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 1 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 1– Process for ILV Assessment Methodology

Phase 1
Define geographic extent of properties under consideration for ILV

No ILV assessment undertaken for these properties at this stage
- Assessments for such properties can be undertaken upon request by EQC for specific properties on a case by case basis if required

Phase 2
Is there sufficient information to assess ILV?

Gather additional information including:
- CPT data
- Borehole logs
- Laboratory test data
- Groundwater information

Phase 3
Assess each property for ILV

Stage 1 assessment
- Does the geotechnical information and corresponding liquefaction vulnerability assessments reconcile with land damage observations relative to the levels of estimated shaking for the main CES events?
- Is the ILV assessment straightforward based on the available information?

Stage 2 assessment
- Undertake further assessment of geological and topographical issues (including site visits) detailed specific analyses of the available geotechnical information, further sensitivity analysis of liquefaction vulnerability assessments and review laboratory test data.

Phase 4
Does the property satisfy the two ILV engineering criteria?

- Based on engineering judgement, is a property vulnerable to material liquefaction damage in up to 100 year return period levels of earthquake shaking?
- Based on engineering judgement, has the vulnerability of the property to liquefaction damage materially increased 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?

No
Property does not qualify for ILV

Yes
Property qualifies for ILV

Feedback
No
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).
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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 shaking¹ 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 (MW) = 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, the material increase in liquefaction vulnerability is likely to have occurred in a single event.

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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.
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.

![Maps showing areas where liquefaction triggering is predicted for small, medium and large levels of earthquake shaking](image)

*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** ($\gamma$) = 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).
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;
- Progradation 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.
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 Ballegoooy 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
earquakes 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.

  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

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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 MW. 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) 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.](image)

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](image-url)

**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.

![Histograms showing BDR correlations with observed land damage, liquefaction related subsidence and differential foundation settlement.](image)

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.
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.
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.
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); 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.

- Define geographic extent of properties under consideration for ILV.
  - Rural, commercial and Port Hills properties.
  - All TC1, TC2, TC3 and flat land residential Red Zone properties.

Phase 2: Is there sufficient information to assess ILV?
- Yes
  - Refer to Figure 9.1
- No
  - Gather additional information including:
    - CPT data
    - Borehole logs
    - Laboratory test data
    - Groundwater information

Assess each property for ILV:
- Stage 1 assessment
  - Does the geotechnical information and corresponding liquefaction vulnerability assessments reconcile with land damage observations relative to the levels of estimated shaking for the main CES events?
  - Is the ILV assessment straightforward based on the available information?
- Stage 2 assessment
  - Undertake further assessment of geological and topographical issues (including site visits) detailed specific analyses of the available geotechnical information, further sensitivity analysis of liquefaction vulnerability assessments and review laboratory test data.

Does the property satisfy the two ILV engineering criteria?
- Yes
  - Property qualifies for ILV
- No
  - Property does not qualify for ILV

Refer to Figure 4.1

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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 \( \Delta \)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.