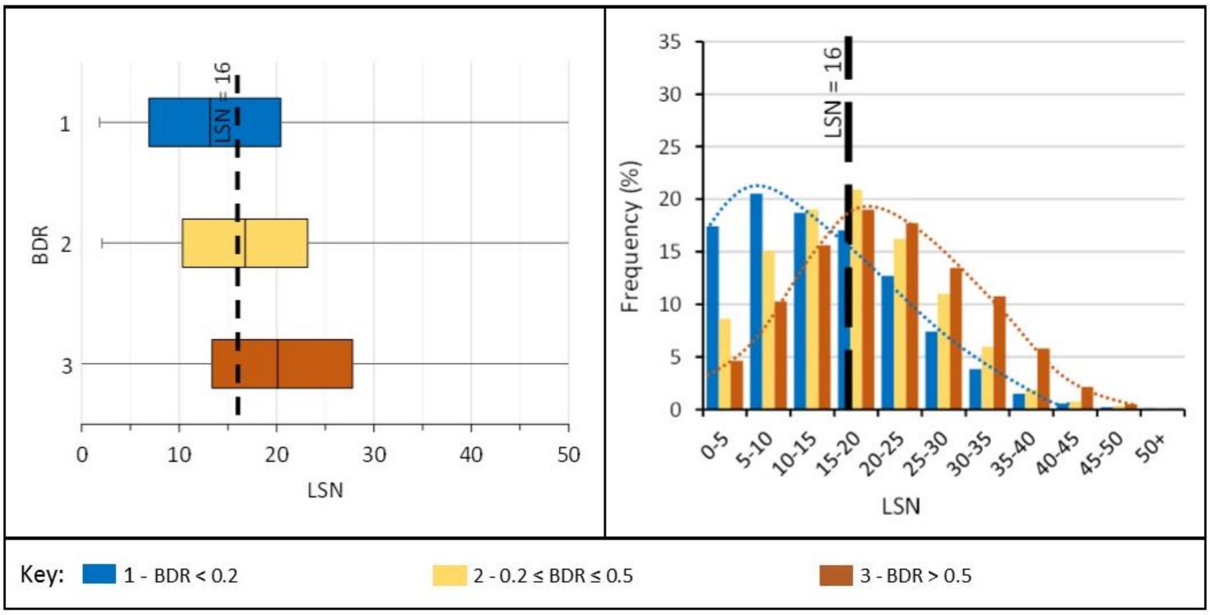


Figure 7.2: (a) Box and whisker plot showing the distribution of BDR for the residential dwellings in the TC3 and residential Red Zone areas correlated against LSN for the September 2010, February 2011 and June 2011 earthquake events (b) histogram showing the distribution of BDR correlated against LSN.

Similarly to the land damage correlations (shown in Figure 7.1), Figure 7.2 shows that the LSN values greater than 16 characterise properties with a distribution of higher BDR values whereas LSN values of less than 16 characterise properties with a distribution of lower BDR values.

The information on land damage and BDR demonstrate that an LSN value of 16 is an appropriate indicator of material liquefaction vulnerability. Of the two data sets considered, the land damage data set is the most relevant.

7.3.2 International Literature on Land Vulnerability

As noted in Section 7.2, the Ishihara (1985) criteria are internationally recognised and widely used in engineering practice to assess the potential for liquefaction damage at the ground surface due to liquefaction of underlying soil layers. Notwithstanding the limitations discussed in Section 7.2, the Ishihara (1985) criteria are a useful tool for comparison with estimated LSN values which are greater than and less than 16.

To develop his criteria, Ishihara plotted observations of the expression of liquefied material at the ground surface using the thickness of the overlying non-liquefying surface layer (H_1) or "crust" and the thickness of the underlying liquefied material (H_2). These observations were used to define boundary curves that separated those sites where liquefied material was expressed at the ground surface from sites that where it was not. These boundary curves were developed for M_W 7.5 earthquakes at 0.2g, 0.3g and 0.4 to 0.5g levels of earthquake shaking.

The important points to note with the Ishihara (1985) criteria are that:

- Soil profiles which plot to the left hand side of the boundary curve are potentially vulnerable to a material level of liquefaction related ground damage; and
- Soil profiles which plot to the right hand side of the boundary curve are not potentially vulnerable to a material level of liquefaction related ground damage.

It is noted that the LSN contour of 15 in Figure 7.3 runs parallel with the Ishihara H_1 – H_2 boundary curve (up to a non-liquefying H_1 crust thickness of 5m) and that it provides results that are reasonably consistent with the land damage criteria proposed by Ishihara (1985).

For LSN values of less than 15, the Ishihara (1985) criteria suggests that no material damage would be expected regardless of the thickness of the underlying H_2 liquefying soil layer. Whereas, for LSN values greater than 15 the Ishihara (1985) criteria indicate material liquefaction damage would be expected. Van Ballegooy et al. (2015a) provides further detail about the similarity between the Ishihara (1985) criteria and LSN.

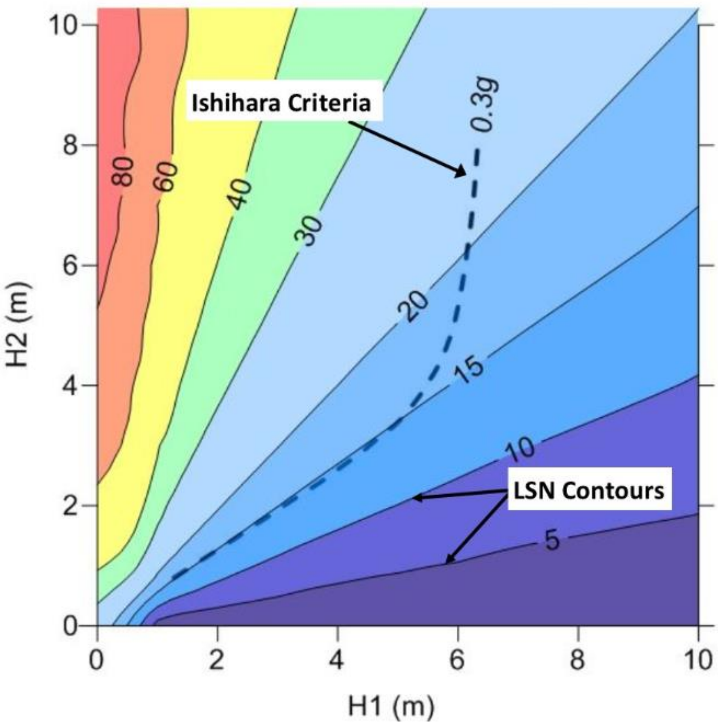


Figure 7.3: The Ishihara (1985) ground damage threshold for M7.5 0.3g compared to contours of LSN for ground shaking of M6 0.3g.

It is noted that the LSN contours in Figure 7.3 are based on M6 0.3g levels of earthquake shaking but the Ishihara (1985) boundary curve was developed from land damage observation data from earthquakes of approximately M7.5 0.3g levels of earthquake shaking. Therefore the absolute values from the LSN contours should not be directly compared to the Ishihara (1985) boundary curve.

If an equivalent Ishihara (1985) boundary curve was to be developed for M6 0.3g levels of earthquake shaking, it is expected that it would plot slightly to the left of the M7.5 0.3g boundary curve. This indicates that an LSN indicator value of 16 at M6 0.3g levels of earthquake shaking is not inconsistent with the Ishihara (1985) criteria.

7.3.3 The MBIE (2012) Guidelines for Rebuilding on Liquefiable Soils in Christchurch

The cumulative frequency graphs of estimated LSN for M6 0.3g levels of earthquake shaking based on post-CES ground surface levels are shown in Figure 7.4. This figure shows that between 50 to 60% of the TC3 properties have an M6 0.3g LSN value of more than 16 based on post-CES ground surface levels. As noted in Section 3.8, approximately 45% of the TC3 properties require more robust foundation solutions (i.e. enhanced TC3 foundations or TC2 foundations in conjunction with ground improvement) to manage the more severe liquefaction vulnerability on those properties.

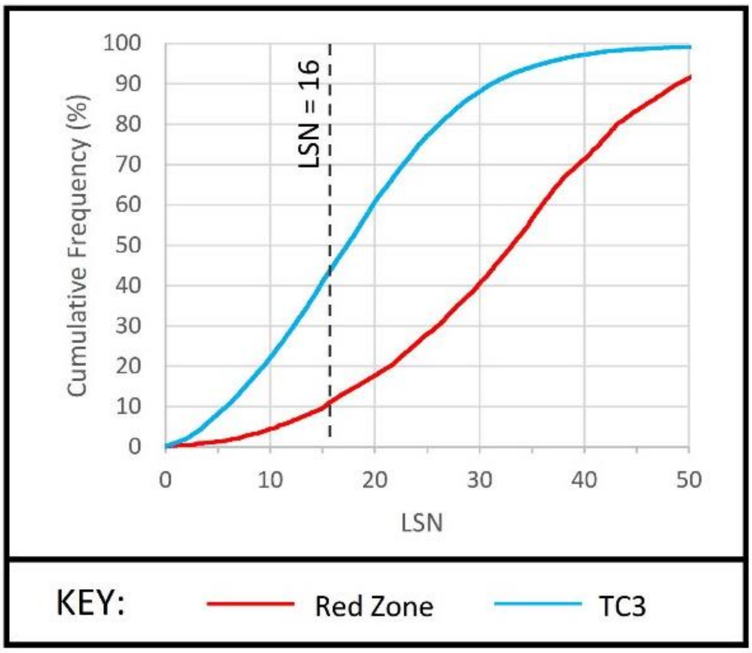


Figure 7.4: Cumulative frequency graphs of the estimated LSN for TC3 and residential Red Zone properties for M6 0.3g levels of earthquake shaking based on post-CES groundwater levels.

While the MBIE criteria for designing residential foundation systems is based on SLS (25 year return period) and ULS (500 year return period) levels of earthquake shaking, the majority of the population of properties which require enhanced TC3 foundations largely coincides with the population of TC3 properties where the 100 year return period (M6 0.3g) LSN value is greater than 16 based on post-CES ground surface levels.

Conversely, Figure 7.4 also shows that between 40 and 50% of the TC3 properties have an M6 0.3g LSN value of less than 16 based on post-CES ground surface levels. As noted in Section 3.8 approximately 55% of the TC3 properties can use TC2 foundations.

Therefore, an LSN value of more than 16 is generally consistent with the MBIE criteria for when enhanced TC3 foundations are required and hence implies that the level of liquefaction vulnerability is considered to be material.

As discussed in Section 3.8, due to the relatively low additional cost coupled with significant benefits, it is current engineering practice to specify TC2 foundation solutions on soils that are susceptible to liquefaction. Therefore TC2 foundation solutions are considered to be standard conventional designs that do not take particular account of material liquefaction vulnerability.

Conversely, enhanced TC3 foundation solutions generally include extensive ground improvement and represent a considerable additional cost over and above the TC2 foundation solutions. Enhanced TC3 foundation solutions or TC2 foundations with ground improvement are required when the estimated liquefaction vulnerability is material.

It is important to reiterate that, due to the inherent limitations of the LSN parameter (discussed in Section 7.2.2 and **Appendix A**) the LSN value of 16 is one of several indicators, rather than a strict threshold value, in the determination of whether or not a property is considered vulnerable to a material level of liquefaction damage (*Criterion 1*).

7.4 Material Change in Liquefaction Vulnerability (*Criterion 2*)

In order to determine whether or not a property has had a material change in vulnerability to liquefaction damage as a result of ground surface subsidence caused by the CES (*Criterion 2* in Section 2.4) it was necessary to determine the magnitude of change between the pre-CES and post-CES liquefaction vulnerability of a property which represents the difference between land which has not had a material change in vulnerability to liquefaction damage and land which has materially changed in vulnerability to liquefaction damage.

Land can be considered to have materially increased liquefaction vulnerability where:

- The observed and measured changes are such that, having regard to uncertainty associated with the liquefaction analysis, it is more likely than not that a change in vulnerability has occurred; and
- The measured change is such that, from an engineering perspective, the use and amenities of the land as a building platform and for other related purposes, can be said to have adversely changed.

In order to use the LSN parameter as an indicator to assess whether or not a property has had a material change in liquefaction vulnerability as a result of ground surface subsidence caused by the CES (*Criterion 2* in Section 2.3) it was necessary to establish a change in LSN from the pre-CES to the post-CES ground surface elevation (i.e. **ΔLSN**) value that is representative of this material change in liquefaction vulnerability.

For the purposes of the ILV Assessment Methodology a ΔLSN value of 5 is considered to be generally representative of this material change in liquefaction vulnerability.

The selection of a ΔLSN value of 5 as an indicator of this transition takes into account both an assessment of the materiality of change in vulnerability, and that the LSN parameter has a number of inputs which have measurement uncertainty and analysis uncertainty. These input and analysis uncertainties result in an uncertainty in the calculation of LSN at any given CPT location. The ΔLSN value used as an indicator for material change in liquefaction vulnerability needs to reflect this level of uncertainty.

It is important to note that the ΔLSN value of 5 is one of several tools, rather than a strict threshold value, in the determination of whether or not a property has had a material change in liquefaction vulnerability (*Criterion 2*). The application of the ΔLSN value in conjunction with these other tools in the determination of *Criterion 2* is described in Section 8.

This sub-section describes:

- The uncertainty of the measurement of the input parameters and liquefaction triggering analyses; and
- The materiality of different levels of change in liquefaction vulnerability.

7.4.1 Uncertainty in Measurement of Input Parameters

The level of uncertainty associated with the liquefaction analysis is dependent on the particular parameter being considered. In some cases, independent observations can be used in the manual process to reduce the level of uncertainty.

The uncertainty of LSN is dependent on the measurement uncertainty of the input parameters and liquefaction triggering analyses which are part of the LSN calculations. A ΔLSN of 5 is considered to be the minimum level of estimated change which provides confidence, given those uncertainties, that on the balance of probabilities a change has occurred.

The significant variables that contribute to the uncertainty of LSN are listed below:

1 Earthquake ground motions (M_W and PGA);
2 Liquefaction triggering to calculate LSN;
3 Post-liquefaction volumetric strain (ε_v) to calculate LSN;
4 Depth to groundwater estimates;
5 CPT measurement accuracy; and
6 Spatial variation and interpolation of LSN values at CPT locations.

Each of these variables and their associated uncertainty are discussed in turn below.

Earthquake ground motions

The estimation of the regional 100 year return period ground motions in the Class D sub-soils in Christchurch have inherent uncertainty. This is the most significant source of uncertainty in the calculation of LSN. However these regional values are specified in the MBIE guidelines and are assumed as a prescribed value as detailed in Section 5.3. Therefore, the level of uncertainty associated with the regional 100 year return period ground motions has not been evaluated.

However, throughout the Class D subsoils in Christchurch, the site specific ground response varies. Therefore, the actual level of 100 year return period ground shaking at a specific site is likely to vary spatially from the MBIE specified 100 year return period value.

Figure 7.5a shows the corresponding distribution in the difference of the LSN values estimated at each CPT location. This figure demonstrates that 90% of the LSN differences at all the CPT locations, for the uncertainty in a site specific PGA of ±0.02g, are within ±2 LSN points.

Liquefaction triggering to calculate LSN

The Boulanger and Idriss (2014) liquefaction triggering methodology requires selection from a range of input parameters. These parameters include I_c cutoff, FC estimation, P_L and soil density. As discussed in Sections 3.3 and 3.4, default upper bound parameters (consistent with engineering design practice) have typically been assumed.

Detailed studies (summarised in **Appendix A**) show that these parameters vary from site to site and also between soil layers giving rise to reasonably large uncertainty. However, during the detailed manual assessment process (described in Sections 8, 9 and 10), if the predicted liquefaction triggering assessment and associated LSN values were inconsistent with the observed land performance, then these variations were considered and factored in accordingly. The manual assessment process therefore reduces the amount of uncertainty associated with liquefaction triggering.

Lees et al. (2015) showed that the I_c cutoff parameter in Christchurch soils can vary within a soil layer from 2.4 to 2.6. Lees et al. (2015) also showed that the C_{FC} parameter for estimating FC from I_c typically varies between 0 and 0.3 for the Christchurch soils. While the manual assessment process associated with the ILV Assessment Methodology reduces the uncertainty associated with liquefaction triggering it is not entirely eliminated.

Figure 7.5 (c, d & e) show the distribution in the difference of the estimated LSN values at each CPT location when allowing for I_c cutoff variability (2.4 to 2.6), C_{FC} (0 to 0.1) and P_L (15% to 50%). Figure 7.5c shows that approximately 60% of the LSN differences at all the CPT locations for the I_c cutoff range of 2.4 to 2.6 are less than 2 LSN points and 85% of the LSN differences are less than 5 LSN points. Similarly, Figure 7.5d shows that approximately 85% of the LSN differences for the C_{FC} range of 0 to 0.1 are less than 5 LSN points. Figure 7.5e shows a much larger distribution of the LSN differences at all the CPT locations for the P_L range of 15% to 50% with approximately 90% of these differences being less than 6 LSN points.

In addition, the following are also sources of uncertainty associated with liquefaction triggering:

- The liquefaction triggering assessments assume that the groundwater pressures below the depth of the groundwater surface increase hydrostatically and that the soil is fully saturated below this level. However, there are areas in Christchurch where the groundwater comprises a system of perched layers within the complex soil structure and hence the water pressures do not increase hydrostatically which affects the liquefaction triggering calculations; and
- In some areas, the soil below the groundwater surface has been found to be partially saturated which also affects liquefaction triggering.

Post–liquefaction Volumetric Strain (ε_v) to calculate LSN

The LSN parameter uses the Zhang et al. (2002) post-liquefaction volumetric densification strain (ε_v) empirical equations as discussed in **Appendix A**. These empirical equations have inherent uncertainty and transitioning between layers of soils of different density can further compound this uncertainty.

Depth to groundwater

The depth to groundwater estimates have the following uncertainties:

- 30 to 35% of the area of the pre- and post-CES DEM used to represent the ground surface has a deviation greater than 0.1m and 45 to 65% of the area of the DEM has a deviation greater than ±0.05m from the ground surface. Refer to **Appendix G** for further discussion about accuracy of the LiDAR data;
- The level of the groundwater surface is based on an interpolation of groundwater levels in wells at large spacings. However the groundwater level throughout Christchurch is relatively flat so it is possible to develop groundwater surfaces with wide spaced well data with reasonable confidence.
- The groundwater surface in urban Christchurch is estimated to have an uncertainty in the order of 0.1 to 0.2m. Therefore, the depth to groundwater (estimated by the DEM elevation minus the groundwater surface elevation) has a measurement error in the order of 0.2m to 0.3m. However, with the manual review process discussed in Sections 8, 9 & 10 it is reasonable to reduce this uncertainty estimate to ±0.2m.

Figure 7.5b shows the distribution in the difference of the estimated LSN values at each CPT location when allowing for a GWD uncertainty of ±0.2m. It shows that approximately 70% of the LSN differences at all the CPT locations for GWD uncertainty of ±0.2m are within ±2 LSN points and approximately 90% are within ±4 LSN points.

CPT measurement accuracy

CPTs are used for the calculation of LSN. Some variability in CPT test results can be expected as the CPTs have been carried out by a range of contractors with a range of equipment in Christchurch over a number of years. In identical soils two CPTs are expected to have slightly varying results due to measurement error.

CPTs which had a valid calibration certificate were done in accordance with American Society for Testing and Materials (ASTM) D5778-12 (ASTM, 2012). This standard requires a baseline zero calibration to be completed at the beginning and end of every CPT sounding. ASTM D5778-12 allows for a 2% tolerance in load cell drift at the beginning and end of every CPT test which translates to an error of approximately 2% for both q_c and fs. Therefore the CPT q_c and f_s are likely to vary by 2% as a result of this measurement error.

Figure 7.5f shows the distribution in the difference of the estimated LSN values at each CPT location when allowing for a 2% uncertainty in q_c. It shows that approximately 80% of the LSN differences at all the CPT locations for q_c uncertainty are within ±1 LSN points. Close to 100% of the LSN differences are within ±2 LSN points.

It is noted that in some cases lower LSN values are estimated at slightly lower q_c values (as shown by the negative difference in the histogram in Figure 7.5f). This is because for some CPTs slightly lower q_c values result in a small increase in I_c, resulting in some soil layers having an I_c value that increases from just below to just above the I_c cutoff value of 2.6, which are therefore assessed as not susceptible to liquefaction.

Spatial variation and interpolation of LSN values at CPT locations

The estimated LSN value at each CPT location is spatially variable and therefore the resolution of LSN interpolated between each CPT will also be variable. In some areas in Christchurch this spatial variation in estimated LSN is relatively small and does not contribute significantly to the uncertainty associated with LSN. However, in other areas this spatial variation is more significant and accordingly needs to be managed with the manual assessment process.

The worked example summarised in **Appendix L** demonstrates this spatial variability in LSN, the effect it has on interpolation in the automated ILV model and how it is managed in the ILV Assessment Methodology.

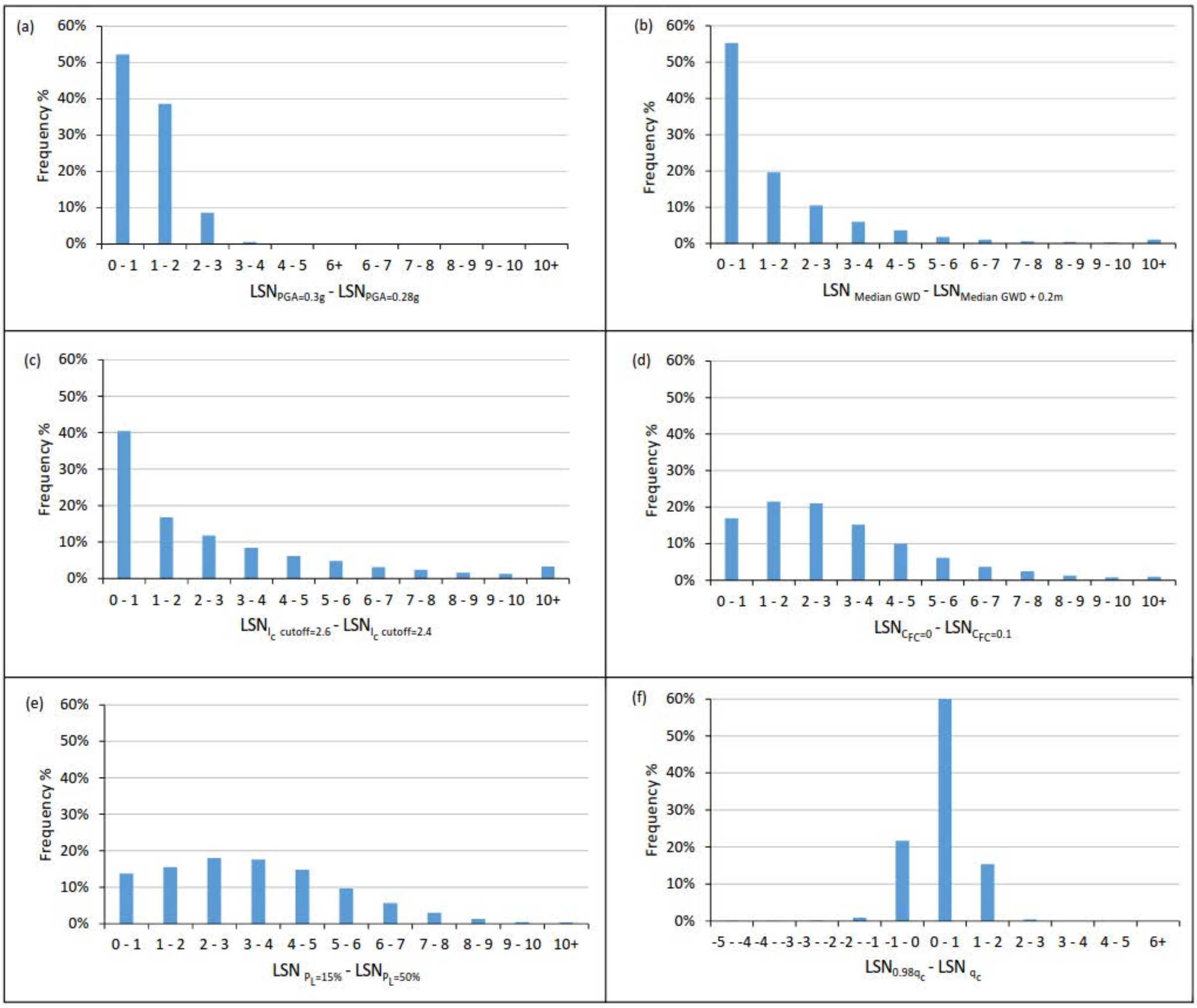


Figure 7.5: shows the distribution in the difference of the estimated LSN values for all CPTs available on the CGD at the end of July 2015 for: (a) the difference in LSN estimated for PGA = 0.3 and 0.28g, (b) the difference in LSN estimated for median GWD and Median GWD + 0.2m, (c) the difference in LSN estimated for I_c cutoff = 2.4 and I_c cutoff = 2.6, (d) the difference in LSN estimated for C_{FC} = 0.0 and C_{FC} = 0.1, (e) the difference in LSN estimated for P_L = 15% and P_L = 50% and (f) the difference in LSN estimated for q_c and $0.98q_c$.

Summary of Uncertainties

It is important to note that not all of the uncertainties which are listed above translate into LSN uncertainty at a particular site. For example Leeves et al. (2015) showed that the LSN sensitivity to I_c cutoff is greater in western Christchurch whereas sensitivity to C_{FC} is greater in eastern Christchurch. Similarly, the groundwater surface is reasonably flat in eastern Christchurch and as a result is associated with less uncertainty. Conversely, in western Christchurch there is more uncertainty associated with the groundwater surface due to its upwards gradient towards the west. This variability is applicable to most of the uncertainties discussed above.

Therefore, it is not appropriate to attempt to combine all of these uncertainties together. However, it is reasonable to assume that a given site will be affected by some of them.

In the ILV Assessment Methodology, manual assessment has been included as an integral component to address the uncertainties of the inputs into LSN. It includes a review of the dataset of the CES including land damage observations, geological and topographic assessments, detailed specific analysis of the geotechnical information, review of laboratory test data, and further sensitivity analyses of liquefaction vulnerability assessments.

However, while manual review can be used to mitigate some of this uncertainty it cannot account for all of the error. Considering all of the above, based on engineering judgement, a ΔLSN of 5 is considered the minimum practical value for the assessment of ILV to enable confidence that, on the balance of probabilities, a change has occurred.

7.4.2 Materiality

As a result of the ground surface subsidence caused by the CES, both the land and the residential buildings on properties which have ILV now have a greater likelihood of more severe liquefaction related damage. That is, a greater likelihood in future M6 0.3g levels of earthquake shaking of:

- Moderate-to-severe liquefaction related land damage; and
- Building Damage Ratio (**BDR**) greater than 0.5.

A 5 to 10% increase in the likelihood of moderate-to-severe land damage or high BDR, is the minimum change that would be taken into account, as a matter of engineering judgement, for re-evaluating design assumptions and land use decisions.

Figure 7.6 and Figure 7.7 show how the likelihood of the liquefaction related damage increases with LSN in ΔLSN increments of 5 for the land damage and BDR correlations that were shown in Figures 7.1 and 7.2 respectively.

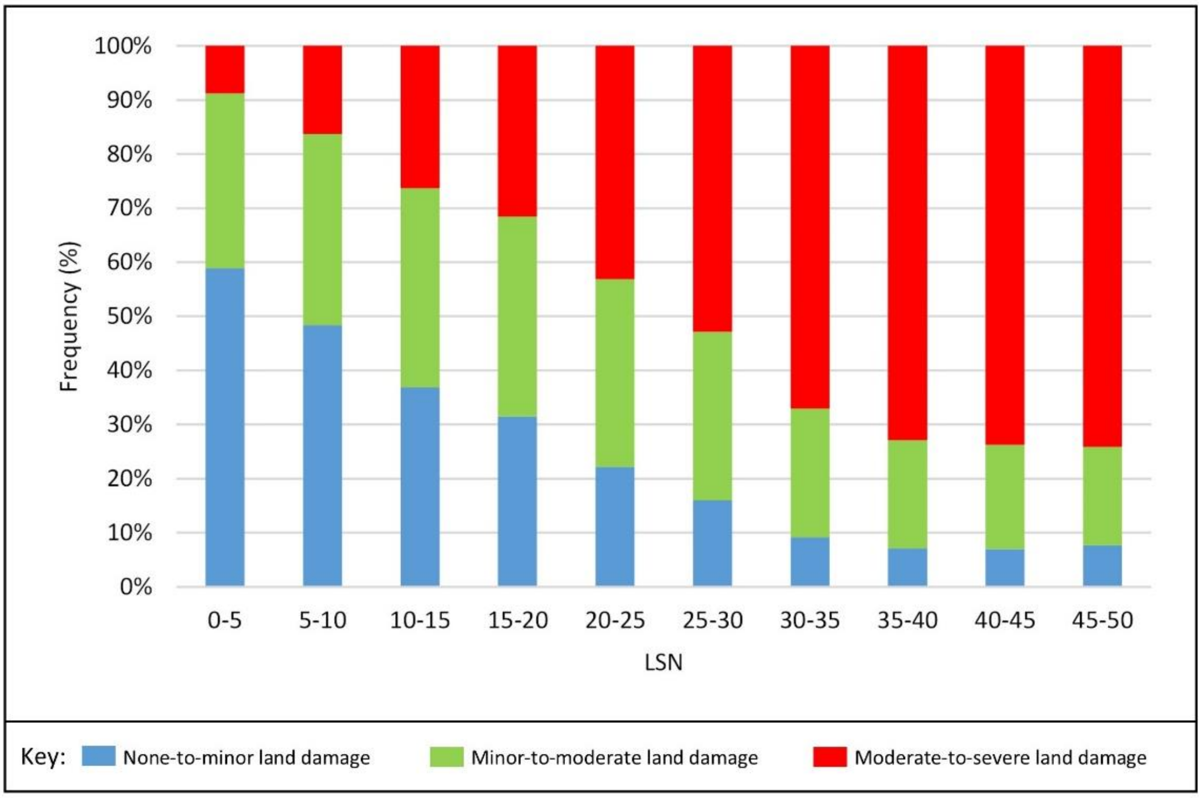


Figure 7.6: Frequency bar chart showing the likelihood of none-to-minor, minor-to-moderate and moderate-to-severe land damage for different LSN bands based on data from the TC3 and residential Red Zone properties.

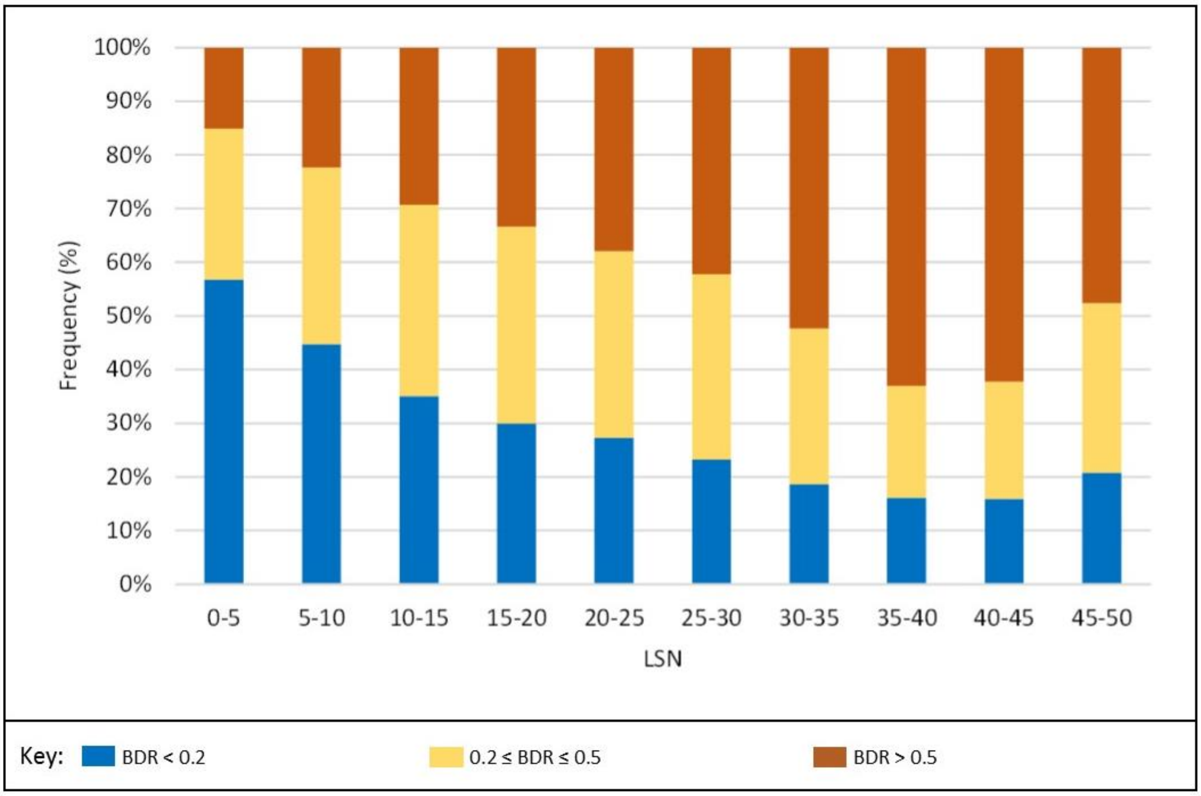


Figure 7.7: Frequency bar chart showing the likelihood of BDR values of less than 0.2, 0.2 to 0.5 and greater than 0.5 for different LSN bands based on data from the TC3 and residential Red Zone properties.

Figure 7.6 shows that a ΔLSN value of 5 results in approximately a 10 percentage point increase in the likelihood of moderate-to-severe liquefaction land damage in the range of LSN values from 15 to 40 which is the typical range of estimated post-CES LSN values for most of the ILV properties. Similarly Figure 7.7 shows that a ΔLSN value of 5 results in approximately an 8 percentage point increase in the likelihood of BDR exceeding 0.5 in the range of LSN values from 15 to 40.

Based on engineering judgement a 5 to 10% increase of vulnerability is considered to be a material value for re-evaluating design assumptions and decisions, and hence a corresponding ΔLSN value of 5 is a good indicator of a material change in Liquefaction Vulnerability.

7.4.3 Summary of Uncertainty and Materiality

Having regard to uncertainties in the assessment methodology, a ΔLSN of 5 is considered the minimum practical value for the assessment of ILV to enable confidence that, on the balance of probabilities, a change has occurred.

There are also good engineering reasons to justify a ΔLSN indicator of 5 points as the minimum level of estimated change in liquefaction vulnerability that could be regarded as material. A ΔLSN indicator of 5 points indicates a 5 to 10% increase in the likelihood of moderate-to-severe land damage or high BDR. This is the minimum change that would be taken into account, as a matter of engineering judgement, for re-evaluating design assumptions and land use decisions.

Based on this engineering advice, EQC has asked T+T to adopt a ΔLSN of 5 as an indicator of material change in liquefaction vulnerability. Whether or not this is significant to a property owner will be assessed by EQC's valuers in *Criterion 3* (refer to Section 2.4).

It is important to reiterate that, the ΔLSN value of 5 is one of several tools, rather than a strict threshold value, in the determination of whether or not a property has had a material change in liquefaction vulnerability (*Criterion 2*).

7.5 Median and Mean LSN

Finally, in order to use the LSN parameter for assessment of liquefaction vulnerability, it is necessary to determine what account to take of seasonal variation in vulnerability, and therefore LSN.

The groundwater level in the Christchurch area varies naturally from season to season, and from year to year. For the parts of the Christchurch area where ground surface subsidence has occurred (i.e. areas that may potentially meet *the engineering criteria*), this range of variation in the depth to the groundwater is typically 0.5m above and below the median groundwater surface.

Because the groundwater levels are continually fluctuating, the liquefaction vulnerability of the land (as represented by the LSN parameter) also fluctuates above and below the median value. However, because the LSN parameter has a depth-weighting factor, the LSN value increases more due to a rise in the groundwater level than it decreases due to a lowering in the groundwater level. This means that the variability in the LSN value over time is not equally distributed about the median. Furthermore, the presence of layers of non-liquefying soils within the range of groundwater fluctuation will affect the distribution of LSN over time.

A significant amount of work was undertaken to investigate the difference between the median and mean liquefaction vulnerability as a result of fluctuating groundwater levels and the influence this would have on the assessment of liquefaction vulnerability in the Christchurch area. Further detail about this work is provided in **Appendix H**.

The key findings from this work were:

- When considering the mean and median post-CES LSN values and their respective ΔLSN values, from a technical perspective, neither is more correct than the other. In general it could be considered that:
  - Because engineering design is likely to be based on the median groundwater level, the median post-CES LSN is more representative of the level of engineering effort (e.g. ground improvement or enhanced foundations) that would be specified in practice;
  - Because the liquefaction vulnerability has a non-uniform variation with time, the mean post-CES LSN is more representative of the average exposure to the liquefaction hazard over time; and
  - There is not a significant difference between the spatial distribution of the median post-CES LSN and the mean post-CES LSN at M6 0.3g levels of earthquake shaking. Similarly, there is also not a significant difference between the spatial distributions of the ΔLSN values (as a result of ground surface subsidence caused by the CES) for the median and mean estimated LSN cases.

Based on the above information, EQC asked T+T to apply *the engineering criteria* using the median and/or the mean liquefaction vulnerability approaches. This approach is more inclusive than adopting either the median or the mean LSN parameter exclusively, and accounts for both measures having strengths in predicting different vulnerability impacts (engineering levels and average hazard exposure over time, respectively).

8 Automated ILV Modelling and Manual Assessment Process – Common Features

8.1 Purpose and Outline

The objective of this section of the report is to describe key details of the ILV assessment process which are common to both the Stage 1 and Stage 2 assessments outlined in the process in Figure 4.2. The Stage 1 and Stage 2 assessment processes are described in Sections 9 and 10 respectively.

This section describes:

- The development and purpose of the automated ILV model, including a discussion of some of its inherent limitations;
- The manual ILV assessment process which is consistent across both the Stage 1 and Stage 2 methodologies; and
- The differences between the automated ILV model and the manual ILV assessment results.

8.2 Automated ILV Model

In order to assist with the manual ILV assessment process for the 140,000 urban residential properties in Christchurch (discussed in Sections 8.3, 9 and 10), an automated ILV model was developed using the CPT-based LSN parameter. This model was used to indicate on a regional basis the areas where the residential properties are likely to qualify for ILV. It was also used as a tool to help the assessing engineers with spatial interpolation in the manual assessment process (refer to Section 8.3.2.5). It was particularly useful for determining ΔLSN values for properties which had subsided more than the adjacent roads (ΔLSN values can be extracted from the automated ILV model).

8.2.1 Automated ILV Model Outline

An outline of the automated ILV assessment model is shown in Figure 8.1.

The first part of the automated ILV assessment model assesses the M6 0.3g mean and median LSN at each CPT location based on the post-CES DEM and the various groundwater surfaces (discussed in Section 5.4).

Approximately 18,000 CPT investigations have been undertaken across Christchurch. Of these 18,000 CPTs approximately 15,000 have been undertaken in a manner that provides a sufficient length of soil profile for the purposes of estimating LSN at the test location. The remaining 3,000 CPTs are missing portions of information, generally as a result of predrilling at the surface to avoid services or termination of the test prior to reaching the required depth.

A process of LSN slicing has been developed to make use of the estimated vertical LSN slice increments available in the 3,000 CPTs that do not contain a sufficient length of soil profile. A number of constraints are applied to the slicing process to ensure only relevant vertical LSN slice increments from nearby CPT investigations are used to fill in incomplete portions of the CPT profiles. These limitations are discussed in **Appendix I**.

The purpose of applying the slicing method was that the mean and median LSN values at each CPT could be standardised to the same depth of soil profile (i.e. the top 10m) and relatively compared. Following the slice interpolation process the mean and median LSN values at each CPT location were then interpolated to produce LSN contour maps. The geospatial LSN values for both the mean and median LSN cases were then estimated for the ILV assessed land area using both the median and mean LSN contour maps.

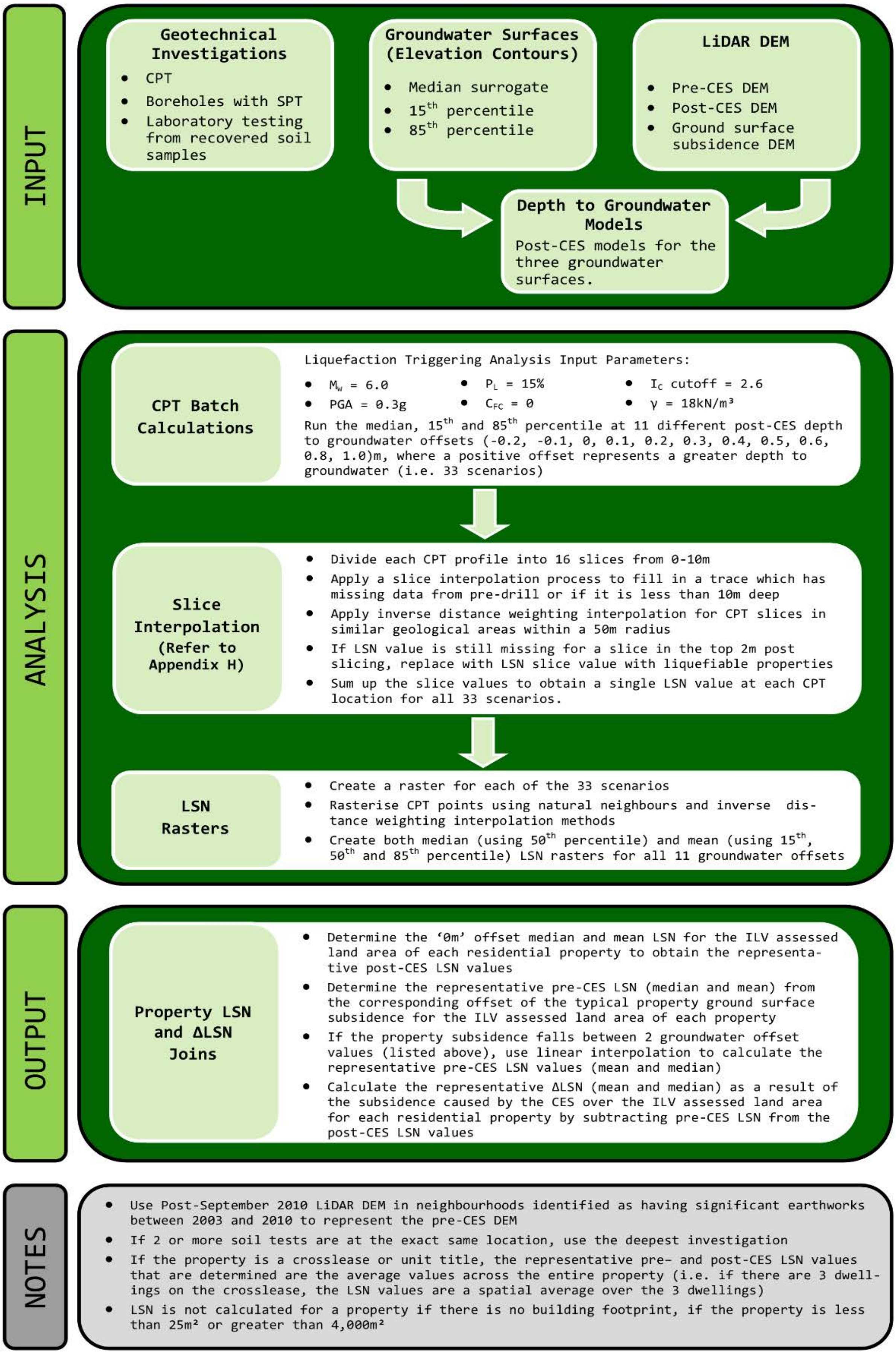


Figure 8.1: Automated model process for assessing the likely ILV status.

8.2.2 Automated ILV Model Results

The maximum estimated representative post-CES LSN value for each property (i.e. the maximum estimated LSN value from the median or mean cases) is shown in Figure 8.2. Estimated LSN values less than 16 (i.e. the blue areas in Figure 8.2) generally indicate the land areas which are not expected to be vulnerable to a material level of liquefaction damage at M6 0.3g levels of earthquake shaking based on the post-CES ground surface levels.

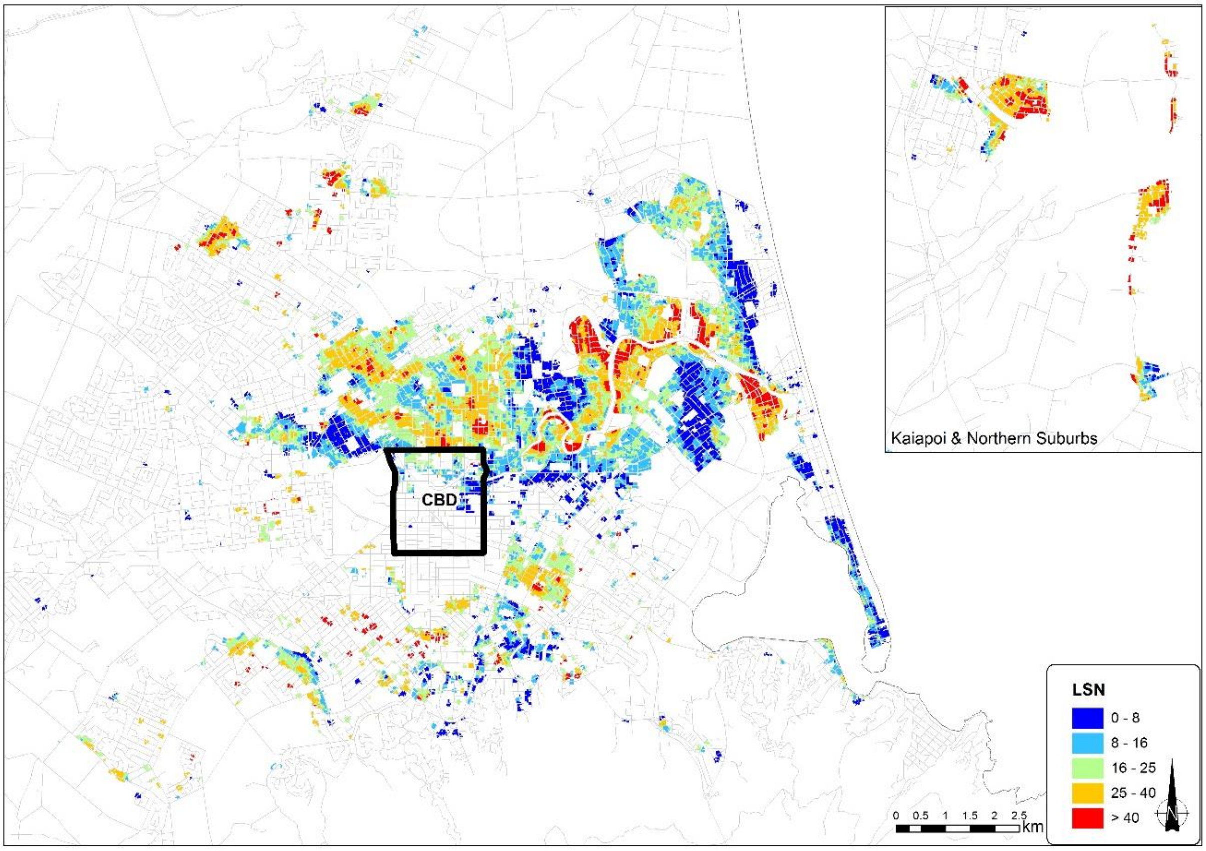


Figure 8.2: Estimated maximum LSN for M6 0.3g levels of earthquake shaking based on the post-CES ground surface levels.

Estimated LSN values greater than 16 (i.e. the green, orange and red areas in Figure 8.2) generally indicate the land areas which are expected to be vulnerable to a material level of liquefaction damage at the post-CES ground surface levels. These areas indicate the residential properties throughout the region that would be likely to satisfy *Criterion 1* in the ILV eligibility assessment process (refer to Section 2.4). The white areas on the map indicate either non-residential properties or urban residential properties where there was an insufficient density of CPT information to sensibly calculate LSN values.

While the automated assessment of the LSN value on each property is based on a 25m x 25m DEM (to determine the depth to groundwater), the assessment of the ΔLSN for each property is based on a 5m x 5m difference DEM used to estimate the ground surface subsidence as a result of the CES. This resolution of the difference DEM was used to appropriately estimate the ΔLSN as a result of the more localised ground surface subsidence of each property.

Initially a 5m x 5m grid post-CES DEM was used for the assessment of the LSN value for each property for the automated ILV model. However, this resolution was too high and resulted in significant noise in the model. This is because of DEM interpolation error resulting in areas where the LiDAR survey points could not capture the ground surface due to structures and vegetation (refer to **Appendix G**). This commonly occurs in areas where the properties are built up higher than the roads. In flat areas the depth to groundwater is a lot more consistent.

In areas of topographic variability the estimation of LSN values would result in a large amount of variability between the CPTs pushed in the roadways (which typically had higher estimated LSN values due to the shallower depth to the groundwater surface) and the CPTs undertaken on residential properties (which typically had lower estimated LSN values due to the deeper groundwater surface because the property was elevated).

The resulting LSN maps were also inconsistent with the land damage observations from the main CES earthquakes and they did not represent the same patterns of observed land damage performance. Therefore, for the automated ILV model, a 25m x 25m post-CES DEM was used to spatially smooth out the variability in the depth to groundwater. This resulted in significantly smoother LSN maps which were more consistent with the observed land damage performance.

The next part in the automated ILV assessment model repeats the process outlined above with groundwater offsets of -0.2, -0.1, 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8 and 1.0m from the various groundwater surfaces (where positive offset values represent a greater depth to groundwater). This is to determine the difference in liquefaction vulnerability (ΔLSN) between the post-CES and the pre-CES estimated LSN values.

Based on the geospatial median ground surface subsidence from the LiDAR derived difference 5m x 5m DEMs, for the approximate land area covered under the EQC Act, the corresponding median and mean estimated ΔLSN geospatial median ΔLSN value for the median and mean cases was determined for each property. The maximum representative estimated ΔLSN value for each property (i.e. the maximum from the estimated median or mean cases) is shown in Figure 8.3.

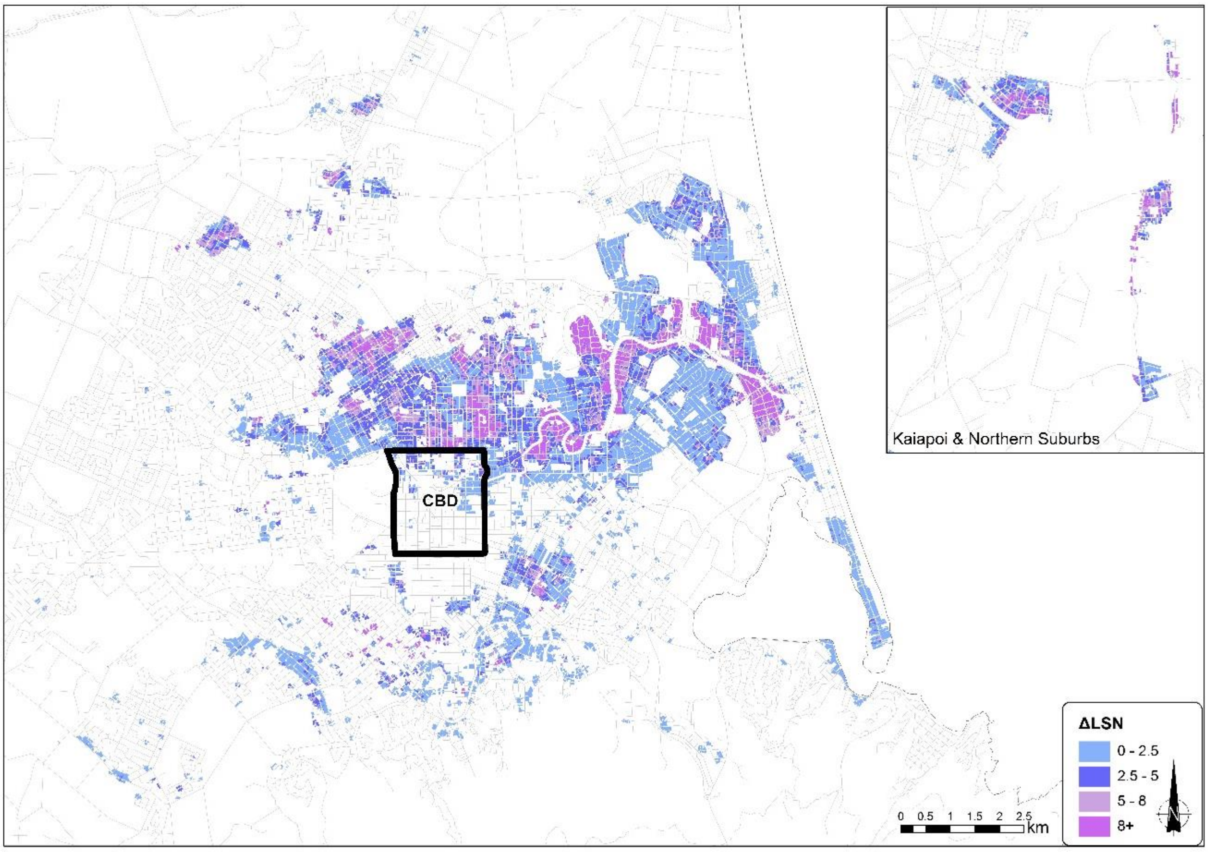


Figure 8.3: Estimated maximum ΔLSN for M6 0.3g levels of earthquake shaking for the ground surface subsidence over the CES.

The properties that potentially satisfy the two *engineering criteria* (Section 2.4) based on the automated assessment of ILV (i.e. where the post-CES LSN value is greater than 16 and ΔLSN value is greater than 5) are identified in red in Figure 8.4.

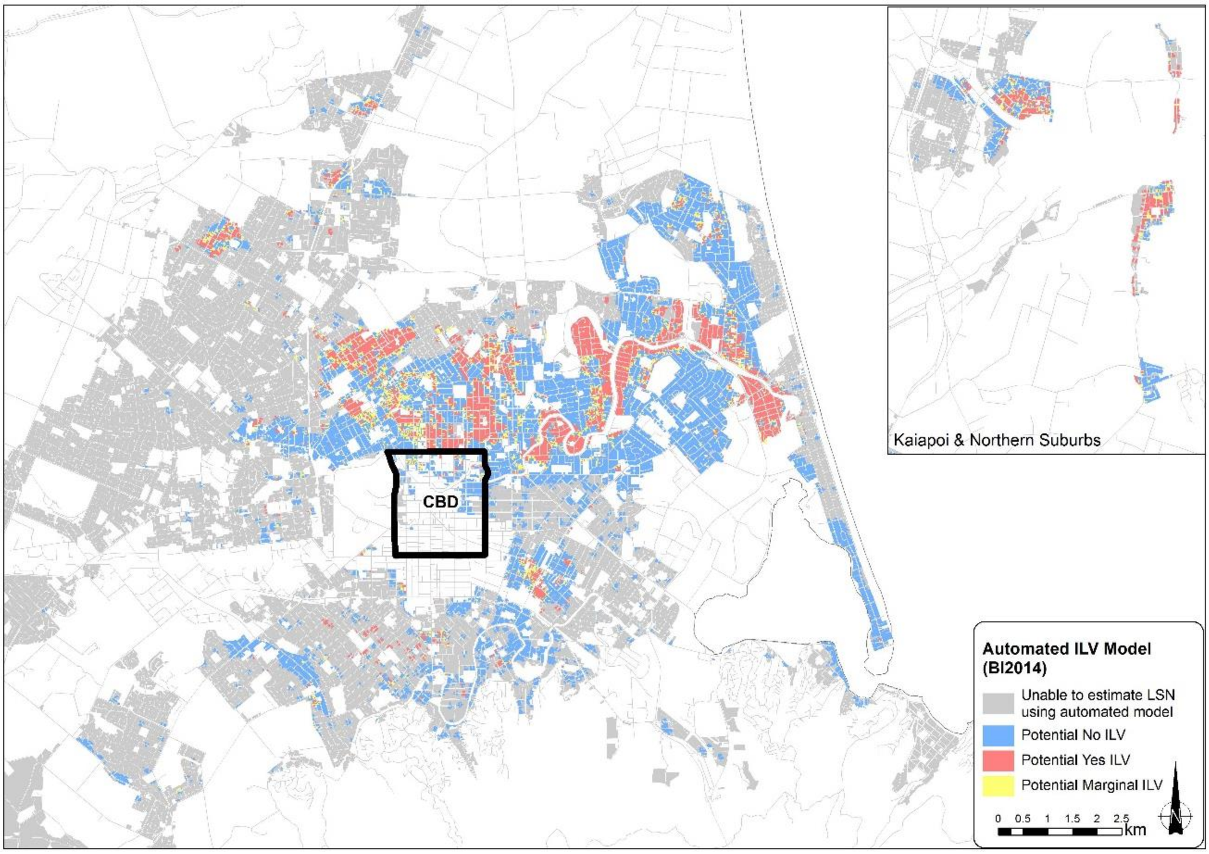


Figure 8.4: Spatial distribution of urban residential properties likely to be eligible for ILV using the ILV automated model.

The marginal ILV cases based on the automated ILV model (i.e. where the post-CES LSN value is between 14 and 16 and ΔLSN value is greater than 5 or the post-CES LSN value is greater than 16 and ΔLSN value is between 4 and 5) are identified in yellow in Figure 8.4.

At a regional scale, it is apparent that the majority of properties likely to qualify for ILV on an automated basis are clustered together. These clusters are mainly in the eastern parts of Christchurch along the banks of the Avon River and to the north of the CBD. These areas generally coincide with the areas where the observed land damage and ground surface subsidence were most severe (refer to Section 3.7.3 and 3.7.4).

It is noted that the marginal properties (i.e. the yellow areas in Figure 8.4) are generally occurring as thin transition zones between the areas likely to qualify for ILV and the areas unlikely to qualify for ILV.

8.2.3 Automated ILV Model Limitations

While the automated ILV model is a very useful tool for the manual assessment process, it has four over-arching limitations. These four limitations are:

- **Interpolation across geological boundaries -** The automated ILV model involves linear interpolation between discrete CPT locations. The model therefore does not account for nonlinear geological or topographic transitions (e.g. old infill river channels or open watercourses) which may occur between the CPT locations.

Theoretically, this limitation could be overcome by increasing the density of the CPTs to a 10m x 10m grid pattern[6], however this is not technically feasible. Practically, this limitation is overcome by the manual assessment process which uses engineering judgement to manually interpolate and extrapolate between the geotechnical data point locations. This allows the ILV assessment to include more geotechnical information and ensures that the methodology is not applied mechanically (i.e. it adheres with the objectives consistent with the Land Declaratory Judgment discussed in Section 2.6).

The Stage 2 ILV assessment of worked example 1 in Section 10.3 provides a good demonstration of how the manual assessment process has been used to overcome this limitation.

- **Variable ground conditions –**The two ground conditions that affect the estimation of liquefaction vulnerability with the LSN parameter the most are relative soil density directly affecting the measurement of q_c and FC. In parts of Christchurch, both of these ground conditions can vary significantly over short distances within the same geological unit.

  Given that the automated ILV model involves linear interpolation between discrete CPT locations, the model is unable to capture this ground variability and can result in the prediction of significantly different liquefaction vulnerability for areas with consistent ground damage across the CES.

  This limitation is overcome by the application of engineering judgement in the manual assessment process to determine on the balance of probabilities which ground conditions are the most representative of the observed land damage across the CES. This is also important to ensure that the methodology is not applied mechanically.

  The Stage 2 ILV assessment of worked example 5 in **Appendix L** provides a good demonstration of how the manual assessment process has been used to overcome this limitation.

- **Slicing of adjacent CPT investigations –** As discussed previously in this section, LSN slicing (as described in **Appendix I**) is an important part of the automated ILV model to improve the automated results at a regional level. However, as the slicing process estimates ground conditions from nearby CPT traces and in some areas ground conditions are spatially variable and the sliced values are not necessarily representative of the actual ground conditions at that CPT location.

  This limitation is overcome in the manual assessment process through the use of the CPT classification process described in Section 8.3.2.3.

- **LSN estimation limits -** The estimation of LSN and hence the automated ILV model is subject to uncertainties which cannot be appropriately captured with the use of the current investigation and liquefaction triggering assessment tools. The only way to overcome this is to use engineering judgement to manually review the results of the automated model with reference to the performance of the land during the CES relative to the estimated event specific levels of earthquake shaking for each main CES event.

  The nature of the uncertainties and natural complexities and its effect on the calculation of LSN is discussed in detail in Section 7.2.2.

- **Cross lease and unit titles –** The representative pre and post CES LSN values on cross lease and unit titles are the average values across the entire property (i.e. if there are three

[6] The current density of geotechnical investigations is approximately 50m apart with higher density of geotechnical data points in areas where there is significant liquefaction related land damage and dwellings require rebuilding, and lower density in areas where there has been less liquefaction related land damage.

dwellings on the cross lease, the LSN values are a spatial average over the three dwellings). However, in a very small number of cases, the available information has indicated that different ILV qualifications are appropriate for properties under the same cross lease or unit title. In these cases engineering judgement has been used to overcome this limitation and the automated model has been overruled with the appropriate ILV qualification.

8.3 Manual ILV Assessment Process

The process for determining ILV qualification was divided into the seven tasks presented in Figure 8.5. This process was the same for both the Stage 1 and Stage 2 assessments. The key difference between the two stages was the level of detail applied, with the more complex Stage 2 assessments requiring more detailed analysis.

Figure 8.5: Overview of the ILV manual assessment process.

The qualification process begins with consideration of regional level data followed by consideration of local data packs comprising a number of neighbouring properties (typically 20 for areas of reasonable complexity). The data packs are described in Sections 8.3.2.1, 9.2.2 and 10.2.2.

As appropriate, specific analysis was undertaken for each group of properties prior to the determination of the ILV status. Each qualification status for every property was then technically reviewed by senior engineers to ensure an appropriate and consistent outcome was reached for all 140,000 urban residential properties in Christchurch. The results were then entered into a database before the final review by the senior technical review team and the project director.

Each of the tasks in Figure 8.5 is described in turn below:

- Section 8.3.1 discusses the regional data analysis (Task 1 in Figure 8.5);
- Section 8.3.2 discusses the local and specific data analysis (Tasks 2 and 3 in Figure 8.5);
- Section 8.3.3 discusses the determination of the ILV status (Task 4 in Figure 8.5); and
- Section 8.3.4 discusses the review and quality assurance and control processes that have been applied (Tasks 5, 6 and 7 in Figure 8.5).

8.3.1 Regional Data Analysis (Task 1 in Figure 8.5)

In order to understand regional visual patterns and potential sources of error relevant to the assessment of liquefaction vulnerability and change in vulnerability for a cluster of properties in each information pack the information sources listed below were reviewed at a regional scale.

For each information source, the engineer undertaking the assessment would note relevant information that was not always evident in the zoomed in views provided in the ILV assessment packs.

The information sources reviewed in the regional data analysis included:

- **Land damage observations and estimated PGA for the main CES earthquakes** – These maps (shown in Figure 3.6) were used to investigate the correlation between the event specific land damage observations relative to the estimated event specific groundwater levels and estimated PGA for each event. Typical questions that would be considered when reviewing these maps were:
  - How do the land damage observations relate to the estimated PGA values experienced during the earthquake sequence within the area of the data pack?
  - Given the distribution of the seismic monitoring stations, what level of certainty is associated with the estimated PGA? That is, are the PGA contours rapidly changing or gradually changing in the area of the data pack? In areas of higher uncertainty, does this uncertainty help to explain the observed land damage with reference to the estimated LSN values at the CPT locations within the area being assessed in the data pack?
  - Does the area regionally have sufficient ground surface subsidence such that the liquefaction vulnerability may have materially increased as a result of the CES? Conversely, does the area generally have less than 0.1m of ground surface subsidence so that the liquefaction vulnerability of the area is unlikely to have materially increased as a result of the CES?
- **Observed ground cracking and horizontal ground surface movement** – These maps were used to understand how the magnitude and direction of horizontal land movements correlate with observed land damage and topography. Typical questions that would be considered when reviewing these maps were:
  - Was the observed ground surface subsidence within the pack area influenced by lateral spread?
  - Was the observed land damage within the pack area predominantly caused by lateral spreading?
  - Would there have been land damage in the main CES events if lateral spreading had not occurred, and if so, does this help explain the calculation of low LSN values even though

there has been observed land damage (refer to Section 8.4 for further discussion on understanding the mechanisms causing the observed land damage)?

- **Ground surface elevation -** These maps were used to look for topographic transitions that could indicate changes in the underlying geology and geomorphology over the area being assessed. Typical questions that would be considered when reviewing these maps were:
  - Does the data pack cover an area which transitions over an old terrace feature?
  - Is the data pack within a low-lying part of Christchurch which could be affected by elevated groundwater levels?
  - Are the CPTs located at an elevation that is representative of the elevation of property?
- **Geological and soil maps –** These maps help identify if there are different geological units mapped in the surrounding area that are susceptible to liquefaction. Typical questions that would be considered when reviewing these maps were:
  - What is the liquefaction susceptibility of the geological units which are mapped in the area covered by the pack?
  - Does the pack cover an area which transitions from one mapped geological unit to another?
- **Groundwater surface elevation maps** – These maps were used to understand the regional variation in the groundwater surface and the effect this may have on liquefaction vulnerability. Typical questions that would be considered when reviewing these maps were:
  - Is the groundwater surface shallow enough for the area to be potentially materially vulnerable to liquefaction damage? Conversely, is the groundwater surface too deep for the area to be materially vulnerable to liquefaction damage?
  - Is the groundwater surface very shallow such that the LSN parameter is potentially hypersensitive to very small changes in the depth of the groundwater surface?
- **Total change in elevation and liquefaction related ground surface subsidence** – These maps (shown in Figure 3.8) were used to look for patterns in the change in ground surface elevations that may not be obvious when zoomed in. Typical questions that would be considered when reviewing these maps were:
  - Are there areas of higher localised subsidence within the area covered by the pack which may indicate the location of infilled stream channels?
  - Are there error bands in the LiDAR which could influence the estimated $\triangle$LSN values for each property within the data pack (as discussed in **Appendix G**)?

Note that for Stage 1 the regional maps were accessed from the CGD electronically. This enabled the assessing engineers to zoom in and out of the maps and therefore they could observe both regional and local trends. For Stage 2 the maps were available both electronically on the CGD and in large (A0) hardcopy format.

8.3.2 Local and Specific Data Analyses (Tasks 2 and 3 in Figure 8.5)

As part of the ILV assessment process for both Stage 1 and Stage 2 assessments:

- The CPT and borehole data within a pack was reviewed;
- Liquefaction triggering and liquefaction vulnerability sensitivity assessments were undertaken for each CPT;
- Each CPT and borehole and the associated liquefaction triggering and vulnerability assessments were manually assessed and classified for ILV.

These classifications were then reviewed and correlated with the local maps presented in the ILV assessment packs with reference to observations made during the regional assessment. Whenever there was doubt about the quality of the recorded land damage the observations were verified with reference to the aerial imagery that was collected following each of the four main earthquake events.

This process was followed to check that the classification of the CPT data points reconciled with the information presented in the local maps. When the classification of the CPT data points reconciled with the information in the local maps and the regional assessment observations, then the properties in the pack would have an ILV decision made in accordance with the *engineering criteria* listed in Section 2.4.

If the classification of the CPT data points did not reconcile with the information in the local maps and the regional assessment observations, then the CPTs liquefaction triggering and vulnerability analyses would be further examined to understand the reasons for the inconsistencies between the observed and predicted land performance before undertaking the ILV decisions.

Figure 8.6 is a flowchart which summarises the steps involved in this process. Further detail about each step in Figure 8.6 is provided as follows:

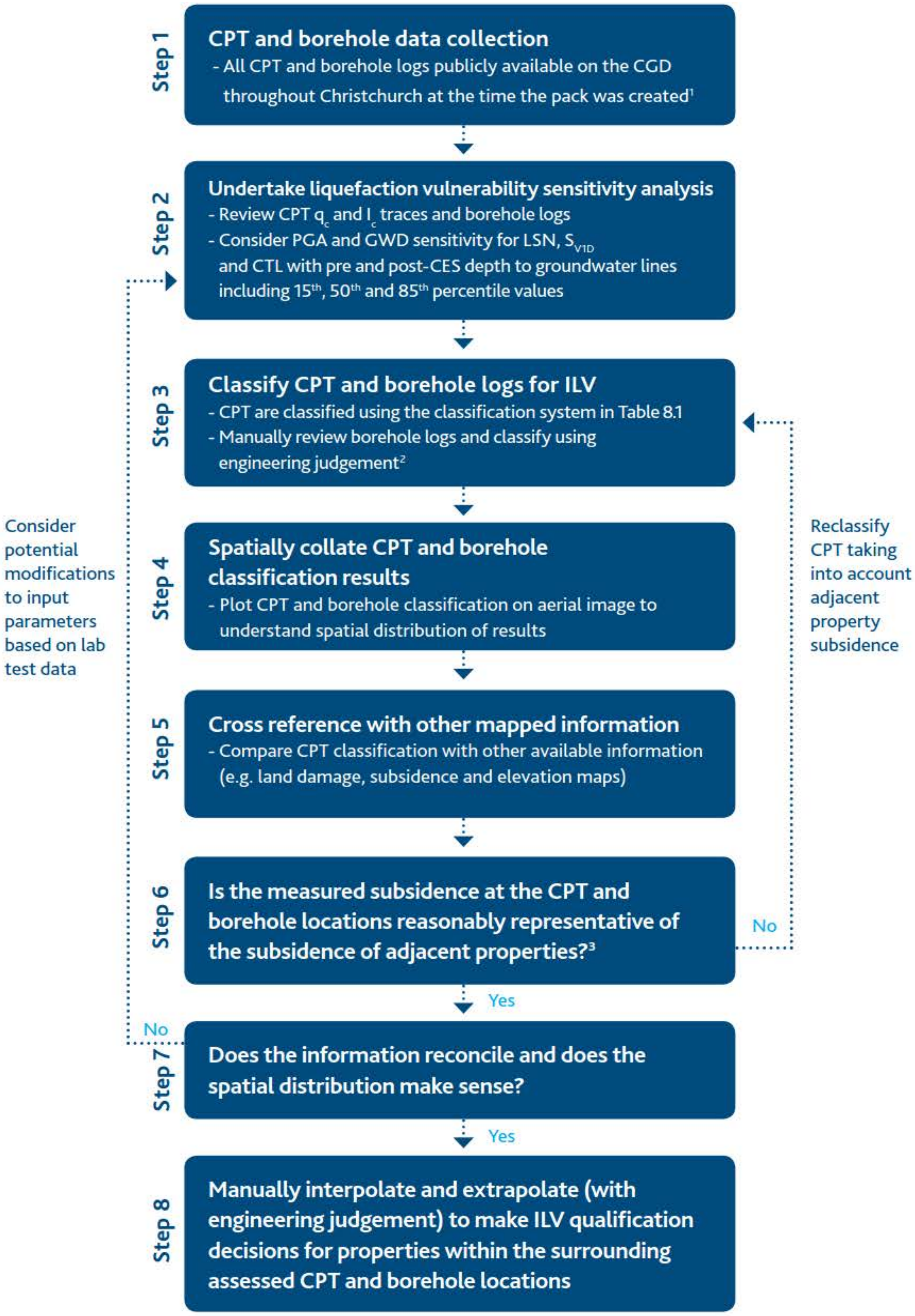
- **Step 1** – The collation of CPT and borehole data information is discussed in Section 8.3.2.1;
- **Step 2** – The liquefaction triggering and vulnerability sensitivity analyses undertaken for each CPT are discussed in Section 8.3.2.2;
- **Step 3** – The classification of CPTs and borehole logs for ILV is discussed in Section 8.3.2.3;
- **Steps 4 to 7** – The spatial collation of the CPTs and borehole classification results and correlation with the other mapped data are discussed in Section 8.3.2.4; and
- **Step 8 –** The manual interpolation of ILV qualification decisions is discussed in Section 8.3.2.5.

As part of the local and specific data analyses for each pack prior to undertaking steps 1 - 8, pre-CES aerial photography was reviewed to identify areas where the pre-CES LiDAR elevations are not representative of the actual pre-CES elevation of the property at the time of the September 2010 earthquake event. This was generally in areas of residential development where earthworks had occurred between 2003 (when the pre-CES LiDAR was flown) and September 2010.

These anthropogenic changes to the land mean that the 2003 based LiDAR data are not necessarily an appropriate representation of the pre-CES ground surface. This may result in negative subsidence in the difference DEMs (i.e. apparent uplift). To remove this error, the post-September LiDAR was used as a proxy to represent the pre-CES ground surface elevation. This removed the apparent uplift and captured the subsidence from the other main CES events (i.e. February 2011, June 2011 and December 2011).

An allowance based on engineering judgement was made during the ILV qualification to account for the likely ground surface subsidence that would have occurred in such areas during the September 2010 earthquake event. This allowance was based on a review of the subsidence in the surrounding area.

The majority of properties without an appropriate pre-CES DEM were not assessed as vulnerable (i.e. did not satisfy *Criterion 1*). Therefore, the limitations of not knowing the estimated amount of ground surface subsidence as a result of the CES for the majority of these properties was not important for ILV assessment purposes.



1 Note that the number of CPT and borehole logs available on the CGD has continued to increase throughout the time of ILV assessment. Each pack was compiled using all the information publicly available at the time the pack was created.

2 Qualitative equivalent to the quantitative CPT criteria.

3 This occurred when CPT were undertaken within the road-ways which often did not subside as much as the adjacent residential properties.

Figure 8.6: Local and specific ILV manual assessment process (refer to tasks 2, 3 and 4 in Figure 8.5).

Also while undertaking the local and specific analysis tasks, approximately 2,000 properties were identified as requiring additional geotechnical investigation data in order to proceed with the analysis and complete the ILV assessment. The decisions process for the collection of additional data is outlined in Figure 4.2. The majority of these properties were in areas where land is categorised as TC2 and there was observed land damage as a result of the CES events. As this additional geotechnical information was obtained it was analysed and incorporated into ILV assessment packs.

8.3.2.1 CPT and Borehole Data Collation (Step 1 in Figure 8.6)

Prior to being able to undertake the manual assessment of ILV the publicly available CPTs and borehole data needed to be collated. This geotechnical information was compiled by teams of science and engineering graduates into *ILV assessment packs*. Each ILV assessment pack includes all the publicly available maps listed in Section 4.4 and the CPTs and borehole logs on the CGD at the time the pack was created.

As a result of the update to the liquefaction triggering assessment methodology (Boulanger & Idriss, 2014), the Idriss and Boulanger (2014) method was applied and the ILV assessment process was started again in July 2014 (refer to the evolution of the ILV Assessment Methodology in **Appendix C**). The final Stage 1 packs were made from July 2014 onwards and the Stage 2 packs were made from January 2015 onwards. Therefore, most of the available geotechnical information has been incorporated into the ILV assessments.

The specific detail about the creation of ILV assessment packs for Stage 1 and Stage 2 are covered in Sections 9.2.2 and 10.2.2 respectively.

8.3.2.2 Liquefaction Vulnerability Assessment of CPT Data (Step 2 in Figure 8.6)

Liquefaction triggering assessment analyses were undertaken at each CPT location. The results were examined to develop an understanding of the ground profile at each CPT location, the soil layers which are likely to liquefy at M6 0.3g levels of earthquake shaking and the whether or not the land (based on the interpreted soil profile) is likely to be vulnerable to liquefaction related damage.

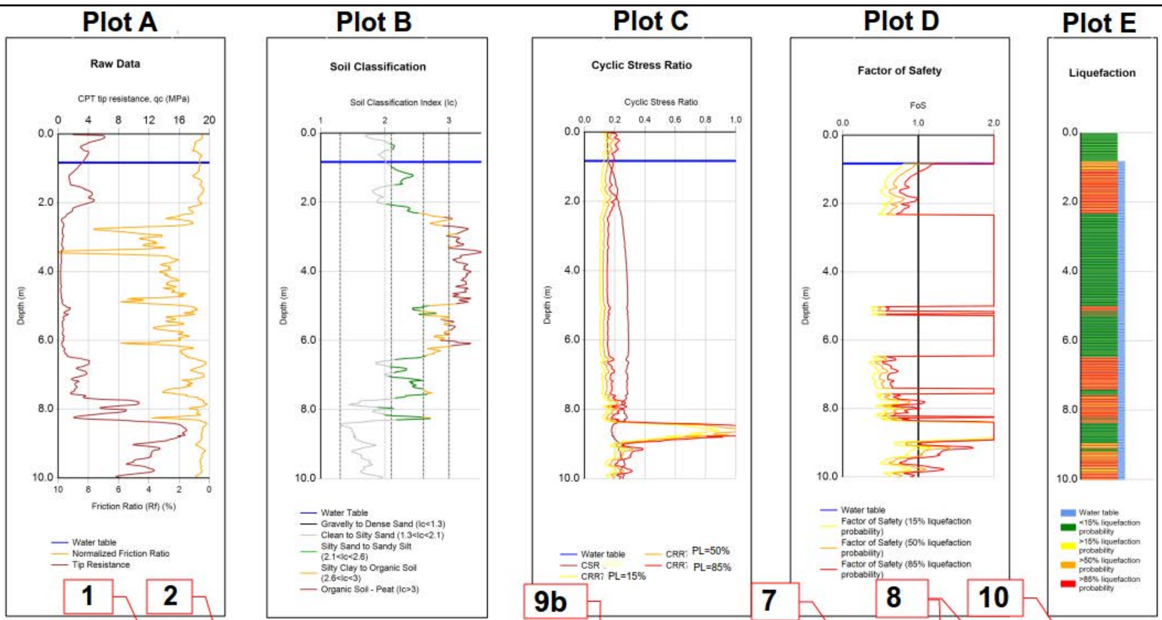
Liquefaction vulnerability parameters were estimated for the Cumulative Thickness of Liquefaction (**CTL**), S_{V1D} and LSN using the median post-CES depth to groundwater. Sensitivity analyses of these parameters for PGA and depth to groundwater were also undertaken for the CTL, S_{V1D} and LSN liquefaction vulnerability parameters to further inform whether or not the land at the CPT location is likely to be vulnerable to liquefaction. The use of these sensitivity analyses in the ILV Assessment Methodology is discussed in detail in the latter parts of this section.

A standard CPT liquefaction triggering and vulnerability analysis comprising two output pages was created. It summarised the most pertinent information and was included for each CPT in the information packs. Copies of these summary pages are given in the Stage 1 and Stage 2 worked examples included in the **Worked Example Material**.

Screenshots showing examples of these summary CPT-based liquefaction triggering and vulnerability analyses are provided below to highlight pertinent features. The bottom of the first summary page (refer to Figure 8.7) and a screenshot of the top of the second summary page (refer to Figure 8.8) provide the general information.

- The general information section includes:
  - **1** – CGD ID number;
  - **2** – The date on which the CPT was undertaken;
  - **3** – The drilling company;
  - **4** – The make and model of the rig used to push the CPT;

- **5 –** The supervising company (i.e. the engineering firm that supervised the investigation);
- **6** – The total depth of the CPT;
- **7** – The depth to which the hole was predrilled (if any);
- **8** – The assumed predrilled soil parameters (if required);
- **9a and 9b** – Pre-CES and post-CES depth to the median groundwater surface respectively;
- **10** – The assumed unit weight of the soil;
- **11** – The value of site specific Fines Content Correlation Coefficient (C_{FC}) (discussed in Section 3.4);
- **12** – The I_c cutoff limit applied in the liquefaction triggering assessment;
- **13a and 13b** – LSN values estimated for both pre-CES and post-CES ground surface levels respectively. These are estimated based on the median groundwater condition assuming a P_L value of 15% (P_L is discussed in Section 3.4 and **Appendix A**);
- **14** – The ΔLSN values as a result of the subsidence caused by the CES based on the change to the depth to the median groundwater surface.



	CPT Name	CGDID	Investigation Date	Event and PGA	Magnitude	PGA (g)	GWD (m)	Trigger Method	Settlement Method	Pre-drill Depth (m)	Qc (MPa)	Fs (MPa)	γ (kN/m³)
INPUT	STA-POD02-CPT10TT	15566	25/01/2013	User Specified	6	0.3	0.8	BI2014	ZRB	0.02	2	0.01	18

	Exceedance Probability		S - Calculated Settlement (mm)	CTL - Cumulative Thickness of Liquefaction (m)	LPI - Liquefaction Potential Index	LSN - Liquefaction Severity Number	CT - Crust Thickness (m)	LPI Ishihara
OUTPUT	PL=	15%	104	4.4	13	36		14
	PL=	50%	97	4	9	33		9
	PL=	85%	81	3.3	6	26		5

Figure 8.7: Example of the first summary page of the CPT-based liquefaction triggering and vulnerability sensitivity analysis for M6 0.3g levels of earthquake shaking at the median depth to groundwater levels.

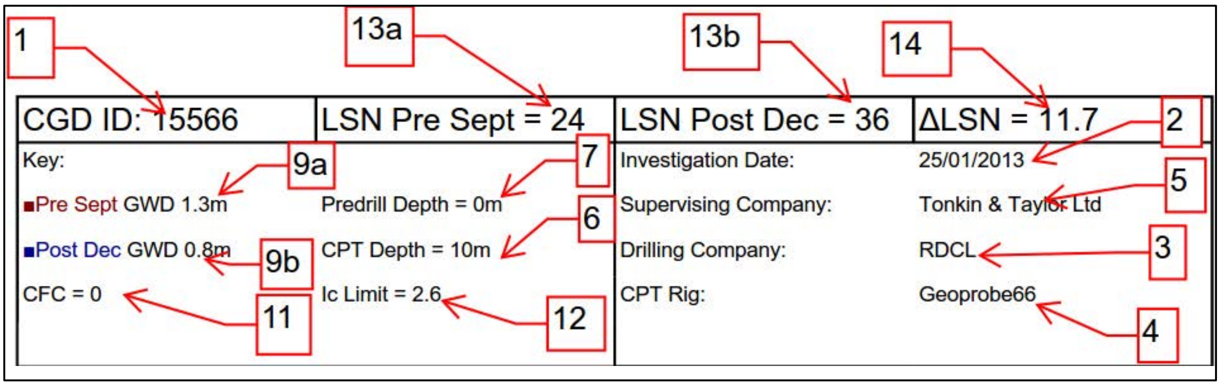


Figure 8.8: Example of information section from the top of the second page of the CPT-based liquefaction vulnerability sensitivity assessment analysis.

Plots A to E in Figure 8.7 present the results of the liquefaction analysis with depth over the top 10m of the soil profile. On all of these plots the blue line indicates the groundwater level assumed in the analysis. Each plot is described in turn as follows:

- **Plot A –** This plot shows the raw data collected from the CPT. The red line shows the q_c **in** MPa, and the yellow line shows the sleeve friction (**f_s**) as a ratio of the tip resistance (**R_f**). The CPT test data are typically collected at 10 to 20mm intervals, giving an effectively continuous measurement of the soil profile with depth.
- **Plot B –** This plot shows the I_c which is estimated based on the normalised q_c and f_s based on the iterated results presented by Robertson & Wride (1998). The I_c parameter can be used to assess the behaviour of the soil, and whether it responds as a fine grained or coarse grained material. The higher the I_c parameter, the more fine grained the material behaviour is.

  The dashed black vertical lines show various ranges of I_c value that are typically associated with different soil types. The I_c value is plotted with a different colour for each typical soil type, as explained in the legend below the plot. For the typical liquefaction analyses in this report, where the estimated I_c exceeds 2.6 the soil is assessed to be too fine grained to liquefy (refer to Section 3.3). In some cases a sensitivity analysis is undertaken to assess the effects of changing this I_c cut off value.
- **Plot C –** The Cyclic Stress Ratio (**CSR**) is a normalised parameter that represents the cyclic stress predicted to occur in the soil for a given earthquake scenario to the vertical effective stress, as a ratio of the vertical effective stress in the soil. The CSR parameter represents the "demand" side of the liquefaction triggering analysis.

  The CRR is an estimate of the cyclic stress above which liquefaction triggering is predicted to occur. The CRR parameter represents the "capacity" side of the triggering analysis. The CRR is estimated using the Boulanger and Idriss (2014) empirical liquefaction triggering from the case history database, which includes significant uncertainties and natural variability (discussed further in **Appendix A**). To help understand this uncertainty, three different CRR profiles are shown on the plot, representing 15%, 50% and 85% certainty of the cyclic stress ratio above which liquefaction triggering is expected from the case history database. As discussed in Section 3.4, this is referred to as the P_L parameter in the Boulanger and Idriss (2014) liquefaction triggering method.
- **Plot D –** The Factor of Safety (**FS**) against liquefaction triggering is based on the ratio of the "capacity" to the "demand" (i.e. the CRR to the CSR). Three different FS profiles are plotted, corresponding to different levels of certainty that liquefaction triggering will occur at a specified level of earthquake shaking and depth to groundwater based on the empirical case

history database. If soils are assessed as being too fine-grained to liquefy (i.e. I_c value greater than the cutoff value, which is typically taken as I_c=2.6), then they are plotted with FS > 2.

- **Plot E -** This plot shows a simplified profile of results of the liquefaction analysis, with the different colours representing different levels of probability that liquefaction triggering will occur.

Sensitivity of the CTL, S_{V1D} and LSN liquefaction vulnerability parameters to PGA and depth to groundwater for the second page of the CPT liquefaction vulnerability assessment analyses are shown in Figure 8.9 and Figure 8.10.

An example of the sensitivity to varying PGA section of the summary CPT analysis page is shown in Figure 8.9. As annotated, the bold blue and red curves on each of the graphs represent the sensitivity to PGA based on the pre-CES and post-CES median depth to groundwater surfaces respectively. The light blue and light orange curves represent the same groundwater conditions but estimated using the 50th and 85th P_L values. The horizontal dashed line is the LSN = 16 indicator value for material vulnerability (discussed in Section 7.3).

The CTL and S_{V1D} sensitivity to PGA curves represent the same variables as annotated on the LSN sensitivity to PGA curve.

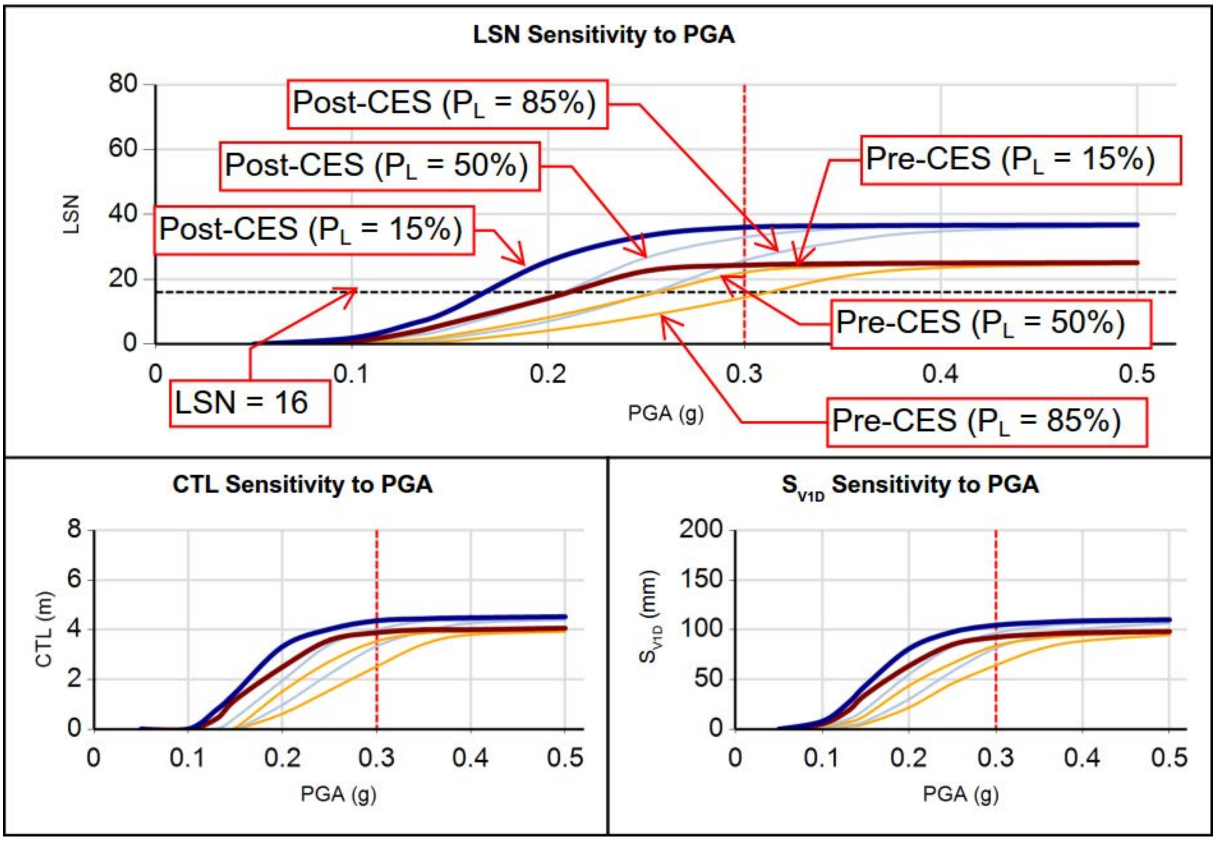


Figure 8.9: Example screenshot of the second page of the CPT-based liquefaction vulnerability analyses for a CPT showing the sensitivity of the estimated liquefaction vulnerability parameters to PGA for a M_W 6.0 earthquake.

The LSN sensitivity to PGA curve can be used in the following ways:

- **Assess the LSN and ΔLSN values at levels of ground shaking <u>up to</u> M6 0.3g** – The maximum LSN value occurs at the highest considered levels of earthquake shaking (i.e. M6 0.3g) and at lower levels of PGA, the LSN values decrease. However, the maximum ΔLSN does not always occur at the highest considered levels of earthquake shaking (i.e. M6 0.3g) and often can occur at lower levels of PGA. In accordance with *Criterion 2* (Section 2.4) for the assessment of ILV, the change in liquefaction vulnerability is considered at <u>up to</u> M6 0.3g levels of earthquake shaking.

The LSN sensitivity to PGA curves make this assessment practically possible based on manual assessment of the PGA sensitivity analysis. This is important in instances where the ΔLSN at 0.3g is less than 5 but at levels of earthquake shaking lower than 0.3g the ΔLSN is greater than 5. This phenomenon has been referred to as "stress change" in this report. An example of a CPT with stress change is shown in Example J8 in **Appendix J** and is described in further detail in Section 8.3.2.3.

- **Reconcile the observed land performance through the CES relative to the estimated earthquake shaking with the estimated liquefaction vulnerability** - By correlating the land performance observations through the CES relative to the estimated earthquake shaking for the main CES events, with the LSN curves can be used to assist in evaluating whether the LSN parameter appropriately estimates the liquefaction vulnerability for the site.

  For example, with reference to Figure 8.9 if the estimated ground shaking during the September 2010 earthquake was 0.2g in the location where the CPT was undertaken, the assessing engineer would consider whether or not the pre-CES LSN value of 14 reconciles with the land damage observations. For an estimated pre-CES LSN value of 14 none-to-minor land damage would be expected.

  If the recorded land damage observations in the September 2010 earthquake were none-to-minor, the assessing engineer would conclude that the LSN value of 14 is appropriately predicting the observed performance for this particular event. If a similar assessment demonstrated a good fit for each of the other CES earthquakes, the assessing engineer would conclude that the LSN tool as a whole was providing a good fit for the assessment of ILV. Therefore they would have confidence in using the predicted M6 0.3g LSN value at that CPT location as an indicator for material liquefaction vulnerability.

  However, if the recorded land damage observations in the September 2010 earthquake were moderate-to-severe, the assessing engineer would conclude that the LSN value of 14 was probably not appropriately predicting the observed performance for this particular event. If a similar assessment demonstrated a poor fit for each of the other CES earthquakes, the assessing engineering would conclude that the LSN tool as a whole was probably not appropriately predicting the observed performance for that site. Unless laboratory specific data to modify the liquefaction triggering inputs (i.e. I_c-cutoff and C_{FC}) would improve the calibration, then the LSN tool could not be used for the assessment of ILV at that location. When the LSN tool could not be used the other liquefaction vulnerability indicators listed in Section 7.2 would be considered. Generally, when these situations occurred in the Stage 1 process, the property was assigned Stage 2 status and reassessed using the detailed processes outlined in Section 10.

  These assessments at each CPT location were undertaken with consideration of the uncertainty there may be associated with the information available. This is particularly important with respect to the estimated levels of earthquake shaking.

- **Understand the uncertainty in the LSN calculation at M6 0.3g levels of earthquake shaking -** By comparing the PGA sensitivity curves for the 15th, 50th and 85th P_L parameters at M6 0.3g an assessment of the uncertainty with respect to liquefaction triggering and the LSN parameter can be made.

  In the example in Figure 8.9, at M6 0.3g levels of earthquake shaking the LSN curves for the 15th and 50th P_L input parameters are indicating similar values which provides a higher level of certainty in the assessment of liquefaction vulnerability at this location at these earthquake shaking. However, if there was a significant difference between the values of LSN represented by the 15th and 50th P_L curves at M6 0.3g then there would be a lower level of certainty in the assessment of liquefaction vulnerability at this location. This could help to explain areas where no land damage was observed during the CES when higher LSN values were estimated at a P_L of 15% but significantly lower values were estimated at a P_L of 50%.

The CTL and S_{V1D} sensitivity to PGA curves were typically used to further understand the proportion of the upper 10m of the soil profile predicted to liquefy at different levels of earthquake shaking, and the associated accumulation of volumetric strain which provides an idea of the volume of excess pore water that is likely to be generated. This provides an indication of the differential ground surface settlement that can be expected.

Another example is that there would be a higher level of confidence in the ΔLSN representing a real increase in liquefaction vulnerability as a result of the ground surface subsidence caused by the CES if the ΔCTL value is high and the ΔS_{V1D} value was also high. This indicates the contribution to ΔLSN is coming from a significant change in crust thickness.

Conversely, if the ΔLSN value is high at 0.3g but the ΔCTL and ΔS_{V1D} values are low, then this indicates that the contribution to the ΔLSN parameter is occurring in a relatively thin layer of material which may be close to the ground surface and the LSN parameter may be over-predicting the change in vulnerability to liquefaction due to ground surface subsidence. This phenomenon has been referred to as “hypersensitivity to ΔLSN” in this report. An example of a CPT with hypersensitivity of ΔLSN is shown in Example J10 in **Appendix J** and is discussed further in Section 8.3.2.3.

An example of the sensitivity to varying the depth to the groundwater surface (**GWD**) is shown in Figure 8.10. As annotated, the bold blue and red lines represent the 50th percentile GWD for the post-CES and pre-CES ground surface levels respectively. The light blue and light orange lines represent the 15th and 85th percentile GWD for post-CES and pre-CES ground surface levels respectively. It is important to note that the percentile GWD lines differ from the P_L curves which are discussed with reference to the PGA sensitivity curves in Figure 8.9.

It should be noted that these analyses are for a different CPT than the one presented in Figure 8.7, Figure 8.8 and Figure 8.9. This CPT has been chosen because it clearly shows the separation between the different GWD lines as a result of the ground surface subsidence caused by the CES.

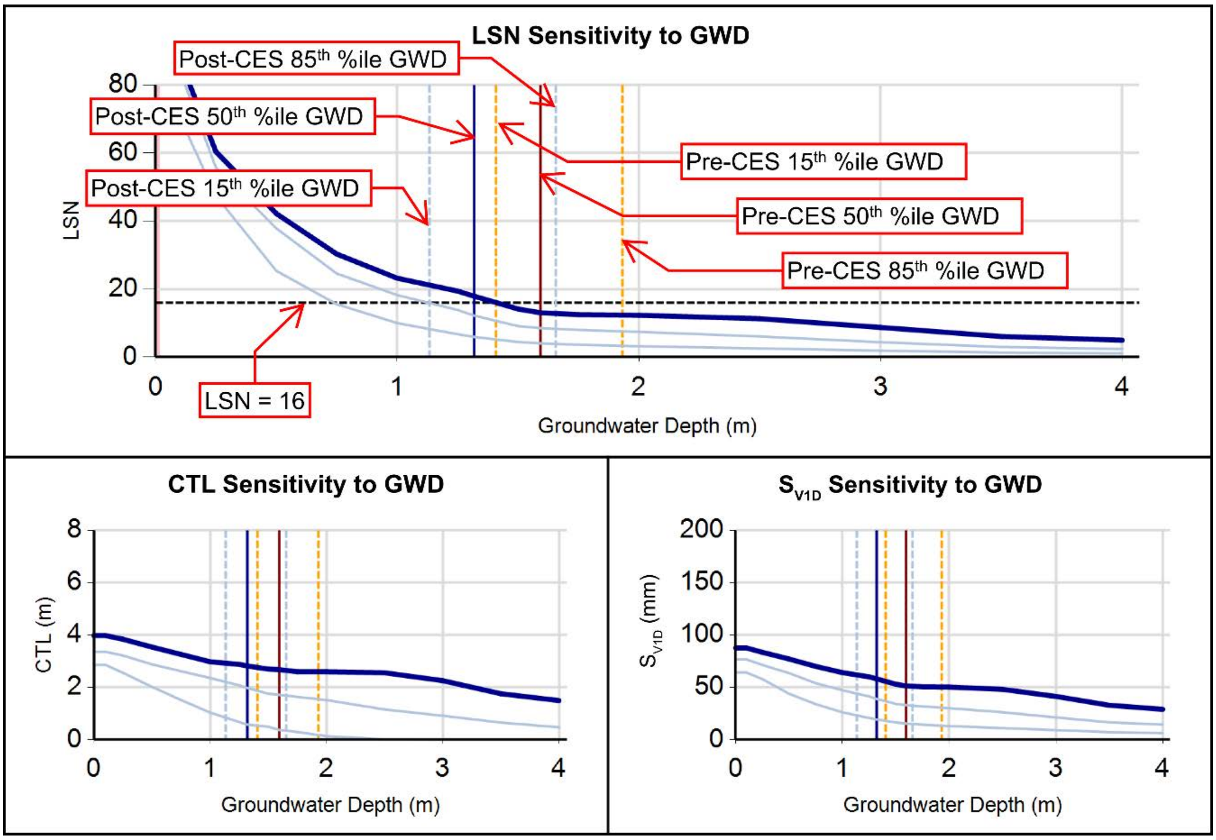


Figure 8.10: Example screenshot of the second page of the liquefaction vulnerability assessment analysis for a CPT showing the sensitivity of the liquefaction vulnerability parameters to GWD at M6 0.3g levels of earthquake shaking for a P_L of 15%.

The LSN sensitivity to GWD curve was used in the following ways:

- **Calculating the mean ΔLSN -** A quick assessment of the mean ΔLSN can be made by averaging the associated ΔLSN values for the difference between the pre-CES and post-CES LSN values for the 15th, 50th and 85th percentile GWD.

  The method of assessment of the mean ΔLSN is demonstrated in Example J3 in **Appendix J** and is discussed further in Section 8.3.2.3. The concept of median and mean LSN and ΔLSN is discussed in detail in Section 7.5 and **Appendix H**.

- **Identifying the predrill component -** In some locations, pre-drilling was undertaken at investigation locations, to safely get past underground services. This means that the CPT data are missing for the important shallow soil layers, typically down to a depth of between 0.8 to 1.5m.

  Example J6 in **Appendix J** shows a predrilled CPT analysis which is affecting the LSN calculation and how this is identified in the LSN sensitivity to GWD curve. The effect of predrill on the calculation of LSN and how this was managed is discussed further in Section 8.3.2.3.

- **Understanding the liquefaction vulnerability of the ground profile -** The sensitivity to GWD curves were useful to build understanding of which components of the ground profile are contributing to liquefaction vulnerability at M6 0.3g.

  Flat portions of the curves indicate either denser or siltier material with a higher resistance to liquefaction whereas steeper portions of the curves indicate material which is either sandier or looser and therefore has a lower resistance to liquefaction. Prior to considering the location of the groundwater in the CPT it was useful to use these curves to develop understanding of the predicted liquefaction resistance of the sub-surface ground profile.

- **Sensitivity to GWD -** Building on the interpretation discussed above, by overlaying the estimated GWD onto the LSN curve the sensitivity of the estimated LSN value to uncertainty in the GWD could be quickly assessed.

  If there was uncertainty in the estimated GWD but the slope of LSN sensitivity to GWD curve was relatively flat then it showed that the estimated LSN was not sensitive to uncertainty of the estimated GWD.

  However, if the LSN sensitivity to GWD curve is sloping then the estimated LSN is sensitive to uncertainty in the estimated GWD and further consideration needs to be given considering whether the soil profile at that location is classified as not vulnerable or materially vulnerable to liquefaction damage. This is particularly important if the estimated median and mean LSN values are near the indicator value of 16 (refer to Section 7.3).

Similar to the PGA sensitivity curves, CTL and S_{V1D} sensitivity to GWD curves represent the same variables as annotated on the LSN sensitivity to GWD curve. These additional parameters assist the assessing engineer to better understand potential reasons for low or high estimated LSN values. As discussed above, they are particularly important if the estimated LSN values are not consistent with the observed land performance throughout the CES.

8.3.2.3 Classification of CPTs and Borehole Logs for ILV (Step 3 in Figure 8.6)

The CPTs were classified using the categories provided in Table 8.1 in order to assess each CPT location for ILV. When there was insufficient density of CPT data the borehole logs were assessed using engineering judgement to provide a qualitative equivalent to the quantitative CPT classifications provided in Table 8.1.

Table 8.1: Classifications used for CPT and borehole review

Symbol	Description	Example
✓	Post-CES median LSN at M6 0.3g greater than or equal to 16 and ∆LSN greater than or equal to 5	J1
×	Post-CES median and mean LSN at M6 0.3g less than or equal to 14; or Post-CES median and mean LSN at M6 0.3g between 14 and 16 and ΔLSN less than 5.	J2
Mean✓	Post-CES mean LSN at M6 0.3g greater than or equal to 16 and mean ∆LSN greater than or equal to 5	J3
NC	Post-CES median and mean LSN at M6 0.3g greater than or equal to 16 and ∆LSN less than 4.	J4
M	Post-CES LSN at M6 0.3g greater than or equal to 16 and ∆LSN between 4 and 5; or Post-CES median and mean LSN at M6 0.3g between 14 and 16 and ∆LSN greater than or equal to 5	J5.1 J5.2
PD	Predrill on CPT affects LSN result	J6
?	CPT data quality is questionable	J7
SC	Stress Change – ∆LSN at M6 0.3g is less than 5; but ∆LSN is greater than or equal to 5 for any M6 PGA less than 0.3g where the corresponding post-CES LSN is greater than 16	J8
S	CPT depth is less than 5m	J9
✓h	LSN > 16 and ΔLSN > 5 at M6 0.3g but LSN is hypersensitive to very small changes in depth of groundwater (typically where groundwater is shallower than 0.5m)	J10
GW issue	Significant difference between the mean and median groundwater levels noted	J11

In addition to assessing the liquefaction vulnerability of soil layers, the borehole logs were particularly useful for identifying the depth and thickness of any gravel layers that were too dense for adjacent CPT to penetrate, and therefore justify using shorter CPT for assessing liquefaction vulnerability.

Table 8.1 shows the symbology that was used to classify the CPTs and borehole logs. The CPTs were classified with reference to the summary CPT analysis pages described in Section 8.3.2.2. Where applicable, the borehole logs were qualitatively assessed using the same classification system. Annotated examples of each of the classifications used in the CPT review are provided in **Appendix J**.

Each of the classifications in Table 8.1 are discussed in turn as follows:

- **CPT classified as ✓** - These CPTs have median LSN and ΔLSN values of greater than or equal to 16 and 5 respectively at levels of earthquake shaking of M6 0.3g. That is, based on the CPT-based liquefaction vulnerability assessment, the point location it represents would potentially qualify for ILV.
- **CPT classified as ✗** - These CPTs have either median or mean LSN values of less than 14 at levels of earthquake shaking of M6 0.3g or median and mean LSN values of between 14 and 16 and ΔLSN less than 5. That is, based on the CPT-based liquefaction vulnerability assessment, the point location they represent would be unlikely to qualify for ILV as it is unlikely that it would satisfy *Criterion 1*.
- **CPT classified as mean✓** - These CPTs have mean LSN and mean ΔLSN values of greater than or equal to 16 and 5 respectively at levels of earthquake shaking of M6 0.3g. That is, based on the CPT-based liquefaction vulnerability assessment, the point location they represent would qualify for ILV.

  The mean ΔLSN can be estimated by averaging the difference between pre-CES and post-CES for the 15^{th}, 50^{th} and 85^{th} percentile GWD. This process is demonstrated in CPT example J3. The concepts of mean and median LSN are introduced is discussed in Section 7.5 and in further in detail in **Appendix H**.
- **CPT classified as NC (i.e. No Change)** – These CPTs have estimated median or mean LSN values of greater than or equal to 16 and estimated median or mean ΔLSN values of less than 4 at levels of earthquake shaking of M6 0.3g. That is, based on the CPT-based liquefaction vulnerability assessment, the point location they represent would be unlikely to qualify for ILV because it is unlikely that it would satisfy *Criterion 2*.
- **CPT classified as M (i.e. Marginal) –** These CPTs have estimated median or mean LSN values of greater than or equal to 16 and ΔLSN between 4 and 5 or estimated median or mean LSN values of between 14 and 16 and ΔLSN greater than 5. That is, based on the CPT-based liquefaction vulnerability assessment, the point location the CPT represents would not qualify for ILV however it does qualify for one of the two *engineering criteria* and is close to qualifying on the other.
- **CPT classified as PD (i.e. Pre-Drill) –** These CPTs are those where prior to undertaking the CPT, the ground was pre-drilled in order to safely clear any buried services. A CPT was only classified as PD if the predrilled component was affecting the zone where the change in the depth to groundwater was occurring.

  If the predrilled component has no effect on the calculation of LSN at the pre- and post-CES estimated GWD because the GWD is below the predrill depth, then the CPT is not classified as PD and one of the other applicable CPT classifications is used.

  As a default, the estimated LSN value assumed a low strength (readily liquefiable) material is present over the predrill depth. This may over-predict the consequences of liquefaction at the site, which may make the results less realistic.

Assuming readily liquefiable material over the predrilled portion of the CPT can be a useful assumption because it provides an appropriate upper bound for the assessment of ILV. That is, if the change in GWD is occurring in part or all of the predrilled portion of the CPT and the estimated LSN is less than 16, then the CPT can be classified as ×. Alternatively, if the estimated LSN is greater than 16 but the ΔLSN value is less than 5 then the CPT can be classified as NC.

As shown in Example J6 in **Appendix J**, to indicate that a CPT has been predrilled, the portion of the LSN sensitivity to GWD which has been predrilled is highlighted in red.

- **CPT classified as ? (i.e. questionable result) –** These CPTs are those where the CPT data are of questionable quality. This was generally identified when a single point location the estimated LSN values (and the other CTL and S_{V1D} parameters) were significantly different from the surrounding estimated LSN values.

  In order to understand the reasons for the questionable result, the raw CPT data was investigated. Common reasons for questionable CPTs were data entry errors such as the use of incorrect units for f_s, negative f_s or incorrect coordinates being supplied for the CPT when it was uploaded to the CGD (i.e. the location address on the PDF of the CPT trace was different from the supplied coordinates). Some of the other common problems with CPT data are discussed in De Pascale et al. (2015).

- **CPT classified as SC (i.e. Stress Change) –** For these CPTs the ΔLSN value is less than 5 at M6 0.3g levels of earthquake shaking but the △LSN at is greater than or equal to 5 for any M6 PGA less than 0.3g where the corresponding post-CES LSN is greater than 16.

- **CPT classified as S (i.e. Short) –** This classification was used when the CPT has been terminated at depths less than 5m[7]. A CPT may have been terminated at depths shorter than 10m because it was used for a specific purpose (e.g. 900 CPT in the CGD are less than 3m deep and come from Orion Group who undertook a large number of investigations prior to the CES for the installation of power poles). Alternatively some CPT are short because the CPT probe encountered soils that were too dense to penetrate (e.g. dense gravel or sand layers).

  While the short CPTs would not be able to give a reliable indication of the potential liquefaction vulnerability of the site, they could still provide valuable insight into the liquefaction vulnerability of the near surface soil layers where the change in groundwater was occurring. Therefore they could potentially give a good indication of the ΔLSN value as a result of ground surface subsidence.

  Alternatively, if the CPT was terminated because it encountered a dense gravel layer, it could be reasonably assessed for ILV based on the shorter length of CPT data available. This was only possible if the thickness and competency of the gravel layer could be confirmed with adjacent borehole data.

- **CPT classified as ✓h (i.e. hypersensitivity to change in GWD) –** This classification was used when the LSN value is greater than 16 and the ΔLSN value is greater than 5 at M6 0.3g levels of earthquake shaking but the calculation of LSN was very sensitive to small changes in the depth to groundwater. That is, based on the CPT-based liquefaction vulnerability assessment, the point location they represent would qualify for ILV but the LSN calculation may be over-estimating liquefaction vulnerability and the change in liquefaction vulnerability.

[7] If a CPT was judged to be terminating into thick dense non-liquefying gravels and refusing, it was unlikely that there would be contribution to LSN from soil layers below the dense gravels. This judgement was applied with reference to nearby borehole data to confirm the thickness of any gravel layers. If the CPT appeared to have terminated without refusal on a dense gravel layer, then consideration would be given as to whether or not the LSN value could be higher (i.e. influence *Criterion 1*) but generally extra length of CPT would not influence ΔLSN (i.e. influence *Criterion 2*). As necessary additional CPTs were undertaken adjacent to these sites (refer to Figure 4.2).

This hypersensitivity to shallow groundwater is attributable to the depth weighted factor in the LSN calculation from approximately 0 to 0.5m below the ground surface. Therefore, this occurs at groundwater depths of less than 0.5m and is characterised by steep spikes in the LSN sensitivity to groundwater depth curve. This results in estimated ΔLSN values of greater than 5 for relatively small estimated ground surface subsidence (e.g. approximately 0.1m) which may not necessarily be representative of material change in liquefaction vulnerability.

- **CPT classified as GW issue (i.e. Groundwater issue) –** This classification was used for those CPTs where there was a significant difference between the 15th and 85th percentile groundwater lines and the 50th percentile groundwater lines. This occurred in areas where the median groundwater model differed significantly from the median surrogate groundwater model. Further detailed information about the median and surrogate median groundwater models is summarised in Section 5.5 and discussed detail in van Ballegooy et al. (2014a).

As appropriate these classifications could be combined to provide further information. Common examples of this include:

- **PD✗ -** that is CPT is predrilled but would not qualify for ILV based on the CPT-based liquefaction vulnerability assessment; or
- **M✓ -** that is CPT is marginal but is very close to qualifying for ILV based on the CPT-based liquefaction vulnerability assessment. An example of M✓ and M✗ are provided as examples J5.1 and J5.2 respectively in **Appendix J**.

8.3.2.4 Spatial Collation of the CPT and Borehole Classification Results and Correlation with the other Mapped Data (Steps 5, 6 and 7 of Figure 8.6)

Following the classification of the CPT summary outputs for each pack, the CPT and borehole classifications were spatially collated on to an aerial image to understand the distribution of the available data. The classified CPT and borehole data were then cross-referenced with the other mapped information such as ground surface elevation, land damage observations for each of the main CES earthquakes, ground surface subsidence and depth to groundwater surfaces.

Due to space constraints on properties CPTs and boreholes were often undertaken within the road ways. In some cases the road ways did not subside as much as the adjacent residential properties. Where this occurred it was necessary to consider whether or not manual adjustments are required to ensure the classification reflects the ground surface subsidence and hence the increase in liquefaction vulnerability which has occurred on the adjacent residential properties (refer to Section 8.2). In these cases the interpolated ΔLSN values for the properties were extracted from the automated ILV model and used to inform appropriate allowances for ΔLSN in such cases.

If the cross-referenced CPT classifications reconciled with the land performance observations (i.e. observed land damage relative to the estimated levels of earthquake shaking, estimated ground surface subsidence and elevation) and the spatial distribution made sense then the property progressed to the next step. If it did not reconcile the property was held back for further detailed review and potential modifications to the input parameters for the liquefaction triggering and vulnerability analyses if supported by laboratory test data (i.e. the Stage 2 process).

8.3.2.5 Manual Interpolation for ILV Qualification Decisions (Step 8 of Figure 8.6)

Engineering judgement was then applied to manually interpolate and extrapolate the CPT and borehole classifications onto the adjacent properties. This task was undertaken with reference to the LSN interpolation model which is described in Section 8.2.

The results from the automated model were not accepted where the information under consideration indicated this was appropriate. For example, the automated model could not interpolate across geological and topographic transitions which were apparent once reconciled with the land damage observations. In such cases, manual adjustments to the interpolation results would be made.

8.3.3 Determine the ILV status (Task 4 in Figure 8.5)

Following the completion of Tasks 1 to 3, Task 4 (in Figure 8.5) was to apply engineering judgement to determine whether or not a property would qualify for ILV in accordance with the *engineering criteria* set out in Section 2.4, by marking the property with either a ☑ or a ☒ as shown in the worked examples summarised in Sections 9.3 and 10.3 and included in the **Worked Example Material**. In order to qualify for ILV the engineer undertaking the assessment would need to have determined that, on the balance of probabilities, the property satisfied both *engineering criteria*.

8.3.4 Internal Review Processes (Task 5, 6 and 7 in Figure 8.5)

The internal review process covers Tasks 5, 6 and 7 in Figure 8.5. Each of these tasks are addressed in turn as follows:

- **Task 5** involved the technical review of each of the ILV decisions. This review was undertaken by senior geotechnical engineers with extensive experience working with the liquefiable soils in the Christchurch area. Each decision was reviewed and feedback was provided to the engineer who undertook the ILV assessment. This step was critical to ensure consistency of outcomes and that the assessors considered all relevant information.
- **Task 6** involved entering the ILV qualification status for each property into a geospatial database and finalising the ILV assessment. The data entry ILV decision for each property was also geospatially checked with the decisions shown on the datapacks. This was important to ensure that there were no data entry errors.
- **Task 7** involved a final review by senior geotechnical engineers and the project director. Each ILV assessment for each property was geospatially reviewed with reference to the surrounding ILV decisions. ILV decisions that appeared to be outliers (i.e. inconsistent with surrounding decisions) were held back for further analysis. This step was critical to ensure that the results were both consistent and explainable. The completion of this task was sign off and authorisation by the project director on behalf of T+T.

8.3.5 Additional Quality Control Processes

Further to the internal review processes outlined above, additional quality control processes were built into the Stage 1 and Stage 2 ILV Assessments.

First, the majority of the Stage 1 packs overlapped between adjacent packs. This intentional overlap resulted in different ILV assessors making ILV assessments on the same property on neighbouring packs. This duplication of ILV assessment on some properties was an inherent quality control aspect to ensure robustness and consistency.

In almost all cases, the duplicate ILV assessments would result in the same outcome, demonstrating that the decision-making was robust. However, where they differed such cases were reviewed, and any lessons of broader application arising from those cases incorporated back into the assessment process. Any different ILV decisions on the same property were identified during the uploading phase (i.e. Task 6 in Figure 8.5).

Second, for the Stage 2 process, while only the properties which were marked as “Stage 2” required ILV assessments to be undertaken, the Stage 2 marking also extended out to surrounding properties where an ILV decision had already been made in Stage 1. For almost all of the cases reassessed by the Stage 2 process the ILV decisions were the same.

8.4 Differentiating between Land Damage due to Lateral Spreading and Free Field Liquefaction

As discussed in Section 6.6 the assessment of *Criterion 1* in the ILV Assessment Methodology excludes the assessment of liquefaction vulnerability due to lateral spreading because vulnerability to lateral spreading was judged to have not increased as a result of the changes to the land that occurred during the CES.

In some areas of Christchurch the land is vulnerable to both lateral spreading and free field liquefaction related land damage at 100 year return period levels of earthquake shaking. In other areas the land is vulnerable only to lateral spreading at 100 year return period levels of earthquake shaking (but not free field liquefaction related land damage).

An example of this would be a property in close proximity to a river or a stream, which has a thick non-liquefying crust relative to the thickness of the underlying liquefying soil layers. While in the free field situation the thick non-liquefying crust would protect the property from material liquefaction damage, the close proximity to the river or stream would result in the non-liquefying crust being compromised (i.e., stretched, cracked, distorted, or displaced) as a result of lateral spreading.

Therefore, to apply the ILV Assessment Methodology, it was necessary to develop a process to differentiate between these different forms of liquefaction vulnerability. This process is applicable in areas where the CPT-based assessment results indicate the land is not vulnerable to free-field material liquefaction damage (i.e. low LSN values) but the land damage observations relative to the estimated level of earthquake shaking indicate moderate to severe land damage occurred and that the property is potentially vulnerable to liquefaction.

Figure 8.11 summarises the process used to differentiate between the two different forms of liquefaction vulnerability.

The initial step is to estimate site specific LSN values for each of the four main earthquakes. This is achieved by reading the LSN values of the LSN sensitivity to PGA curve (refer to Figure 8.9) for a representative CPT using estimated PGA values for each of the four main earthquakes that have been scaled to an equivalent M6 earthquake. The LSN parameter does not take account of the potential for lateral spreading related land damage.

These site specific LSN values are then reconciled with the land damage observations at each site to see if the LSN model fits the observations.

If the LSN values are consistent with the land damage observations then the property is assessed for ILV in the normal manner. If the LSN values are over predicting liquefaction vulnerability then lateral spreading is unlikely to be an issue and reasons for this apparent over-prediction are investigated using the Stage 2 process described in Section 10. If the LSN values are under predicting liquefaction vulnerability relative to the land damage observations, then the possibility of lateral spreading is considered as a potential reason for the land damage sustained at the property.

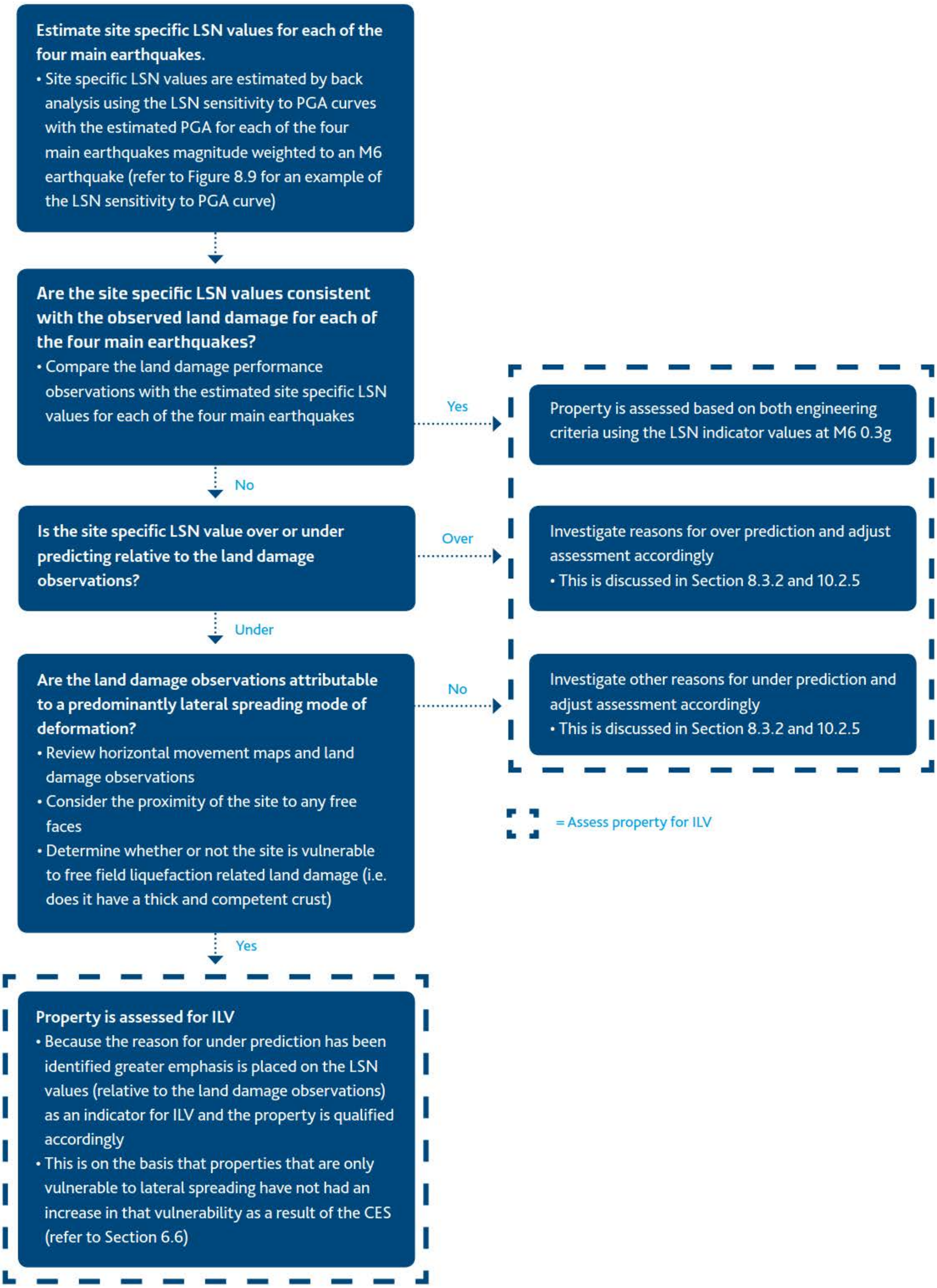


Figure 8.11: Process to differentiate between observed land damage from CES events, with ground motions close to 100 year return period levels of earthquake shaking, due to free field liquefaction vulnerability and lateral spreading vulnerability for properties with low calculated LSN values.

In these cases, the question that was considered for *Criterion 1* was would there have been land damage in the main CES events if lateral spreading had not occurred, and if so, did this help explain the calculation of low LSN values even though there has been land damage observed?

To check for lateral spreading the assessing engineer considers the following factors:

- Do the horizontal movement vectors indicate lateral spreading has occurred during the CES?
- Is the property in close proximity to a free face such as a river bank, road cutting or old river terrace?
- Do the geotechnical investigations indicate that the site has a competent crust overlying liquefiable soil layers such that the site is unlikely to be vulnerable to free field liquefaction damage?
- If all of these factors do not apply then it is likely that the land damage is attributable to free-field liquefaction damage and other reasons for the apparent under prediction of ILV need to be considered (refer to Section 10). If the assessing engineer determines that all of these factors do apply then it is likely that the land damage observations are attributable to lateral spreading only and the property can be assessed as not qualifying for ILV on the basis of not satisfying *Criterion 1*.

8.5 Comparison of Automated ILV Model and Manual ILV Assessment

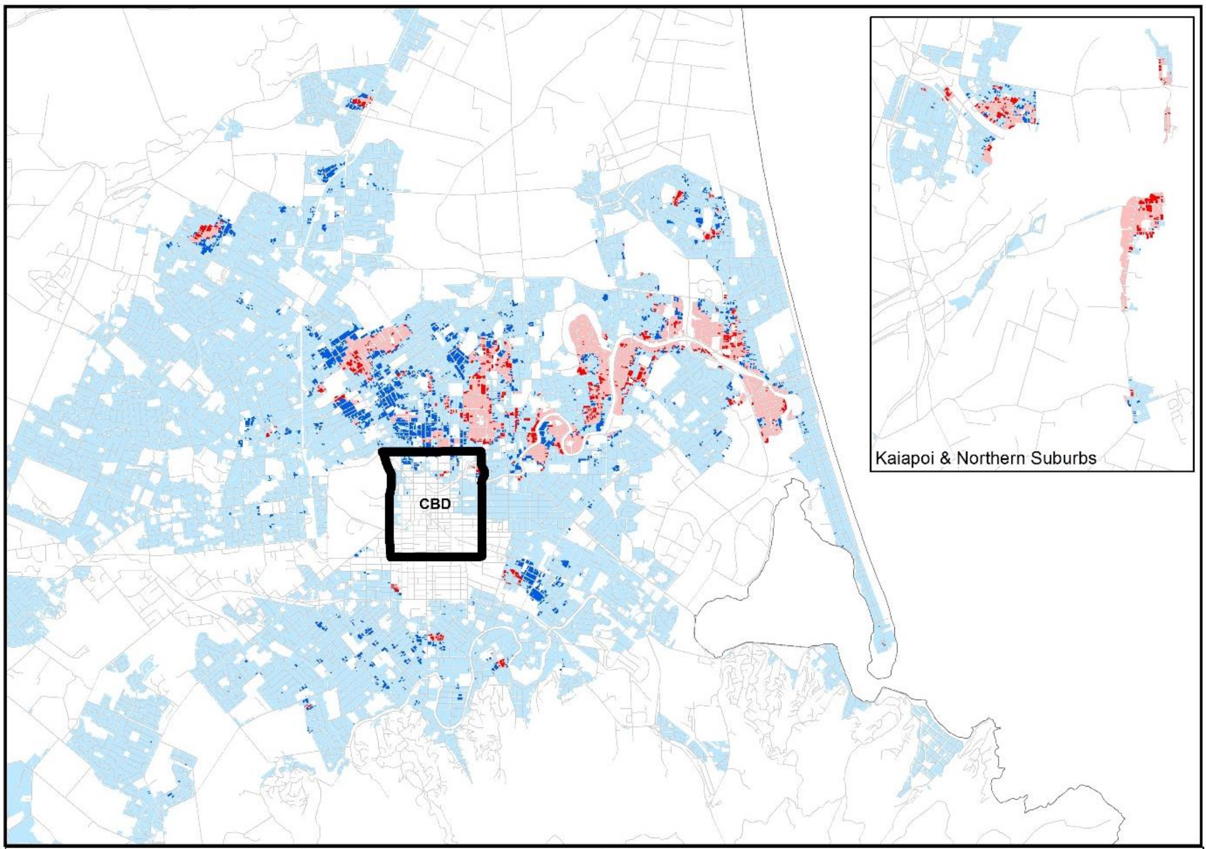
Figure 8.12 shows a map which compares the automated ILV model results (shown in Figure 8.4) with the manually assessed ILV decisions at the completion of the Stage 1 and Stage 2 ILV processes (shown in Figure 10.17).

Properties which qualified for ILV and the automated outcome was “yes” are shown as pale red. Properties which qualified for ILV and the automated outcome was either “no” or “marginal” are shown as dark red.

Properties which did not qualify for ILV and the automated outcome was either “no”, “unable to estimate LSN” or “marginal” are shown as pale blue. Properties which did not qualify for ILV and the automated decision was “yes” are shown as dark blue. Properties in the lighter shades of blue and red are properties where the manual assessment process confirmed the automated outcome.

The properties which are darker shades of blue or red have had automated outcome overturned by the manual process.

The purpose of Figure 8.12 is to demonstrate on a regional scale the difference between the automated ILV model and the outcome from the manual ILV assessment process.



Final ILV Assessment	ILV Automated Model	Number of Properties	% of Properties
Yes	Potential Yes	7,767	78%
Yes	Potential No	1,051	11%
Yes	Potential Marginal	1,099	11%
	Total Yes	***9,917***	***100%***
No	Potential Yes	3,594	3%
No	Potential No	32,880	25%
No	Potential Marginal	2,879	2%
No	Unable to estimate LSN	90,120	70%
	Total No	***129,473***	***100%***

Figure 8.12: Map and tabulated data for ILV decisions comparing the difference between the results from the automated ILV assessment model and the manual ILV assessment process

It is reasonable to group the automated “unable to estimate LSN” outcomes with the automated “no” outcomes (as pale blue) because the majority of these properties were in areas where there was no liquefaction related damage and low levels of ground surface subsidence and therefore they would not satisfy *Criterion 1* and therefore would not qualify for ILV.

Inspection of Figure 8.12 shows that majority of properties in Christchurch are either pale blue or pale red indicating that the manual and automated models have produced very similar results. The data presented in the table in Figure 8.12 which shows that 78% of the manual “yes” decisions were automated “yes” and only 22% of the manual “yes” decisions were automated “no” or “marginal” (i.e. overturned from the automated result). Similarly, 97% of the manual “no” decisions were automated “no”, “marginal”, or “unable to estimate LSN” and only 3% of the manual “no” decisions were automated “yes” (i.e. overturned from the automated result).

This shows that the ILV automated model at a regional level was generally differentiating well between properties with and without ILV.

Figure 8.12 also shows that the dark red and blue properties (i.e. the overturned automated decisions) are primarily confined to transition areas between “yes” and “no”. Most importantly, it was never the case that entire suburbs were overturned. Instead, it was generally marginal cases on the fringes of large blocks of “yes” and “no” decisions. This further demonstrates that the ILV automated model was generally differentiating well between properties with and without ILV.

Finally, Figure 8.12 shows that the majority of dark blue properties (i.e. overturned automated “yes” outcomes) are located in western parts of Christchurch. The soil profile in these areas is generally characterised by highly complex interbedded silts and sands and regions of gravel and peat material. In these areas, the automated model struggled to predict liquefaction vulnerability because, generally, the liquefaction triggering method used in the estimation of LSN over-predicts either the liquefaction triggering or the liquefaction consequence relative to the land damage observations.

9 Stage 1 Assessments

9.1 Purpose and Outline

The purpose of Stage 1 of the ILV land damage qualification process was to classify urban residential properties in Christchurch as either qualifying or not qualifying for ILV in straight forward cases. Where a qualification decision for a property was not straight forward, it was recorded as *Stage 2*. These properties were identified as requiring further manual assessment because they are marginal cases or cases with complex ground conditions, where the predicted land performance is not consistent with the observed performance.

This section of the report describes the Stage 1 assessments in more detail:

- Section 9.2 describes the approach undertaken when assessing properties for Stage 1 ILV qualification;
- Section 9.3 works through an example by applying the approach to a small cluster of properties in the Richmond area to the northeast of the CBD; and
- Section 9.4 summarises the ILV assessment results following the completion of Stage 1 qualification.

The approach to Stage 2 assessments is described in Section 10 of this report.

9.2 Approach to Resolving Stage 1 Decisions

9.2.1 Overview

For the Stage 1 qualification process, packs were created and zoomed into areas with typically 10 to 20 CPTs. Depending on the density of the CPTs and the geological complexity, this could comprise anywhere between 5 to 100 properties. Typically, most packs focused on ILV decisions for 10 to 20 properties in areas of reasonable geological complexity.

A regional assessment of the data was undertaken initially. Any relevant notes (such as over/under-prediction in ground surface subsidence or geological transitions) were marked on the packs. This is described in Section 8.3.1 of this report.

Following the regional assessment, local and specific analysis was undertaken as described in Section 8.3.2 of this report. This included a liquefaction vulnerability sensitivity analysis of each CPT against PGA and depth to groundwater. The CPT data and sensitivity analysis was reviewed to classify the CPTs and boreholes within the area of interest. The CPT and borehole classifications were then spatially compared to the mapped data (i.e. observed land damage, ground surface elevation, etc.). If the datasets reconciled, then properties were qualified or not qualified for ILV accordingly.

When reviewing each pack, the following datasets were considered at both a regional (where applicable) and local level:

- Geological and soil maps;
- Post-CES ground surface elevations;
- Groundwater surface elevation maps;
- High resolution aerial imagery;
- Observed land damage mapped across the area for each of the main CES events relative to the estimated levels of earthquake shaking;
- Estimated vertical change in elevation over the CES;
- The results of automated modelling of ILV; and

- Detailed assessment of the results of all available ground investigation data (CPTs, boreholes and laboratory testing) in the local geographic area.

Using the above information, the objective was to determine for each property within the pack if the available geotechnical data and corresponding liquefaction vulnerability assessments reconciled with the observed land damage relative to the estimated levels of earthquake shaking for the four main earthquake events in the CES. When this was the case, a property was either qualified or not qualified for ILV. Likewise, if it was clear from the data that one or both of the *engineering criteria* would not be satisfied, then that property was assessed as not qualifying for ILV.

Conversely, if it was not clear from the data whether both of the *engineering criteria* would be satisfied and the geotechnical data and observed land damage relative to the estimated levels of earthquake shaking did not reconcile, then a property was recorded as Stage 2 and requiring further review (discussed further in Section 10).

The four parts of the Stage 1 ILV qualification process is summarised in Figure 9.1.

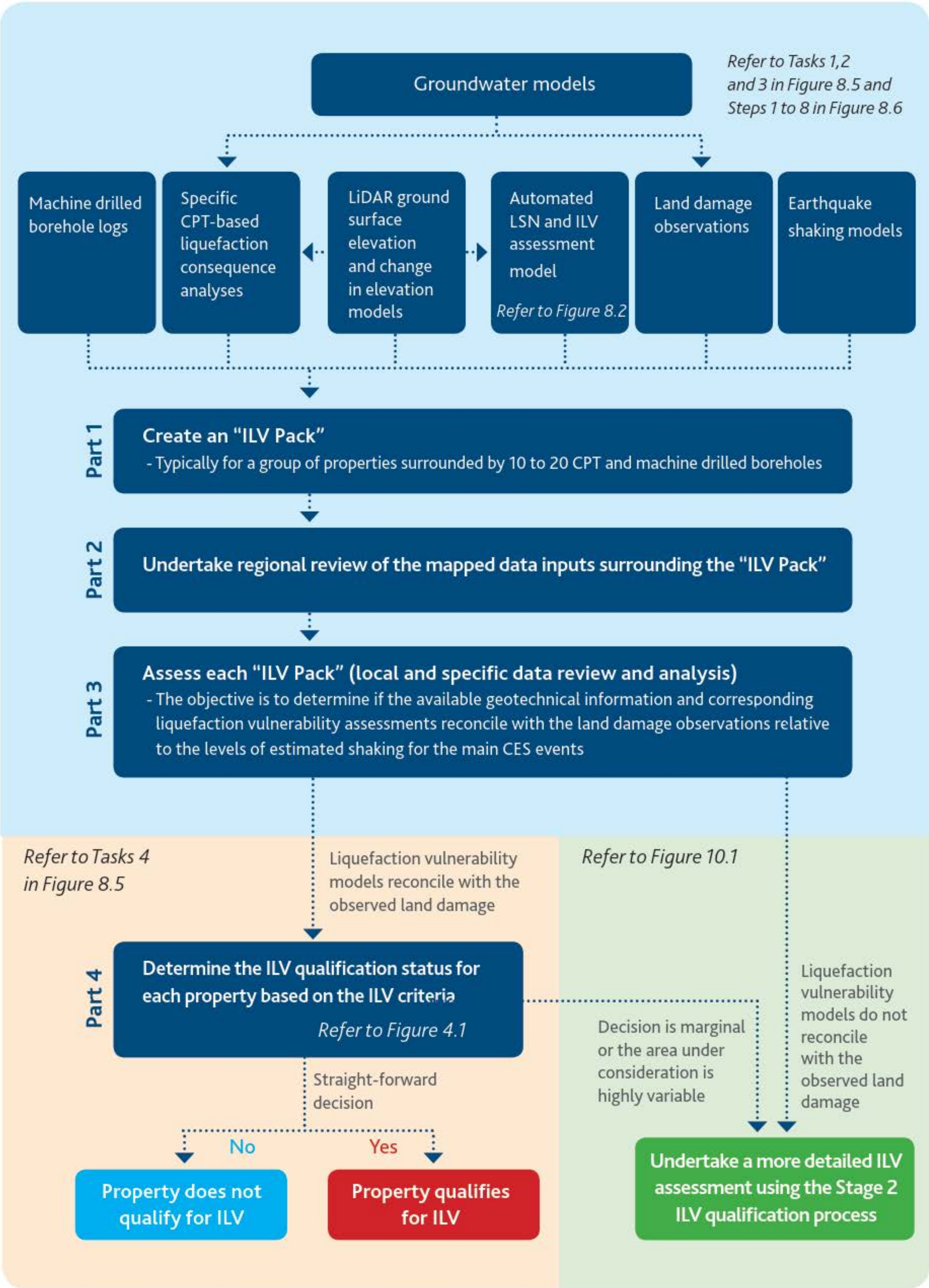


Figure 9.1: Stage 1 ILV qualification approach.

9.2.2 Part 1 - Creating ILV Packs for Stage 1

The size of the area under consideration in each ILV assessment pack was determined largely by the density of the geotechnical investigation information available in the area as well as the geological complexity. In areas where there was a higher density of geotechnical information the packs covered a smaller area. In areas where there was a lower density of geotechnical information and the soil conditions were less geologically complex (in relation to the ILV assessment criterion), the packs covered a larger area. This meant the number of properties under consideration in each pack varied from as few as 5 to as many as 100. A typical pack would cover an area containing approximately 10 to 20 properties. In total more than 3,000 Stage 1 ILV assessment packs were created.

Basing the size of the area under consideration in each pack on the geological complexity and number of geotechnical investigations available was a reasonable approach. It provided the engineer undertaking the assessment with a practical level of resolution of information to apply engineering judgement to the ILV assessment without being overwhelmed with too much information.

In most of the residential Red Zone, where the land damage was consistently moderate-to-severe, the ground surface subsidence was generally greater than 0.5 m, and both the LSN and ΔLSN values were consistently high, the CPT density is lower and the corresponding pack size is larger. This is appropriate because based on observed land performance, the amount of ground surface subsidence and spatial consistency in predicted land performance, it is clear that large parts of the residential Red Zone satisfy both *engineering criteria*.

The CPT density in the TC3 area is much higher than in residential Red Zone or TC2 areas. The land with the worst damage in Green Zone is within the TC3 area and hence, this is where the majority of residential dwellings are being rebuilt.[8] In addition, EQC supplemented geotechnical investigations in TC3 areas with fewer rebuilds to improve the resolution at which the ILV assessments could be undertaken.

The CPT density in TC2 is generally similar to that in residential Red Zone although there are small isolated pockets in the TC2 area with higher CPT density because of poor land performance resulting in more residential buildings requiring rebuilding. As a result, fewer investigations have been undertaken in these areas. However, the majority of the land performed well in TC2 across the CES. As a result, the majority of these properties can be assessed as not qualifying for ILV land damage on the basis that the observed land performance demonstrated they did not satisfy *Criterion 1*. In the small isolated pockets of land within TC2 which did not perform well throughout the CES, EQC completed supplementary investigations to enable the ILV assessment in these areas to occur at a higher resolution.

It is important to note that the ILV Assessment Methodology included a process for undertaking further geotechnical investigations where there was an insufficient density of geotechnical data to determine the ILV qualification status for a given area. If the engineer undertaking the ILV assessment determined that a different level of detail was more appropriate for the ILV assessment pack, the pack was sent back to be reformatted accordingly.

9.2.3 Part 2 - Regional Assessment (Task 1 in Figure 8.5)

No additional regional considerations were made in the Stage 1 process over and above those listed in Section 8.3.1.

[8] In TC3 areas, undertaking geotechnical investigations is a pre-requisite prior to designing new foundations for residential buildings as per the MBIE guidelines (refer to Section 3.8).

9.2.4 Part 3 - Local and Specific Assessment (Task 2 and 3 in Figure 8.5)

No additional local and specific considerations and steps were made in the Stage 1 process over and above those listed in Section 8.3.2.

9.2.5 Part 4 - ILV Qualification Assessment (Task 4 in Figure 8.5)

Properties were qualified or not qualified for ILV in Stage 1 if:

- **No land damage at levels of earthquake shaking equal to or above M6 0.3g –** Despite the geotechnical data indicating liquefaction vulnerability (i.e. LSN > 16), if there was no recorded land damage in areas where the estimated level of earthquake shaking in the CES was in excess of M6 0.3g and there was reasonable confidence in the shaking estimates, the property would be assessed as not having ILV. The absence of observed land damage in such an event provided a clear and reasonable basis not to qualify the properties for ILV because it would not satisfy *Criterion 1.* Secondary information such as small values of estimated liquefaction related subsidence were also used to support these decisions.

  In order for this conclusion to be reached, there needed to be a reasonable level of certainty in the accuracy of the estimated levels of earthquake shaking and that the land damage observations within the area of consideration were consistent (i.e. that there were no pockets of liquefaction ejecta on the properties under consideration and there was no liquefaction ejecta visible on the adjacent roads).
- **All available data reconciled –** The geotechnical data and the liquefaction vulnerability assessment analyses at each CPT location was in agreement with the observed land damage throughout the CES (i.e. the estimated LSN values are consistent with the observed land damage at respective estimated PGA values) and the estimated ground surface subsidence was such that that straightforward ILV decisions could be made. This was the case for approximately 90% of the ILV decisions.

  In some cases, while the available data did reconcile, the liquefaction vulnerability and change in vulnerability (LSN and ΔLSN values respectively) were close to the indicator values and it was not clear whether both of the *engineering criteria* would be satisfied (i.e. the cases were marginal). These properties were held back for further assessment using the Stage 2 process.
- **No estimated subsidence across the CES –** Despite the geotechnical data indicating liquefaction vulnerability (i.e. LSN > 16), if there were areas with consistently low levels of estimated ground surface subsidence, the property would be assessed as not having ILV. The absence of estimated ground surface subsidence across the CES provided a clear and reasonable basis to qualify the property as no for ILV because it would not satisfy *Criterion 2.*

  This was often applicable in south-western parts of Christchurch where there were only minor observations of liquefaction related land damage and in south eastern parts of Christchurch where tectonic movement has resulted in raising of the ground surface level resulting in no overall change in the liquefaction vulnerability.

Properties where the qualification was not straightforward and required further manual assessment were identified for the Stage 2 ILV qualification process.

9.2.6 Criteria for further review

The properties that were qualified as Stage 2 in Stage 1 can be categorised into one of three sub-categories. These categories are as follows:

1 Properties requiring further detailed review because the ILV qualification was marginal (i.e. borderline cases close to the indicators for the *engineering criteria*);

2 Properties requiring further detailed review because the ground conditions were complex; and

3 Properties where pre-CES LiDAR DEM is not representative of the ground surface elevations and post-September LiDAR DEM extents were insufficient to undertake an engineering assessment of ILV.

9.2.6.1 Marginal or Complex Cases

The first two categories of the Stage 2 properties identified in the Stage 1 qualification process were properties which were *marginal* or *complex*.

A property was considered to be *marginal* if it was close to the margins of qualifying for ILV on the basis of *Criterion 1* and/or *Criterion 2.* Typical indicators of properties that were marginal with respect to *Criterion 1* included minor-to-moderate land damage observations at levels of ground shaking of M6 0.3g or equivalent and estimated LSN values of between 14 and 16. Typical indicators of properties that were marginal with respect to *Criterion 2* included moderate levels of estimated total ground surface subsidence and estimated ΔLSN values of between 4 and 5.

A property was considered to be *complex* if it had one or more of the following issues:

- **Geological and topographical boundaries –** The estimated LSN value for a given property was potentially unreliable due to geological and topographical boundaries such as river banks, infilled stream channels, terraces and other changes in elevation, but the mapped information available as part of the Stage 1 assessment process was not of sufficient accuracy to determine where the transition zones occurred;
- **Variable prediction of LSN –** The estimated LSN values for CPT across a localised area were highly variable with no apparent differentiation of land damage observations throughout the area;
- **Potential under-prediction of LSN –** The estimated LSN value for a given property was lower than would be anticipated for the level of ground shaking experienced during the CES and the land damage observations recorded;
- **Potential over-prediction of LSN –** The estimated LSN value for a given property was higher than would be anticipated for the level of ground shaking experienced during the CES and the land damage observations recorded; and
- **Potential hypersensitivity of ΔLSN –** The estimated ΔLSN value for a given property was higher than would be anticipated for the level of ground surface subsidence as a result of the CES where the groundwater surface is in close proximity to the ground surface (as discussed in Section 8.3.2.2 and 8.3.2.3).

9.2.6.2 Insufficient LiDAR Survey Coverage

The third category of the Stage 2 properties identified in the Stage 1 qualification process is properties with insufficient LiDAR survey coverage.

As discussed in Section 8.3.2, properties with 2003 LiDAR DEM elevations that were not representative of the pre-CES ground surface elevations were identified using aerial photography. The majority of these properties were assessed as not qualifying for ILV land damage as they did not satisfy *Criterion 1* (refer to Section 2.4).

However, there is one large residential development in Northwood where earthworks occurred between 2003 (when the pre-CES LiDAR was flown) and the September 2010 event, which required more detailed assessment. In addition, the post-September LiDAR was not flown in this area despite the September 2010 event being the main CES event that caused land damage and potential liquefaction-related subsidence in that area.

Following a review of the available data, the size of the area with insufficient LiDAR was reduced to properties which had observed land damage following the September 2010 event and would most likely satisfy *Criterion 1*. These properties are identified in Figure 9.5. Without knowing the amount of ground surface subsidence which has occurred on a property, the ΔLSN could not be determined in this area.

Around 600 properties are affected by this lack of data. Section 10.2.4 outlines the process used to resolve the ILV assessments in this area.

9.3 Stage 1 Worked Example

To demonstrate the Stage 1 manual review process the following worked example is summarised below. The full ILV data pack for this case study is included in the **Worked Example Material**. The location of this worked example is shown in Figure 9.2.

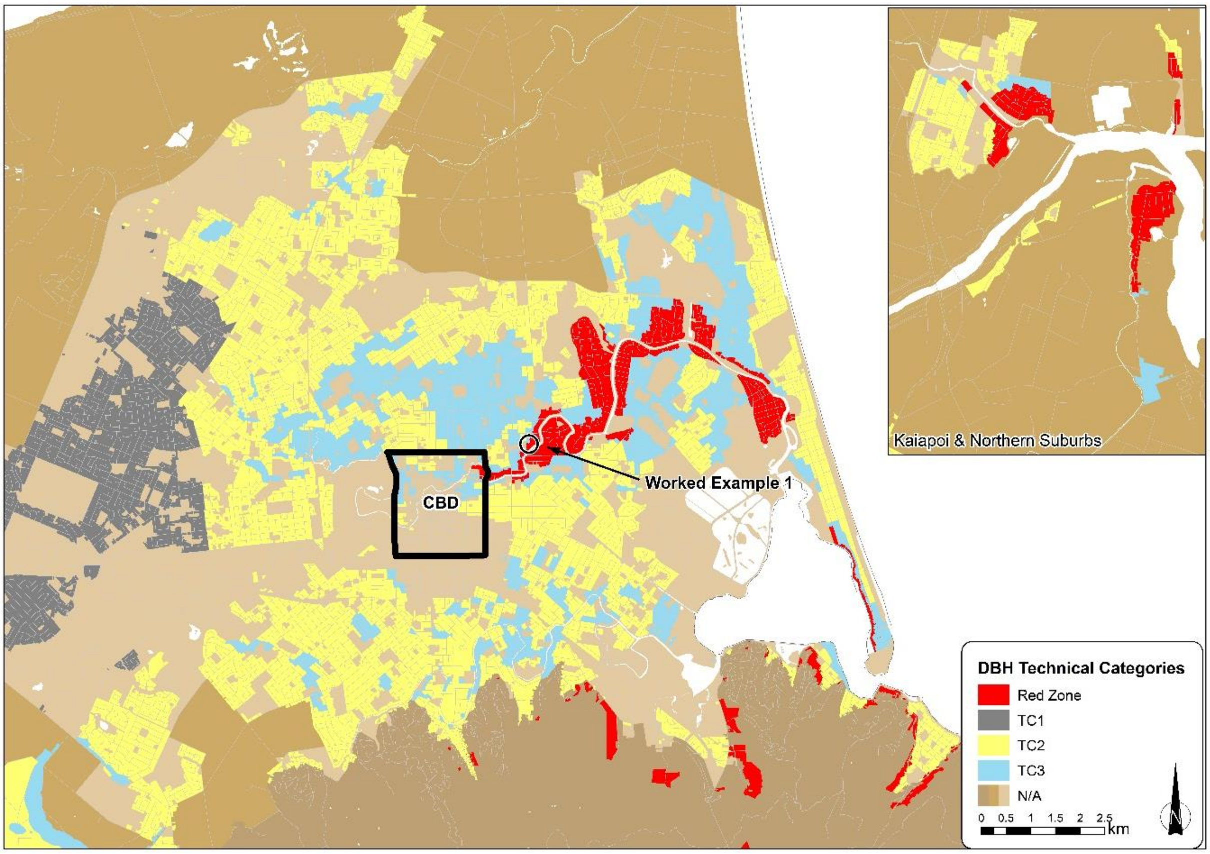


Figure 9.2: Map of the MBIE residential TC areas in Christchurch on flat land for the urban residential buildings in Christchurch showing the Stage 1 worked example 1 location.

This worked example shows a relatively simple assessment where engineering judgement generally supports the automated ILV model results. The assessment process is summarised as follows:

- **Regional Assessment (Task 1) -** The observed land damage maps indicate a transition from land which has performed well during the CES to the west of the assessed area to land which has performed poorly during the CES to the east of the assessed area. The elevation map shows a topographic transition from land to the west which sits higher than the land to the east. This lower lying area indicates shallower groundwater and potentially a thinner non-liquefying crust. There are no apparent LiDAR error bands over the assessment area. Most of these trends can be observed in Figure 9.3.

- **Local and Specific Assessment (Task 2 and 3) –** A review of the aerial photography shows no residential development occurred between the 2003 pre-CES LiDAR and the September 2010 earthquake event. The automated model map indicates properties to the left do not qualify for ILV while those to the right qualify for ILV. All but one of the CPT is coded as either a ✓ or a ✗ (as set out in Section 8.3.2.3) based on whether or not the CPT location meets the ILV *engineering criteria.* The CPT classified with a **?** is not considered because the raw file uploaded to the CGD contains q_c and f_s but no associated depth. The location of the CPTs and the associated classifications are shown in Figure 9.4.
- **ILV Qualification Assessment (Task 4) -** Comparison of the CPT ✓ and ✗ classifications shown in Figure 9.4 with the CES ground surface elevation, depth to groundwater, September 2010 observed land damage, worst observed land damage across the CES and total ground surface subsidence maps shown in Figure 9.3 indicate good spatial agreement.

  The CPTs identified with a ✗ are all located on land with a higher elevation and deeper depth to groundwater (i.e. a thicker non-liquefying crust). They are also on land which has performed well following the September 2010 levels of shaking (roughly equivalent to an M6 0.3g levels of earthquake shaking) and only subsided by around 0.2 to 0.3m.

  Conversely, the CPTs identified with a ✓ are located on land with a lower elevation and shallower depth to groundwater (i.e. a thinner non-liquefying crust). They are also on land which has performed poorly following the September 2010 levels of shaking (roughly equivalent to 0.3g M6 levels of earthquake shaking) and subsided by more than 0.5m.

  The automated ILV model map is supported by the CPT classifications which are plotted on Figure 9.3 and therefore most of the properties in the assessment area are qualified with either a ☑ or an ☒ as per the automated ILV model as also shown in Figure 9.4. One of the properties sits on a transition zone between qualifying and not qualifying for ILV. The ILV model result indicates the property does not qualify for ILV but the observed land damage and ground surface subsidence maps indicate significant levels of land damage. Therefore, this property has been categorised as Stage 2 and requiring further manual assessment. It is described in more detail in worked example 1 in Section 10.3.1.

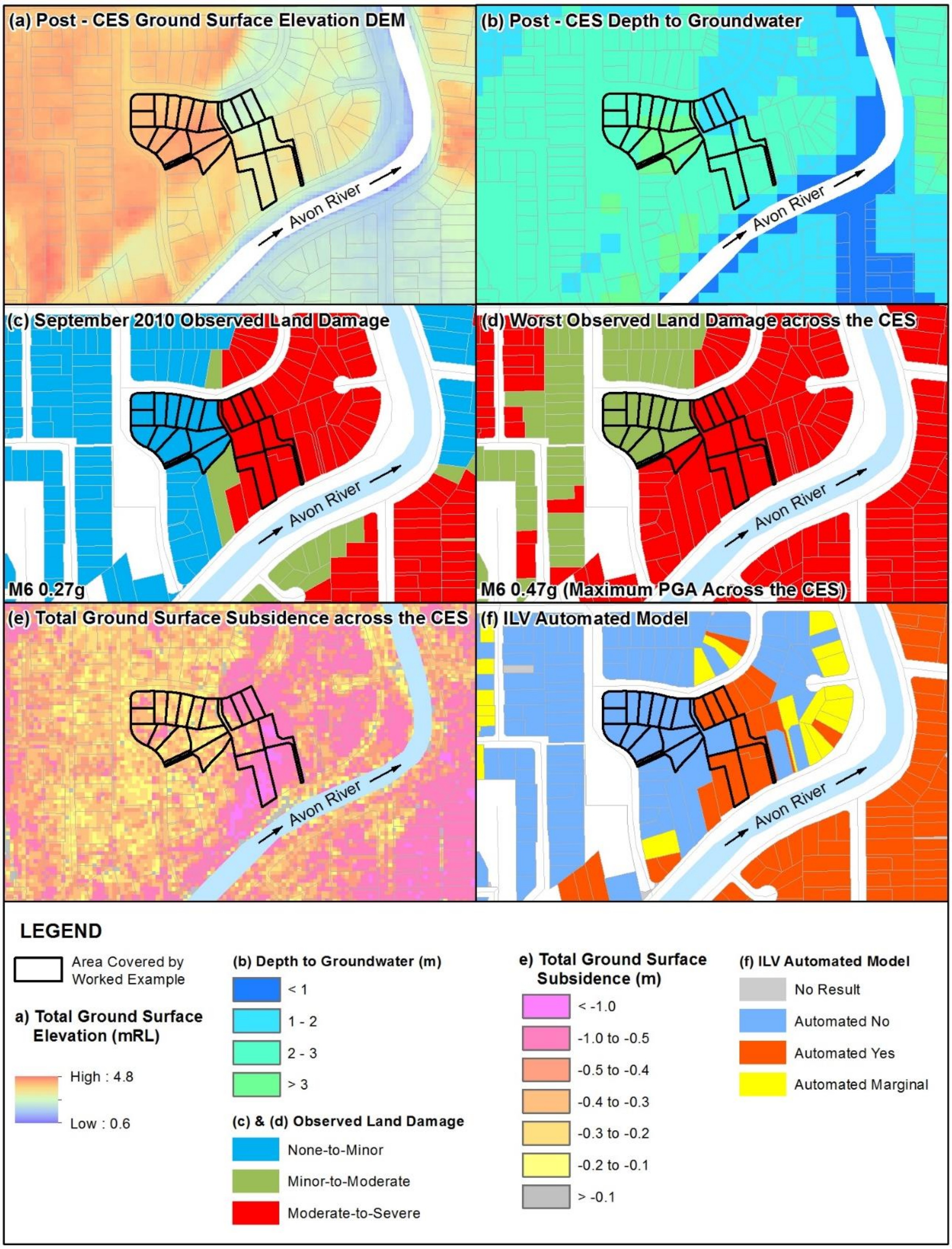


Figure 9.3: A series of maps used when assessing a cluster of properties in Richmond, for the Stage 1 qualification process. (a) post-CES ground surface elevation; (b) post-CES depth to groundwater; (c) September 2010 observed land damage; (d) worst observed land damage across the CES; (e) total ground surface subsidence across the CES; (f) automated ILV model results.

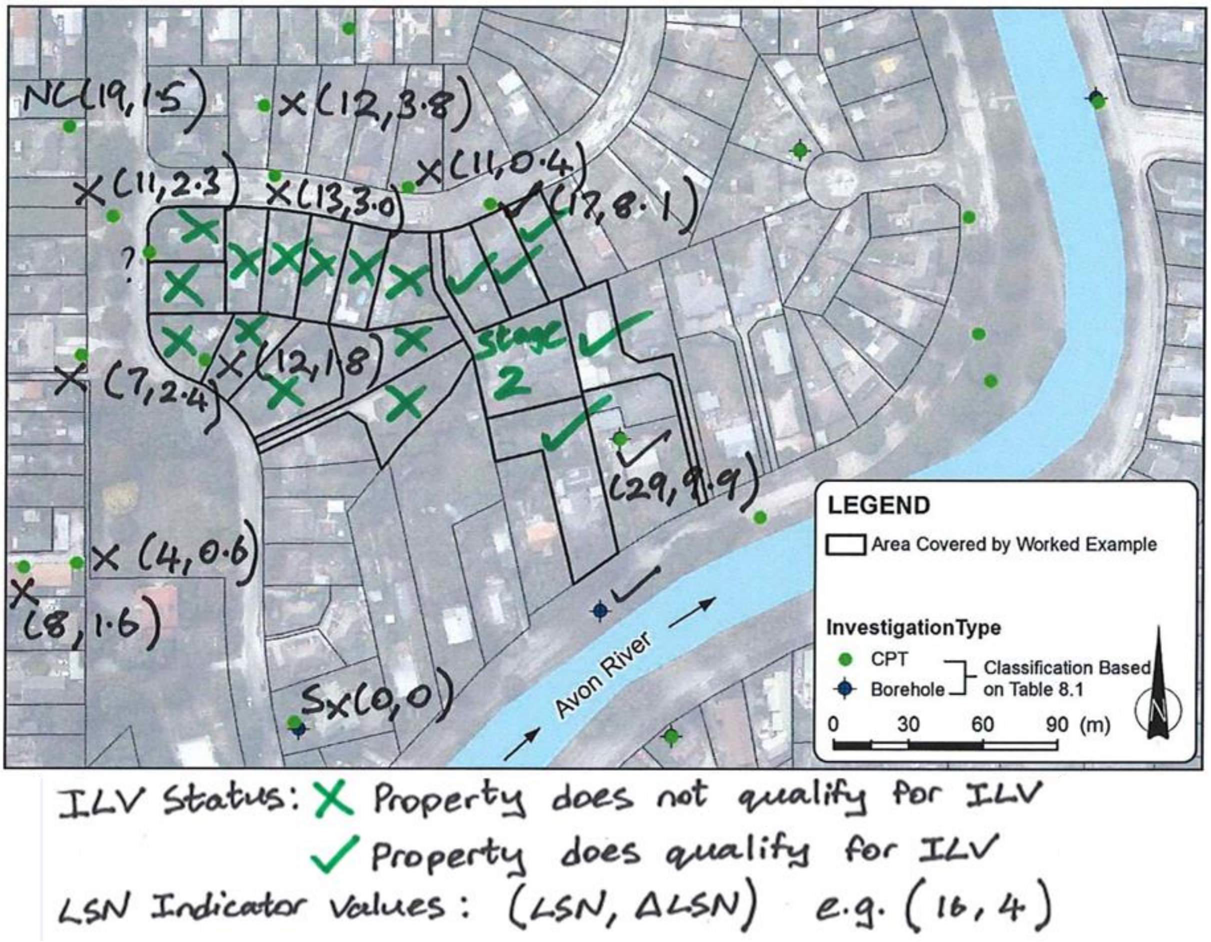


Figure 9.4: The location and classification of the CPTs and boreholes and the ILV qualification of the properties for the Stage 1 manual assessment pack around 12 Flesher Ave, Richmond.

9.4 ILV Assessment Results following the Completion of the Stage 1 Process

In total more than 3,000 Stage 1 ILV packs were assessed. The spatial distribution of these Stage 1 ILV qualifications is shown in Figure 9.5. The majority of the properties qualifying for ILV are located in the eastern parts of Christchurch along the banks of the Avon River and to the north of the CBD. These are the areas where the observed land damage through the CES and ground surface subsidence over the CES was most severe.

The properties which passed to Stage 2 are located predominantly on the fringe of the areas of properties qualifying for ILV. The greatest number of Stage 2 properties is in the area to the north of the CBD where groundwater is generally shallow and the soils are often more silty and highly interbedded. The observed land damage in these areas was not as severe as indicated by the CPT-based LSN and S_{V1D} parameters which predict significant liquefaction triggering should have occurred in the soil profile.

As indicated on Figure 9.5, the properties with insufficient LiDAR discussed in Section 9.2.6.2 are located in the northern suburb of Northwood.

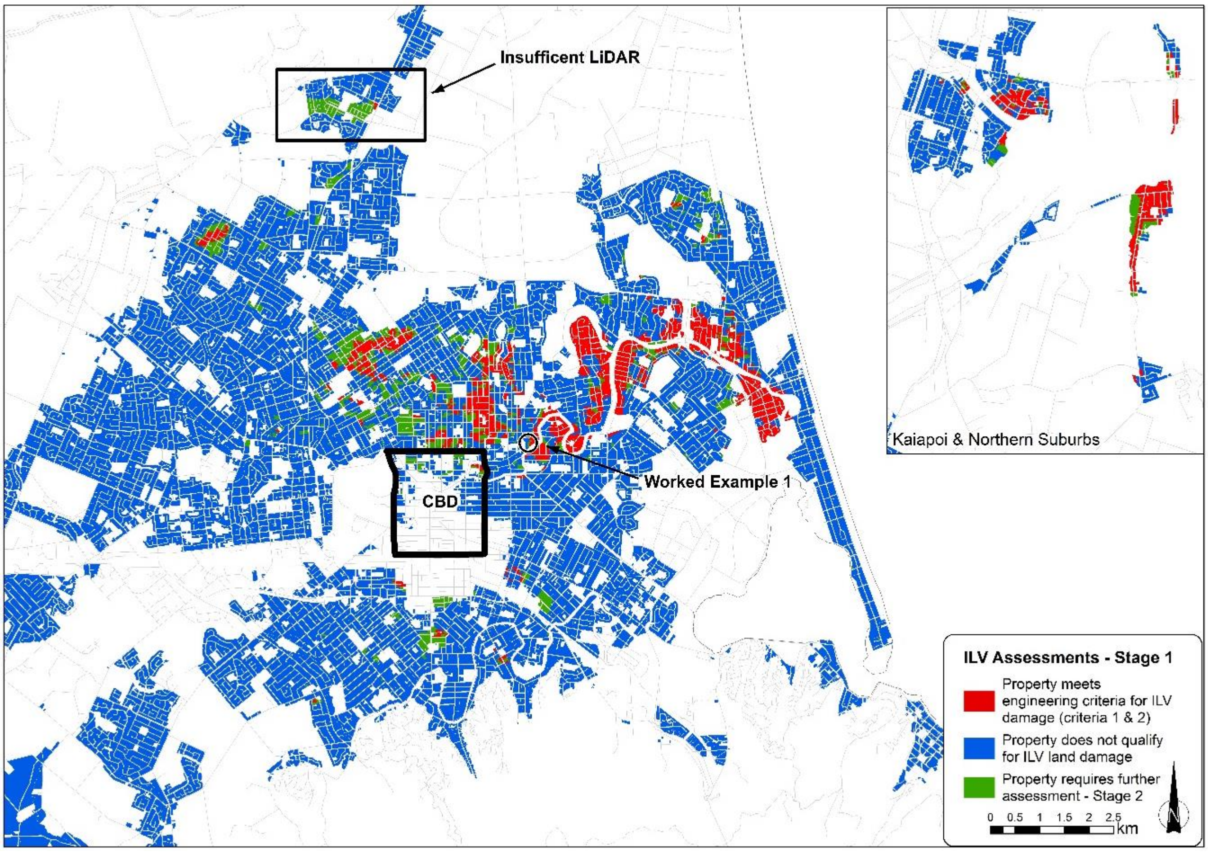


Figure 9.5: ILV assessment results after the completion of Stage 1 and worked example location. Note the white areas on the map represent the non-urban and non-residential land in Christchurch.

Table 9.1 below shows the categorisation of ILV land damage following Stage 1 qualifications divided into their respective TC1, TC2, TC3 and residential Red Zone areas. It is noted that 97% of the properties qualifying for ILV are in areas categorised as either TC3 or residential Red Zone (i.e. 3,403 TC3 properties plus 4,715 Red Zone properties out of a total 8,366 properties assessed as qualifying for ILV).

Table 9.1: ILV Land Damage Qualification following Stage 1 by Technical Category and Residential Red Zone

Technical Category	ILV assessment results following the completion of the Stage 1 Process		
	Number of properties which meet engineering criteria for ILV	Number of properties which do not qualify for ILV	Number of properties which require a further Stage 2 assessment
TC1	0	23,267	0
TC2	248	77,630	3,144
TC3	3,403	21,361	3,088
Red Zone	4,715	2,066	468
Total	8,366	124,324	6,700

* The property counts are based on the QPID database (maintained by Quotable Value Ltd) which existed at the time of the CES. The number of properties/QPIDs does not necessarily represent the number of claims.

10 Stage 2 Assessments

10.1 Purpose and Outline

Each of the 6,700 residential properties in Christchurch identified as requiring further review following the Stage 1 qualification process were assessed as qualifying or not qualifying for ILV land damage using the Stage 2 assessment process.

This section of the report describes the Stage 2 assessment process in more detail:

- Section 10.2 describes the approach undertaken when assessing properties for Stage 2 ILV qualification;
- Section 10.3 works through four examples of how the Stage 2 process was applied to small clusters of properties; and
- Section 10.4 summarises the results of the ILV assessments following the completion of the Stage 1 and 2 ILV assessment processes.

10.2 Approach to Resolving Stage 2 Decisions

10.2.1 Overview

In order to determine whether or not a Stage 2 property should qualify for ILV, the methodology presented in Figure 10.1 was applied.

In Part 1 of the approach, Stage 2 packs were produced at a scale of 1:2,500 at A3 and covered anywhere between 25 to 300 properties which were classified as requiring further assessment during the Stage 1 assessment process. These new packs included a significant amount of additional information from the Stage 1 packs.

In Part 2 of the approach, all Stage 2 properties were assessed for relevant geological or topographical issues. Following desktop review of the available information there were a number of sites where additional field observations were considered necessary. The engineers undertaking the ILV assessment visited each of these sites to undertake property inspections and map any significant geological features. This involved the assessment of these features at both a regional and local level and considered how specific analyses could be used to resolve these issues. The rest of the assessment along with all other properties assessed in Stage 2 were done as desk-top studies.

The rest of the ILV assessment was an iterative process which generally involved grouping CPT and borehole data based on the regional and local analysis of the mapped information. This process identified areas with similar land characteristics and observed performance. Specific analysis of the grouped data would then be undertaken. Based on insight gained from this specific analysis the grouping in the regional and local analysis would then be reconsidered to further refine the specific analysis.

Part 3 of the approach was to review the spatial distribution of the geotechnical data surrounding Stage 2 properties and associated liquefaction vulnerability assessments. This geotechnical information would then be compared to the observed land performance through the CES to evaluate if there were areas with over prediction, under prediction and variable prediction (i.e. complex cases).

The geotechnical data and liquefaction vulnerability sensitivity assessments would then be interrogated to understand the potential reasons for the over, under and variable prediction. Where appropriate adjustments to the liquefaction triggering and vulnerability input parameters were made and the LSN value was re-estimated accordingly. As with the other parts of the approach this sometimes involved reiteration of the regional, local and specific analysis tasks in Figure 8.6.

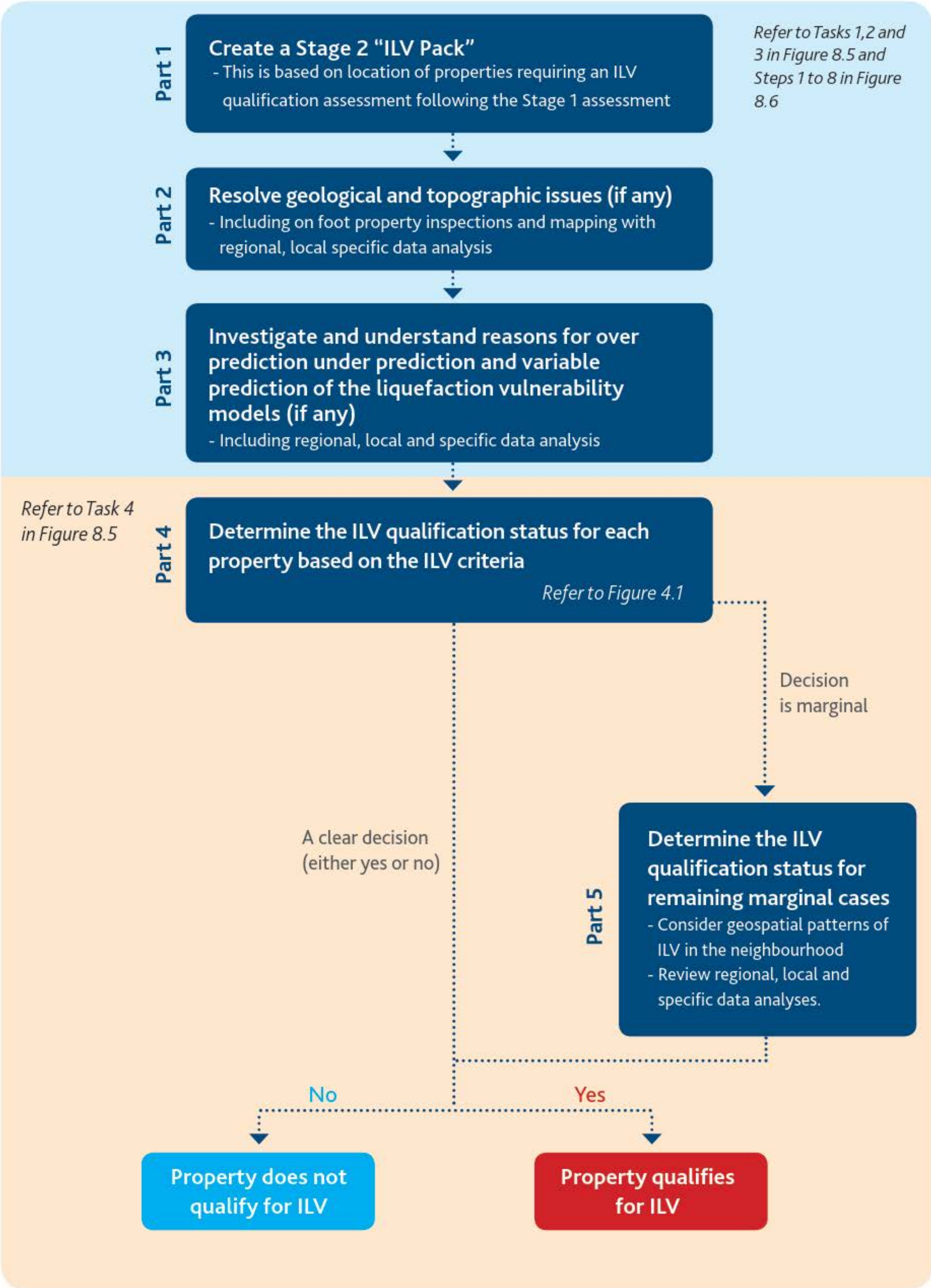


Figure 10.1: Stage 2 ILV qualification approach.

Part 4 of the approach was to determine the ILV qualification status for each property based on the *engineering criteria* discussed in Section 2.4. For some properties the work undertaken in Parts 1 to

3 resulted in a clear decision of either yes or no for the ILV qualification status. For these properties the same process as the Stage 1 ILV qualification assessment was applied.

For other properties, despite the work undertaken, the decision remained marginal. In these cases the following factors would be considered as supporting a property being confirmed as eligible for ILV:

- Surrounding properties are eligible for ILV land damage;
- Observed land damage in September 2010 is either minor-to-moderate or moderate-to-severe;
- Worst observed land damage for the CES is moderate-to-severe;
- The estimated LSN value is sensitive to small changes in PGA (i.e. LSN < 16 at PGA of 0.3g and LSN >16 at PGA of 0.32g); and
- The property has subsided significantly (i.e. more than 0.3m).

Based on the consideration of these factors the engineer undertaking the assessment would determine which properties are, on the balance of probabilities, materially vulnerable to liquefaction damage and had a material change in liquefaction vulnerability. It is noted that the more of these factors that are applicable, the more likely it is that engineering judgement would consider a property as qualifying for ILV.

Conversely, properties which do not have many of the factors listed above, and therefore are not likely to be materially vulnerable to liquefaction damage and/or not likely to have had a material change in liquefaction vulnerability, would not qualify for ILV.

10.2.2 Creating ILV Packs for Stage 2

Part 1 of the approach to the Stage 2 ILV assessment (refer to Figure 10.1) was the creation of the ILV information packs. Unlike the Stage 1 ILV assessment packs, the Stage 2 packs covered a standardised area of properties of 1:2,500 scale at A3. Creating the packs at this scale provided an appropriate balance between being able to practically consider all the relevant information for the assessment of ILV and limiting the number of ILV assessment packs to a manageable number. This resulted in 98 Stage 2 ILV assessment packs with the number of properties requiring assessment in each pack varying from 25 to 300.

When reviewing each pack, the following datasets were considered at both a regional and local level (these are the same data sets that were considered for the Stage 1 assessments):

- Geological and soil maps;
- Post-CES ground surface elevations;
- Groundwater surface elevation maps;
- Observed land damage mapped across the area for each of the main CES events relative to the estimated levels of earthquake shaking;
- Estimated vertical change in elevation over the CES;
- CPT and laboratory test based analyses including the following:
  - The results of automated modelling of ILV on the residential properties;
  - Median and mean LSN parameter values at the CPT locations as well as interpolated values for the residential properties;
  - Median and mean ΔLSN parameter values at the CPT locations as well as interpolated values for the residential properties; and

- Detailed assessment of the results of all available ground investigation data (CPTs, boreholes and laboratory testing) in the local geographic area.

In addition to the information available in the Stage 1 ILV assessment packs the Stage 2 packs included maps of the following information:

- CPT and laboratory test based analyses including the following:
  - Median normalised CPT tip resistance (**q_{C1N}**) at 1m thick layers for the top 5m of the ground profile;
  - Median I_c values at 1m thick layers for the top 5m of the ground profile;
  - Depth to the first soil layer greater than 0.5m thick with a q_c of more than 20MPa;
  - Sensitivity analysis of LSN to small changes in PGA (0.28 to 0.32g) based on the median groundwater surface for M_W 6.0 ground motions;
  - Sensitivity analysis of LSN to P_L (15% to 85%) based on the median groundwater surface for M6 0.3g levels of earthquake shaking;
  - Correlation of the liquefaction susceptibility parameter (Bray & Sancio, 2006) with I_c based on CPT data paired with laboratory test data;
  - Correlation of FC with I_c based on CPT data paired with laboratory test data; and
  - Sensitivity analysis of LSN to different FC-I_c correlations (expressed as C_{FC} parameter) and I_c cutoff values based on the median groundwater surface for M6 0.3g levels of earthquake shaking.

Worked examples showing all the information available in the Stage 2 regional maps and ILV assessment packs are included in **Appendix K** and the **Worked Example Material** respectively. Note that the example packs are undertaken on 1:2,500 scale on A4 (i.e. not A3 as presented in the full Stage 2 packs).

In addition to the information included in the packs, the aerial photography after each CES event, the geological maps, soil maps, historical land use maps and historical drainage maps would also be reviewed electronically through the CGD viewer.

10.2.3 Regional Assessment (Task 1 in Figure 8.5)

As discussed in Section 8.3.1, for each pack a regional assessment of information was undertaken in order to understand regional visual patterns and potential sources of error relevant to the assessment of liquefaction vulnerability and change in vulnerability. For each information source, the engineer undertaking the assessment would note relevant information on the Stage 2 packs that was not always evident in the zoomed in views provided in the ILV assessment packs.

The information used for the regional review of the Stage 2 assessments was provided in the form of A1 hardcopy maps. The maps used in the Stage 2 assessment process are provided on A4 at 1:60,000 scale at A3 in **Appendix K**. In addition to the maps discussed in Section 8.3.1 the maps reviewed in the regional data analysis for Stage 2 included:

- **Median normalised CPT tip resistance (q_{C1N}) for the top 5m of the ground profile –** These maps were used to understand the spatial variability in q_{C1N} in the top 5m of ground and the effect this may have on the estimated LSN value.[9] Typical questions that would be considered when reviewing these maps was:

[9] Note that these maps were only considered in conjunction with the I_c discussed below. Where $I_c > 2.6$ the q_{C1N} values are not meaningful and as such are not used.

- Are there spatial transitions between high q_{C1N} and low q_{C1N} values indicating a geological change from loser/softer soils to denser/stiffer soils in the area of the assessment pack?
- Do the areas with low and high q_{C1N} spatially coincide with areas of similar land performance in the area of the ILV assessment pack?

- **Median I_c values at 1m thick layers for the top 5m of the ground profile –** These maps were used to understand the the spatial variability of I_c over the top 5m of ground. Typical questions that would be considered when reviewing these maps were:
  - Are there spatial transitions between low I_c and high I_c values indicating a geological transition change from sandy/silty soil behaviour to silty/clayey soil behaviour in the area of the assessment pack?
  - Do the areas with low and high I_C spatially coincide with areas of similar land performance in the area of the ILV assessment pack?
  - Will adjustments to the I_c cutoff value result in changes to the way in which LSN is estimated (where supported by laboratory test data)?
  - Will adjustments to the FC-I_c correlation change the way LSN is estimated (where supported by laboratory test data)?
- **Depth to the first soil layer greater than 0.5m thick with a q_c of more than 20MPa –** These maps were used to investigate whether or not the area under consideration is underlain by dense soil layers or if the CPT trace extends for the full 10m length in looser/softer soils. A typical question that would be considered when reviewing these maps was:
  - In the area under consideration, is the depth to dense soils spatially coinciding with areas of similar land performance?
- **Sensitivity analysis of LSN to PGA based on the median groundwater surface for a M_W 6.0 earthquake –** This was undertaken for PGA values of 0.28, 0.3 and 0.32g and was used to understand the spatial sensitivity of the LSN parameter to minor changes in PGA either side of M6 0.3g. Typical questions that would be considered when reviewing these maps were:
  - Does a small change in PGA within the pack area significantly change the estimated LSN value?
  - Does this change in the estimated LSN value indicate that small changes in soil properties significantly change the estimated LSN near the M6 0.3g levels of earthquake shaking? This was particularly important near transition zones between properties which qualify for ILV and properties which do not qualify for ILV.
- **Sensitivity analysis of LSN to P_L based on the median groundwater surface for M6 0.3g levels of earthquake shaking –** This was undertaken for P_L values of 15%, 50% and 85% and was used to understand the uncertainty associated with liquefaction triggering and therefore the estimated LSN parameter. Typical questions that would be considered when reviewing these maps were:
  - Does the area under consideration still cross the LSN indicator values for ILV qualification at P_L = 50% and P_L = 85%?
  - Do the P_L = 50% and P_L = 85% LSN values better reconcile with the observed land damage in the area where the LSN P_L = 15% were not reconciling (i.e. over and under prediction)?
- **Correlation of the liquefaction susceptibility parameter (Bray & Sancio, 2006) with I_c based on CPT data paired with laboratory test data –** This map was used to investigate the correlation between I_c cutoff values and Bray and Sancio (2006) liquefaction susceptibility

criteria derived from laboratory test results. A typical question that would be considered when reviewing these maps was:

- Are the properties in areas where Bray and Sancio's (2006) liquefaction susceptibility criteria indicate that a higher or lower I_c cutoff value relative to the default I_c cutoff value of 2.6 is locally justified based on laboratory test data?

- **Correlation of FC with I_c based on CPT data paired with laboratory test data –** This is expressed as C_{FC} parameter values and was used to understand whether adopting a different C_{FC} value is justified by the FC-I_c correlation derived from nearby laboratory test data. A typical question that would be considered when reviewing these maps was:
  - Is the data pack in an area where a higher or lower value of C_{FC} value relative to the default C_{FC} value of 0 could be locally justified based on laboratory test data?
- **Sensitivity analysis of LSN to different FC-I_c correlations (expressed as C_{FC} parameter) and I_c cutoff values –** This map was used to understand the sensitivity of the LSN value to adjusting the C_{FC} and I_c cutoff values. This was based on the median groundwater surface for combinations of C_{FC} (0 and 0.2) and I_c cutoff values (2.4, 2.6 and 2.8). A typical question that would be considered when reviewing these maps was:
  - Will changes to the C_{FC} and I_c cut off values, as justified by laboratory test data, cause the estimated LSN value in the area to cross the LSN and ΔLSN indicator values for ILV qualification?

10.2.4 Assessment of Ground Surface Subsidence in areas with Insufficient LiDAR

As discussed in Section 9.2.6.2, there is one large residential development in Northwood where earthworks occurred between 2003 (when the pre-CES LiDAR was flown) and the September 2010 event. In addition, the post-September LiDAR was not flown in this area despite the September 2010 event being the main CES event that caused land damage and potential liquefaction related subsidence in that area.

Following a review of the available data, the size of the area with insufficient LiDAR was reduced to properties which had observed land damage following the September 2010 event and would most likely satisfy *Criterion 1*. Without knowing the amount of ground surface subsidence which has occurred on a property, ΔLSN could not be estimated in this area.

In order to estimate the ground surface subsidence for the remaining properties with insufficient LiDAR, council records were reviewed for surveyed locations within the area of interest. The objective of this review was to use the as-built surveys of the area (undertaken following its development for residential use) to provide a baseline level for point estimates of the ground surface subsidence in this area. This would then be used to assist with the development of a suburb wide estimate of the ground surface subsidence in the area.

Unfortunately the number of surveyed Reduced Level (**RL**) locations was insufficient to estimate the likely ground surface subsidence within the area. Therefore, nearby areas with similar observed land performance, similar observed levels of earthquake shaking during the CES and similar ground conditions were identified. The estimated ground surface subsidence for the area with insufficient LiDAR was then assumed to be similar to these nearby areas.

Once the likely ground surface subsidence for this area was estimated (as demonstrated in worked example 4 in Section 10.3.2) the ILV assessment was undertaken using the same process as was applied for other Stage 2 properties.

10.2.5 Local and Specific Assessment (Tasks 2 and 3 in Figure 8.5)

In a similar manner to the regional analysis described in Section 10.2.3, the engineer undertaking the ILV assessment would review the local maps and notes about the relevant information in the assessment report associated with the pack. These notes were used as reference for both the assessing engineer while doing the assessment and the senior geotechnical engineers while undertaking the technical review.

In addition to the ILV manual assessment process (summarised in Figure 8.6 and described in Section 8.3) the Stage 2 specific analysis included additional interrogation of the available geotechnical investigation data and consideration of potential modifications to the input parameters for the estimation of LSN (where supported by laboratory test data). These additional analyses and considerations of the ILV assessment process are listed below:

- **Interrogation of the CPT output values of q_c and I_c –** Variation in q_c and I_c were considered both spatially and by grouping multiple CPT traces together typically based on areas with similar mapped characteristics. These grouped CPT traces were then plotted against depth.

  The spatial grouping was initially considered by reviewing the maps of the q_{c1N} and I_c values. These maps showed the median values over a 1m thick layer from 0 to 5m below the ground surface. Reviewing the spatial distribution of q_{c1N} and I_c helped the assessing engineers to understand any spatial patterns in the sub-soil profile and thereby explain any variability observed in the liquefaction vulnerability parameters relative to the mapped land damage from the CES events.

  It is noted that q_{c1N} was used in these maps so that the q_c for each 1m layer thickness (in conjunction with the I_c maps) could be directly compared to the Boulanger and Idriss (2014) CRR vs q_{c1N} curves. This enabled the assessing engineer to develop a spatial overview of whether or not the layers are likely to liquefy at the corresponding M6 0.3g CSR values.

  While reviewing the spatial distribution of q_{c1n} and I_c provided some understanding of the variation of these parameters with depth, further insight can be gained by plotting groupings of individual traces of q_c and I_c against depth. Typically these plots were grouped according to land damage patterns with the CPT traces coloured according to the classifications used for the CPT provided in Table 8.1.

  An example of these CPT trace plots is provided in Figure 10.2. In this example the CPT traces plotted in red are those that were classified as ✓, the traces plotted in blue are those that were classified as × and the traces plotted in green are those that were classified as NC based on the classifications provided in Table 8.1.

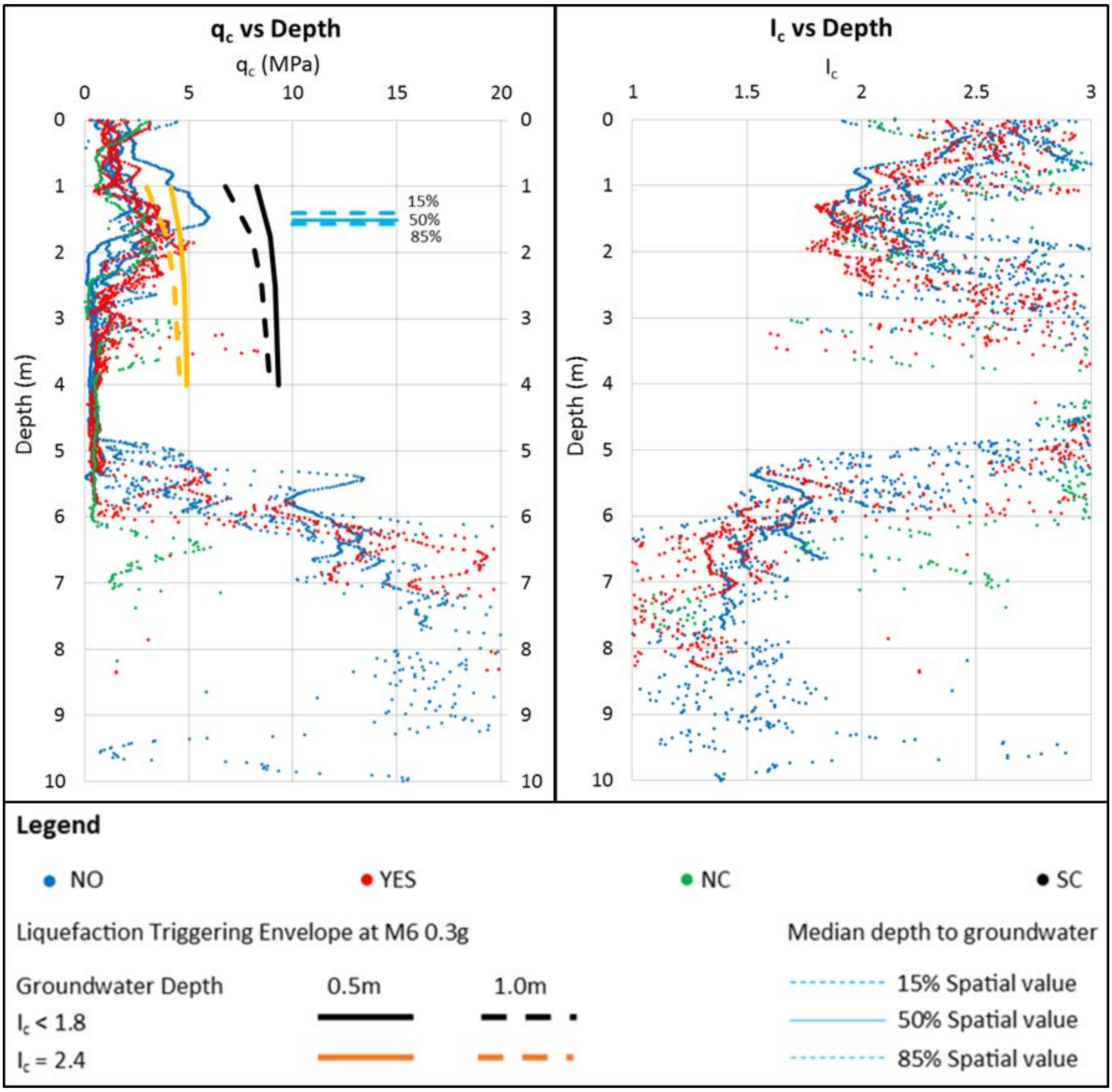


Figure 10.2: Example showing plots of q_c and I_c vs depth for CPTs grouped by CPT classifications provided in Table 8.1.

The black lines on the q_c plot are curves that represent envelopes for liquefaction triggering for an I_c value of less than 1.8 at M6 0.3g levels of earthquake shaking. The development of these envelope curves is discussed in **Appendix A**. q_c values, with corresponding I_c values of less than 1.8, to the left of these curves are predicted to liquefy. q_c values, with corresponding I_c values of less than 1.8, to the right of these curves are not predicted to liquefy. The solid line represents a GWD of 0.5m and the dashed line represents a GWD of 1m.

The indicative depth of the median groundwater surface is also indicated on Figure 8.2 as horizontal lines on the q_c vs. depth plot. It is important to note that these percentiles represent the spatial distribution of the depth to the median groundwater surface.

Interrogation of these CPT traces indicates relatively consistent soil ground conditions within the grouped CPT. The key difference between those classified as ✓ and those classified as × are that the ✓ CPT traces characteristically have slightly lower q_c and I_c values than the × CPT traces. For q_c this is particularly apparent between the critical depth of 1m and 2m below the ground surface.

This method is also useful for determining cases in areas where less severe land damage was observed relative to adjacent areas with similar estimated LSN values where more severe land damage was observed (i.e. where LSN was over predicting vulnerabiity compared with observed land damage). These analyses involved plotting the q_c and I_c traces for areas with similar land performance (at similar levels of earthquake shaking) with the same colours so that the CPT traces for the two areas could be differentiated. Often these analyses showed that the over prediction of LSN was in areas where the ground profile was comprised of a highly interbedded sequence of liquefying and non-liquefying soils. The use of these plots is discussed in the worked examples provided in Section 10.3.

- **Modification of the I_c cutoff liquefaction vulnerability input parameter –** If the assessing engineer considered that the LSN parameter was potentially over-predicting or under-predicting liquefaction vulnerability relative to land damage observations, consideration was given as to whether or not the liquefaction susceptibility of the soils were being appropriately estimated. This was based on review of the available laboratory test data for the geological unit of interest in the surrounding area.

  As discussed in Section 3.3, an I_c value of less than 2.6 is typically indicative of soils that are likely to be susceptible to liquefaction (Robertson & Wride, 1998). Studies undertaken by Lees et al (2015) found that this is an appropriate value to adopt for Christchurch soils.

  However, while these studies determined that a median I_c cutoff value based on the entire CPT data set was appropriate for the Christchurch area, there was localised variation. As such, in localised areas for particular soil layers a higher or lower value of I_c cutoff value could be more appropriate. Further discussion regarding I_c cutoff and its correlation to the Christchurch soils is provided in **Appendix A**.

  The spatial distribution of laboratory test data could be determined by reviewing the local maps which show the correlation of the liquefaction susceptibility parameter (Bray & Sancio, 2006) with I_c based on CPT data paired with laboratory test data. If there was laboratory test data in close proximity to the CPT under consideration then engineering judgement was used to determine whether or not this data was likely to be representative of the soil parameters at the CPT locations of interest. If the liquefaction susceptibility parameter indicated that an alternate I_c cutoff value could provide a more appropriate estimation for liquefaction susceptibility the assessing engineer would rerun the CPT liquefaction vulnerability analysis with this alternate input value as shown in Figure 8.8.

  It is important to note that not all soils are sensitive to adjusting the I_c cutoff value. A quick assessment of the sensitivity of the LSN parameter can be undertaken by reviewing the regional LSN sensitivity to I_c and C_{FC} maps discussed in Section 10.2.3. If these maps indicate that the LSN parameter is insensitive to changes in the I_c cutoff value further investigation is futile. If this is the case alternate means of reconciling the LSN parameter with the other information will need to be investigated.

  Worked example 3 in Section 10.3 demonstrates a case where an alternate I_c cutoff parameter has been used (based on supporting laboratory test data) for the assessment of ILV.

- **Use of the C_{FC} liquefaction vulnerability input parameter** – If the assessing engineer considers that the LSN parameter is potentially over-predicting liquefaction vulnerability relative to land damage observations, consideration could be given as to whether or not the liquefaction triggering of the soils were being appropriately estimated.

  As discussed in Section 3.4, when using the Boulanger and Idriss (2014) liquefaction triggering methodology the FC of the soil being assessed can be obtained from laboratory testing or alternately approximated from I_c. To make this approximation site specific, calibration using the C_{FC} parameter is recommended.

Lees et. al. (2015) found that adopting the default C_{FC} of 0 provided an appropriate upper bound for the prediction of liquefaction triggering in the Christchurch area. Because C_{FC} of 0 is an upper bound value, the effect of the C_{FC} parameter was only considered for cases where the LSN parameter was over predicting liquefaction vulnerability relative to the observed land damage.

Similar to the I_c cutoff value, the C_{FC} parameter was only used if laboratory test data was in close proximity to the CPT under consideration. Engineering judgement was then used to determine whether or not this data was likely to be representative of the soil parameters at the CPT locations of interest. The spatial distribution of laboratory test data could be determined by reviewing the local maps which show the correlation FC with I_c based on CPT data paired with laboratory test data.

As described in Section 8.3.2.2, in a similar way to the use of the P_L parameter, the C_{FC} parameter can be used to understand the uncertainty associated with liquefaction triggering and vulnerability. If the laboratory test data indicated that a C_{FC} value of 0.2 is more appropriate for estimating FC then the estimated LSN value was more likely to be an over estimate of liquefaction vulnerability at the site.

10.2.6 ILV Qualification Assessment (Task 4 in Figure 8.5)

Parts 4 and 5 of Figure 10.1 summarise the approach applied to the qualification of Stage 2 ILV properties. Essentially, the qualification of properties with ILV in Stage 2 is the same as that applied to Stage 1. That is, in order for a property to qualify for ILV, as determined by engineering judgement, it must satisfy both *engineering criteria*. The key difference with the Stage 2 assessments is that the decisions being made were either Marginal or Complex (as described in Section 9.2.6.1) unlike the much simpler Stage 1 assessments.

The primary objective of adopting a two stage assessment process was to ensure that these complex and marginal cases were resolved in a consistent manner with a balanced approach in accordance with the objectives of the ILV Assessment Methodology. There were a number of advantages to holding back the more complex decisions for further manual assessment. These advantages were:

- The experience gained while undertaking the Stage 1 ILV assessment across the wider Christchurch area the assessing engineers were able to calibrate themselves on clear yes and no ILV decisions;
- The engineers undertaking the assessments became more familiar with the inherent limitations of the available information. For example, the accuracy and limitations of the difference DEMs, the accuracy and limitations of the groundwater surfaces and the uncertainty associated with the estimated levels of earthquake shaking when interpreting the observed land performance from the main CES events;
- The engineers undertaking the assessments became familiar with the accuracy and limitations of the LSN parameter and locations where it does and does not reconcile well with the land damage observations throughout Christchurch;
- It provided sufficient time to undertake liquefaction vulnerability sensitivity studies with respect to the sensitivity to PGA, I_c cutoff, C_{FC} and P_L; and
- The surrounding simpler Stage 1 decisions provided the spatial context for the pockets of Stage 2 properties which required further assessment.

Following the completion of the local and specific assessments (i.e. Tasks 2 and 3 in Figure 8.5), the application of the *engineering criteria* for some of the complex cases the ILV decision was now clear (as indicated in Figure 10.1). These properties were assessed as either qualifying or not qualifying for ILV. However, there were still other marginal cases where the decision remained unclear, and other factors (listed in Section 10.2.1) needed to be considered to resolve these cases.

10.3 Stage 2 Worked Examples

To demonstrate the engineering assessment process, worked examples from portions of five different packs are included in supplementary material prepared for the peer reviewers called **"Worked Example Material"**. Summaries of each of these four worked examples are included in this Section.

In addition a fifth worked example has been provided in both summary form and as a full ILV assessment pack in **Appendix L** and the **Worked Example Material** respectively. The purpose of this worked example is to demonstrate the determination of the ILV qualification status for marginal cases and cases with variable prediction of land performance. This worked example is presented in **Appendix L** because it is significantly longer than the other worked examples.

The summaries include the following:

- The reasons why the properties in the examples were assessed as Stage 2 requiring further manual assessment;
- The purpose of including each of these as worked examples in this report; and
- The results of the Stage 2 assessment process with the pertinent reasons for these outcomes.

The five worked examples have been chosen because they demonstrate typical examples of cases where:

- That the Stage 1 approach provides the same outcome as the Stage 2 approach for the properties assessed as qualifying or not qualifying in the Stage 1 process (worked example 1);
- The over prediction of liquefaction vulnerability by the LSN parameter relative to the land damage observations through the CES (worked example 2);
- The resolution of geological and topographic issues (worked example 3);
- The use of laboratory data to modify the default input parameters for CPT-based liquefaction triggering and vulnerability (worked example 3);
- The determination of the ILV qualification status for properties with insufficient LiDAR to determine the ground surface subsidence as a result of the CES (worked example 4); and
- The determination of the ILV qualification status for marginal cases and cases with variable prediction of land performance (worked example 5).

The locations of the five Stage 2 worked examples is shown in Figure 10.3.

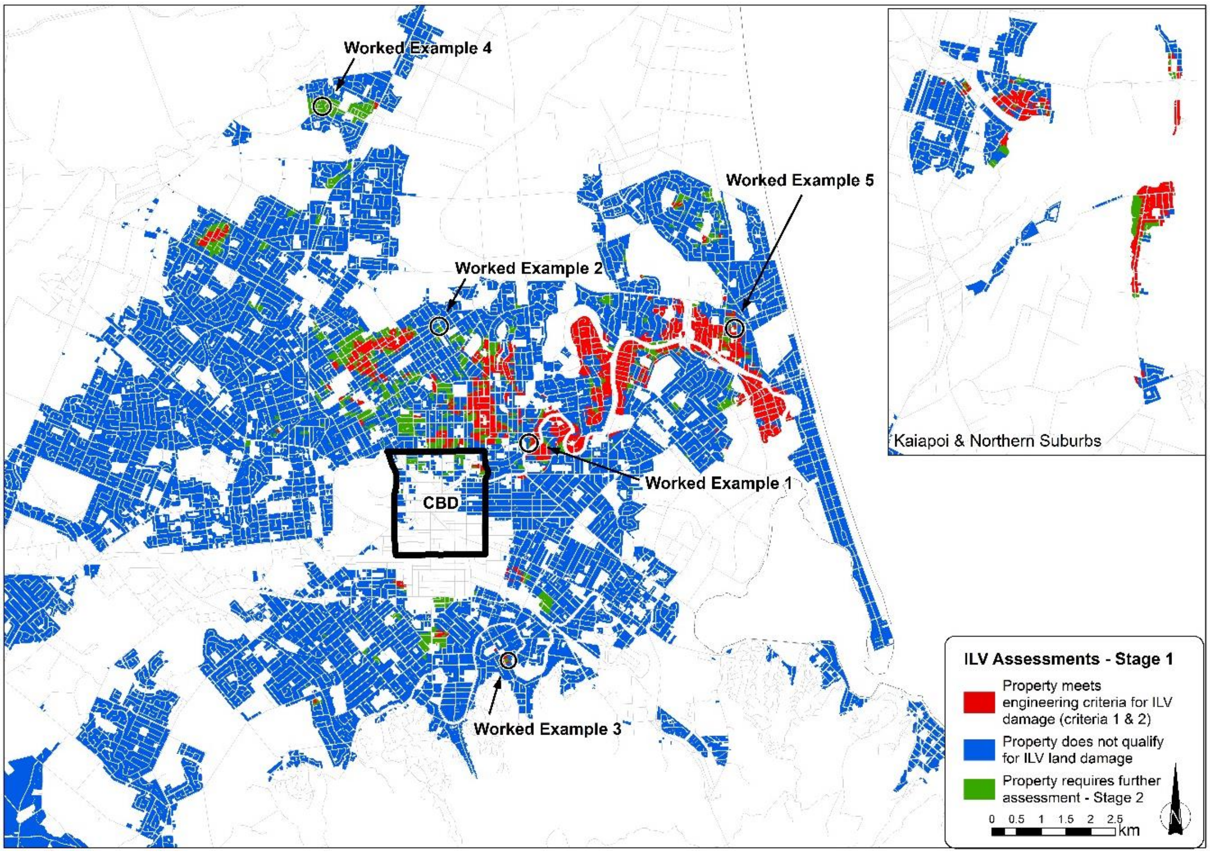


Figure 10.3: ILV assessment results at the completion of Stage 1 (refer to Figure 9.5) showing the Stage 2 worked example locations.

10.3.1 Worked Examples which are Marginal or Complex

The purpose of the three worked examples in this section is to show a range of characteristic issues encountered, demonstrate how these issues were resolved and show how the ILV status for each property was determined using the Stage 2 ILV assessment process.

Worked Example 1 - Richmond

The Stage 2 property in this worked example required further manual assessment because the property was in a transition zone between properties clearly qualifying and clearly not qualifying for ILV and it was not apparent as part of the Stage 1 assessment process whether this property would clearly satisfy both *engineering criteria* for ILV qualification.

The purpose of this worked example is to demonstrate an assessment where engineering judgement is used to classify a property that transitions between properties clearly qualifying and not qualifying for ILV.

Stage 1 Assessment

The property in this worked example was identified in the pack used as the Stage 1 worked example (Section 9.3). The properties surrounding the Stage 2 property were also re-assessed for ILV using the Stage 2 assessment process to demonstrate the consistency of the qualification process in both Stage 1 and Stage 2.

Stage 2 Assessment

The automated ILV model indicates that this Stage 2 property is unlikely to qualify for ILV. However, based on manual assessment, the decision for this Stage 2 property overturned the automated ILV model outcome and hence the property has been assessed as qualifying for ILV.

The full example pack including discussion and analysis of all the information listed in Section 10.2.2 along with the regional, specific and local analyses (described in Sections 10.2.3, 10.2.4 and 10.2.5 respectively) is included in the **Worked Example Material**. This full pack demonstrates the complete process for determining the ILV decision of this property. A summary of the pertinent reasons for this ILV assessment outcome are as follows:

- **Regional Assessment (Task 1) –** The observed land damage maps indicate a transition from land which has performed well during the CES to the west of the assessed area to land which has performed poorly during the CES to the east of the assessed area. The transition zone is indicated on the maps in Figure 10.4. The elevation map shows a topographic transition from land to the west which sits higher than the land to the east. This lower lying area indicates shallower groundwater and potentially a thinner non-liquefying crust. There are no apparent LiDAR error bands over the assessment area which indicates that there is no local bias in the LiDAR derived ground surface subsidence model. Most of these trends can be observed in Figure 10.4.

  The additional regional maps produced for the Stage 2 process do not provide any useful additional information that is pertinent to this worked example.

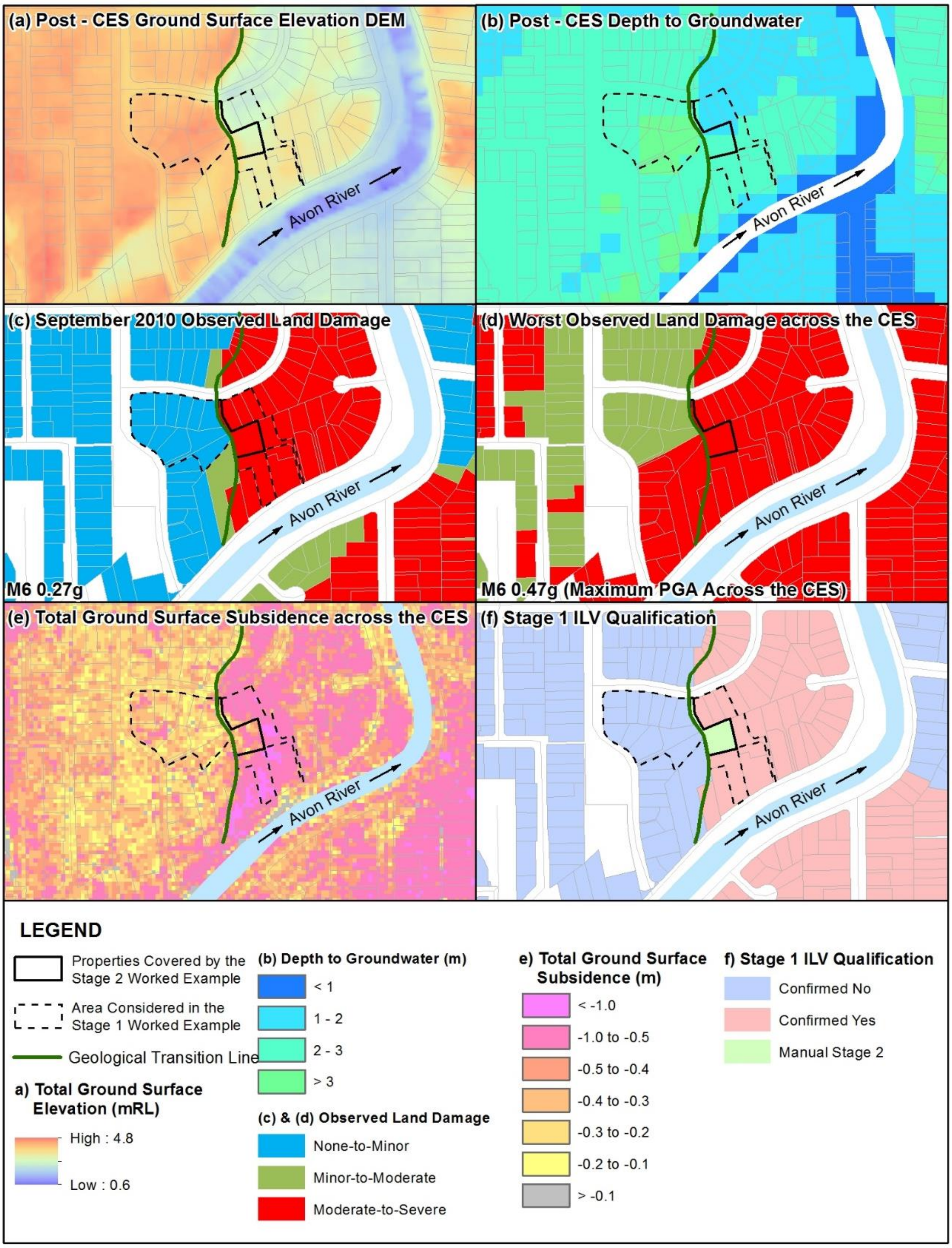


Figure 10.4: A series of maps used when assessing a cluster of properties around 12 Flesher Ave, Richmond, for the Stage 2 qualification process. (a) post-CES ground surface elevation; (b) post-CES depth to groundwater surface; (c) September 2010 observed land damage; (d) worst observed land damage across the CES; (e) total ground surface subsidence across the CES; (f) Stage 1 ILV qualification results.

- **Local and Specific Assessment (Task 2 and 3) –** The Stage 2 property in this example (the property shaded green in Figure 10.4f) is situated between properties which are clearly qualifying and not qualifying for ILV. The automated ILV model result indicates that the remaining Stage 2 property does not qualify for ILV (refer to the **Worked Example Material**) but the observed land damage and ground surface subsidence maps indicate significant levels of land damage.

Review of the area indicates that this property sustained severe observed land damage in the September 2010 event. This event was equivalent to M6 0.27g levels of earthquake shaking using the Idriss and Boulanger (2008) MSF. The LDAT report for the property records severe lateral spreading with a vertical offset 80-220mm.

All but one of the CPTs and boreholes are coded as either a ✓ or a × based on whether or not the CPT location meets the ILV *engineering criteria* and are shown in Figure 10.5. The CPT labelled with a ? is not considered because the raw file uploaded to the CGD contains q_c and f_s values but no associated depth. These CPT codes are plotted on the subsidence map as shown on Figure 10.5.

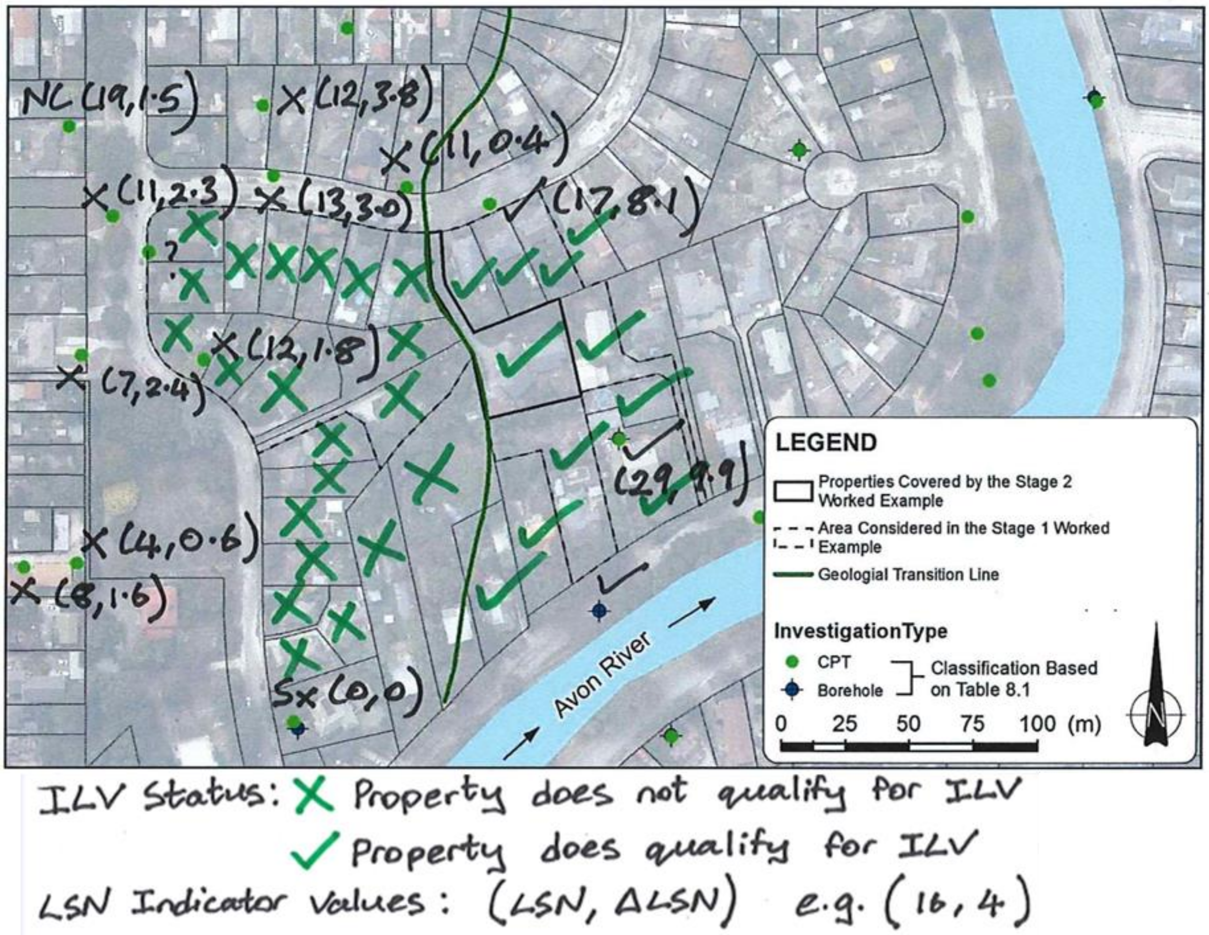


Figure 10.5: The location and classification of the CPTs and boreholes and the ILV qualification of the properties for the Stage 2 manual assessment pack around 12 Flesher Ave, Richmond.

Review of the median and mean LSN maps in the ILV assessment pack (refer to the **Worked Example Material**) shows that the property requiring Stage 2 assessment has estimated median and mean LSN of between 16 to 18. While this is greater than the indicator value of 16 for material liquefaction vulnerability (refer to Section 7.4), these LSN values are lower than the likely LSN value for a property with moderate-to-severe land damage as recorded in the September 2010 event (M7.1 0.20g).

Review of the median and mean ΔLSN maps in the ILV assessment pack (refer to the **Worked Example Material**) shows that this property has estimated median and mean ΔLSN of less than 4. This is less than the indicator value of 5 for material change in liquefaction vulnerability (refer to Section 7.5). This does not reconcile well with the relatively high levels of ground surface subsidence observed on this property throughout the CES.

Therefore, on the basis of the review of the available data, this property was assessed to be a complex case due to under prediction of liquefaction vulnerability and change in liquefaction vulnerability as a result of the ground surface subsidence caused by the CES (Part 3 Figure 10.1).

Review of the post-CES ground surface elevation (Figure 10.4a) indicates that the property is located on a similar elevation to the CPTs to the east which are classified as ✓. Similarly the land damage observations during the September 2010 event (Figure 10.4c) indicate similar performance to the properties with ✓ CPTs to the east.

The total ground surface subsidence across the CES (Figure 10.4e) indicates less ground surface subsidence has occurred on this property relative to the properties with ✓ CPTs. However the high density of the vegetation on the property indicates that this could be attributed to localised error in the difference DEM models. The difference DEM is potentially under estimating the actual ground surface subsidence of this property resulting in a lower automated ΔLSN value for the property. The total ground surface subsidence is most likely similar to the ground surface subsidence on the adjacent properties on the eastern side of the transition line indicated on Figure 10.4e.

In addition the linear interpolation in the automated ILV model for estimating ΔLSN values on the property is being unduly influenced by the × CPTs to the west of the property. The ground surface elevation, depth to groundwater and land damage performance of the property is most appropriately characterised by the ✓ CPT to the east of the property.

- **ILV Qualification Assessment (Task 4) –** Comparison of the CPT ✓ and × classifications shown in Figure 10.5 with the CES ground surface elevation, depth to groundwater, September 2010 observed land damage, worst observed land damage across the CES and total ground surface subsidence maps shown in Figure 10.4 indicate good spatial agreement.

  The CPTs identified with a × are all located on land with a higher elevation and deeper depth to groundwater (i.e. a thicker non-liquefying crust). They are also on land which has performed well following the September 2010 levels of shaking (roughly equivalent to an M6 0.3g levels of earthquake shaking) and only subsided by around 0.2 to 0.3m.

  Conversely, the CPTs identified with a ✓ are located on land with a lower elevation and shallower depth to groundwater (i.e. a thinner non-liquefying crust). They are also on land which has performed poorly following the September 2010 levels of shaking (roughly equivalent to 0.3g M6 levels of earthquake shaking) and subsided around over 0.5m.

  The automated ILV model map is supported by the CPT codes which are plotted on the subsidence map. Therefore, most of the properties in the assessment area are qualified with either a ☑ or an ☒ as per the automated ILV model as shown in Figure 10.5. Thus the outcome from the Stage 2 process is consistent with the qualifications made during the Stage 1 process.

  Based on the detailed review during the local and specific analysis the Stage 2 property clearly satisfies *Criterion 1*. The difference DEM and the automated model are judged to be under predicting change in vulnerability for this property. Furthermore the properties to the east of the transition zone all qualify for ILV (i.e. surrounding clear ILV decisions) and have performed similarly during the CES events.

  Therefore, once these factors are considered, based on engineering judgement it was determined, on the balance of probabilities, that this Stage 2 property also satisfies *Criterion 2* and therefore also qualifies for ILV land damage as indicated by the ☑ on this property in Figure 10.5.

Worked Example 2 - Mairehau

The Stage 2 properties in this worked example required further manual assessment because the liquefaction vulnerability analyses at the CPT locations within the area were resulting in variable LSN values.

The purpose of this worked example is to demonstrate the use of engineering judgement to undertake the ILV assessment of a group of Stage 2 properties where the ground conditions are complex and the land damage observed during the earthquakes did not conclusively demonstrate whether the land was materially vulnerable to liquefaction. This example is also a case where the qualification decision was not clear and demonstrates the use of some of the additional considerations for ILV qualification for marginal cases (listed in Section 10.2.1).

Stage 1 Assessment

The CPTs with the higher estimated LSN values (i.e. with LSN values greater than 16) were dispersed through the area of Stage 2 properties. The maximum estimated levels of earthquake shaking (M6 equivalent) occurred during the February 2011 event and were just above the M6 0.3g levels of shaking at which the ILV assessments are undertaken. All the other main CES events had levels of shaking less than the M6 0.3g assessment level. There was no corresponding mapped land damage for those events in the area and only the February 2011 event caused small localised areas with some minor-to-moderate land damage. Therefore, these Stage 2 properties could be considered as potentially not satisfying *Criterion 1* based on observed land performance.

However, in this area the CES caused 0.3 to 0.5m of ground surface subsidence. As a result the predicted liquefaction vulnerability in the area has potentially increased, and it could not be clearly concluded that the observed land performance was a good indicator for future performance. It was therefore unclear during the Stage 1 process whether or not *Criterion 1* was or was not satisfied, and these properties were included in the Stage 2 assessment process.

Stage 2 Assessment

These properties are in an area where organic silty peat layers are near to the ground surface. This soil type may result in over-prediction of liquefaction triggering and liquefaction vulnerability, and in turn lead to the automated ILV model indicating that properties in the area are likely to qualify for ILV. Based on manual assessment, the automated ILV assessment for all the Stage 2 properties in this area were overturned and are assessed as not qualifying for ILV.

The full example pack including discussion and analysis of all the information listed in Section 10.2.2 along with the regional, specific and local analyses (described in Sections 10.2.3, 10.2.4 and 10.2.5 respectively) is included in the **Worked Example Material**. This full pack demonstrates the complete process for determining the ILV decision of these properties. A summary of the pertinent reasons for this ILV assessment outcome are as follows:

- **Regional Assessment (Task 1) –** Unlike worked example 1, there are no apparent regional features indicating geological transition zones. Geological maps suggest this area is underlain by alluvial sand and silt with interbedded layers of peat (Brown & Weeber, 1992). This is supported by the historical land use maps available on the CGD showing that the land in this area previously bordered an area of swamp where surface water was often present (MBIE, 2012).

  The observed land damage maps indicate consistent land performance throughout the CES with no damage observed for all events except for some isolated patches of minor-to-moderate land damage for the February 2011 event where the levels of earthquake shaking were just above the M6 0.3g ILV assessment level as shown in Figure 10.6.

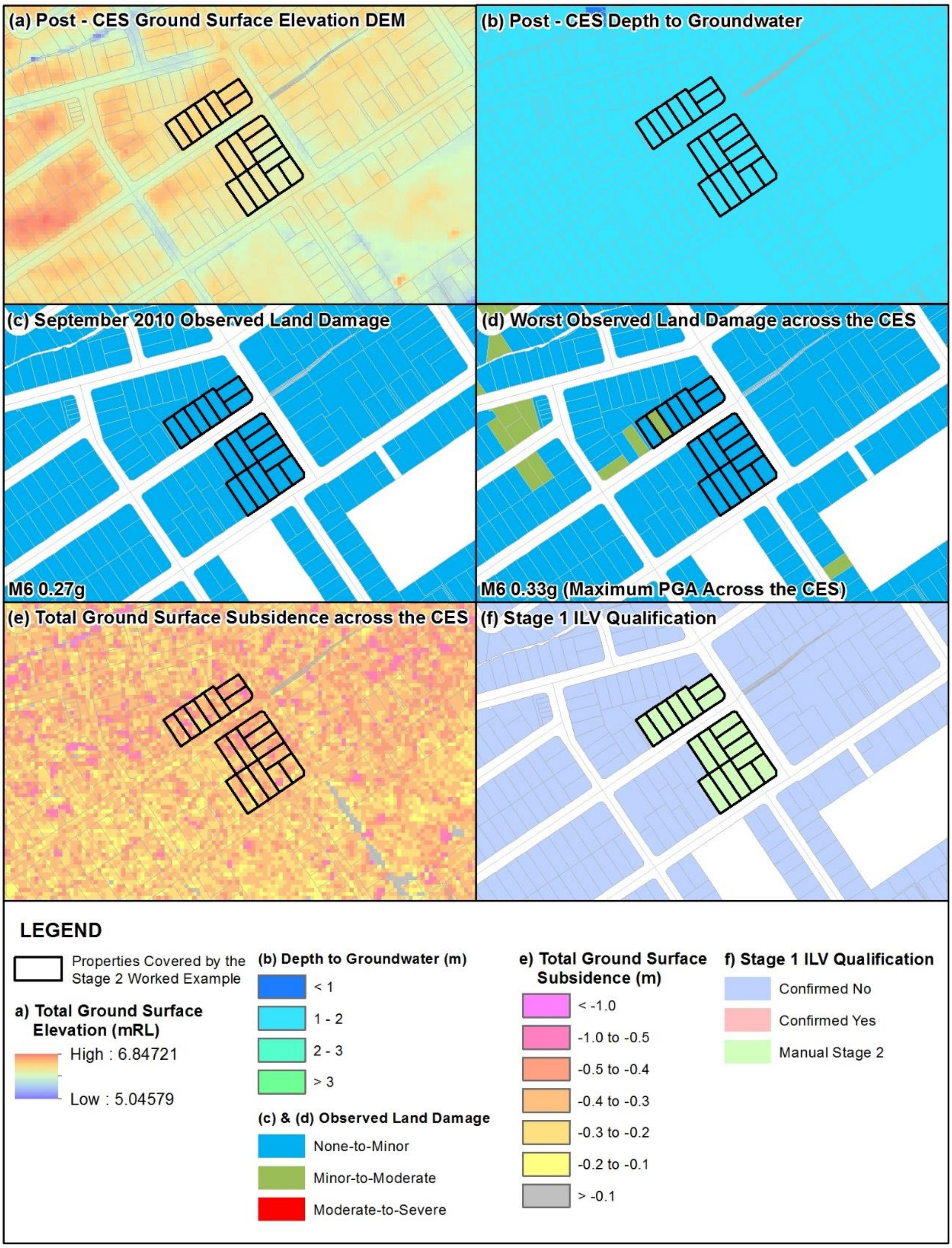


Figure 10.6: A series of maps used when assessing a cluster of properties in the suburb of Mairehau for the Stage 2 qualification process. (a) post-CES ground surface elevation; (b) post-CES depth to groundwater surface; (c) September 2010 observed land damage; (d) worst observed land damage across the CES; (e) total ground surface subsidence across the CES; (f) Stage 1 ILV qualification results.

The ground surface elevation map shows that the land around the Stage 2 properties is reasonably flat and the depth to the median groundwater surface is between 1 to 2m below the ground surface throughout the area. The area has typically subsided between 0.3 to 0.5m across the CES based on the difference DEM models. Although there is a small NEE-SWW LiDAR error band over the area over-estimating the ground surface subsidence, this error is assessed as being less than 0.1m.

The additional regional maps produced for the Stage 2 process do not provide any additional information that is pertinent to the reasons for the ILV decisions in the worked example.

- **Local and Specific Assessment (Task 2 and 3) –** Some isolated patches of minor-to-moderate land damage were mapped for the February event. The February event had levels of earthquake shaking just above the M6 0.3g ILV assessment level (refer to Figure 10.6d). In addition the LDAT report records indicate some minor differential ground surface settlement has occurred as a result of the CES on some of the Stage 2 properties with CPTs on them (refer to Figure 10.7).

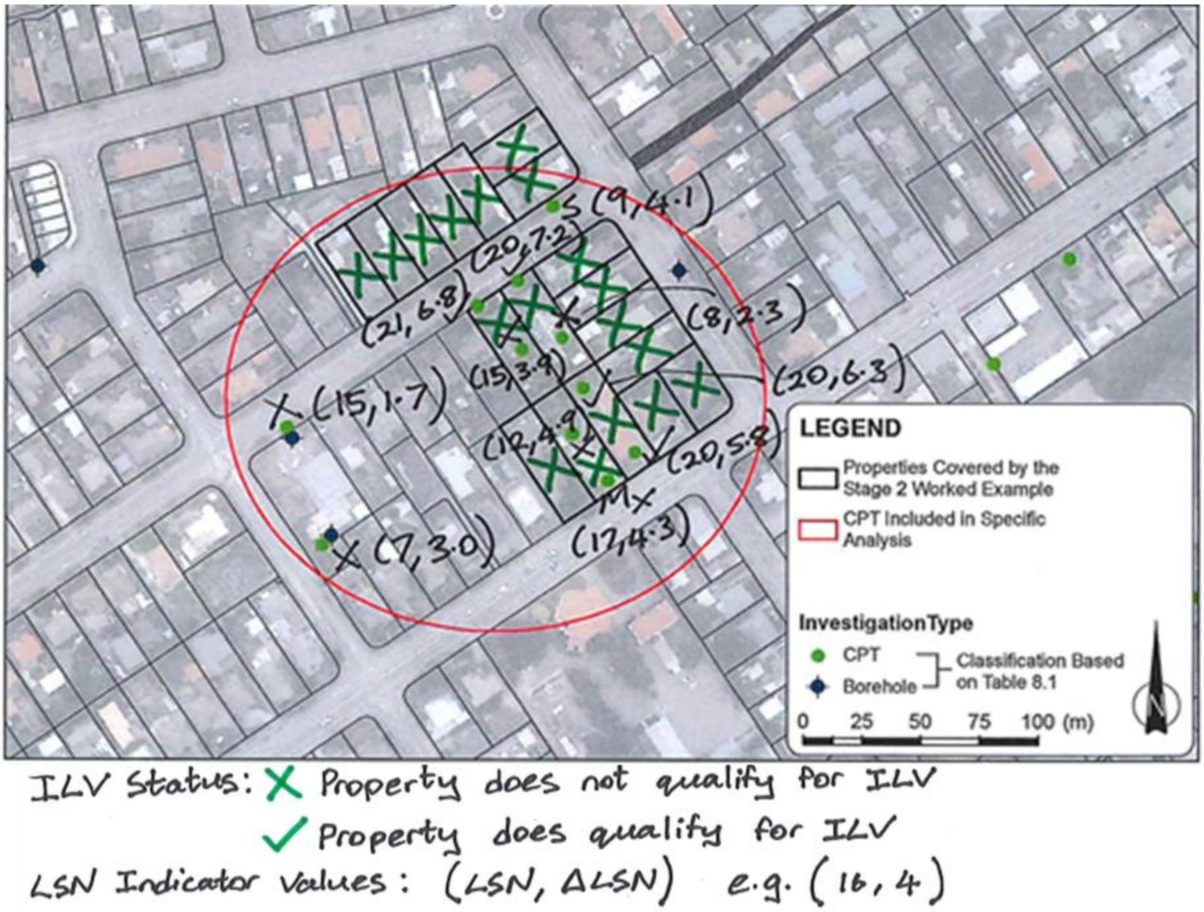


Figure 10.7: The location and classification of the CPTs and boreholes and the ILV qualification of the properties for the Stage 2 manual assessment pack around the suburb of Mairehau.

The automated ILV model shows variable decisions indicating the northern and south eastern properties as qualifying for ILV with the remainder of properties not qualifying or marginal (refer to the **Worked Example Material**, Figure WE2-10 for the automated ILV model). Subsurface data suggests relatively low soil density and interbedded layers of sand, silt and organic materials in the upper 5m (as shown on the q_{C1N} and I_c maps in the assessment pack in the **Worked Example Material** and the CPT traces in Figure 10.8). This is consistent with the expected soil profile of a drained swamp area as discussed in the regional analysis.

Eight CPTs in the area are clustered within four properties and have variable classification (i.e. predominantly ✓ and ✗ with one CPT classified as M/NC) with no apparent spatial trends. The remaining surrounding CPTs also have variable classification (i.e. ✓and ✗). All the CPTs classified as ✓ have estimated LSN values at M6 0.3g which are marginally over the indicator value of 16. All the CPTs within the area have a very similar profile as indicated in Figure 10.8 irrespective of their classification. The difference between a CPT being ✓ or ✗ depends on minor variation in the sequencing of the interbedded sand, silt and organic layers.

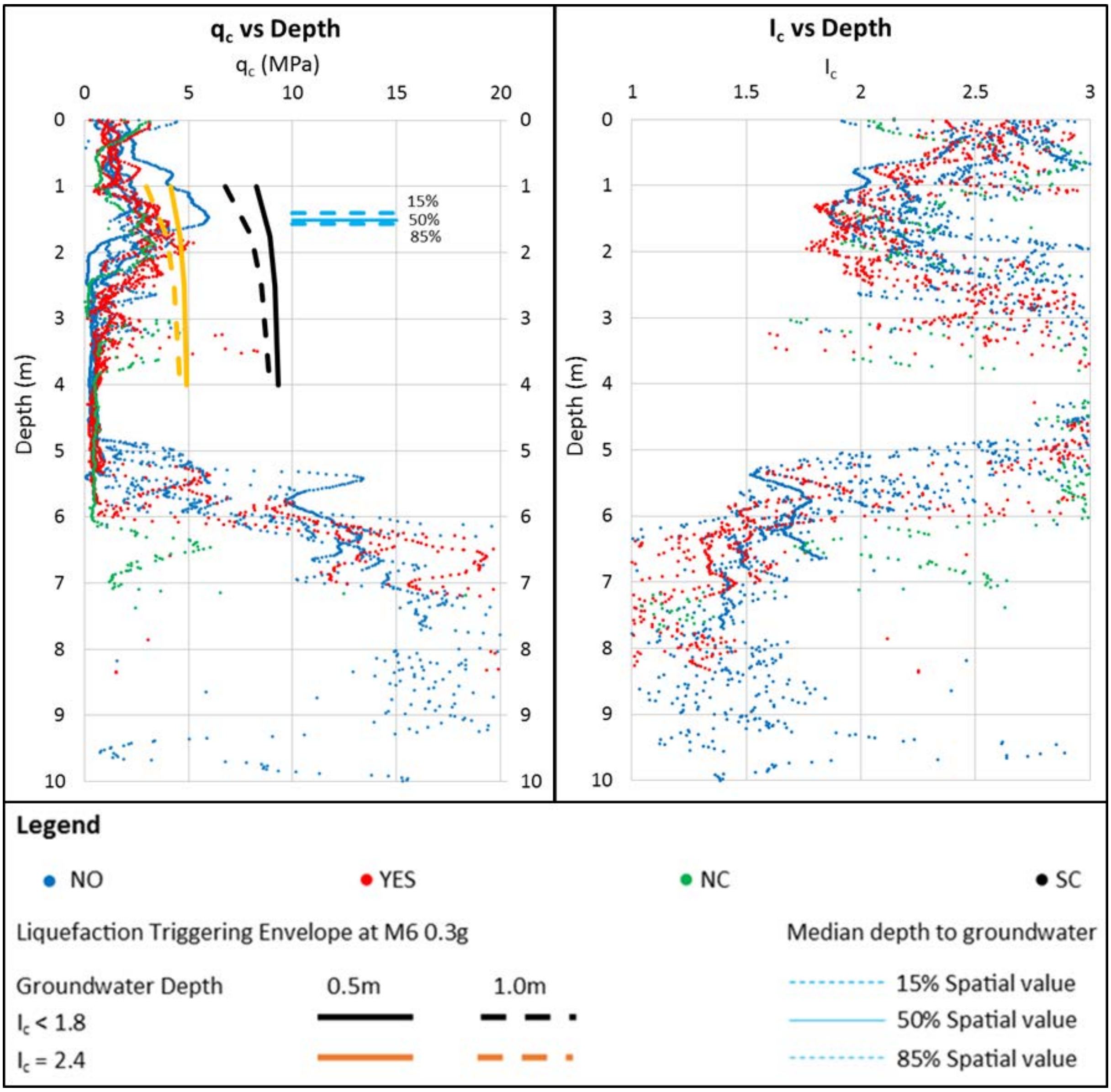


Figure 10.8: Plots of q_c and I_c vs depth for CPsT grouped by CPT classifications for the CPTs identified in Figure 10.7.

- **ILV Qualification Assessment (Task 4)** – Inspection of the borehole logs and CPT analyses indicates that the subsurface profile includes some layers of soil material where liquefaction triggering is predicted at M6 0.3g levels of earthquake shaking. Evidence for this is provided in the form of isolated ground surface manifestation of liquefaction (sand boils and differential ground surface subsidence) from the CES at these levels of earthquake shaking.

  However, these layers are not continuous across the area or even over short distances on individual properties. Therefore, these liquefying soil materials are most likely contained within lenses rather than continuous layers. The simplified one dimensional assumptions inherent in the LSN parameter (and other CPT-based liquefaction vulnerability parameters) are likely to over-estimate liquefaction vulnerability in these situations. The sequencing of these lenses varies over relatively short distances and results in varying estimated LSN values with no apparent spatial patterns.

The CPTs which are classified as a ✓ have estimated LSN values at M6 0.3g which are marginally over the indicator value of 16.

On the basis that:

– The CPTs classified as ✓ have estimated LSN values that are only marginally greater than the indicator value of 16;
– The liquefying soil layers are not continuous;
– The isolated liquefying lenses are resulting in minor isolated expression of liquefaction at the ground surface (i.e. they are not causing material liquefaction land damage); and
– The surrounding properties with similar ground surface profiles and similar land performance through the CES do not qualify for ILV;

based on engineering judgement, it was determined, on the balance of probabilities, that these properties do not satisfy *Criterion 1* - that is, they are not vulnerable to material liquefaction damage. Therefore, these properties are assessed as not qualifying for ILV and have been marked with a ⊠ on Figure 10.7 accordingly.

Worked Example 3 - St Martins

The Stage 2 properties in this worked example required further manual assessment because the automated ILV model was unable to account for the complexity of ground conditions encountered in this area.

The purpose of this worked example is to demonstrate an ILV assessment that requires the resolution of geological and topographic issues and the incorporation of site specific inputs into the liquefaction vulnerability assessment (i.e. the I_c cutoff parameter) based on applicable laboratory test data.

Stage 1 Assessment

Review of the available information shows that this complexity of ground conditions is not being captured in the automated ILV model. This complexity is a combination of a subsurface profile which is not horizontally stratified, the groundwater surface getting deeper as the ground surface slopes down towards the river and the default I_c cutoff parameter is not providing an accurate representation of the liquefaction susceptibility of the soils. This complexity was not able to be easily resolved using the Stage 1 process therefore a detailed review using the Stage 2 process was required.

Stage 2 Assessment

Review of the automated ILV model indicates that all but one of the Stage 2 properties under consideration potentially does not have ILV. As a result of the ILV Stage 2 assessment, properties which did not qualify for *Criterion 2* using the automated model have been assessed as qualifying for ILV based on engineering judgement.

The full example pack including discussion and analysis of all the information listed in Section 10.2.2 along with the regional, specific and local analyses (described in Sections 10.2.3, 10.2.4 and 10.2.5 respectively) is included in the **Worked Example Material**. This full pack demonstrates the complete process for determining the ILV decision of these properties. A summary of the pertinent reasons for this ILV assessment outcome are as follows:

- **Regional Assessment (Task 1) –** The ILV assessment pack is located on the outer side of a meander of the Heathcote River. The elevation maps indicate the Stage 2 properties are on an elevated terrace that is nearly flat with the Heathcote River to the east deeply incised into the topography. The groundwater surface slopes up gently from the river but the ground surface rises rapidly and then flattens out. This results in a deeper depth to the groundwater surface nearer the river which then becomes shallower with distance from the river.

  There were no land damage observations in the area during the September 2010 event at levels of earthquake shaking close to the M6 0.3g ILV assessment level. Moderate-to-severe land damage was observed in February 2011 when the shaking levels were approximately double (M6 0.6g) with localised spreading occurring on the properties bordering on the edge of the terrace adjacent to the Heathcote River.

  There are minor apparent LiDAR error bands over the assessment area however the majority of the ground surface subsidence appears to be attributable to land damage as a result of the CES. Review of the map showing the depth to the first hard layer greater than 0.5m thick indicates that there are potentially shallow gravels within the vicinity of the Stage 2 properties. Most of these trends can be observed in Figure 10.9.

  The additional regional maps produced for the Stage 2 process do not provide any additional information that is pertinent to this worked example.

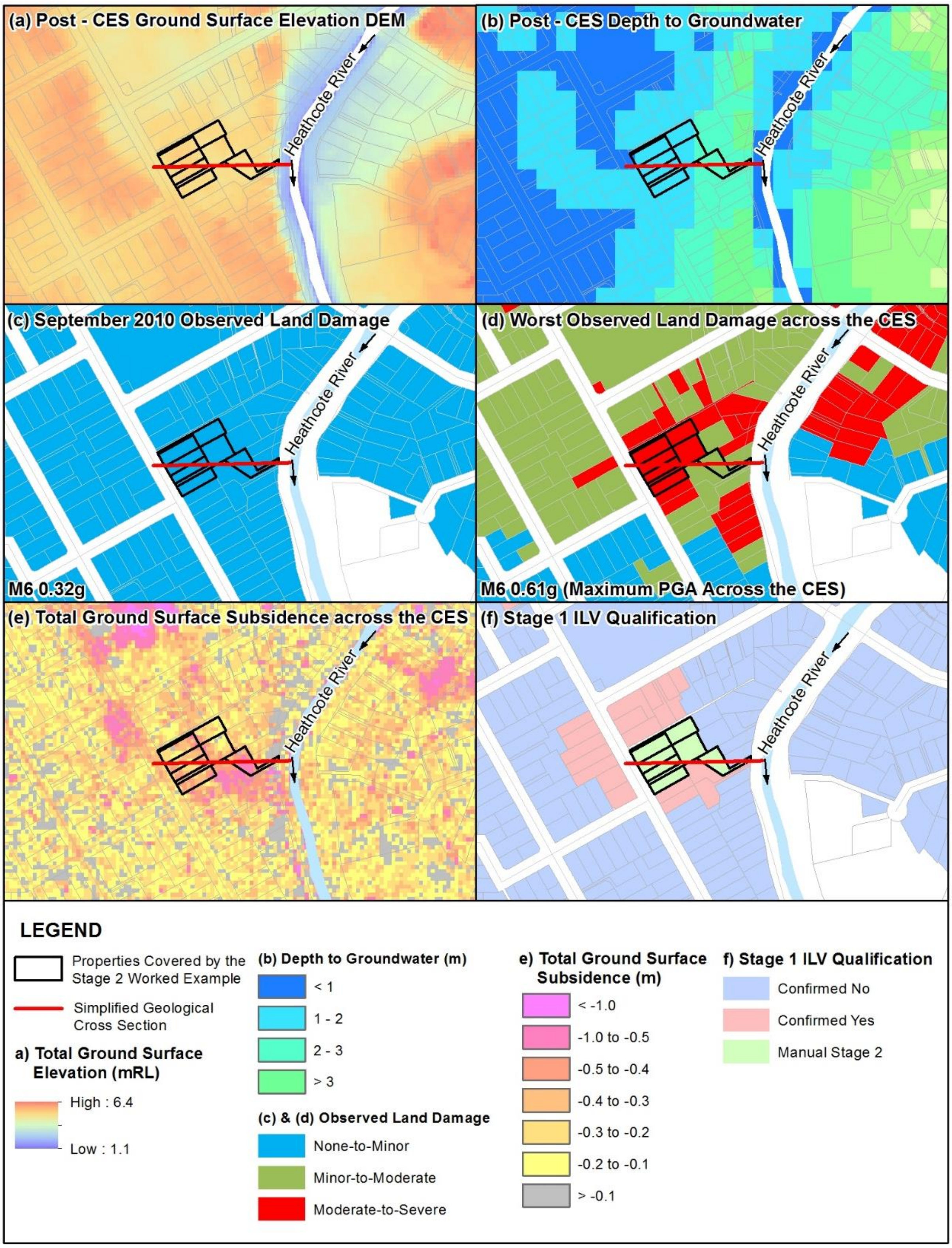


Figure 10.9: A series of maps used when assessing a cluster of properties in the suburb of St Martins, for the Stage 2 qualification process. (a) post-CES ground surface elevation; (b) post-CES depth to groundwater surface; (c) September 2010 observed land damage; (d) worst observed land damage across the CES; (e) total ground surface subsidence across the CES; (f) Stage 1 ILV qualification results.

- **Local and Specific Assessment (Tasks 2 and 3) –** Figure 10.9f shows that the properties requiring further assessment with the Stage 2 process (the properties shaded in green) are surrounded by properties which have been qualified for ILV in the Stage 1 process to the north, west and south. In contrast, the properties to the east have not qualified for ILV.

  Review of Figure 10.9c indicates that this area did not sustain any observed liquefaction damage during the September 2010 event at M6 0.32g levels of earthquake shaking (scaled to a M6 equivalent PGA). Figure 10.9d indicates that the worst recorded land damage for the majority of the Stage 2 properties requiring further assessment is moderate-to-severe. This land damage was observed following both the February and June 2011 earthquake events which are equivalent to 0.61g and 0.32g respectively when scaled to a M_W 6.0 earthquake. Figure 10.9e shows that most of the properties in question have subsided 0.3 to 0.5m with the exception of one property which has subsided more than 0.5m.

  The general trends for the classification of the CPT and Borehole data are shown on Figure 10.10.

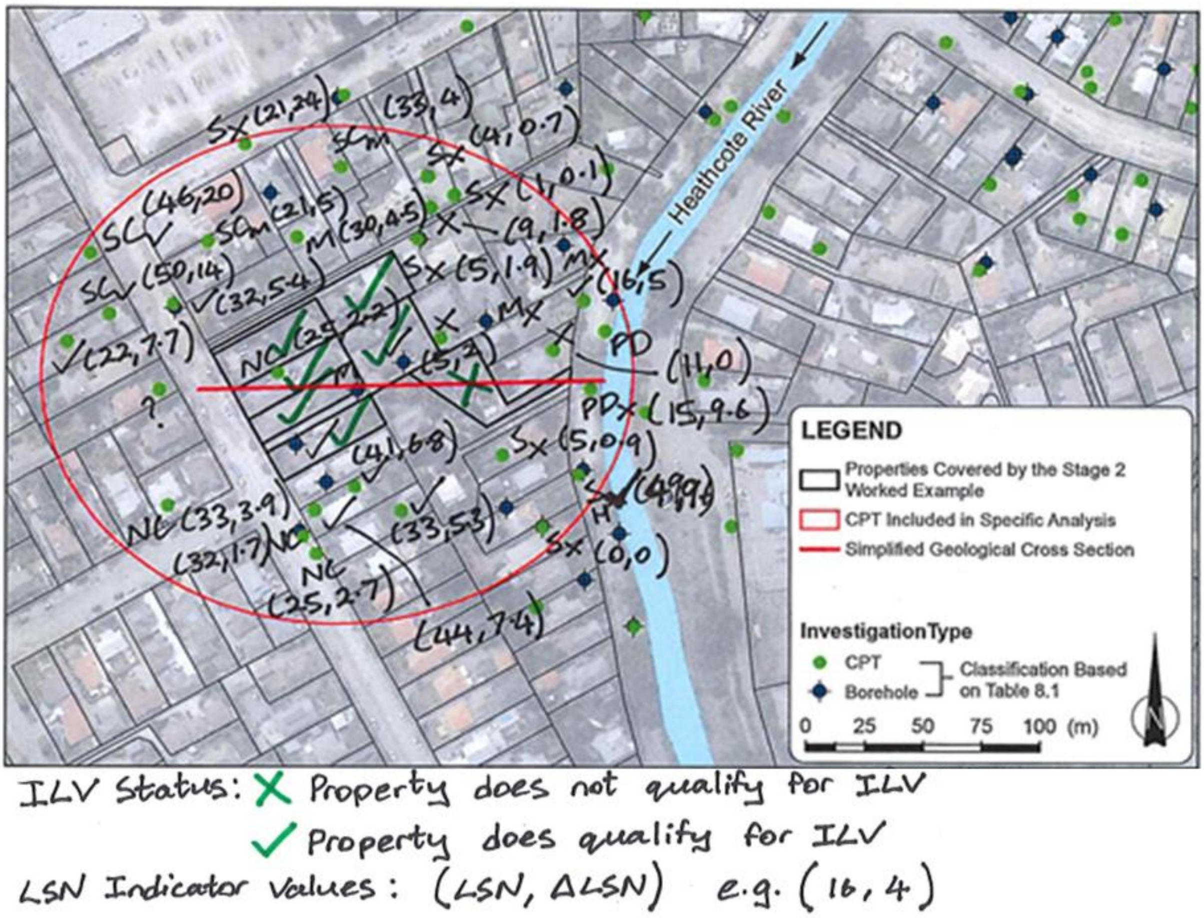


Figure 10.10: The location and classification of the CPTs and boreholes and the ILV qualification of the properties for the Stage 2 manual assessment pack in the suburb of St Martins.

The general trends for the classification of the CPT and Borehole data are shown on Figure 10.10 are as follows:

– CPTs to the north of the properties requiring Stage 2 assessment are predominantly classified as SC (stress change – refer to Table 8.1 in Section 8.3.2.3). Note that these SC CPTs provided the basis for overturning the automated model result for these properties in the Stage 1 assessment;

- CPTs to the east of the properties requiring Stage 2 assessment are predominantly classified as ×. Some of these CPTs are also classified as short (S). Review of the adjacent borehole data indicates that these CPTs are encountering dense gravels and therefore the short CPT can also be classified as ×;
- CPTs to the south and west of the properties requiring Stage 2 assessment are predominantly classified as ✓ with two NC CPTs to the south;
- There is one NC CPT on the properties requiring Stage 2 assessment. Qualitative assessment of the borehole logs on these properties has classified these as ✓ or M.

Plotting the q_c and I_c traces of the CPTs in Figure 10.10 did not provide any additional insight that is pertinent to this worked example.

Inspection of Figure 10.9b indicates that the depth of the groundwater surface is getting shallower as it gets further away from the Heathcote River. As discussed in the regional analysis above, this is due to the groundwater surface rising more slowly away from the river than the ground surface, which rises sharply and then plateaus onto the terrace. Review of the borehole logs and CPT data shows the presence of a gravel layer that is getting shallower as it gets closer to the Heathcote River. A simplified geological cross-section based on this data are provided in Figure 10.11. The indicative location of this cross section is shown on Figure 10.9 and 10.10.

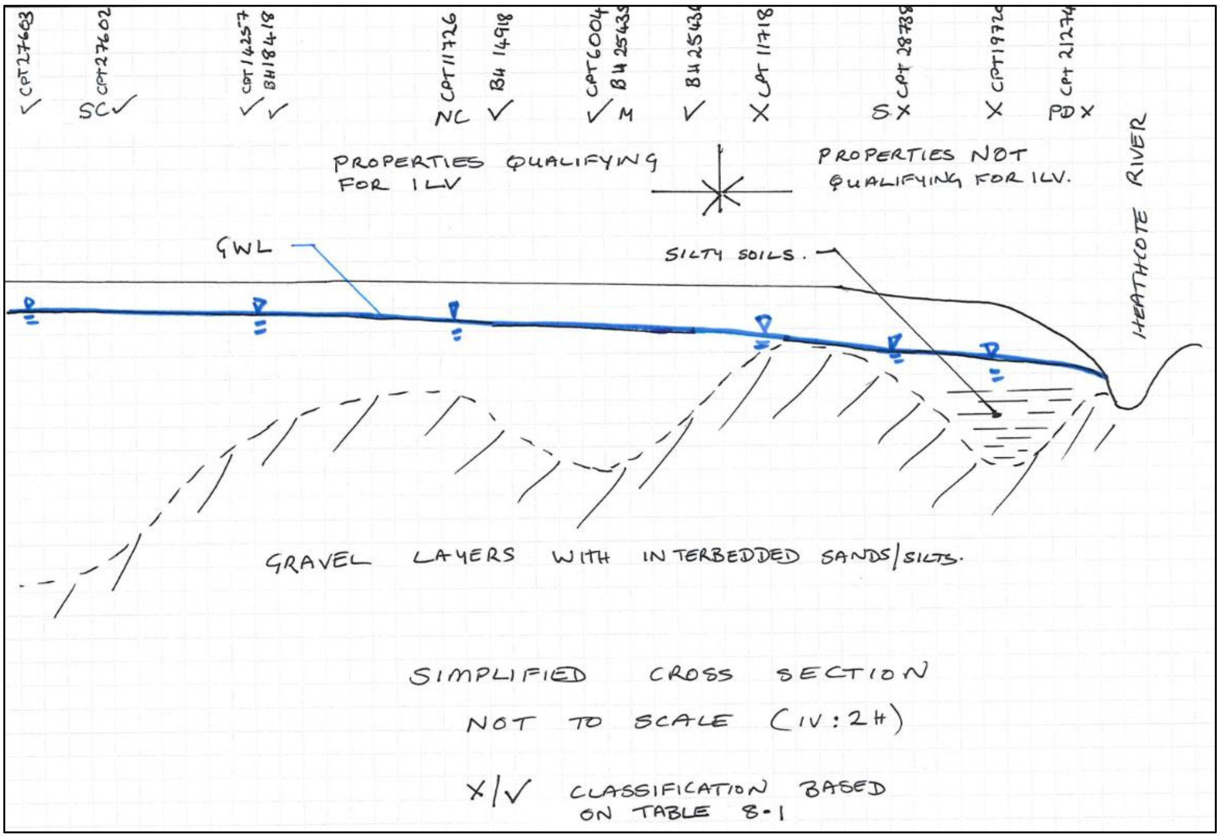


Figure 10.11: Simplified geological cross section for the indicative locations shown in Figures 10.9 and 10.10. The CPT identification numbers are shown in the assessment pack in the Worked Example Material.

Review of the available laboratory test data indicates that there are low plasticity silts which are susceptible to liquefaction within close proximity of the CPT which is classified as NC. Review of the Bray and Sancio (2008) criteria indicates for the soil layers with Atterberg laboratory test data that a revised I_c cutoff of 2.8 is appropriate for this CPT. Reanalysis of this CPT with a revised I_c cutoff value results in a reclassification of this CPT to SC.

- **ILV Qualification Assessment (Task 4) –** The six western Stage 2 properties which are classified by the automated model as not vulnerable have been manually assessed as qualifying for ILV based on the following:
  - Laboratory test results on soil samples recovered from the boreholes indicate low plasticity silts at the ground surface which are susceptible to liquefaction. Reanalysis of the liquefaction vulnerability of the one CPT on the properties requiring Stage 2 ILV assessment has been carried out with the I_c cut-off set to 2.8. This has been done to allow for the increased liquefaction susceptibility of these low plasticity silts. This results in a reclassification of the CPTs on the properties requiring Stage 2 assessment from NC to SC;
  - The boreholes and CPTs indicate liquefiable sands and low plasticity silts overlying a gravel layer that rises from about 12m deep to 2m deep from west to east. Qualitative assessment of the borehole logs indicates that the land beneath the Stage 2 properties has, on the balance of probabilities, satisfied both *engineering criteria;*
  - No land damage was observed during the September 2010 event (M6 0.32g) however in the June 2011 event (M6 0.32g) the land damage was moderate-to-severe. This potentially indicates increasing liquefaction vulnerability for events with similar levels of earthquake shaking as a result of the subsidence and cracking of the non-liquefying crust[10] caused by the February 2011 earthquake event; and
  - Surrounding properties with similar ground surface profiles and similar land performance through the CES have also qualified for ILV.

  Accordingly these properties have been marked with a ☑ on Figure 10.10 to indicate that based on engineering judgement both *engineering criteria* have been satisfied and therefore these properties qualify for ILV.
- The one Stage 2 property to the south east has been assessed as not qualifying for ILV based on the following:
  - Surrounding CPTs to the east and north east indicate these locations are not vulnerable to liquefaction;
  - Review of the boreholes and CPTs indicates that the gravel layer present beneath the area is becoming shallow (3m deep as shown in Figure 10.11). In addition, the groundwater levels are lower as the water surface approaches the stream bank (refer to the simplified geological cross section in Figure 10.11) resulting in the land being assessed as not materially vulnerable to liquefaction at M6 0.3g levels of earthquake shaking; and
  - Adjacent properties to the north and east with similar ground surface profiles do not qualify for ILV.

  Accordingly this property has been marked with a ☒ on Figure 10.10 to indicate that based on engineering judgement *Criterion 1* is more likely than not to have been satisfied and therefore this property does not qualify for ILV.

[10] As discussed in Section 6.7, the increase in liquefaction vulnerability due to ground cracking is not considered as part of the assessment of ILV. This is because it has been assumed that the compensation provided for ground cracking will be used to re-instate the crust to its pre-CES integrity. However, these ground cracks would not have been repaired at the time of the June 2011 event and therefore it is important to note this potential effect on liquefaction vulnerability when reviewing the land damage observations in subsequent events.

10.3.2 Worked Example with Insufficient LiDAR

Worked Example 4 – Northwood

The Stage 2 properties in this worked example required further manual assessment because there was insufficient LiDAR data available to assess *Criterion 2*. However, upon detailed review using the Stage 2 process, it was apparent that there was sufficient evidence from land damage observations and geotechnical data to demonstrate that the properties do not qualify for ILV on the basis of not satisfying *Criterion 1*.

Stage 1 Assessment

The majority of the geotechnical data available for these properties indicated that the area was not vulnerable. However, minor-to-moderate land damage was mapped for some of these properties following the September 2010 event. The September 2010 earthquake had the highest levels of earthquake shaking compared to the other CES events. However, the level of shaking was slightly less than the M6 0.3g levels of earthquake shaking. Therefore, as mapped damage was noted at shaking levels less than M6 0.3g, the properties were deemed to potentially satisfy *Criterion 1*. Therefore a Stage 2 manual assessment was required to determine if the properties satisfied the *engineering criteria*.

The insufficient LiDAR data was due to earthworks undertaken in the area in the period between 2003 and September 2010. While a LiDAR survey over the area was undertaken in 2003, due to the earthworks undertaken following this, a reliable estimation of ground surface elevation immediately prior to the September 2010 earthquake event was not available for the area.

Additionally, a LiDAR survey was undertaken following the February 2011 and June 2011 event but was not undertaken following the September 2010 and December 2011 events. This resulted in insufficient data to determine the change in ground surface elevation due to the CES. This is necessary to undertake ILV assessment.

Stage 2 Assessment

The purpose of this worked example is to demonstrate the use of engineering judgement in assessing the ILV status of Stage 2 properties in an area where there is insufficient LiDAR information. Due to the insufficient LiDAR data being available in the area, the automated ILV model is not reliable. Therefore, the ILV assessment is based on manual assessment of geotechnical investigations assuming a reasonable estimate for the ground surface subsidence and engineering judgement.

The full example pack including discussion and analysis of all the information listed in Section 10.2.2 along with the regional, specific and local analyses (described in Sections 10.2.3, 10.2.4 and 10.2.5 respectively) is included in the **Worked Example Material**. This full pack demonstrates the complete process for determining the ILV decision of these properties. A summary of the pertinent reasons for this ILV assessment outcome are as follows:

- **Estimation of Ground Surface Subsidence -** Because a reliable estimate of ground surface subsidence was not available for the area, a number of nearby suburbs, which experienced similar level of shaking and liquefaction related land damage, were examined for the purpose of estimating the ground surface subsidence which would most likely have occurred. It was considered that an area that experienced similar level of shaking, similar levels of observed liquefaction related land damage and underlain by similar ground and groundwater conditions would provide a reasonable estimate of subsidence that is likely to have occurred in the area concerned in this pack. An area in Casebrook (approximately 1km to the south west of this pack) was found to be the closest match to the area discussed in this worked example.

September 2010 earthquake produced the greatest level of shaking in Casebrook, with the level of shaking estimated to be M6 0.27g. This is comparable to the level of shaking observed in the area concerned (M6 0.25-0.26g). Minor-to-moderate land damage was observed in Casebrook, which is again comparable to the land damage observed in the area concerned.

The ground conditions (plot of q_c and I_c against depth) and groundwater conditions for Casebrook and those underlying Stage 2 properties are shown in Figure 10.12. Ground conditions were found to be very similar. The groundwater level in Casebrook was however found to be shallower than groundwater level in Northwood. However, this is expected to have a relatively minor effect on the ground surface subsidence estimated.

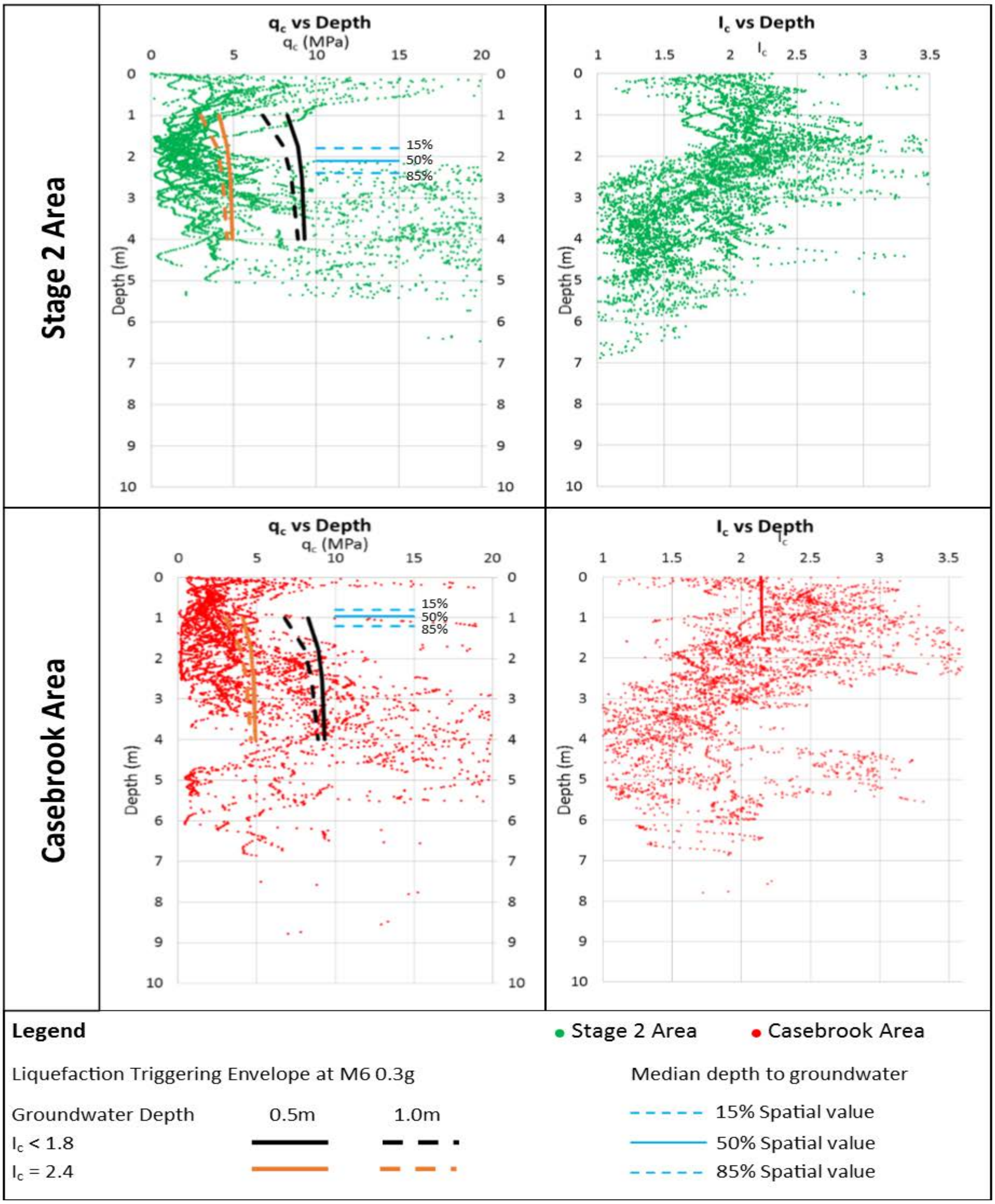


Figure 10.12: Plots of CPT q_c and I_c profiles in the Stage 2 Area and the Casebrook area.

The subsidence of the Casebrook residential properties was analysed by estimating the median difference DEM change in ground surface elevation for each property. A frequency histogram plot of the estimated subsidence for each of the residential properties in Casebrook is shown in Figure 10.13.

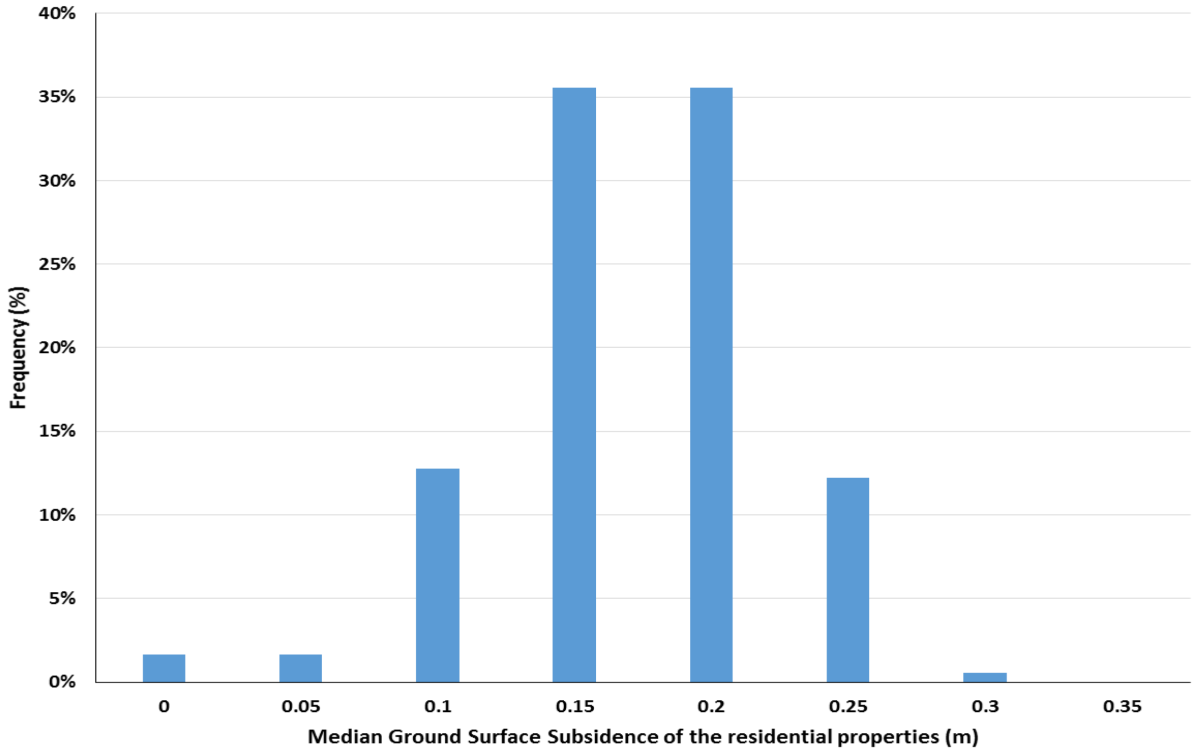


Figure 10.13: Frequency plot of ground surface subsidence of the residential properties in the Casebrook area.

The median and 85% ground surface subsidence of the properties in the Casebrook area was estimated to be 0.18m and 0.22m respectively. Properties with a median ground surface subsidence greater than 0.3m were not observed in the area. Based on the analysis undertaken, a subsidence of 0.3m was assumed as an upper bound for the ILV assessment of Stage 2 properties in Northwood.

- **Regional Assessment (Task 1)** – The ILV assessment pack discussed in this worked example is located approximately 8km north of the Christchurch CBD. Due to the location of the area, the September 2010 event produced the greatest intensity of shaking (M6 0.25-26g) relative to the other CES events with none-to-moderate damage mapped.

  Based on post-June LiDAR survey, a gentle downward gradient was noted from NW to SE with a difference in elevation of approximately 3.5m over a distance of approximately 1km. The groundwater level was observed to typically follow the ground surface elevation with the median depth to groundwater noted to vary between 1 and 4m over the area. The ground surface elevation and groundwater levels are shown in Figure 10.14a & b.

  Review of median q_{C1N} and I_c over the upper 5m and the depth to hard layer shows that typically loose to medium dense material behaving like a sand to low plastic silt is encountered in the upper 4 to 6m, underlain by dense sandy gravel to gravel. Correlations of the liquefaction susceptibility parameter proposed by Bray and Sancio (2006) using I_c from CPT and laboratory testing indicated that the material in the upper 5m were susceptible to liquefaction in the area. Correlations of fines content and I_c from CPTs resulted in majority of the C_{FC} parameters that were estimated being greater than 0.2. However, the LSN was found to be not significant sensitive to change in the I_c cutoff or change in the C_{FC} parameter in this area.

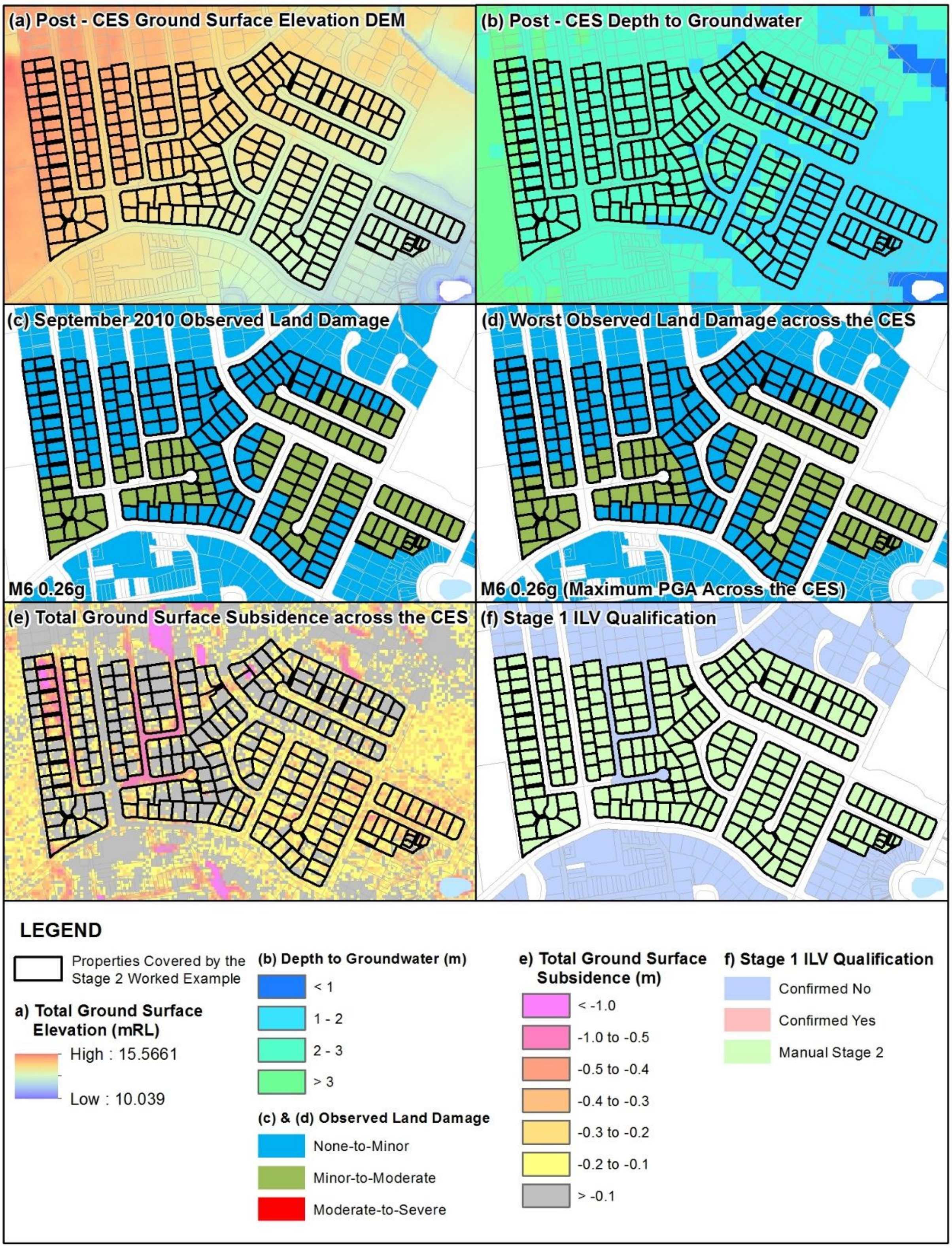


Figure 10.14: A series of maps used when assessing a cluster of properties in Northwood for the Stage 2 qualification process. (a) post-CES ground surface elevation; (b) post-CES depth to groundwater surface; (c) September 2010 observed land damage; (d) worst observed land damage across the CES; (e) total ground surface subsidence across the CES; (f) Stage 1 ILV qualification results.

- **Local and Specific Assessment (Task 2 and 3) –** The September 2010 event produced the greatest level of shaking in the area relatively to the other CES earthquake but was less than a

M6 0.3g level of earthquake shaking. However, review of LSN versus PGA relationship for the CPTs present in this area showed that the LSN value typically plateaued at M6 PGA of 0.20 to 0.25g. This would indicate that while the area has not been shaken at the reference M6 0.3g levels, significantly more liquefaction related land damage is not predicted to occur from 1 in 100 year levels of shaking.

None-to-minor and minor-to-moderate land damage was observed in the area following the September 2010 event (refer to Figure 10.14c). High resolution aerial photography, commissioned by Ministry of Civil Defence and Emergency Management, of Christchurch was taken following the September 2010 event. However, the aerial photography did not extend to the area. Lower quality imagery taken on the 5th of September and supplied by Digital Globe was available on Google Earth (Google Earth Imagery, 2010) and showed only minor surface expression of ejecta at localised locations. Additionally, a sample of LDAT reports undertaken on properties with minor-to-moderate observed land damage after September 2010 were reviewed. The LDAT inspection were undertaken in the period between September 2010 and February 2011 with majority of the LDAT reports indicating no evidence of land damage with a small number indicating minor ejecta and differential settlement within the property parcel.

The post-June ground surface elevation varied between RL 15.4m and RL 12.1m over the Stage 2 properties, with the roads noted to be at a lower elevation than the adjacent properties. The groundwater level typically varied between 1.5m and 3m below ground level over the Stage 2 properties.

The CPTs near the area and their classifications are provided in Figure 10.15.

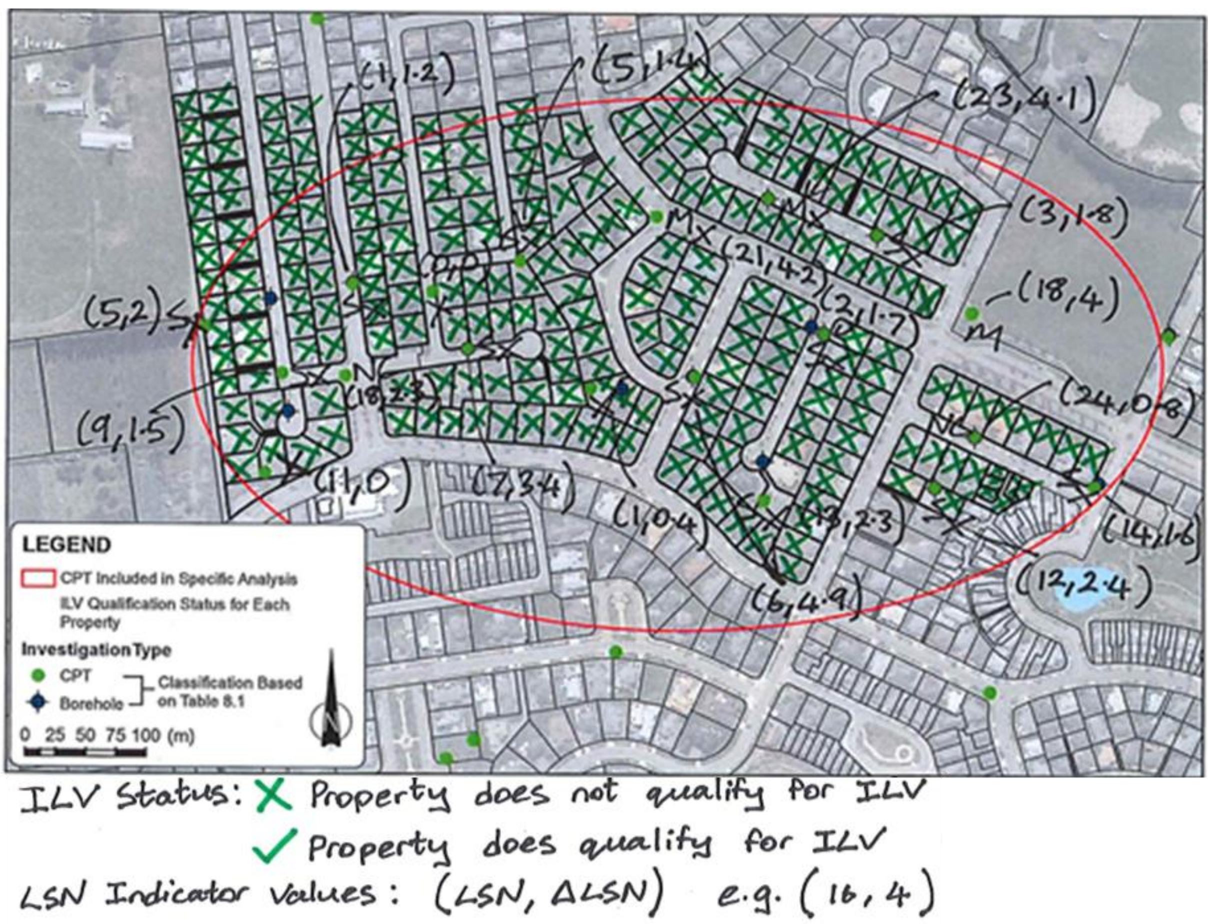


Figure 10.15: The location and classification of the CPTs and boreholes and the ILV qualification of the properties for the Stage 2 manual assessment pack in Northwood

19 CPTs that are relevant to the area were manually assessed for the ILV *engineering criteria* using the upper bound estimate of ground surface subsidence of 0.3m. The estimated LSN values for 16 of the CPTs indicated that the land is not vulnerable with the LSN typically varying between 5 and 13. The remaining 3 CPTs indicate the land is vulnerable, with LSN typically varying between 16 and 24. However, these CPTs do not indicate a material increase in vulnerability (i.e. ΔLSN > 5) event with an assumed 0.3m of ground surface subsidence. Plots of q_c and I_c against depth with the CPTs grouped into their CPT classifications is shown in Figure 10.16.

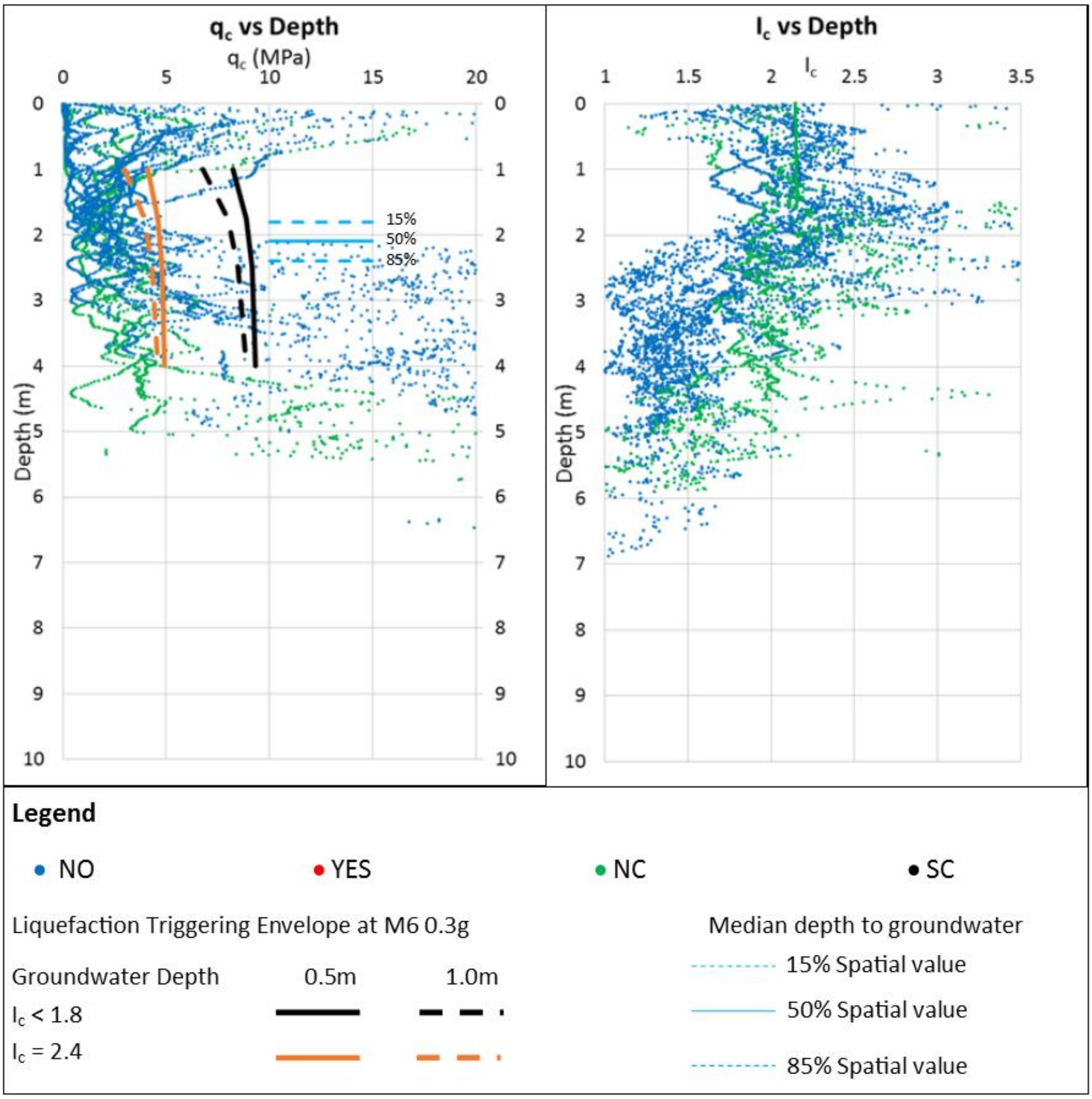


Figure 10.16: Plots of qc and Ic vs depth for CPT grouped by CPT classifications for the CPTs identified in Figure 10.7.

The majority of the CPTs indicate that the land is not vulnerable, which correlates well with the land damage observations which show that the land damage is only minor. As shown in Figure 10.16, CPTs that indicated the land to be vulnerable showed an underlying gravel layer was encountered at a slightly deeper depth at the respective locations. Additionally, all CPTs that indicate the land to be vulnerable were located on the road, which was at a lower elevation than the adjacent properties. As a result these CPTs have a shallower depth to groundwater and may not be characteristic of the vulnerability of the residential properties.

Even using an upper bound estimate of ground surface subsidence of 0.3m, the CPTs clearly indicate that the area does not satisfy *Criterion 2*.

Additional information available in the local data pack produced for this worked example does not provide any additional information that is pertinent for this worked example. The full pack provided in the **Worked Example Material** provides a complete summary of the information available in the local data pack.

- **ILV Qualification Assessment (Task 4) –** All Stage 2 properties have been assessed as not qualifying for ILV because they are not materially vulnerable.

  Because minor-to-moderate land damage was mapped in the area, it was considered that the properties may potentially satisfy Criterion 1 during stage 1 assessment. However, further review of the properties during Stage 2 assessment have shown that:

  - A detailed review of the land damage observations indicate only minor damage due to liquefaction in the area and at localised locations. The land damage due to liquefaction is therefore unlikely to be material
  - The majority of the CPTs indicate the land should be classified not vulnerable, mainly due to the shallow gravel layer encountered between 4 and 6m below the ground surface and the groundwater level being between 1.5 and 3m below ground surface.
  - Review of LSN against PGA also indicated that the LSN generally does not increase beyond a PGA of 0.25g. Therefore, while the area has not been shaken at the reference M6 0.3g levels, significant more land damage due to liquefaction would not be expected from this reference level of shaking in this area.
  - Accordingly all the properties have been assessed as not vulnerable.

10.4 ILV Assessment Results at the Completion of Stage 2

The spatial distribution of the ILV land damage qualifications following Stage 2 is shown in Figure 10.17. When comparing this figure to Figure 9.5, it can be concluded that most of the properties which were assessed as qualifying for ILV via the Stage 2 process are located predominantly on the fringe of the areas assessed as qualifying for ILV via the Stage 1 process. Very few new clusters of properties which qualified for ILV were established during the Stage 2 process. Most of the 'Stage 2' properties in eastern Christchurch qualifying for ILV were as a result of engineering assessment concluding that the LSN was under predicting liquefaction vulnerability. On the other hand, a large number of the 'Stage 2' properties to south and north west of the CBD which did not qualify for ILV were as a result of engineering assessment concluding that the LSN was over predicting the liquefaction vulnerability.

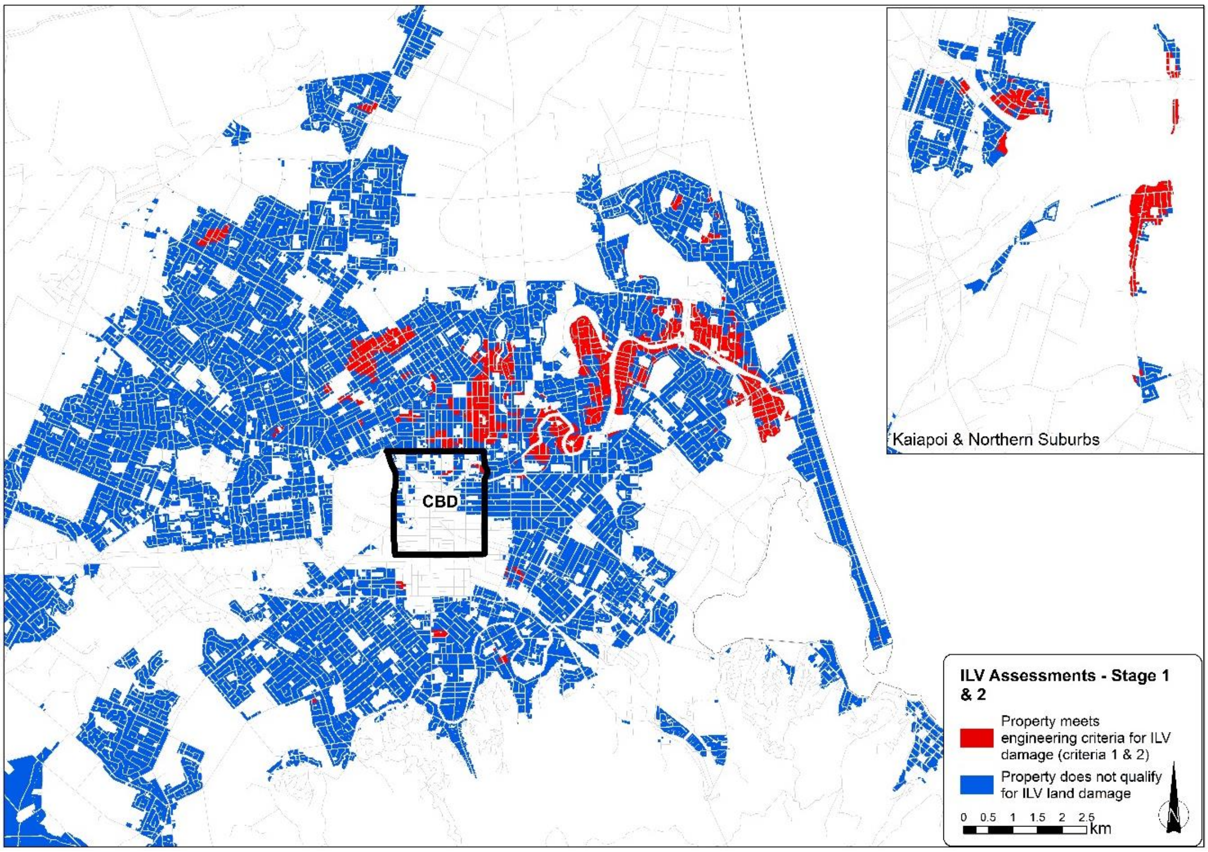


Figure 10.17: ILV assessment results after the completion of Stage 2. Note the white areas on the map represent the non-urban and non-residential land in Christchurch.

Table 10.1 below shows the categorisation of ILV land damage following Stage 2 qualifications divided into their respective TC1, TC2, TC3 and residential Red Zone areas.

Table 10.1: ILV Land Damage Qualification following Stage 2 by MBIE Technical Category and CERA Residential Red Zone

Technical Category	ILV assessment results following the completion of the Stage 2 Process	
	Number of properties which meet the engineering criteria for ILV	Number of properties which do not qualify for ILV
TC1	0	23,267
TC2	510	80,512
TC3	4,386	23,466
Red Zone	5,021	2,228
Total	9,917	129,473

* The property counts are based on the QPID database (maintained by Quotable Value Ltd) which existed at the time of the CES. The number of properties/QPIDs does not necessarily represent the number of claims.

11 Review of the ILV Assessment Results

11.1 Purpose and Outline

This section of the report provides a summary of the approach taken to further classify properties that did not qualify for ILV as well as describing a number of other sense checks that have been performed on the ILV assessment results, including:

- Correlation of ILV Assessment results with liquefaction vulnerability indicators;
- Correlation of ILV Assessment results with change in liquefaction vulnerability indicators;
- Comparison of the automated ILV model and the manual ILV assessment results;
- Review of Stage 1 ILV Assessments that were overturned during the Stage 2 process; and
- Detailed review of ILV property attributes.

On the basis of the regional review set out in this section of the report, the ILV assessment process has generated results that are spatially correlated and consistent with the areas where ILV land damage is expected based on the typical characteristics outlined in Section 4.3.

Equally, the results demonstrated that the approach to ILV assessment has not been applied mechanically and that it does not exclude consideration of factors that are relevant to any particular case. This is demonstrated by the fact that some properties that were identified by the automated ILV model as potentially not qualifying for ILV have been manually assessed as qualifying for ILV and vice versa.

11.2 Spatial Presentation of Results

The outcome of the ILV assessment process presented in Figures 4.1 and 4.2, comprised two groupings, these being:

- Properties that qualify for ILV (i.e. properties which have satisfied both *Criterion 1* and *Criterion 2*); and
- Properties that do not qualify for ILV (i.e. properties which have not satisfied either *Criterion 1* and/or *Criterion 2*).

The results are plotted spatially in Figure 10.17 and the number of properties in each group is summarised in Table 10.1. 9,917 properties have been assessed as qualifying for ILV. The 129,473 properties that do not qualify for ILV, can be further classified as follows:

- **Properties not materially vulnerable to liquefaction (NV)**: where the residential land does not have a material vulnerability to liquefaction damage after the CES at M6 0.3g levels of earthquake shaking (i.e. it does not satisfy *Criterion 1)*; and
- **Properties materially vulnerable to liquefaction but with no material change in liquefaction vulnerability (LV)**: where the residential land has a material vulnerability to liquefaction damage after the CES, at M6 0.3g levels of earthquake shaking (i.e. satisfy *Criterion 1)*. However the vulnerability of the residential land to liquefaction damage in future earthquakes has not materially increased at up to M6 0.3g levels of earthquake shaking as a result of ground surface subsidence of the land caused by the CES (i.e. does not satisfy *Criterion 2)*.

The process used to classify properties that did not qualify for ILV as NV and LV is summarised in **Appendix M**.

The spatial distribution of NV and LV properties are shown in Figure 11.1. When comparing Figure 11.1 to Figure 10.17, it can be seen that a large number of properties that did not qualify for ILV in the northern, central, eastern and southern areas of Christchurch, have been classified as LV.

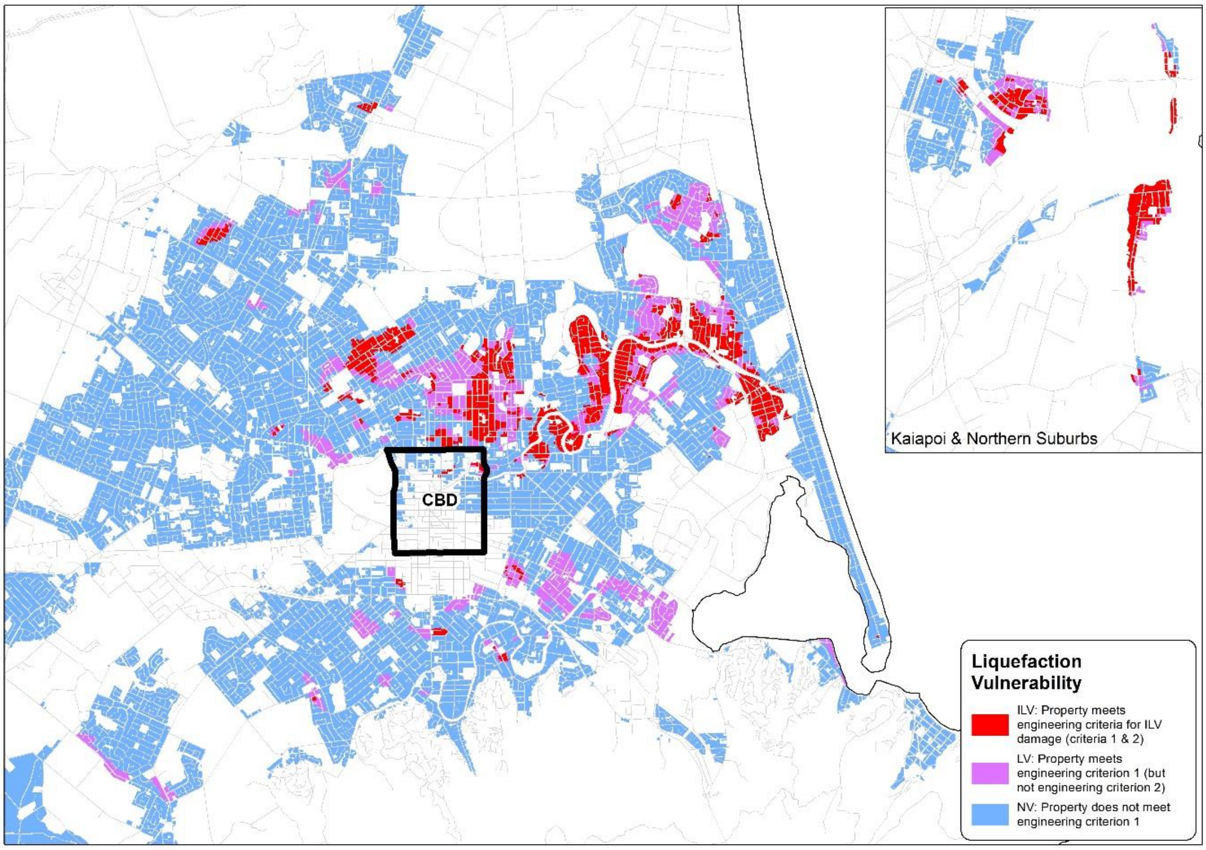


Figure 11.1: ILV assessment results after the completion of Stage 2 also showing the NV and LV properties. Note the white areas on the map represent the non-urban and non-residential land in Christchurch.

Table 11.1 below shows the categorisation of NV, LV and ILV results divided into their respective TC1, TC2, TC3 and residential Red Zone areas.

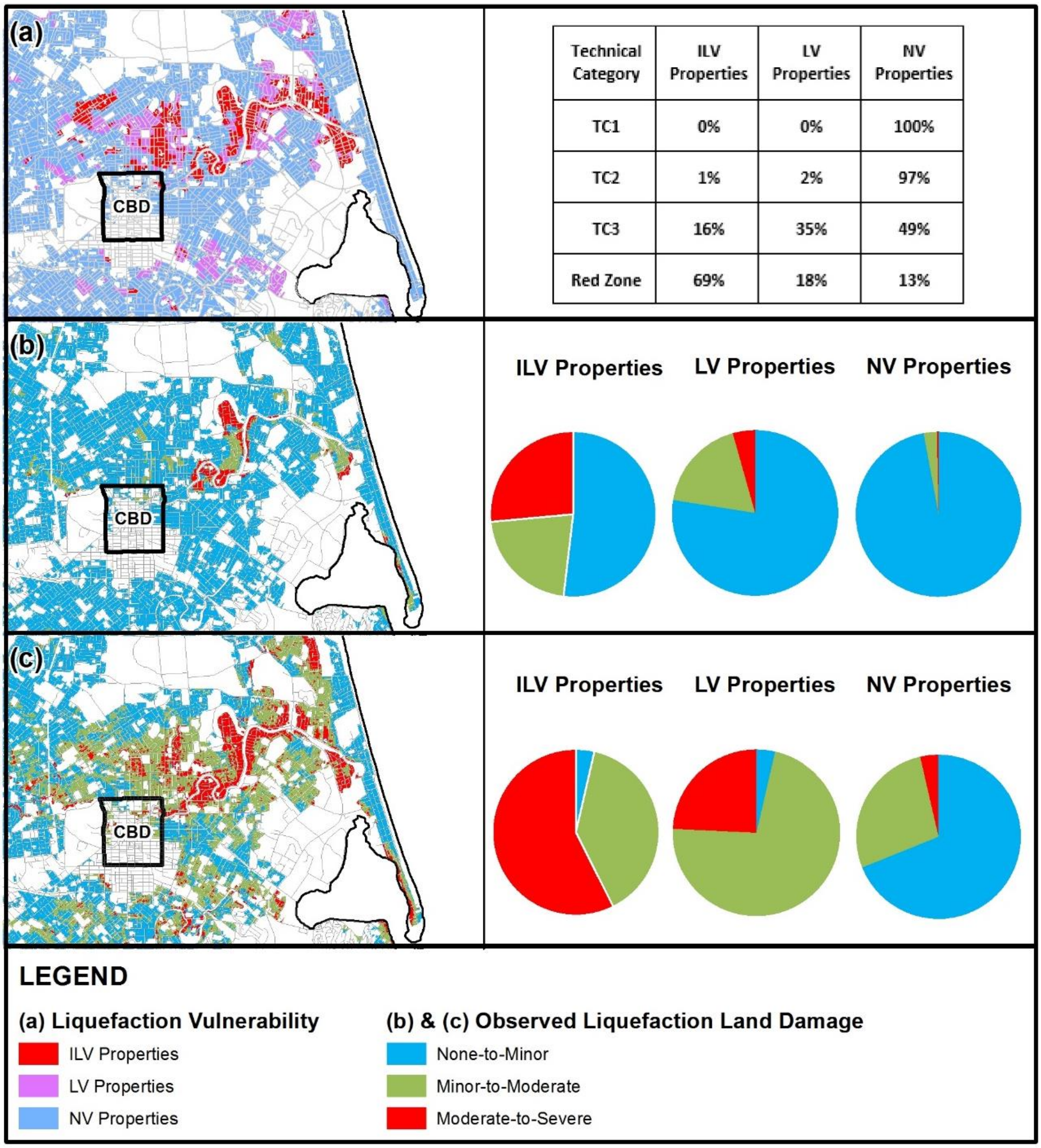
Table 11.1: NV, LV and ILV classification by MBIE Technical Category and CERA Residential Red Zone

Technical Category	Number of properties which meet the engineering criteria for ILV	Number of properties materially vulnerable to liquefaction (LV)	Number of properties not materially vulnerable to liquefaction (NV)
TC1	0	0	23,267
TC2	510	1,867	78,645
TC3	4,386	9,693	13,773
Red Zone	5,021	1,272	956
Total	9,917	12,832	116,641

* The property counts are based on the QPID database (maintained by Quotable Value Ltd) which existed at the time of the CES. The number of properties/QPIDs does not necessarily represent the number of claims.

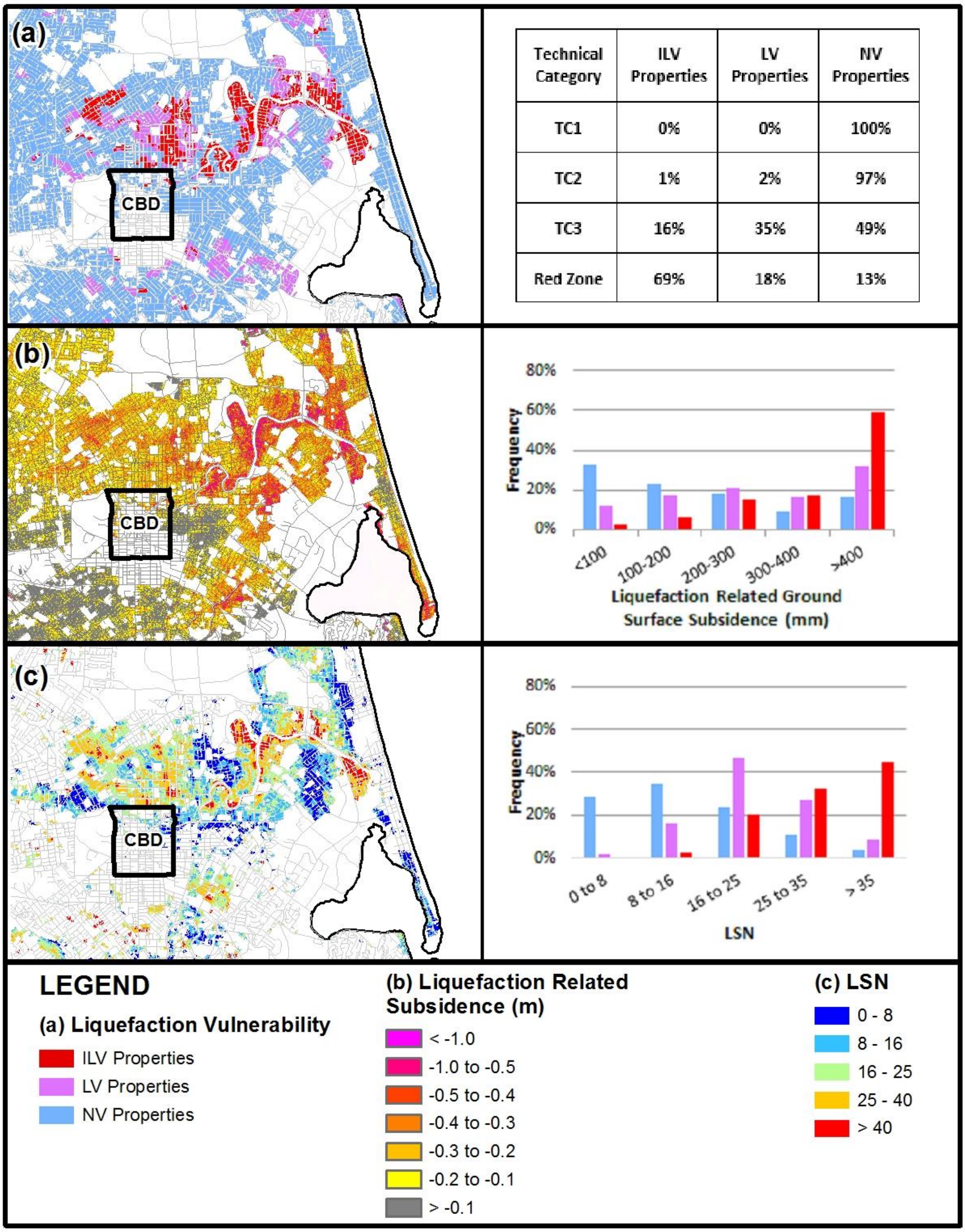
11.3 Correlation of ILV Assessment Results with Liquefaction Vulnerability Indicators

Figure 11.2 and Figure 11.3 demonstrate the spatial correlation between the properties which qualify for ILV land damage and the land related liquefaction vulnerability indicators. These indicators include mapped land damage, estimated liquefaction related ground surface subsidence, and estimated LSN.



Technical Category	ILV Properties	LV Properties	NV Properties
TC1	0%	0%	100%
TC2	1%	2%	97%
TC3	16%	35%	49%
Red Zone	69%	18%	13%

Figure 11.2: Summary maps and statistics including: (a) properties which qualify for ILV; and do not qualify for ILV but are materially vulnerable to liquefaction (LV); and are not materially vulnerable to liquefaction (NV), (b) observed land damage after 4 September 2010 earthquake and (c) worst observed land damage during the CES.



Technical Category	ILV Properties	LV Properties	NV Properties
TC1	0%	0%	100%
TC2	1%	2%	97%
TC3	16%	35%	49%
Red Zone	69%	18%	13%

Figure 11.3: Summary maps and statistics including: (a) properties which qualify for ILV; do not qualify for ILV but are materially vulnerable to liquefaction (LV); and are not materially vulnerable to liquefaction (NV), and (b) estimated liquefaction related ground surface subsidence from the CES and (c) estimated LSN values for M6 0.3g levels of earthquake shaking with post-CES ground levels.

The areas qualifying for ILV generally coincide with the areas characterised by moderate-to-severe land damage, higher liquefaction related ground surface subsidence (typically greater than 0.3m) and higher LSN values (typically greater than 16).

Areas not materially vulnerable to liquefaction generally coincide with the areas which have none-to-minor land damage, less liquefaction related ground surface subsidence (typically less than 0.3m) and lower estimated LSN values (typically less than 25). These trends are also evident in the associated pie graphs and histograms shown in and Figure 11.2 and Figure 11.3.

Similarly, Figure 11.4 shows the spatial correlation between the properties which qualify for ILV land damage and the building related liquefaction vulnerability indicators including assessed building damage costs and BDR (refer to Section 3.7.5). The areas qualifying for ILV generally coincide with the areas which have significant numbers of buildings with assessed building damage greater than $100k, and BDR greater than 0.5.

Areas not qualifying for ILV but materially vulnerable to liquefaction generally coincide with the areas which have significant numbers of buildings with assessed building damage greater than $50k, and a wide range of BDR values.

Areas not materially vulnerable to liquefaction (NV) generally coincide with the areas which have significant numbers of buildings with assessed building damage less than $50k, and BDR less than 0.2. These trends are also evident in the associated pie graphs and histograms shown in Figure 11.4.

In summary, Figure 11.2 to Figure 11.4 show the population of properties qualifying for ILV have characteristically performed very differently compared to the population of properties which are not materially vulnerable to liquefaction (NV). As anticipated, the characteristics of the two populations correlate well with the typical attributes discussed in Section 4.3.

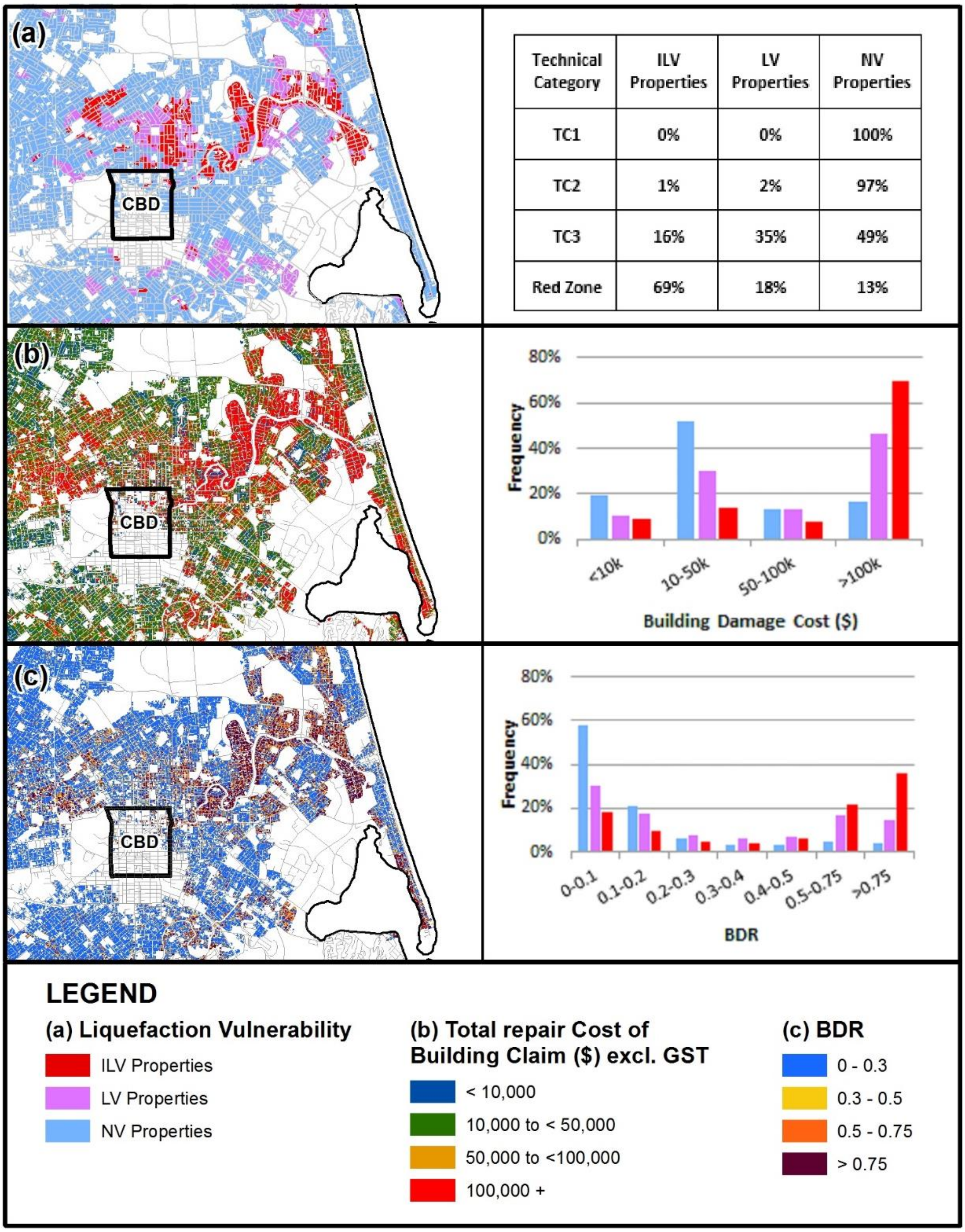


Figure 11.4: Summary maps and statistics including: (a) properties which qualify for ILV; do not qualify for ILV but are materially vulnerable to liquefaction (LV); and are not materially vulnerable to liquefaction (NV) and, (b) cumulative building damage costs as a result of the CES and (c) cumulative BDR as a result of the CES.

11.4 Correlation of ILV Assessment Results with Change in Liquefaction Vulnerability Indicators

Figure 11.5 shows the spatial correlation between the properties which qualify for ILV land damage and the change in liquefaction vulnerability indicators including the estimated total ground surface subsidence and estimated ΔLSN.

The areas qualifying for ILV generally coincide with the areas which have higher total ground surface subsidence (typically greater than 0.3m) and higher estimated ΔLSN values (typically greater than 5).

Areas not materially vulnerable to liquefaction (NV) generally coincide with the areas which have ground surface subsidence typically less than 0.3m and lower estimated ΔLSN values (typically less than 5). These trends are also evident in the associated histograms shown in Figure 11.5.

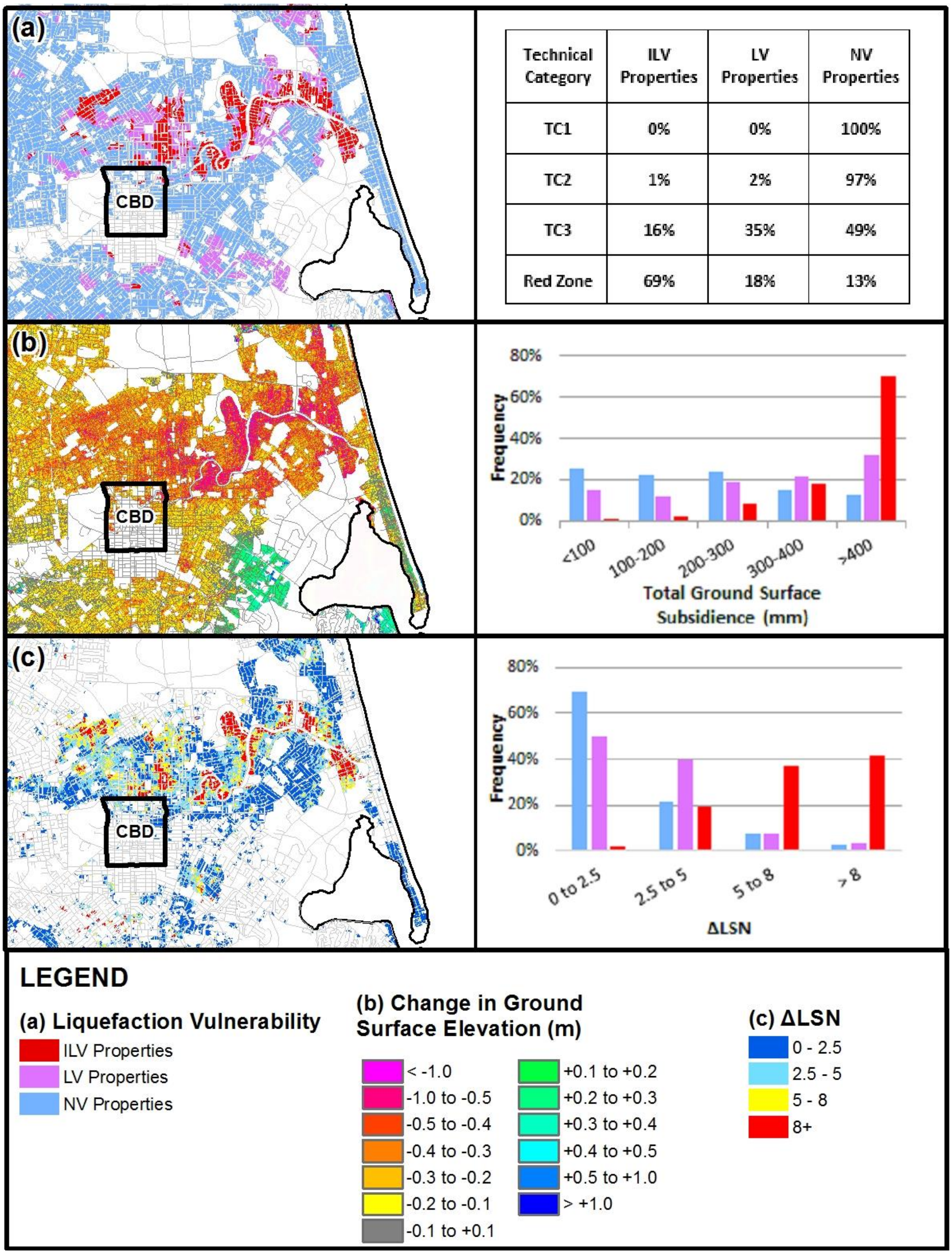


Figure 11.5: Summary maps and statistics including: (a) properties which qualify for ILV, do not qualify for ILV but are materially vulnerable to liquefaction (LV,) and are not materially vulnerable to liquefaction (NV); (b) the total ground surface subsidence over the CES, and (c) the automated ΔLSN values at the M6 0.3g levels of earthquake shaking as a result of the ground surface subsidence caused by the CES.

11.5 Comparison of the Automated ILV Model and the Manual ILV Assessment Results

Figure 8.12 shows a map which compares the automated ILV model results (shown in Figure 8.4) with the final manually assessed ILV decisions (shown in Figure 10.17). The data presented in Figure 8.12 demonstrates that generally the automated ILV model was doing a good job of differentiating between properties that have ILV land damage those that do not. However, there were areas where the automated ILV model needed to be overturned.

The automated ILV model results were primarily overturned by the manual ILV process on the fringes of areas qualifying for ILV. 2,150 of the automated ILV no results were confirmed as qualifying for ILV using the manual process. 3,594 of the automated ILV yes results were confirmed as not qualifying for ILV using the manual process. While as a percentage of the total property count the number of overturned results is small, in absolute terms this relatively significant number of overturned decisions demonstrates that the ILV Assessment Methodology is being applied in accordance with the requirement in the Land Declaratory Judgement that it is not applied mechanically (refer to Section 2.4).

11.6 Review of Overturned Stage 1 ILV Assessments

As noted in Section 8.3.5, for the Stage 2 process, while only the properties which were marked as “Stage 2” required ILV assessments to be undertaken, the Stage 2 marking also extended out to surrounding properties where an ILV decision had already been made in Stage 1. For almost all of the cases reassessed by the Stage 2 process the ILV decisions were the same.

Of the 132,690 urban residential properties where an ILV decision was made in Stage 1 (refer to Section 9.4), only 84 of the properties which did not qualify for ILV based on the Stage 1 process were overturned and qualified for ILV under the Stage 2 ILV assessment process. This is less than 0.1% of the decisions made in Stage 1.

Similarly, only 122 properties which qualified for ILV based on the Stage 1 process were overturned and did not qualify for ILV under the subsequent Stage 2 process. This is also less than 0.1% of the decisions made in Stage 1.

Most of these overturned decisions involved properties in transition zones between areas where properties qualified for ILV and areas where properties did not qualify for ILV. In some cases the change in qualification decision between Stage 1 and Stage 2 was as a result of additional geotechnical investigation data which had become available on the CGD between the Stage 1 pack being compiled (in July 2014) and the Stage 2 pack compilation (in January 2015).

The low number of differing decisions for overlapping packs from Stage 1 and the low number of properties with overturned Stage 1 decisions by the Stage 2 process demonstrates a robust set of assessment processes were developed and implemented to achieve the ILV Assessment Methodology objectives outlined in Section 2.6.

11.7 Detailed Review of ILV Property Attributes

This section reviews in greater detail some of the typical attributes of properties which do and do not qualify for ILV land damage (refer to Sections 4.3 and 11.4 for further discussion about the typical attributes of properties that do and do not qualify for ILV).

The attributes reviewed include land damage observations, estimated LSN, total estimated ground surface subsidence and estimated ΔLSN. There is a relatively small percentage of properties that have qualified for ILV despite having some of the attributes of properties that do not qualify for ILV.

Correspondingly, there is a small percentage of properties that have not qualified for ILV despite having some of the attributes of properties that have qualified for ILV.

Reasons as to why this small percentage of properties may have attributes which do not fit their ILV qualification status are explained in this section.

It is important to note that the LSN and ΔLSN histograms (shown in Figure 11.3 and 11.5 respectively) are skewed because the approximately 90,000 properties with an “unable to estimate LSN” outcome (discussed in Section 8.2 and shown in Figure 8.12) are not able to be included in these analyses. The majority of the properties with “null” values were in areas where there was no liquefaction related land damage and low levels of ground surface subsidence and therefore they would not qualify for ILV.

Therefore, most of these properties would have estimated LSN and ΔLSN values of less than 16 and 5 respectively, and if they were able to be included in the histograms there would be an increase in the percentage of properties in these categories of LSN and ΔLSN values. Therefore, the LSN and ΔLSN histograms would show an even stronger differentiation between the two populations of properties that have and have not qualified for ILV if the “unable to estimate LSN” outcomes were included.

11.7.1 Properties that Qualify for ILV despite having Attributes of Properties that would not Qualify for ILV

The pie graphs of observed land damage in the third row of Figure 11.2 shows that a small proportion (less than 5%) of properties that qualified for ILV have none-to-minor land damage as the worst recorded land damage across the CES. This includes some properties that were not vulnerable prior to the CES but have become vulnerable due to ground surface subsidence caused by the CES. It also includes properties with land damage which were mapped as none-to-minor due to the removal of ejecta prior to inspection but which in fact had damage that was evident during the detailed LDAT inspections or liquefiable material which originated from beneath the property being ejected at a nearby location.

The histogram in the third row of Figure 11.3 shows that a small proportion (less than 5%) of properties that qualified for ILV have estimated LSN values of less than 16 and therefore would not qualify for ILV based on an automated approach (i.e. they would not satisfy *Criterion 1*). This apparent under-prediction of LSN could be attributed to either an interpolation error, spatial variability or the use of incorrect input parameters in the estimation of LSN.

The histogram in the second row of Figure 11.5 shows that a small proportion (less than 5%) of properties that qualify for ILV have total estimated ground surface subsidence of less than 0.2m. These relatively low levels of ground surface subsidence for a property which qualifies for ILV are attributable to issues such as errors in the difference DEMs (discussed in **Appendix G**) which have been corrected as part of the manual assessment process.

The histogram in the third row of Figure 11.5 shows that approximately 20% of properties that qualify for ILV have an estimated ΔLSN of less than 5 and therefore would not qualify for ILV based on an automated approach. This under-prediction of ΔLSN is attributable to limitations of the interpolation process in the automated model, limitations in the default parameters used for the liquefaction triggering assessment in the estimation of LSN and the influence of stress change discussed in Section 8.3.2.3. The limitations of the ILV automated model from which the estimated ΔLSN values are extracted are discussed in Section 8.2.3.

11.7.2 Properties that do not Qualify for ILV despite having Attributes of Properties that would Qualify for ILV

The pie graph of land damage in the third row of Figure 11.2 shows that a small proportion of properties that did not qualify for ILV and are not considered materially vulnerable to liquefaction, have moderate-to-severe land damage as the worst recorded land damage across the CES (approximately 5% of NV properties). Properties which fall into this category generally include those affected by lateral spread only (refer to Sections 6.6 and 8.4) or properties where the resulting liquefaction related damage is as a result of very high levels of earthquake shaking (typically greater than M6 0.3g).

The histogram in the third row of Figure 11.3 shows that approximately 35% of the NV properties (primarily in the TC3 and Red Zone areas) have estimated LSN values of more than 16. These high values of LSN are primarily resulting from areas where there is over prediction of LSN due to limitations in the default parameters for the liquefaction triggering assessment in the estimation of LSN and over prediction of LSN due to the complex interbedded silts and sands primarily found in western parts of Christchurch (refer to Section 3.6).

The histogram in the second row of Figure 11.5 shows that a significant number of properties (approximately 70% of LV properties and 50% of NV properties) that did not qualify for ILV have total estimated ground surface subsidence of more than 0.2m. These relatively high levels of ground surface subsidence for a property which did not qualify for ILV are primarily due to:

- NV properties which are not materially vulnerable to liquefaction damage at M6 0.3g levels of earthquake shaking (i.e. the property does not satisfy *Criterion 1*); and
- LV properties which are materially vulnerable to liquefaction but have not had a material change in liquefaction vulnerability due to the composition of the crust materials (i.e. the property satisfies *Criterion 1* but not *Criterion 2*).

The histogram in the third row of Figure 11.5 shows that approximately 10% of LV properties and 10% of the NV properties have an estimated ΔLSN of greater than 5 and therefore would potentially qualify for ILV based on an automated approach. This over-prediction of ΔLSN is primarily attributable to interpolation limitations in the ILV automated model from which the estimated ΔLSN values are extracted and limitations in the default parameters for the liquefaction triggering assessment in the estimation of LSN.

It is important to note that, using the summary statistics discussed in Section 11, each of the attributes is presented in isolation. However, the ILV Assessment Methodology is based on a balance of probabilities approach based on all the available information. The attributes of each property and data set are should therefore considered collectively.

Accordingly, consideration of these statistics in isolation should not result in a conclusion that an error has occurred in the ILV assessment process. When all the datasets of a particular property are considered, then on the balance of probabilities the correct ILV assessment has been made.

12 Conclusions

The key conclusions of this report can be summarised as follows:

1 The residential areas of Christchurch are located on an alluvial plain formed by complex geological processes. This has resulted in large areas with liquefaction susceptible soils (low plasticity sandy to silty soil deposits with varying degrees of saturation, relative density and a relatively shallow ground water levels). As a result, large areas of Christchurch are vulnerable to liquefaction damage, with some areas being vulnerable to liquefaction damage at relatively low levels of earthquake shaking whereas other areas require higher levels of earthquake shaking before liquefaction damage is manifested.

2 The Canterbury Earthquake Sequence triggered widespread liquefaction, resulting in substantial ground surface subsidence across large parts of the Christchurch area. In some areas this subsidence has reduced the depth of the non-liquefying crust (generally the soil's layer thickness between the ground surface and the ground water level) and therefore materially increased the vulnerability of the land to liquefaction damage in future earthquake events.

3 As this ground surface subsidence is a physical change to the land, and a material increase in liquefaction vulnerability may have an adverse impact on the use and amenity of the land, this increase in vulnerability of the land meets the definition of Natural Disaster Damage under the EQC Act, as determined by the High Court in the Land Declaratory Judgement.

4 The ILV Assessment Methodology described in the report:

  a Provides a consistent basis for the assessment and settlement of claims involving ILV damage and is consistent with EQC's obligations under the EQC Act;

  b Uses the best available information that has been gathered by EQC and others, including 18,000 CPTs, 4,000 boreholes, 6,000 laboratory soil sample tests, water levels from 1,000 groundwater monitoring wells, aerial photography and extensive land damage mapping undertaken following each of the four main earthquakes, and the results of aerial (LiDAR) surveys flown before the CES and after each of the four main earthquakes to estimate the ground surface elevations;

  c Applies the best available scientific understanding of liquefaction vulnerability, developed following the Canterbury earthquakes, including the development of a new liquefaction vulnerability parameter, Liquefaction Severity Number (LSN); and

  d Results in an individual assessment of the circumstances of each property, taking into account all available information relevant to that property, including the results of ILV modelling and the application of engineering judgement.

5 The assessment of ILV is based on a series of appropriate and reasonable assumptions. In particular:

  a Basing the assessment of vulnerability on the same seismic demand before and after the Canterbury earthquakes is considered reasonable and reflects the current level of vulnerability of land in Christchurch;

  b Basing the assessment of vulnerability on up to a 1 in 100 year return period level of earthquake shaking is considered reasonable and is consistent with the approach taken to other natural hazards to land in New Zealand;

  c Using ground motions of M6 0.3g to represent the 1 in 100 year return period level of shaking is considered reasonable and is consistent with the MBIE Guidance levels of shaking used for the assessment of seismic hazard for residential buildings in Canterbury;

d Using the current groundwater levels (in particular, the 15^{th}, 50^{th} and 85^{th} percentile levels) is considered reasonable and it is uncertain what effect future land use changes and climate change may have on ground water levels;

e Basing the assessment of vulnerability on the post-CES soil strength and stiffness characteristics is considered reasonable and there is no reliable evidence that the characteristics of the soil in Christchurch have changed materially as a result of the earthquakes;

f The potential for lateral spreading from future earthquake shaking has not increased as a result of the changes to the land caused by the CES. Therefore, when assessing criteria 1, lateral spreading vulnerability does not need to be considered when determining whether a property is materially vulnerable to liquefaction damage;

g Assuming that other forms of land damage that may increase liquefaction vulnerability if left unrepaired (such as cracks) have been properly repaired is considered reasonable given that EQC is settling those forms of land damage by paying claimants repair costs; and

h Long access ways are not considered in the assessment of ILV.

6 In order to assess whether land is materially vulnerability to liquefaction damage in 1 in 100 year return period levels of shaking (*Criterion 1*), and whether its vulnerability has materially increased in up to 1 in 100 year return period levels of shaking (due to ground surface subsidence as a result of the earthquakes) (*Criterion 2*), it is necessary to determine the level of vulnerability or change in vulnerability that should be regarded as material.

7 For the purposes of assessing ILV in Christchurch, it was determined that:

a LSN 16 or greater was an appropriate indicator of land being materially vulnerable; and

b A change of LSN 5 or greater was an appropriate indicator of a change in vulnerability being material,

although, due to the inherent limitations in the modelling of the LSN parameter, these are both indicators, amongst several others, rather than strict threshold values to be applied to each property. Ultimately, the calculated LSN parameters for a property are used in conjunction with engineering judgement to determine (based on all the available information) whether land is materially vulnerable, and whether its vulnerability has materially increased.

8 In order to properly assess individual properties and in order to ensure consistency between properties, it was necessary to consider them in light of regional and local information. Properties were assessed in geographically based groups, which varied in size depending on the complexity and quantity of information available.

9 For the significant majority of the 139,390 properties in TC1, TC2, TC3 and Red Zone that were assessed, it was clear during an initial assessment whether they had ILV damage because the results of the automated ILV modelling were consistent with the other available information, particularly observed land damage. Whether these properties had ILV damage was therefore able to be determined in Stage 1 of the assessment process.

10 For 6,700 properties, the assessment was more complicated and required more in depth consideration of all of the available information. Whether these properties had ILV damage was determined in Stage 2 of the assessment process.

11 Following the completion of this two stage assessment process, the properties that meet the engineering criteria for ILV damage (*Criteria 1 & 2*) are summarised in Table 12.1 and geospatially shown in Figure 12.1.

Table 12.1: Properties that meet the ILV engineering criteria following Stage 2 by MBIE Technical Category and CERA Residential Red Zone

Technical Category	ILV assessment results following the completion of the Stage 2 Process	
	Number of properties which meet engineering criteria for ILV	Number of properties which do not qualify for ILV
TC1	0	23,267
TC2	510	80,512
TC3	4,386	23,466
Red Zone	5,021	2,228
Total	9,917	129,473

* The property counts are based on the QPID database (maintained by Quotable Value Ltd) which existed at the time of the CES. The number of properties/QPIDs does not necessarily represent the number of claims.

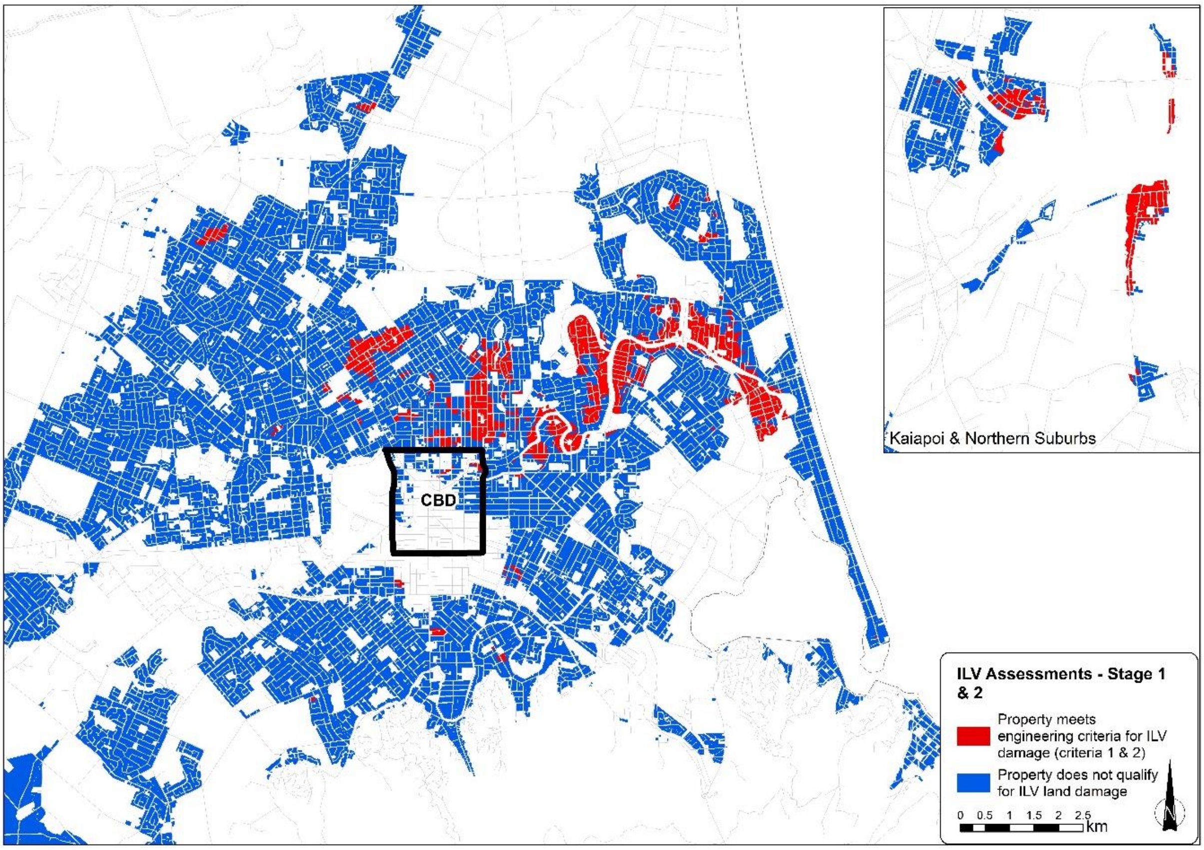


Figure 12.1: ILV assessment results after the completion of Stage 2 process. Note the white areas on the map represent the non-urban and non-residential land in Christchurch.

12 Figure 12.1 shows the location of properties with ILV land damage. These results are consistent with the areas where ILV land damage was expected, given the typical characteristics of land with such damage. These typical attributes include:

Criterion 1

- Areas with moderate-to-severe liquefaction related land damage for the earthquake events with estimated levels of ground shaking close to or less than 100 year return period levels of earthquake shaking;

- Areas with a thin non-liquefying crust, generally in areas where the groundwater table is close to the ground surface;
- Areas with relatively high estimated liquefaction related ground surface subsidence over the earthquakes;

Criterion 2

- Areas with an increase in severity of land damage observations during subsequent events with comparable levels of earthquake shaking;
- Areas with relatively high levels of estimated ground surface subsidence across the earthquakes. Note the total ground surface subsidence incorporates both the liquefaction related subsidence and the tectonic component; and
- Areas with sandier and looser materials in the near surface soils below the groundwater surface.

13 These properties, assessed as having satisfied the two *engineering criteria* for ILV damage, now need to be considered by EQC's valuers to determine if the third valuation *Criterion* is satisfied.

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15 Glossary

This glossary defines the specific meaning of certain words and phrases used in this report. Note that some words and phrases used in this report have different definitions and meanings in other literature.

American Society for Testing and Materials (ASTM)	A not-for-profit organisation globally recognised for the development and publication of international voluntary consensus standards for materials, products, systems and services.
Australian Aerial Mapping (AAM) Pty	A geospatial information technology provider. LiDAR surveys were acquired by AAM Pty pre-September 2010 and post-February 2011 on behalf of Environment Canterbury, CCC, Selwyn District Council and Waimakariri District Council.
Borehole (BH)	A small diameter vertical soil core mechanically drilled for geotechnical investigation purposes. This includes examination and recording of soil characteristics of the core by an engineering geologist or geotechnical engineer, in-situ testing of the soil to characterise its strength and stiffness properties and collection of soil samples for laboratory testing.
Box and Whisker Plot	A graphical representation of the median, upper quartile, lower quartile, maximum and minimum values of a dataset. The median value is represented by the middle line bisecting the box. The upper quartile and lower quartile values are represented by the right side and left sides of the box. The maximum and minimum values are represented by the right and left most ends of the whiskers.
Building Damage Ratio (BDR)	The ratio between the cost to repair earthquake related damage to a residential building and the greater of the replacement value or valuation of that building.
Canterbury Earthquake Recovery Authority (CERA)	An agency established by the Government to lead and coordinate the ongoing recovery effort following the September 2010 and February 2011 earthquakes. As of 1 February 2015, it is a Department Agency within the Department of the Prime Minister and Cabinet.
Canterbury Earthquake Sequence (CES)	The sequence of earthquakes and aftershocks in the Canterbury area from 4 September 2010 to the end of 2011. This included four main earthquakes on 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011.
Canterbury Geotechnical Database (CGD)	An online database established by CERA and now managed by MBIE. The CGD was set up to promote sharing of existing and new geotechnical and Christchurch recovery related information between professional engineers, EQC, insurers and local territorial authorities.

Change in LSN (ΔLSN)	A measure of the change in liquefaction vulnerability due to ground surface subsidence caused by the CES.
C_{FC} Parameter	A fitting parameter for the FC correlation within the Boulanger and Idriss (2014) liquefaction triggering methodology that can be adjusted based on site-specific laboratory data.
Christchurch City Council (CCC)	The local council for the Christchurch City area.
Cone Penetration Test (CPT)	A geotechnical in-situ ground investigation test which involves pushing an instrumented steel cone into the ground at a controlled rate measuring the cone tip resistance, sleeve friction and pore water pressure.
CPT Tip Resistance (q_c)	A measure of the force required to push the tip of a CPT probe through a given soil layer.
Criterion	A principle or standard by which something may be judged or decided.
Crust	The non-liquefying soil layers from the ground surface to the first liquefied soil layer.
Cumulative Thickness of Liquefaction (CTL)	An estimate of the total thickness of soil layers that are predicted to liquefy at a given level of earthquake shaking. It is typically estimated from CPT soundings.
Cyclic Resistance Ratio (CRR)	A representation of the ability of the ground to resist liquefaction due to seismic shaking.
Cyclic Stress Ratio (CSR)	A representation of the seismic demand imposed by an earthquake to trigger liquefaction.
Department of Building and Housing (DBH)	Previously the government agency of the New Zealand government responsible for developing and implementing building legislation in New Zealand. In March 2012 the DBH was integrated into MBIE.
Difference DEM	Derived by calculating the difference between two DEMs of the same land area obtained at different times. Used to estimate the change in ground surface elevation between two survey dates.
Differential Settlement	Uneven subsidence of the foundation or columns supporting a structure.
Digital Elevation Model (DEM)	A model of the ground surface elevation derived from a LiDAR survey that consists of a regular grid of equal size cells (i.e. 1m x 1m, 5m x 5m, 25m x 25m, etc.). The elevation at the centre of each

	cell is derived by taking the median elevation of all of the LiDAR ground classified point elevations within that cell.
Earthquake Commission (EQC)	A government owned entity responsible for carrying out the statutory functions set out in the Earthquake Commission Act 1993. This includes natural disaster insurance for residential property, administration of the natural disaster fund and funding research and education into natural disasters and ways of reducing their impact.
Engineering Advisory Group (EAG)	A group of engineers that provide advice to MBIE to develop relating guidance documents for rebuilding and repairing residential buildings following the CES. The EAG was established in October 2010 to fast track and streamline the response to the CES.
Environment Canterbury	The regional council for the Canterbury area.
EQC Act	The Act of parliament that details the provisions of a home owners entitlements for EQC insurance cover.
Fines Content (FC)	A laboratory test used to estimate the percentage of soil by weight that is finer than 75 microns (or 63 microns where specified).
Factor of Safety (FS)	The ratio of resisting forces to disturbing forces.
Free Face	An steep slope such as a river bank, road cutting or old river channel towards which lateral spreading could occur.
Free Field Liquefaction	Liquefaction damage that is unrelated to lateral spreading.
Geological and Nuclear Sciences (GNS)	A government owned entity which provides Earth, geoscience and isotope research and consultancy services.
Ground Classified Points	The points within the LiDAR survey point cloud that were classified as being reflected from the ground. These are classified using both automated and manual methods.
Groundwater	Water present beneath the ground surface in soil pore spaces and in the fractures of rock formations.
Groundwater Depth (GWD)	The depth from the ground surface to the groundwater surface. For the purposes of this report, this is estimated by calculating the difference between the post-CES DEM and the median groundwater surface.
Groundwater Surface Elevation	The height of the groundwater surface above sea level. For the purposes of this report, this is estimated using groundwater surface models derived from groundwater monitoring well data.

I_c Cutoff	An estimate of the threshold above which soils are not considered to be susceptible to liquefaction.
Increased Liquefaction Vulnerability (ILV)	An increase in vulnerability of the land to liquefaction related damage. For the purposes of this report this is due to ground surface subsidence.
Insurance Council of New Zealand (ICNZ)	Industry body representing the fire and general insurance industry in New Zealand.
Ishihara H_1 Layer	The non-liquefying soil layer from the ground surface to the first liquefied soil layer.
Ishihara H_2 Layer	The liquefying soil layer underlying the Ishihara H_1 layer (i.e. the non-liquefying crust).
Ishihara inspired Liquefaction Potential Index (LPI_{ISH})	A liquefaction vulnerability parameter developed by Maurer et al. (2015).
Laboratory Tests	Laboratory based tests undertaken on either disturbed or undisturbed samples obtained from the field to characterise various soil properties. For the purposes of this report this term is used to refer to Fines Content (FC), Particle Size Distribution (PSD) and Atterberg Limits tests.
Land Damage Assessment Team (LDAT)	The engineering team that carried out detailed property inspections of residential land damage following the CES events and dwelling foundations around Canterbury to provide information for the dataset dwelling foundation damage.
Land Information New Zealand (LINZ)	A government organisation responsible for managing land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, managing Crown property and supporting government decision making around foreign ownership.
Lateral Spread	A consequence of liquefaction where horizontal movement of upper soil layers occurs relative to soil layers at greater depth. It is measured as the global horizontal movement of a block of land.
Lateral Stretch	A consequence of liquefaction where the magnitude of horizontal movement of upper soil layers occurs non-uniformly. It is measured as the difference between the horizontal movement of two observation points over a given length.
Levels of earthquake shaking	The PGA and M_w of an earthquake event.

Light Detection and Ranging (LiDAR)	A method used to survey large areas using laser range-finding technology. LiDAR can be undertaken from an aeroplane (an aerial survey) or on the ground.
LiDAR Survey Point Cloud	The complete set of data supplied for a LiDAR survey. Specifically, the x, y, z location that each laser impulse which was captured during the survey. The points are also classified to indicate the type of surface that they were reflected from, with the most LiDAR returns classified as either ground or non-ground classified points.
Liquefaction	The process by which earthquake shaking increases the water pressure in the ground in sandy and silty soil layers resulting in temporary loss of soil strength. Liquefaction can give rise to significant land and building damage, for example through the ejection of sediment to the ground surface, differential settlement of the ground due to volume loss in liquefied soil and lateral movement of the ground
Liquefaction Consequence	The effects of liquefaction e.g. liquefaction ejecta, ground surface subsidence, differential settlement, lateral spread, buoyancy of underground structures and ground cracking.
Liquefaction Ejecta	Where water and liquefied soil material is ejected to the ground surface. Commonly observed as cone shaped piles of soil on the ground surface.
Liquefaction Potential Index (LPI)	A liquefaction vulnerability parameter developed by Iwasaki et al. (1978; 1982).
Liquefaction Related Ground Surface Subsidence	The ground surface subsidence attributable to the consequences of liquefaction. For the purposes of this report this is estimated by calculating the difference between the Total Ground Surface Subsidence and the estimated vertical tectonic movement as a result of the CES.
Liquefaction Severity Number (LSN)	A liquefaction vulnerability parameter developed by Tonkin + Taylor Ltd.
Liquefaction Susceptibility	The susceptibility of a soil to liquefaction, which is dependent on its compositional characteristics. Soils that are cohesive in nature such as clays with high plasticity are not susceptible to liquefaction.
Liquefaction Triggering	The initiation of liquefaction from shaking, commonly caused by earthquakes. Shaking must be sufficiently intense to trigger or initiate liquefaction. The shaking level that triggers liquefaction varies for different soils.
Liquefaction Vulnerability	The exposure of the land to damage at the ground surface from soil layers liquefying.

Liquefaction Vulnerability Parameters	Calculated parameters which can be used to estimate Liquefaction Vulnerability – e.g. CTL, LPI, LPI_{ISH}, S_{V1D} and LSN.
Liquefiable	Soil that is able to liquefy (i.e. is susceptible to liquefaction).
Liquefying	Soil that is subjected to the seismic demand necessary to trigger liquefaction.
Liquid Limit (LL)	The w_c at which the behaviour of a soil changes from plastic to liquid.
Magnitude (M_w)	A measure of earthquake energy. For the purposes of this report it is estimated using the Richter magnitude scale.
Magnitude Scaling Factor (MSF)	A factor applied in the Boulanger and Idriss (2014) liquefaction triggering methodology used to account for earthquake duration effects on the triggering of liquefaction.
Ministry of Business Innovation and Employment (MBIE)	The government department that administers the Building Act. It includes what was previously the Department of Building and Housing (DBH).
Ministry of Civil Defence and Emergency Management	The government department that provides policy advice to government, ensures there is coordination at local, regional and national levels and manages the central government response for large scale civil defence emergencies that are beyond the capacity of local authorities.
New Zealand Aerial Mapping (NZAM)	A geospatial information technology provider. LiDAR surveys were acquired by New Zealand Aerial Mapping post-September 2010, post-February 2011, post-June 2011 and post-December 2011 on behalf of Ministry of Civil Defence and Emergency Management and Earthquake Commission.
Non-liquefiable	Soil that are not able to liquefy (i.e. are not susceptible to liquefaction).
Non-liquefying	Soil that is able to liquefy but has not been subjected to the seismic demand necessary to trigger liquefaction.
Non-liquefying Crust	The non-liquefying soil layers from the ground surface to the first liquefied soil layer.
New Zealand Geotechnical Society (NZGS)	The affiliated organization in New Zealand of the International Societies representing practitioners in Soil mechanics, Rock mechanics and Engineering geology.
One Dimensional Volumetric Consolidation Settlement (S_{V1D})	A calculated settlement liquefaction vulnerability parameter recommended by MBIE using a method proposed by Zhang et al. (2002).

Partical Size Distribution (PSD)	An index indicating what sizes of soil particles are present as a percentage by weight in a given soil sample.
Peak Ground Acceleration (PGA)	The maximum acceleration of the ground during an earthquake.
Plasticity Index (PI)	A measure of the plasticity of a soil defined as the difference between the LL and the PL (i.e. PI = LL – PL). Soils with a high PI tend to be clays, soils with a low PI tend to be silts and soils with a PI of 0 tend to be neither silt nor clay.
Plastic Limit (PL)	The w_c at which the behaviour of a soil changes from plastic to non-plastic.
Probability of Liquefaction (P_L) Parameter	A parameter in the Boulanger and Idriss (2014) liquefaction triggering methodology which allows the estimation of the likelihood of liquefaction occurring across a range of probabilities as a result of the uncertainty in the estimation of the CRR.
Reduced Level (RL)	The vertical distance between a survey point and the adopted datum plane. This report uses Lyttelton Vertical Datum 1937 (LVD-37) that has a reduced level of +0.0 mRL.
Residential Green Zone	Land in the Christchurch area that is suitable for residential occupation, though some land may require geotechnical investigation and/or particular types of foundations to minimise any future liquefaction damage.
Residential Red Zone	Land in the Christchurch area where the land has been so badly damaged by the earthquakes that it is unlikely it can be rebuilt on for a prolonged period.
Return Period	The estimated average period between natural hazard events (in this case earthquake shaking levels) of the same size or intensity.
Seismic	Relating to earthquakes or other vibrations of the earth and its crust.
Seismic Demand	The level of earthquake shaking (PGA and M_w) required to trigger liquefaction.
Seismicity	The occurrence or frequency of earthquakes in a region.
Selwyn District Council	The local government authority for Selwyn.
Sleeve Friction (f_s)	A measure of the friction between the sleeve of a CPT probe and a given soil layer.
Soil Behaviour Type Index (I_c)	A CPT-based soil behaviour classification method developed by Robertson and Wride (1998).

Soil Density	The ratio of the mass to the total volume of a soil.
Standard Penetration Test (SPT)	A geotechnical in-situ ground investigation test which involves driving a standard steel probe into the ground measuring the number of blows to drive the probe a certain distance into the ground.
Technical Advisory Group (TAG)	A group of engineering consultants engaged by private insurance companies and their project management offices.
Technical Category (TC)	A classification of land developed by the Department of Building and Housing (now part of Ministry of Business, Innovation and Employment) for geotechnical investigation purposes for repairing and rebuilding residential buildings (up to two storeys) in the Christchurch area. TC's are exclusively within Green Zone Land.
Technical Category 1 (TC1)	Land in the residential green zone where liquefaction damage is unlikely in future large earthquakes. Standard residential foundation assessment and construction is appropriate.
Technical Category 2 (TC2)	Land in the residential green zone where liquefaction damage is possible in future large earthquakes. Standard enhanced foundation repair and rebuild options in accordance with MBIE Guidance are suitable to mitigate against this possibility.
Technical Category 3 (TC3)	Land in the residential green zone where liquefaction damage is possible in future large earthquakes. Individual engineering assessment is required to select the appropriate foundation repair or rebuild option.
Total Ground Surface Subsidence	The ground surface subsidence sustained. This is estimated with difference DEMs derived from LiDAR surveys. This includes both the tectonic vertical movement and any liquefaction related subsidence.
Volumetric Strain (ε_v)	The calculated unit change in volume due to granular soils being shaken into a more compact arrangement. Does not include loss of material due to surface expression of liquefaction.
Waimakariri District Council (WDC)	The local council for the Waimakariri district.
Water Content (w_c)	A laboratory test used to estimate the percentage by mass of water in a soil.

16 Applicability

This report has been prepared by T+T for Chapman Tripp (acting on behalf of EQC) in accordance with the scope of services set out in the contract between T+T and EQC. That scope of services, as described in this report, was developed with Chapman Tripp and EQC. While this report will also be of assistance to professional engineers advising claimants and other interested parties, the interpretation and use of this report in specific circumstances is beyond the control of T+T. Accordingly T+T accepts no liability or responsibility in respect of any use of, or reliance upon, this report by any person other than EQC.

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