Practical Implications of Increased Liquefaction Vulnerability

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1 Introduction

This report is prepared for Chapman Tripp (CT) on behalf of the Earthquake Commission (EQC) to assist its valuation advisors in developing and implementing a methodology to determine what, if any, diminution of value (DoV) a residential property has suffered as a consequence of Increased Liquefaction Vulnerability (ILV) land damage caused by the 2010-2011 Canterbury Earthquake Sequence (CES).

This report presents the advice that a geotechnical engineer would be expected to give a buyer or seller of a property in Canterbury about the practical implications that result from that property having a material increase in liquefaction vulnerability due to the CES. A material increase in liquefaction vulnerability is defined in the ILV Assessment Methodology Report (T+T, 2015), which provides a detailed methodology for assessing properties that qualified and did not qualify as having ILV land damage.

In order to provide details of the practical implications for ILV land damage, T+T, in conjunction with EQC’s valuation advisors and legal advisors, have established a set of liquefaction vulnerability severity (“severity”) classifications and change in liquefaction vulnerability severity (“change in severity”) classifications so that all properties with ILV land damage in Canterbury could be classified accordingly. All properties with ILV land damage have been classified in terms of severity both before and after the CES (pre-CES and post-CES), and change in severity due to the CES, for both 100 year and 25 year return period levels of earthquake shaking. The details of the practical implications resulting from a property having ILV land damage are described in this report by reference to these severity and change in severity classifications.

This report should be read in conjunction with the following reports:

- Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology Report (ILV Assessment Methodology) (T+T, 2015);
- IFV and/or ILV Land Damage Consolidated Policy Statement (EQC, 2016a);
- DoV Methodology for ILV (for properties with residential building in place) (EQC 2016b); and
- DoV Methodology for ILV (for where the residential building has been or will be rebuilt) (EQC, 2016c).

1.1 Structure

The report is organised into the following sections:

- **Section 2** provides the background and purpose of this report. It summarises ILV as a form of natural disaster damage and the approach that EQC intends to settle ILV land damage claims. It provides the reasons for and context of the engineering information provided and the objectives and principles adopted for the practical implications assessment.

- **Section 3** describes the severity and change in severity classifications developed by T+T, in conjunction with EQC’s valuation and legal advisors, as well as the methodology used to assess these classifications. Results of T+T’s classification of all properties with ILV land damage in relation to both 100 year and 25 year return period levels of earthquake shaking are provided.

- **Section 4** describes the implications of the different liquefaction vulnerability severity classifications and change in severity classifications for properties where the pre-CES residential building is in place. These practical implications are described in terms of:
  - the increased likelihood of moderate-to-severe liquefaction related land damage; and
  - the increased likelihood of significant liquefaction related building damage.
- **Section 5** provides details of the ground improvement or foundation solutions that residential buildings on properties with ILV land damage may require in order to remove or mitigate the impact of liquefaction vulnerability if they are rebuilt in the future. This is discussed in relation to the severity classifications at 25 year return period levels of shaking, which reflect the relevant requirements of the Building Code (DBH, 2004) and MBIE Guidance (MBIE, 2015).

- **Section 6** describes the practical implications of ILV land damage for new residential buildings constructed using MBIE surface foundation solutions without ground improvement works to repair ILV land damage.

- **Section 7** discusses the practical implications for properties that have both ILV land damage and IFV land damage.

- **Section 8** discusses additional engineering information provided for selected assessment areas, as requested by EQC’s valuation advisors. The additional information was primarily compiled to enable EQC’s valuation advisors to understand the basis of the severity classifications and change in severity classifications for groups of assessment areas where there was a significant difference between the assessed DoV values of adjacent areas. The additional engineering information is provided in Appendix D.
2 Background and purpose of the ILV Practical Implications Report

This Section provides a brief summary of the background to ILV as a form of natural disaster damage and the ways that EQC intends to settle ILV land damage claims in accordance with the EQC Act. The purpose of this Practical Implications Report is also provided. In particular, this Section sets out:

- ILV is a form of natural disaster damage;
- The approach that EQC intends to settle ILV land damage claims;
- Engineering information provided for the ILV DoV Methodology; and
- Objectives and principles adopted for the practical implications assessment.

2.1 ILV is a form of natural disaster damage

In *Earthquake Commission v Insurance Council of New Zealand Incorporated* (the “Land Declaratory Judgment”),¹ the High Court of New Zealand considered whether ILV was a form of “natural disaster damage” for the purposes of the EQC 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 Canterbury earthquake sequence, has sustained natural disaster damage in terms of the Act. These 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 the other purposes usually associated with residential land.”

EQC considers that changes that have reduced the use and amenity of the land can be assessed by reference to whether the market value of the property in question has reduced, and that the identification of ILV therefore involves a combination of engineering and valuation assessments.

EQC has determined that it will apply three criteria in assessing whether residential land has suffered ILV:

- The residential land has a material vulnerability to liquefaction damage after the CES at 100 year return period levels of earthquake shaking² (Criterion 1);
- The vulnerability to liquefaction damage of the residential land in future earthquakes has materially increased at up to 100 year return period levels of earthquake shaking 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).

T+T have developed a methodology for assessing the first and second criteria (together, the “Engineering Criteria”), which is set out in the ILV Assessment Methodology Report (T+T, 2015). Criterion 3 is addressed in a separate report by EQC’s valuation advisors.

Both Engineering Criteria must be met in order for a property to qualify as having ILV land damage. In other words, land that is not materially vulnerable to liquefaction damage after the CES does not have ILV land damage because by definition it cannot have increased in vulnerability in a material way. Equally, land that has been assessed as presently having a material vulnerability to liquefaction in the event of a future earthquake does not qualify as having ILV land damage where that vulnerability existed before the earthquake sequence and was not made materially worse by it.

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¹ *Earthquake Commission v Insurance Counsel of New Zealand* [2014] NZHC 3138, [2015] 2 NZLR 381 at [92].
² 100 year return period levels of shaking refer to Magnitude (M) = 6.0 and Peak Ground Accelerations (PGA) = 0.3g as is consistent with the MBIE Guidance (MBIE, 2015) specified design levels of earthquake shaking (Refer to Section 5 of the ILV Assessment Methodology Report (T+T, 2015)).
The Engineering Criteria were used to determine whether residential land was materially more vulnerable to liquefaction damage in future earthquakes because of changes to its physical state due to the CES. In assessing what changes in liquefaction vulnerability are material, consideration has been given to whether the changes have adversely affected the uses and amenities of the land. These include how the changes affect its suitability as a residential building platform.  

The results of the ILV land damage assessment for all flat land urban residential properties in Canterbury are presented in Figure 2.1. In this figure:

1. The red properties are those assessed as qualifying for ILV land damage as they meet the two Engineering Criteria.
2. The purple properties have been assessed as being materially vulnerable to liquefaction at 100 year return period levels of earthquake shaking (Criterion 1) but have not had sufficient material change in liquefaction vulnerability across the CES as a result of ground surface subsidence (Criterion 2) (i.e. they do not meet Criterion 2).
3. The blue properties have been assessed as not being materially vulnerable to liquefaction at 100 year return period levels of earthquake shaking (i.e. they do not meet Criterion 1).
4. White areas on the map represent non-residential or rural properties and are outside of the scope of the T+T ILV assessment work.

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3 Refer to Section 7.3 of the ILV Assessment Methodology Report (T+T, 2015) for more in-depth discussion of materiality.
The approach that EQC intends to settle ILV land damage claims

The Land Declaratory Judgement also considered the approach that EQC may take to settle ILV land damage claims. The Court declared that:

“The settlement of claims compliant with the Act for natural disaster damage to residential land involving Increased Liquefaction Vulnerability may be approached on the basis of the Commission:

(a) indemnifying the claimant against his or her financial loss by an appropriate payment, including by payment of:

(i) the costs of relevant and appropriate repair or reinstatement activities; or

(ii) in appropriate circumstances, by payment of the loss of market value of the insured land together with any associated residential buildings;” or

(b) at the option of the Commission, by undertaking relevant and appropriate repair or reinstatement activities.”

This report has been written for the purposes of assisting EQC’s valuation advisors to develop an ILV DoV Methodology to determine what, if any, loss of market value (or diminution of value (DoV)) a residential property has suffered as a consequence of ILV land damage caused by the 2010-2011 Canterbury Earthquake Sequence (CES).

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The ILV Policy Statement (EQC, 2016a) defines how DoV is to be assessed by its valuation advisors in appropriate circumstances where the residential building remains in place:\textsuperscript{5} as:

“the discount from the price that would have been paid for the property (the residential land and residential buildings combined) that would be agreed between a willing buyer and a willing seller because of the ground surface subsidence to the land, with knowledge about that change and its impact on the vulnerability of the land to liquefaction in future earthquake events, the cost of repair options, and advice from competent and reasonable advisors taking account of the information available to EQC.”

For more information regarding EQC’s policy and methodology for settling ILV land damage claims, refer to the following documents:

- IFV and/or ILV Land Damage Consolidated Policy Statement (EQC, 2016a);
- DoV Methodology for ILV (for properties with residential building in place) (EQC 2016b); and
- DoV Methodology for ILV (for where the residential building has been or will be rebuilt) (EQC, 2016c).

\section*{2.3 Engineering information provided for the DoV methodology}

To assist EQC’s legal and valuation advisors develop an ILV DoV methodology, EQC has requested that T+T provide the information that a geotechnical engineer would be able to provide a buyer or seller of a property about what a change in liquefaction vulnerability means in a practical sense. That is, the practical implications of a property having ILV land damage.

Key elements of the ILV DoV Methodology that EQC has asked T+T to consider in preparing the practical implications report are:

1. The level of detail a buyer and seller would obtain from a geotechnical engineer for the purpose of a report obtained prior to purchase, that is, a study using publically available information with no additional geotechnical investigations undertaken; and
2. The practical implications of ILV land damage that reflect future use of the property (e.g., building a new residential building on the site at some point in the future) should be assessed on the basis of the currently applicable regulations for that activity, and not take into account any future potential regulatory changes; and
3. The practical implications of ILV land damage for each property should be provided by reference to the pre-CES physical state (i.e. the ground surface level prior to the CES), the post-CES physical state (i.e. the ground surface level after the CES) and the change in the physical state (i.e. the amount of subsidence that occurred over the CES).\textsuperscript{8}

The practical implications of ILV land damage and the methodology to determine this has been developed iteratively in conjunction with EQC’s valuation advisors and legal advisors solely to assist EQC and its valuation experts in developing an ILV DoV methodology. The information provided in this report has therefore taken into account feedback from EQC’s valuation and legal advisors as to what aspects of ILV land damage and what associated practical implications are relevant to the development of the ILV DoV methodology.

\textsuperscript{5} Refer to the IFV and/or ILV Land Damage Consolidated Policy Statement (EQC, 2016a) at [50.1].
\textsuperscript{6} Refer to the DoV Methodology for ILV (EQC, 2016b) at [33.7].
\textsuperscript{7} Refer to the DoV Methodology for ILV (EQC, 2016b) at [33.8].
\textsuperscript{8} Refer to the DoV Methodology for ILV (EQC, 2016b) at [33.6].
2.4 Objectives of the Practical Implications Report

EQC has requested that T+T develop a methodology that enables the practical implications of ILV land damage to be assessed in a robust and consistent manner.

Additionally, EQC has advised T+T that the objectives of the practical implications assessment are to:

- Provide a basis for settlement of claims involving ILV land damage that is consistent with EQC’s obligations under the EQC Act and is 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 Land Declaratory Judgement, EQC has also requested that T+T ensure that the practical implications assessment:

- 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 methodology for assessing practical implications of ILV land damage and the approach that has been adopted satisfies each of these standards. Certain simplifying assumptions, as described in the ILV Assessment Methodology (T+T, 2015), which are not considered to be material to the outcome of the assessment have been made.

2.5 Important principles adopted for the Practical Implications Report

2.5.1 Standard of assessment

EQC has advised T+T that claims for damage to residential land must be assessed on the balance of probabilities, as determined by the Land Declaratory Judgement. EQC has therefore instructed T+T to provide the advice that a geotechnical engineer is more likely than not to provide to a buyer or seller of a property concerning the practical implications of ILV land damage, having regard to publicly available information.

Accordingly, T+T have provided the advice on the practical implications of ILV land damage that it considers to be the most appropriate engineering advice for a property with ILV land damage, taking into account what T+T considers to be the current best scientific understanding of ILV land damage, and the limitations in the prediction of liquefaction related land damage at different levels of earthquake shaking.

2.5.2 Relevant publicly available information is taken into account

Relevant publicly available information has been taken into account in assessing the severity and change in severity of properties with ILV land damage in Canterbury. 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 the ILV Assessment Methodology Report (T+T, 2015)). This data has been analysed as well as the other publicly available data on the New Zealand Geotechnical Database (NZGD) (MBIE, 2012) relevant to the assessment of ILV land damage.

9 Prior to 1 June 2016, the New Zealand Geotechnical Database (NZGD) was referred to as the Canterbury Geotechnical Database (CGD).
The assessment of the practical implications of ILV land damage described in this report relies, to the extent it is relevant, on the same information that was used by T+T for the assessment of whether residential properties in Canterbury have qualified for ILV land damage in the CES (refer to Section 5 of the ILV Assessment Methodology report (T+T, 2015)). In addition, observations from the February 2016 earthquake were considered in the assessment of severity and change in severity in parts of Canterbury.

2.5.3 **Assessment of ILV Practical Implications is made across the CES**

For the reasons given in the ILV Assessment Methodology (T+T, 2015), the engineering methodologies developed to assess the impact of ILV land damage for the CES can only practically be undertaken by considering ground surface subsidence across the CES. For the same reasons, the assessment of the practical implications of ILV land damage is also assessed across the full CES.
3 Liquefaction vulnerability severity classification

This Section of the report describes the process of classifying the severity and change in severity of the portfolio of properties with ILV land damage in Canterbury. In particular, this Section sets out:

- the return period levels of shaking at which the classifications were assessed;
- a summary of the severity and change in severity classification methodology, and the information taken into account during the assessment; and
- a summary of the results of the severity classification assessment. This is presented as both:
  - a set of maps for the post-CES severity, pre-CES severity, and change in severity at both 100 year and 25 year return period levels of shaking; and
  - tabulated results of the portfolio of properties for the post-CES severity, pre-CES severity, and change in severity at 100 year and 25 year return period levels of shaking.

Full details of the methodology for undertaking the liquefaction vulnerability severity classification assessment are presented in Appendix A, and full results of this assessment are provided in Appendix B.

3.1 Severity classification methodology overview

In order to provide details of the practical implications for ILV land damage, T+T, in conjunction with EQC’s valuation advisors and legal advisors, have established a set of liquefaction vulnerability severity (“severity”) classifications and change in liquefaction vulnerability severity (“change in severity”) classifications so that all properties with ILV land damage in Canterbury could be classified for both 100 year and 25 year return period levels of earthquake shaking.

This Section provides a summary of the severity and change in severity classification assessment methodology. Further details of the methodology are provided in Appendix A.

3.1.1 Return periods used for classification

3.1.1.1 Selection of 100 year and 25 year return period levels of shaking

A 100 year return period level of earthquake shaking was selected for assessment as it is consistent with the level of earthquake shaking used for the assessment of ILV land damage. The reasons for assessing material vulnerability to liquefaction at 100 year return period levels of shaking are set out in Section 6.3 of the ILV Assessment Methodology Report (T+T, 2015).

A 25 year return period level of earthquake shaking was also selected for assessment. This was chosen for the following reasons:

- EQC’s valuation advisors requested that a more frequent return period level of earthquake shaking be assessed as they considered that this would be an important factor for a buyer or seller of a property in Canterbury;
- A 25 year return period is consistent with the ILV Assessment Methodology (T+T, 2015), which assessed properties for ILV land damage at up to 100 year return period levels of shaking;
- A 25 year return period is the lowest level of earthquake shaking provided in the MBIE Guidance (MBIE, 2015). A detailed seismicity study would be required to determine levels of earthquake shaking at return periods less than 25 years, which is outside the scope of this work – being the advice that a geotechnical engineer would be expected to give a buyer or seller of a property in Canterbury;
- A 25 year return period level of earthquake shaking is consistent with the design of residential buildings in New Zealand; and
A 25 year return period is the lowest level of earthquake shaking that T+T considers to be suitable for severity and change in severity assessment due to the lack of observed land damage at return periods less than 25 years.

Further details of the relevance of the 25 year return period level of shaking is included in Section 5.3. An additional consideration in the design of residential buildings in New Zealand is the 500 year return period level of shaking (Ultimate Limit State design). This is considered not relevant to the assessment of ILV and is discussed in Section 5.3 of this report and outlined in detail in Section 6.3.1 of the ILV Assessment Methodology Report (T+T, 2015).

Severity and change in severity classifications were assigned to properties with ILV land damage for both 100 year return period levels of earthquake shaking (i.e. $M_w = 6.0$ and $PGA = 0.30g$) and 25 year return period levels of earthquake shaking (i.e. the greater of the $M_w = 7.5$ and $PGA = 0.13g$, and $M_w = 6.0$ and $PGA = 0.19g$ scenario). These levels of earthquake shaking are consistent with the values used in the ILV Assessment Methodology (T+T, 2015) and specified in the MBIE Guidance (MBIE, 2014a; MBIE, 2015).

The severity and change in severity classifications have been determined for these discrete levels of earthquake shaking only and do not give an indication of the severity or change in severity at return periods between 25 years and 100 years. Consideration of liquefaction vulnerability at return period levels of shaking other than 25 years and 100 years is discussed in Section 5.3 of this report and outlined in detail in Section 6.3.1 of the ILV Assessment Methodology Report (T+T, 2015).

### 3.1.1.2 Liquefaction vulnerability at other return period levels of shaking

The assessment of severity and change in severity has been undertaken at 100 year and 25 year return period levels of earthquake shaking only. Accordingly, it is not possible at present to provide the severity and change in severity classifications at other return periods. It is also not possible to provide the return period level of shaking at which a property becomes materially vulnerable to liquefaction. However, some general observations are possible.

Data provided in Appendix D (discussed in Section 8) shows the change in LSN values as the Peak Ground Acceleration (PGA), and associated return period, increases for selected assessment areas. This data provides an indication of the severity and change in severity classifications at return periods up to approximately 500 years for each selected assessment area. However, as the LSN values are calculated using the automated ILV model\(^{10}\), over-prediction and under-prediction of the LSN values can occur and engineering judgement needs to be applied when assessing the severity and change in severity classifications.

For the assessment of ILV severity and change in severity, it is important to also consider all other relevant information such as land damage observations, estimated total change in ground surface elevation as a result of the CES, subsurface soil conditions, and ground surface elevation when determining the severity and change in severity classifications. As such, the LSN and $\Delta$LSN values cannot be reliably used in isolation to determine at which return period level of shaking a property becomes materially vulnerable to liquefaction. They also cannot be used in isolation to determine when the change in vulnerability might transition from No Change to Minor or change in severity at a particular level of earthquake shaking.

However, what can be inferred from the LSN versus PGA curves is the slope and maximum LSN value at different return periods. In some assessment areas, the LSN curves indicate liquefaction triggering at low levels of earthquake shaking, resulting in material liquefaction vulnerability at 25 year return period levels of shaking. However, these areas may reach a maximum cumulative thickness of liquefying material at less than 100 year return period levels of earthquake shaking so that, for example, the 100 year return period severity classification may only be Medium. In other

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\(^{10}\) Refer to Section 8 of the ILV Assessment Methodology Report (T+T, 2015).
assessment areas, LSN versus PGA curves indicate no material liquefaction triggering at 25 year return period levels of earthquake shaking but vulnerability continues to increase as the level of shaking increases up to and beyond 100 year return period levels. This results in an area that has, for example, no material vulnerability at 25 year return period levels of earthquake shaking and Medium to High severity classifications at 100 year return period levels of shaking.

For properties that have been assessed as having ILV land damage at 100 year return period levels of earthquake shaking, it can be concluded that if those properties have No Change in severity or are Not Vulnerable at 25 year return period levels of shaking, there is likely to be an increase in vulnerability at some return period between 25 years and 100 years. However, as explained in the preceding paragraphs, there are limitations in determining the nature and extent of that change in vulnerability.

3.1.2 Classification undertaken using an area/neighbourhood approach

All of the properties with ILV land damage in Canterbury were classified using the information outlined in Section 3.1.3 and by applying engineering judgement. However, unlike the ILV Assessment Methodology (T+T, 2015), an area/neighbourhood approach was employed for severity and change in severity classification purposes rather than a property specific assessment. The reasons for this are as follows:

- An area wide assessment is considered the most appropriate for assessing liquefaction vulnerability in the context of the practical scenario that T+T was asked to assess, given that wider ground investigations in an area of geologic similarity should be considered when characterising performance (Russell et al., 2015);
- The engineering advice for a buyer or seller of a property is anticipated to utilise existing information and not require detailed site specific analysis, primarily due to cost constraints inherent in a typical property pre-purchase due-diligence assessment;
- The existing geotechnical investigation data was obtained and collated as part of the ILV Assessment Methodology.\(^\text{11}\) As such, the density of available investigation data does not allow individual properties to be classified into various extents of severity and change in severity but does support an area/neighbourhood severity assessment;
- The science of the prediction of liquefaction vulnerability used for ILV qualification has been developed specifically to assess whether a property is materially vulnerable to liquefaction at 100 year return period levels of earthquake shaking. It was not developed to determine the extent of severity and extent of change in severity once a property qualifies for ILV land damage at 100 year return period levels of shaking;
- The science of the prediction of liquefaction vulnerability has also been developed and calibrated for the larger (100 to 500 year) return period levels of shaking and is not tuned for assessment at 25 year return period levels of shaking (as was demonstrated by prediction versus observations of liquefaction in the February 2016 earthquake where shaking was close to 25 year return period levels in parts of Canterbury); and
- Undertaking severity and change in severity assessments for individual properties assessed as qualifying for ILV land damage in Canterbury is not likely to significantly improve the results for those properties compared to an area/neighbourhood assessment methodology given the limitations in the information and science used to make assessments.

In the area/neighbourhood approach, groups of properties with similar observed land performance through the CES, ground surface subsidence over the CES, and topographical characteristics were

\(^{11}\) Refer to Section 5.5 of the ILV Assessment Methodology Report (T+T, 2015) that describes the geotechnical investigation data used in the assessment of ILV as well as Figure 4.2 and Section 4.4.2 of the ILV Assessment Methodology Report that explain the collation of geotechnical investigation data for the purpose of ILV assessment.
identified prior to assessing the severity and change in severity classifications. For the portfolio of properties with ILV land damage, 182 assessment areas were identified, with an average of 55 properties in each area.

The full procedure for identifying these assessment areas is explained in Appendix A and involved reviewing the datasets outlined in Section 3.1.3 to define areas that performed similarly across the CES. The datasets are discussed and fully referenced in Section 5 of the ILV Assessment Methodology Report (T+T, 2015). Once the assessment areas were defined, the liquefaction vulnerability severity and change in severity classifications for properties in the areas could be assessed utilising the same datasets as well as other relevant geotechnical information for that particular group of properties.

3.1.3 Information taken into account

In order to undertake the severity classification and change in severity classification assessments for properties with ILV land damage, the following datasets (available in the NZGD (MBIE, 2012)) were considered:

- Land damage observations, including liquefaction and lateral spreading, following the September 2010, February 2011, June 2011 and December 2011 events, as well as liquefaction observations following the February 2016 event\(^\text{12}\) including:
  - Aerial photography; and
  - Observed land damage from road based and property based liquefaction and land damage mapping.
- Estimated levels of earthquake shaking for the September 2010, February 2011, June 2011 and December 2011 events, as well as the February 2016 event\(^\text{12}\);
- Estimated total change in ground surface elevation across the CES derived from the LiDAR surveys;
- Estimated liquefaction-induced change in ground surface elevation across the CES (i.e. excluding the estimated tectonic component) derived from the LiDAR surveys;
- The ground surface elevation, relative to sea level, estimated using a Digital Elevation Model (DEM) derived from LiDAR surveys of the greater Christchurch area;
- Mapping of lateral spread caused by the CES; and
- Event specific and median groundwater surface elevations.

In addition, the following models were used in the assessment of severity and change in severity classifications:

- Estimated pre-CES Liquefaction Severity Number (LSN) values extracted from the automated ILV model\(^\text{13}\) (for both 100 year and 25 year return period levels of earthquake shaking);
- Estimated post-CES LSN values extracted from the automated ILV model\(^\text{13}\) (for both 100 year and 25 year return period levels of earthquake shaking); and
- Estimated change in LSN (ΔLSN) values across the CES extracted from the automated ILV models\(^\text{13}\) (for both 100 year and 25 year return period levels of earthquake shaking).

The LSN and ΔLSN values from the automated ILV models were used in conjunction with all of the other information and datasets to assess the severity and change in severity classifications for each

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\(^{12}\) Observations from the February 2016 event are not yet available on the NZGD (MBIE, 2012) at the time of writing this report.

\(^{13}\) Refer to Sections 7 and 8.2 of the ILV Assessment Methodology Report (T+T, 2015) for more in-depth discussion about the LSN index and how it is calculated on an automated basis at 100 year return period levels of shaking for the urban residential properties in Canterbury. The same methods were used to generate the automated ILV models at 25 year return period levels of earthquake shaking.
group of properties as a matter of engineering judgement. Further details of the ranges of calculated LSN and $\Delta$LSN values for each of the severity classifications and change in severity classifications are provided in Section 3.1.4 and in detail in Appendix A.

### 3.1.4 Classifications adopted

The pre-CES and post-CES severity classifications and the change in severity classifications used in the severity assessment are provided below.

There are four primary severity classifications for the pre-CES and post-CES scenarios. These are presented below in order of increasing severity:

- Not Vulnerable (NV)\(^{14}\);
- Medium (M);
- High (H); and
- Very High (VH).

For change in severity there are three primary classifications. These are presented below in increasing extent of change:

- No Change (NC)\(^{15}\);
- Minor (Min); and
- Major (Maj).

The details of these classifications and the methodology used to determine the classification for a given group of properties are explained in Appendix A. Details of the practical implications for properties with ILV land damage for each of the severity and change in severity classifications are set out in Sections 4 and 5 of this report.

Lower bound and upper bound LSN and $\Delta$LSN values were used to establish the primary severity classifications and change in severity classifications. The severity and change in severity classifications with ranges of LSN and $\Delta$LSN values for each classification are presented in Figure 3.1 and Figure 3.2 respectively. Further details of the LSN and $\Delta$LSN values assigned to each severity and change in severity classification, and the reasons for these LSN and $\Delta$LSN ranges are provided in Appendix A. It should be noted that for the Medium, High, and Very High severity classifications there is overlap of the LSN ranges between the classifications.

The LSN and $\Delta$LSN values from the automated ILV models, for both the 100 year and 25 year return period levels of shaking, were used in conjunction with all of the other datasets outlined in Section 3.1.3 to assess the severity and change in severity classifications for each group of properties. In many cases engineering judgement was used to make adjustments to the automated LSN and $\Delta$LSN values to calibrate them to the observed liquefaction related land damage relative to the observed levels of earthquake shaking, and to account for subsurface ground conditions and estimated total change in ground surface elevation. These ‘adjusted’ LSN and $\Delta$LSN values were used when determining the severity and change in severity classification of properties with ILV land damage.

For many of the assessment areas in Canterbury, it was not possible to determine a primary severity classification or change in severity classification. These are typically in areas where either there is a lack of data, there are variable ground conditions or there is conflicting information between different datasets. While additional geotechnical investigation data and more detailed assessment could possibly help increase the level of certainty of which primary severity or change in severity

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\(^{14}\) Not Vulnerable refers to no material vulnerability, with materiality set out in Section 7.3 of the ILV Assessment Methodology Report (T+T, 2015).

\(^{15}\) No change refers to no material change, with material change in liquefaction vulnerability set out in Section 7.4 of the ILV Assessment Methodology Report (T+T, 2015).
classification properties could be assigned, some areas are likely to always have uncertainty associated with them due to the limits of the science and understanding around characteristics of vulnerability to liquefaction, resulting in broader ‘OR’ classifications described below.

The severity classifications for those properties where it was not possible to determine a primary classification were identified as:

- Not Vulnerable OR Medium (NV or M);
- Medium OR High (M or H); and
- High OR Very High (H or VH).

For the change in severity classifications these were identified as:

- No Change OR Minor (NC or Min); and
- Minor OR Major (Min or Maj).

The relationships between the ‘OR’ severity classifications and the primary severity classifications are shown in Figure 3.1 and Figure 3.2. It is important to note that for groups of properties in the ‘OR’ severity classifications it is not possible to say where these lie within that classification. For example, for a group of properties in the Medium OR High classification, it is difficult to determine whether the majority of properties are at the medium end, at the high end or somewhere in the middle. The uncertainty associated with a group of properties in an ‘OR’ severity classification means that all that can be inferred is that it lies somewhere within the bounds of the Medium and High severity classifications.

![Figure 3.1: The pre-CES and post-CES liquefaction vulnerability severity classifications, divided into four primary classifications (shown in bold) and three ‘OR’ classifications with the range of LSN values for each classification indicated in the bottom and top right hand corners of the boxes.](image-url)
From an engineering perspective, the usual method of dealing with uncertainty is to take a conservative approach and assume the higher severity classification for design purposes. However, in the case of the advice that a geotechnical engineer would be expected to give a buyer or seller of a property with ILV land damage, it would not be possible to say that one primary severity classification is more likely than the other, as this information is not known. As such, the practical implications for a property with an ‘OR’ classification (i.e. land and building damage, ground improvements and foundation requirements) could be that of the higher or lower classification. It should not be assumed that the practical implications can be taken as the mid-point between the two severity classifications. If new information becomes available or if additional time and cost is available to undertake further assessment then this advice could be reviewed. Even then, however, it may not be possible to refine the uncertainty any further. Accordingly, it would be up to the buyer or seller of the property to decide what to do with this (‘OR’) information.

### 3.1.5 Limitations of the liquefaction vulnerability severity classifications

While the severity and change in severity classifications allow robust and consistent advice to be given in regards to the practical implications of ILV land damage, it is important to recognise that there are uncertainties associated with the assessments.

The ILV Assessment Methodology Report (T+T, 2015) provides a detailed description of uncertainties associated with using the LSN parameter as the preferred tool for liquefaction vulnerability assessment.\(^{16}\) A brief summary of these uncertainties is provided below.

The range of uncertainties associated with the LSN parameter as a tool for liquefaction vulnerability assessment includes:

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

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\(^{16}\) Refer to Section 7.2.2 and 7.4.1 of the ILV Assessment Methodology Report (T+T, 2015).
The significant variables that contribute to the uncertainty of LSN are listed below:

- Earthquake ground motions ($M_w$ and PGA);
- Liquefaction triggering to calculate LSN;
- Post-liquefaction volumetric strain ($\varepsilon_v$) to calculate LSN;
- Depth to groundwater estimates;
- CPT measurement accuracy; and
- Spatial variation and interpolation of LSN values at CPT locations.

These uncertainties are inherent in current investigation and analysis tools.

It is important to note that not all of the uncertainties which are listed above translate into LSN uncertainty at a particular site. Therefore, it is not appropriate to attempt to combine all of these uncertainties together. However, it is reasonable to assume that a given site may be affected by some of them. In the severity and change in severity assessments, engineering judgement has been included as an integral component to address the uncertainties of the inputs into LSN. It includes a review of the datasets including land damage observations, geological and topographic assessments, and detailed specific analysis of the geotechnical information.

The result of this uncertainty is that a severity classification does not predict a particular liquefaction consequence in a specified level of earthquake shaking. Instead, it represents a prediction of a range of possible consequences at a specified level of earthquake shaking.

If a group of properties were considered that all had a severity classification of Medium (with characteristic LSN values between 16 and 25) it is unlikely that the performance of all of the properties would be identical for a given level of earthquake shaking. It is more likely than not that liquefaction related land damage will be minor-to-moderate or moderate-to-severe for the majority of a group of properties classified as Medium, with a few properties having none-to-minor land damage (see section 4 for discussion of the land damage categories). In the same way, the majority of a group of properties with a severity classification of Very High (with characteristic LSN values greater than 30) would be more likely than not to have moderate-to-severe liquefaction related land damage, with very few expected to experience none-to-minor land damage. Statistical information regarding the severity classifications and relationship between LSN and observed land damage is presented and discussed in further detail in Section 4.1.

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

### 3.1.6 Distribution of properties in severity and change in severity classifications

A varied distribution of severity or change in severity classification exists for the properties within assessment areas even though a specific classification was assigned to that area. Some properties in an area with a given severity classification may be at the upper end of that classification, some may be in the middle, and some may be at the lower end. However, there are also likely to be instances of individual properties within an area that actually have a higher or lower severity or change in severity classification than what has been assigned for that area.

A high level of confidence was required for an assessment area to be assigned a certain severity or change in severity classification. That is, based on engineering judgement, most of the properties in an area fitted with the classification assessed. However, absolute certainty that all properties within an area fitted this classification was not able to be attained and there may be instances where some
individual properties are higher or lower than the severity or change in severity classification assessed for an area. For example, in an assessment area classified as High severity, there may be a small proportion of properties that could be classified as Medium and a small proportion of properties that could be classified as Very High. These proportions cannot be quantified as it is not known which properties these may be.

The same varied distribution of severity and change in severity within assessment areas, including a small proportion actually having a lower or higher assessed classification, also applies to the ‘OR’ classifications. The ‘OR’ classifications capture greater levels of uncertainty so that the vast majority of properties in an area fit into that classification but there may still be some properties that fall outside that classification.

### 3.1.7 Transition zones of severity and change in severity between adjacent assessment areas

The assessment of severity and change in severity classifications using an area/neighbourhood approach gives rise to the presence of transition zones at the boundaries of these areas. In the majority of cases there is likely to be a gradual transition from one severity classification to another. For example, between Medium and High assessment areas there will typically be a Medium OR High assessment area.

However, there are instances where there may be large step changes in severity classification or change in severity classification between adjacent areas or at the ILV/not-ILV boundaries. For example, one area may be classified as not-ILV and an adjacent area may be classified as High severity.

In some areas there are geological and topographic features that result in a step change in severity and change in severity between adjacent areas. In these cases the transition is sudden and justified by these features. For example, a river terrace feature where there is a rapid change in elevation may result in an area being classified with High severity (at the lower elevation) adjacent to an area that was assessed to be not-ILV.

In reality, there is likely to be a gradual transition between two adjacent areas that have a step change in severity classifications. For example, at the boundary between Medium OR High and Very High severity classifications there is likely to be a transition zone of High severity that extends into both areas. However, there is not sufficient information available to determine the extent of this transition zone for the same reasons a property specific severity and change in severity assessment was not undertaken, as outlined in Section 3.1.2.

### 3.2 Liquefaction vulnerability severity classification maps

A total of six severity classification maps were created and are shown in Figure 3.3 to Figure 3.8 and are also provided at a larger scale in Appendix B.

- Figure 3.3 shows the **pre-CES** severity classifications for 100 year return period levels of earthquake shaking.
- Figure 3.4 shows the **post-CES** severity classifications for 100 year return period levels of earthquake shaking.
- Figure 3.5 shows the **change in severity** across the CES for 100 year return period levels of earthquake shaking.
- Figure 3.6 shows the **pre-CES** severity classifications for 25 year return period levels of earthquake shaking.
- Figure 3.7 shows the **post-CES** severity classifications for 25 year return period levels of earthquake shaking.
Figure 3.8 shows the **change in severity** across the CES for 25 year return period levels of earthquake shaking.

White areas on the maps represent residential and non-residential properties that did not qualify for ILV land damage in accordance with the ILV Assessment Methodology Report (T+T, 2015) and are outside of the scope of this report.
Figure 3.3: Map showing the pre-CES liquefaction vulnerability severity classifications for 100 year return period levels of earthquake shaking.

Figure 3.4: Map showing the post-CES liquefaction vulnerability severity classifications for 100 year return period levels of earthquake shaking.
Figure 3.5: Map showing the change in liquefaction vulnerability severity classifications across the CES for 100 year return period levels of earthquake shaking.
Figure 3.6: Map showing the pre-CES liquefaction vulnerability severity classifications for 25 year return period levels of earthquake shaking.

Figure 3.7: Map showing the post-CES liquefaction vulnerability severity classifications for 25 year return period levels of earthquake shaking.
3.3 Liquefaction vulnerability severity classification results

The results of pre-CES and post-CES severity classifications for the portfolio of properties with ILV land damage are shown in Table 3.1 and Table 3.2 for the 100 year and 25 year return period levels of earthquake shaking respectively. The results for the change in severity classification for both the 100 year and 25 year return period levels of shaking are presented in Table 3.3. The number of properties with ILV land damage in each classification are split into Residential Green Zone (green text) and Residential Red Zone (red text). Further subdivision of results are presented in Appendix B.

As expected, properties have a lower severity classification or the same severity classification for 25 year return period levels of earthquake shaking when compared to the severity classifications at 100 year return period levels of earthquake shaking. The 100 year return period results have a larger proportion of properties in the top right-hand side of Table 3.1 whereas the 25 year return period results have a larger proportion of properties in the bottom left-hand side of Table 3.2. For the 100 year return period results, it is noted that the Residential Red Zone properties are predominantly in the top right hand portion of the table whereas the Residential Green Zone properties are towards the bottom left hand portion of the table. For the 100 year post-CES severity, Not Vulnerable and Not Vulnerable OR Medium were not applicable in accordance with the ILV Assessment Methodology (T+T, 2015).

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17 The total number of properties with ILV land damage at the time of preparation of this report is 9987, which is slightly higher than the total number of properties shown in Table 10.1 and Table 11.1 in the ILV Assessment Methodology Report (T+T, 2015) (9917). This increase is the result of reassessment of the ILV qualification of properties following the February 2016 earthquake and where additional geotechnical investigations were available.
Table 3.1: Number of properties in the Residential Red Zone (red text) and Residential Green Zone (green text) with ILV land damage in each liquefaction vulnerability severity classification for 100 year return period levels of earthquake shaking.

<table>
<thead>
<tr>
<th>Pre-CES Liquefaction Vulnerability Severity Classification</th>
<th>Very High</th>
<th>H or VH</th>
<th>High</th>
<th>M or H</th>
<th>Medium</th>
<th>NV or M</th>
<th>Not Vulnerable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-CES Liquefaction Vulnerability Severity Classification</td>
<td>0 86</td>
<td>223 500</td>
<td>26 710</td>
<td>0 967</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Very High</td>
<td>174 557</td>
<td>1479 8</td>
<td>441 338</td>
<td>12 732</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>M or H</td>
<td>0 0</td>
<td>334 113</td>
<td>1861 26</td>
<td>0 500</td>
<td>710 0</td>
<td>967 223</td>
<td>26 0 NA</td>
</tr>
<tr>
<td>Medium</td>
<td>0 0</td>
<td>174 557</td>
<td>1479 8</td>
<td>441 338</td>
<td>12 732</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>NV or M</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Not Vulnerable</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Notes:
1. Boxes with NA are properties that are not applicable for the severity classification of the portfolio of properties with ILV land damage at 100 year return period levels of earthquake shaking.
2. 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.

Table 3.2: Number of properties in the Residential Red Zone (red text) and Residential Green Zone (green text) with ILV land damage in each liquefaction vulnerability severity classification for 25 year return period levels of earthquake shaking.

<table>
<thead>
<tr>
<th>Pre-CES Liquefaction Vulnerability Severity Classification</th>
<th>Very High</th>
<th>H or VH</th>
<th>High</th>
<th>M or H</th>
<th>Medium</th>
<th>NV or M</th>
<th>Not Vulnerable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-CES Liquefaction Vulnerability Severity Classification</td>
<td>0 210</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Very High</td>
<td>0 210</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>M or H</td>
<td>0 1576</td>
<td>0 19</td>
<td>1576 19</td>
<td>1708 667</td>
<td>2262 1324</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Medium</td>
<td>0 10</td>
<td>1576 19</td>
<td>1708 667</td>
<td>2262 1324</td>
<td>1708 667</td>
<td>2262 1324</td>
<td>1708 667</td>
</tr>
<tr>
<td>NV or M</td>
<td>966 21</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Not Vulnerable</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA NA NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Notes:
1. Boxes with NA are properties that are not applicable for the severity classification of the portfolio of properties with ILV land damage at 25 year return period levels of earthquake shaking.
2. 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.
For the change in severity results presented in Table 3.3, it is also noted that no Residential Green Zone properties have been assessed to have had Major change. The majority of Residential Green Zone properties have experienced No Change or No Change OR Minor change at 25 year return period levels of shaking and Minor Change at 100 year return period levels of shaking. A greater proportion of Residential Red Zone properties had at least a Minor change in severity at 25 year return period levels of shaking whereas the majority of Residential Green Zone properties had No Change OR Minor change at 25 year return period levels of shaking and Minor or Minor OR Major change at 100 year return period levels of shaking. It is noted that No Change or No Change OR Minor were not applicable for the 100 year return period levels of shaking in accordance with the ILV Assessment Methodology (T+T, 2015).

Table 3.3: Number of properties in the Residential Red Zone (red text) and Residential Green Zone (green text) with ILV land damage in each change in liquefaction vulnerability severity classification for both 100 year and 25 year return period levels of earthquake shaking.

<table>
<thead>
<tr>
<th>Change in 100 year return period Liquefaction Vulnerability Severity Classification</th>
<th>Major</th>
<th>NC or Min</th>
<th>Minor</th>
<th>No Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>8</td>
<td>264</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Minor</td>
<td>36</td>
<td>657</td>
<td>89</td>
<td>6</td>
</tr>
<tr>
<td>Minor</td>
<td>1615</td>
<td>2517</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. None of the portfolio of properties with ILV land damage have a change in liquefaction vulnerability severity classification of No Change or No Change OR Minor at 100 year return period levels of earthquake shaking, which is consistent with the ILV Assessment Methodology Report (T+T, 2015).
2. 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/QPIIDs does not necessarily represent the number of claims.

3.4 Discussion of liquefaction vulnerability severity classification results

A comparison between Figure 3.3 and Figure 3.4 shows that the severity classifications of properties with ILV land damage have either stayed the same or become more severe at 100 year return period levels of earthquake shaking. While this exercise tries to classify liquefaction vulnerability severity, it is important to remember that it is not a discrete dataset. All properties with ILV land damage have undergone material change in vulnerability at up to 100 year return period levels of earthquake shaking. Properties in assessment areas that have stayed in the same severity classification across the CES have therefore effectively moved from the lower end of a severity classification to the upper end of that same classification. This is discussed further, in relation to increases in the likelihood of land and building damage, in Section 4.
4 Practical implications: Increased land and building damage in a future earthquake event

This Section of the report describes the practical implications for properties with ILV land damage in a future earthquake event where the pre-CES residential building is in place. For these properties, it is assumed that no ground improvement works have been undertaken and there have been no strengthening works to the existing foundations, other than being repaired to return it to the pre-CES condition. The practical implications are described in relation to the severity and change in severity classifications identified in Section 3 of this report.

The practical implications for a property with ILV land damage in a future earthquake event are best assessed by considering:

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

Statistical data provided in the ILV Assessment Methodology Report (T+T, 2015) enable the likelihood and increase in likelihood of moderate-to-severe land damage and significant liquefaction related building damage for pre-CES residential buildings to be assessed for each severity classification and change in severity classification outlined in Section 3.1.4.

While there are four primary severity classifications and three ‘OR’ classifications, the severity classifications actually lie on a continuous spectrum and do not have predefined boundaries. In this regard, for land damage and building damage, it means that at 100 year and 25 year return period levels of earthquake shaking there is little difference between a property that goes from the upper end of Medium, for example, to the lower end of High severity classifications (pre-CES to post-CES) and a property that goes from the lower end of Medium to the upper end of Medium severity classification (pre-CES to post-CES). The most significant practical implication, from an engineering perspective and in terms of increased land and building damage, is that it has had a material increase in vulnerability.

Table E1 in Appendix E summarises the ILV change in risk profile in terms of the likelihood of increased land damage and building damage for pre-CES residential buildings for each of the liquefaction vulnerability severity classifications. Details of how these likelihoods have been assessed and the practical implications of these risks are provided below.

4.1 Increased likelihood of moderate-to-severe liquefaction related land damage

As a result of the ground surface subsidence caused by the CES, properties with ILV land damage are now more likely to suffer moderate-to-severe land damage in a future earthquake event than they would have before the CES. Moderate-to-Severe land damage includes sand ejecta, differential ground surface subsidence, greater levels of undulation, and ponding. Additionally, material liquefaction related land damage is now likely to occur at more frequent intervals (shorter return periods) than before the CES.

The increase in moderate-to-severe land damage is presented in Figure 4.1, which shows the likelihood that a property may suffer moderate-to-severe land damage for different LSN bands. This is based on land damage observations immediately following the major earthquake events in the CES as well as automated LSN calculations. The liquefaction vulnerability severity classifications are overlaid on the histogram in Figure 4.1 along with a trend line showing the change in likelihood of moderate-to-severe land damage as the LSN and associated severity classification increases.
The meaning of the various land damage observation categories (i.e. the blue, green and red portions of the histogram in Figure 4.1) is described in Appendix C, and examples of what the various land damage categories actually look like can be seen in the photographs which are included in Appendix C.

Figure 4.1: Frequency bar chart showing the likelihood of none-to-minor, minor-to-moderate and moderate-to-severe land damage for different LSN bands based on data from the TC3 and Residential Red Zone properties, and indicating the relationship to the liquefaction vulnerability severity classifications.

As discussed in Section 3.1.4 and detailed in Appendix A, the severity classifications were defined by a range of characteristic LSN values, with overlap of LSN boundaries between the Medium, High, and Very High classifications. The trend line shows how the chance of moderate-to-severe land damage increases as LSN and associated liquefaction vulnerability severity increases. This information was used to develop Table E1 in Appendix E.

It is important to note that the trend line used to determine the likelihood of moderate-to-severe land damage for each severity classification deviates from the statistical data at high and low LSN values (i.e. less than 5 and greater than 40). This deviation is based on review of the severity classification results, the observed land damage for each main earthquake in the CES and the automated LSN values. These showed that at high LSN values the automated ILV model tends to over-predict in some assessment areas where none-to-moderate land damage was observed. At the other end of the spectrum, at low automated LSN values, lateral spreading, rather than isolated liquefaction, is considered to have caused the moderate-to-severe land damage observations. Therefore, engineering judgement was applied to anticipate a higher likelihood of moderate-to-severe land damage at very high LSN values and lower likelihood of moderate-to-severe land damage at low LSN values.
4.2 Increased likelihood of significant liquefaction related residential building damage

As a result of the ground surface subsidence caused by the CES, pre-CES residential buildings on properties with ILV land damage are now more likely to suffer increased building damage in future earthquakes. This includes overall settlement, planar and out-of-plane distortions, lateral extension or ‘stretch’ of the floor and foundations, and damage to specific foundation elements. Additionally, material liquefaction related building damage is now expected to occur at more frequent intervals (shorter return periods) than before the CES.

Figure 4.2 shows the likelihood of residential building damage for automated LSN values from 0 to 50. Building damage is represented by building damage ratio (BDR), as a result of the CES, for the portfolio of pre-CES residential buildings. 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 liquefaction vulnerability severity classifications are overlaid on the histogram in Figure 4.2 along with trend lines showing the change in BDR greater than 0.5 and BDR less than 0.2 as the LSN and associated severity classification increases.

![Figure 4.2: Frequency bar chart showing the likelihood of building damage ratios (BDR) for TC3 and Residential Red Zone pre-CES residential buildings for different LSN bands and liquefaction vulnerability severity classifications.](image)

Notes:
1. BDR data obtained directly from Section 7.4.2 of the ILV Assessment Methodology Report (T+T, 2015).

When the BDR of a residential building is greater than 0.5, the damage to that building is deemed to be 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

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18 Refer to Section 7.3 of the ILV Assessment Methodology Report (T+T, 2015) for an in depth discussion of the increased building damage due to ILV land damage.
the cost of repair would exceed the cost of rebuilding. BDR values between 0.2 and 0.5 typically represent practical repairable damage such as linings and internal fit out 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.

The trend lines in Figure 4.2 show how the chance of significant structural damage increases and the chance of minor non-structural damage decreases as LSN and associated liquefaction vulnerability severity increases. This information was used to develop Table E1 in Appendix E.

Figure 4.3 presents correlations of BDR with observed land damage and liquefaction related ground surface subsidence and has been taken from the ILV Assessment Methodology Report (T+T, 2015). It shows that properties with a BDR greater than 0.5 are closely correlated with the properties where moderate-to-severe land damage has been observed in the CES. It also shows that these properties correlate with properties where the estimated liquefaction related ground surface subsidence is high (i.e. greater than 0.4m). Conversely, BDR values are low in areas where there was none-to-minor land damage and where little to no liquefaction related ground surface subsidence occurred.

![Histograms showing BDR correlations with observed land damage in the CES, and liquefaction related ground surface subsidence (after T+T, 2015).](image)

It is noted that these correlations are for the entire portfolio of pre-CES residential buildings and do not account for different subsets of foundation construction type. Rogers et al. (2015) show that there is a strong spatial correlation between areas with high BDR and areas where observed land damage was moderate-to-severe and the measured liquefaction related ground surface subsidence is high (i.e. greater than 0.3m). Analysis of BDR in relation to these datasets clearly showed that there is little difference in BDR for different foundation types when the land performs either well or poorly, but in areas with marginal performance (neither good nor poor) the difference in BDR is markedly better for older Type B foundation systems (timber floor with concrete perimeter ring beam) compared to newer Type C systems (concrete slab).19

The performance of pre-CES residential buildings on properties with ILV land damage is dependent on many factors (e.g. building geometry, building weight, construction details, ground conditions, etc.) and some residential buildings may accommodate changes in vulnerability to liquefaction better than others.

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19 Type B and C foundation types are as described in the MBIE Guidance (MBIE, 2015) – Part A Section 2.
Heavier residential buildings, such as those with brick and tile claddings or those constructed on concrete slab foundations, as well as complex shaped residential buildings (i.e. L shaped houses) did not generally perform well during the CES. These buildings are considered to have an increased likelihood of building damage in future earthquake events and may have an increased chance of being uneconomical to repair as a result of ILV.

In contrast, lightweight residential buildings comprising timber floor foundations and weatherboard cladding and residential buildings with simpler shapes (i.e. small rectangular houses) generally performed better than the heavier and complex shaped residential buildings during the CES. As such, lightweight residential buildings are considered to have a lower increased likelihood of damage and are potentially more suitable for repair following future earthquake events.

The MBIE Guidance (MBIE, 2015) recognises the effect that building weight has on the performance of the structure and recommends the removal of heavy materials for liquefaction vulnerable properties in the TC3 area. This is further clarified in Figures 14.1 and 14.2 of the MBIE Guidance (MBIE, 2015), which recommends the removal of heavy roofing and cladding when undertaking the repair, and rellevelling or rebuilding of residential building foundations if geotechnical investigation and assessments indicate they are vulnerable to liquefaction related damage at 25 year return period levels of earthquake shaking.

However, it should be noted that every residential building is unique and is likely to perform differently under similar levels of earthquake shaking. Accordingly, the ability of geotechnical and structural engineers to assess how an individual building is likely to perform on properties with ILV land damage may not be possible due to the large number of variables that need to be considered. As such, engineering advice is likely to be generalised if based on a limited assessment of the foundation type and the weight of the cladding and roofing materials and the effect of these on the resilience of the building.

4.3 Impact of increased liquefaction vulnerability on services

Increased vulnerability to liquefaction is not expected to adversely affect services within residential properties (e.g. storm water, waste water, water supply, power, gas and communications) any more than shaking damage caused by a future earthquake. Although difficult to assess, it is likely that an increased vulnerability to liquefaction on a property would only result in a small increase in the risk of damage to services in future earthquakes. However current construction practices for new services are expected to provide adequate mitigation for this.

While liquefaction may have been responsible for some damage to underground services, observations from around Christchurch, and in particular in places like Rangiora, indicate that liquefaction was not always responsible for damage to older, more brittle services (such as clay pipes). In Rangiora, such services were damaged where there was no recorded liquefaction. It is thought that the damage to these services is likely to have been caused by ground oscillation (compression and stretching) during the earthquakes.

Most residential services are confined within the upper non-liquefiable crust and impose a minimal load on the ground below. Many of the very old storm water, waste water and some water supply and gas services were commonly installed using non-flexible conduits (comprising concrete pipe, clay pipe and steel or iron tubing). However, in areas prone to liquefaction it is now standard practice to use flexible conduits for all services between the residential building and the service provider network. The MBIE Guidance (MBIE, 2015) recommends that services are laid down in a snake pattern to provide extra length should ground extensions occur. Using flexible conduits with sealed joints also helps to prevent intrusive damage due to tree roots, which is a common problem in concrete and clay pipes.
5 Practical implications: Potential increase in ground improvement and building foundation requirements for properties with ILV land damage

This Section of the report describes the practical implications of ILV land damage in relation to likely future building requirements. The practical implications are described in relation to the severity and change in severity classifications identified in Section 3 of this report.

Where the ground surface subsidence caused by the CES has resulted in a property going from one severity classification to a higher classification at 25 year return period levels of earthquake shaking, more resilient ground improvement works or stiffer and stronger building foundations may be needed to meet the Building Code requirements than would have been required if the ground surface subsidence had not occurred.

Where ground surface subsidence caused by the CES has not changed the severity classification of a property at 25 year return period levels of earthquake shaking, ground improvement works and building foundation requirements are not expected to be different to what would have been required if no ground surface subsidence had occurred.

In some instances, more resilient ground improvement works or stiffer and stronger building foundations may have been required for a property in its pre-CES condition (i.e. the pre-CES level of liquefaction vulnerability) due to other non-ILV factors. These factors include the weight and shape of the building, minimum floor level to achieve flooding requirements and whether the property is assessed as being in a lateral spreading area at 500 year return period levels of earthquake shaking. In these circumstances, where the ground improvement works or enhanced foundations are required to address other non-ILV factors, it is also possible that there is no need for any additional ground investigation works or more enhanced foundations than what would have been required in its pre-CES condition.

For the above scenarios, it is assumed that the same design method is used for residential buildings in the pre-CES condition as would be used for the post-CES condition, and that the seismic design actions for both pre-CES and post-CES scenarios are the same. This is consistent with Section 6.3 of the ILV Assessment Methodology Report (T+T, 2015). However, amendment 12 to building verification method B1/VM1 (MBIE, 2014b) has increased the seismic design requirements for all building designs in the Canterbury region (for structures with periods less than 1.5s). As such, the scenarios above are on the basis that the foundation requirements in the pre-CES condition would be determined using the updated seismic design actions in amendment 12 to B1/VM1.

5.1 Options to enable the construction of new residential buildings on properties with ILV land damage

For the construction of new residential buildings on land that is materially vulnerable to liquefaction, there are two practical options:

- **Option 1**: Ground improvement solutions in accordance with the MBIE Guidance (MBIE, 2015); or
- **Option 2**: Surface foundation solutions in accordance with the MBIE Guidance (MBIE, 2015).

For new residential buildings, both Option 1 and Option 2 may be possible, however, on some sites there are likely to be practical constraints for undertaking Option 1. These practical constraints include soil conditions, site access, flooding, lateral spreading potential, dewatering requirements,
and building type/layout. Where any of these constraints apply, Option 2 would generally to be chosen for a new residential building.  

### 5.1.1 Option 1: Ground improvement solutions in accordance with the MBIE Guidance

Land on properties with ILV land damage cannot be restored to its pre-CES condition by raising the ground surface to its pre-CES levels unless this is done on a suburb wide scale (refer to T+T, 2016a). However, ground improvement works are an alternative way of returning the liquefaction performance of the land back to pre-CES levels of performance instead of raising the land to repair the ILV land damage caused by the ground surface subsidence. EQC has undertaken extensive work to determine the effectiveness and cost of a range of ground improvement solutions on land that is vulnerable to liquefaction. These ground improvement solutions are described in a Residential Ground Improvement Report (EQC, 2015) and are included in the MBIE Guidance (MBIE, 2015).

Option 1 involves constructing ground improvement solutions in accordance with the MBIE Guidance (MBIE, 2015) such that TC2 foundations may be used (provided no other non-ILV factors require more enhanced building foundations). Where the property has ILV land damage, ground improvement solutions in accordance with the MBIE Guidance is intended to return the liquefaction performance of the ground back to at least the level it was prior to the CES.

While properties with ILV land damage can theoretically be repaired on sites with pre-CES residential buildings in place, the practicalities of doing this often means that significant additional costs would need to be allowed for due to the need to lift or relocate the residential building during the ground improvement works. As such, all but one of the ground improvement solutions described in the Residential Ground Improvement Report (EQC, 2015) have been developed for sites where residential building has been or will be removed (i.e. a vacant site). A summary of these standard ground improvement design methods, along with the indicative construction costs, is provided in the Residential Ground Improvement Report (EQC, 2015) and a list of the methods is provided below:

- 4m deep stone columns (Type G5a);
- 4m deep driven timber poles (Type G5b);
- 1.2m deep reinforced cement stabilised raft (Type G2a);
- 1.2m deep reinforced gravel raft (Type G1d); and
- Horizontal Soil Mixed (HSM) beams.

Should a property owner wish to undertake ground improvements where there is a pre-CES residential building on the property, Horizontal Soil Mixed (HSM) beams may be considered. T+T have prepared a separate report that presents the practical and engineering constraints for this ground improvement method (T+T, 2016b).

### 5.1.2 Option 2: Surface foundation solutions in accordance with the MBIE Guidance

Option 2 involves constructing new residential buildings on land that is vulnerable to liquefaction and has not had ground improvement works undertaken by using appropriate MBIE TC3 or TC2/TC3 hybrid surface foundation solutions outlined in the MBIE Guidance (MBIE, 2015). It should be noted that TC3 or TC2/TC3 hybrid foundation solutions do not improve or repair the land (i.e. make it less vulnerable to liquefaction), instead, they are designed to mitigate the damage to the residential building in future earthquakes and make it easier and less costly to re-level when compared to pre-

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20 For building extensions it may not always be possible to mix existing substandard foundations with new foundations that are stiffer. As such, some residential building alterations may trigger complete foundation strengthening or replacement as part of building consent requirements.
CES residential buildings. The expected performance of new residential buildings constructed using MBIE surface foundation solutions is discussed in more detail in Section 6.

5.2 Design Methods for constructing new residential buildings on properties with ILV land damage

The ground improvement and surface foundation solutions described in Section 5.1 (Options 1 and 2) can be designed using one of three methods:

- Design Method 1 – simplified liquefaction evaluation assessment using the calculated settlement index ($S_{LV}$) and threshold criteria to determine the applicability of standard ground improvement and surface foundation solutions in accordance with the MBIE Guidance (MBIE, 2015); or
- Design Method 2 - specific liquefaction vulnerability severity classification based engineering assessment (using LSN and engineering judgement) to determine the applicability of standard ground improvement and surface foundation solutions in accordance with the MBIE Guidance (MBIE, 2015) and NZ Building Code (DBH, 2004) performance objectives; or
- Design Method 3 – specific liquefaction vulnerability severity classification based engineering assessment and design of non-standard (customised) ground improvement and surface foundation solutions in accordance with the NZ Building Code (DBH, 2004) performance objectives.

A summary of the Design Methods and their relative design costs$^{21}$, construction costs (referred to as construction premium) and level of conservatism for each Design Method is provided in Table 5.1.

Of these methods, Design Method 1 anecdotally appears to be the most commonly adopted by engineers in Canterbury in relation to rebuilding residential buildings damaged in the CES. Design Method 3 is not expected to be commonly adopted due to the increased design and construction costs associated with the customised foundation solutions and as such, this Method is not discussed further in this report.

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$^{21}$ These include but are not limited to customised designs, specifications, drawings etc.
**Table 5.1:** Relative design costs, construction premium and level of conservatism for residential building Design Methods.

<table>
<thead>
<tr>
<th>Engineering assessment</th>
<th>Design Method 1</th>
<th>Design Method 2</th>
<th>Design Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground improvement and foundation solutions</td>
<td>Standard</td>
<td>Standard</td>
<td>Non-Standard</td>
</tr>
<tr>
<td>Design costs</td>
<td>Low</td>
<td>Low to medium</td>
<td>High</td>
</tr>
<tr>
<td>Construction premium</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Level of conservatism (increase foundation costs)</td>
<td>Low to High</td>
<td>Low to medium</td>
<td>Low</td>
</tr>
</tbody>
</table>

### 5.2.1 Design Method 1: Simplified liquefaction evaluation assessment to determine the applicability of standard ground improvement and foundation design solutions

Design Method 1 for assessing liquefaction vulnerability is based on simplified procedures using the calculation of the CPT-based $S_{V1D}$ parameter and does not use engineering judgement.\(^{22}\)

As discussed in Table A4.2 in Appendix A of the ILV Assessment Methodology Report (T+T, 2015), the $S_{V1D}$ parameter is not sensitive to depth to groundwater and hence does not change significantly as a result of the ground surface subsidence. Therefore, the ground surface subsidence caused by the CES is unlikely to have altered the standard design solutions that would be applied in accordance with the MBIE Guidance (MBIE, 2015). As a result, the practical implication is that there is unlikely to be an effect on ground improvement and surface foundation design solutions and costs from ILV land damage using Design Method 1.

### 5.2.2 Design Method 2: Specific liquefaction vulnerability severity assessment to determine the applicability of standard ground improvement and foundation solutions

The MBIE Guidance (MBIE, 2015) also allows for specific engineering assessment to determine the appropriate standard ground improvement and foundation solutions for a residential building. For specific engineering assessment, alternative analysis methodologies such as the severity classification based on the $LSN$ parameter instead of the $S_{V1D}$ parameter, may be used, which takes into account the depth to groundwater (i.e. non-liquefying crust thickness) and applies engineering judgement.\(^{23}\)

Using Design Method 2 can in some areas provide a more appropriate and less costly ground improvement or surface foundation solution compared to Design Method 1. However, despite this, Design Method 2 is not commonly used in rebuilding properties damaged in the CES due to lack of current understanding of the methodology by geotechnical professionals.

Table 5.2 summarises the standard ground improvement and surface foundation solutions and their respective costs that can be used for each severity classification based on Design Method 2. The information in Table 5.2 is also provided in an alternative tabular format in Table E2 in Appendix E.

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\(^{22}\) Refer to Section 7 of the ILV Assessment Methodology Report (T+T, 2015).

\(^{23}\) Refer to Sections 7, 8, 9 and 10 of the ILV Assessment Methodology Report (T+T, 2015)
Where the ground surface subsidence caused by the CES has resulted in a property going from one severity classification to a higher classification at 25 year return period levels of earthquake shaking, more resilient ground improvement solutions or stiffer and stronger surface foundation solutions may be needed to meet the Building Code requirements than would have been required if the ground surface subsidence had not occurred (using Design Method 2 and assuming no other constraints exist). In contrast, where the severity classification at 25 year return period levels of earthquake shaking has remained unchanged, ground improvement and foundation solutions are not expected to be different to what would have been required if no ground surface subsidence had occurred, irrespective of whether there is ILV land damage.

However, as the notes in Table 5.2 and Table E2 indicate, the suitability of a particular ground improvement or surface foundation solution depends on a number of factors in addition to the vulnerability of the land to liquefaction. In particular, the following may act as constraints:

- the weight and shape of the building to be built. Heavy construction types or more complex building shapes may require a higher specification of ground improvement or foundation solutions;
- the management of flood issues. If flooding issues require higher floor levels then this may negate the use of ground improvement solutions and also require a higher specification foundation solution; or
- lateral spreading hazards. For areas subject to lateral spreading, higher specification of ground improvement and foundation solutions may be required to address this hazard.

Accordingly, the impact of ILV land damage on ground improvement and foundation costs, even for Design Method 2, depends on the presence or absence of one or more of these constraints. For example, if a material lateral spreading hazard exists on a property, a change in severity classification (for example, from Not Vulnerable to Medium) may not increase ground improvement or foundation requirements, as a higher specification of ground improvement or foundation that is capable of dealing with Medium severity liquefaction hazard was always required on the property due to the lateral spreading hazard.

There is no practical way to assess on a property by property or group by group basis, which constraints may be present for the full population of properties with ILV land damage. Therefore there is no practical way to assess the adverse impact of ILV land damage, if any, on ground improvement and surface foundation solutions by taking these constraints into account.

While the Christchurch City Council maintains a database of floor level requirements for any properties that have applied for a building consent, this data does not exist for all properties with ILV land damage. The assessment of lateral spreading for residential buildings is based on an ultimate limit state (ULS) earthquake event (500 year return period levels of earthquake shaking). The MBIE Guidance (MBIE, 2015) recommends an observation based assessment method, however this method has limitations as the ULS event was not experienced in all areas of Canterbury during the CES. Therefore, lack of any evidence of lateral spreading in areas of Canterbury that did not experience 500 year levels of earthquake shaking does not confirm lateral spreading will not occur at these levels of shaking.

An alternative way of assessing lateral spreading is to use analytical methods, however there are currently only a limited number of empirical methods of assessing lateral spreading and no single method is able to provide a consistent and reliable method of assessing lateral spreading risk.

As a fall back option in the MBIE Guidance (MBIE, 2015), lateral spreading may be considered in ground improvement and foundation design based on simplified criteria of distance from the free face of a river/stream or other steep changes in ground elevation. However, using this method is likely to lead to a large number of false positive and false negative results.
**Table 5.2:** Ground improvement and surface foundation solutions for each severity classification at 25 year return period levels of earthquake shaking. Design solutions are based on specific engineering assessment and selecting appropriate standard MBIE ground improvement and foundation design solutions (MBIE, 2015).

<table>
<thead>
<tr>
<th>Liquefaction vulnerability severity classification at 25 year return period levels of earthquake shaking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Not Vulnerable</strong></td>
</tr>
<tr>
<td>Surface foundation only solutions (MBIE TC2 and TC3 enhanced foundations)</td>
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<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Ground improvement solutions with MBIE TC2 enhanced foundations</td>
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<tr>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1 Dollar values are obtained from Rawlinsons cost estimates provided to T+T by Chapman Tripp (16 November 2015) and the Residential Ground Improvement Report by EQC (2015b). The values are per m\(^2\) of the floor area for a single story residential building and exclude investigation, design, consenting costs (refer to the EQC (2015b) report for further details).

2 Design solutions may not be applicable in lateral spread zones (refer Section 12.2 MBIE Guidance (MBIE, 2015)).

3 Design solutions may be applicable in lateral spread zones (refer Section 12.2 MBIE Guidance (MBIE, 2015)). However, further analysis is required to estimate the global lateral movement, lateral stretch, vertical displacements, and depth of the displacements in order to design appropriate foundation solutions.

4 Design solutions may not be applicable if higher floor levels (>400mm) are required to achieve the minimum required floor levels for flooding purposes.
Design solutions may not be applicable if higher floor levels (>600mm) are required to achieve the minimum required floor levels for flooding purposes.

Design solution may not be applicable if higher floor levels (>1m) are required to achieve the minimum required floor levels for flooding purposes.

Because the groundwater table is now closer to the ground surface, the construction cost of some ground improvement works options (i.e. shallow soil cement and gravel rafts), in some areas, may be greater (by approximately $5,000) because of the need for groundwater control during construction.

Design solutions are generally suitable for light/medium weight buildings only.

Design solutions are generally suitable for heavy weight single storey or light/medium weight two storey buildings only.

Design solutions are generally suitable for heavy weight single and two storey buildings.

An additional layer of geogrid is required in lateral spread areas. Costs have not been adjusted to allow for this but the increase in cost for additional geogrid are not expected to be significant.

Stone columns only suitable where the liquefiable soils causing the lateral spreading issues are less than 4m below ground level.

Site specific assessment of soil properties is required to confirm suitability of stone columns.

5.3 Relevance of 25 year and 500 year return period levels of earthquake shaking for Design Method 2

As part of the ILV Assessment Methodology, EQC asked T+T to assess liquefaction vulnerability at 100 year return period levels of earthquake shaking. This return period was adopted considering design parameters for land hazard identification and design parameters for buildings in New Zealand, as outlined in Section 6.3.1 of the ILV Assessment Methodology Report (T+T, 2015).

During the iterative process outlined in Section 2.3 of this report, EQC’s valuation advisors requested the practical implications of ILV land damage be provided at a lower return period more relevant for the consideration of a buyer or seller of a property in Canterbury. Further details are provided in Section 3.1.1. Accordingly, T+T proposed that 25 year return period levels of shaking be considered for Design Method 2 because this aligns with the requirements for foundation design in the New Zealand Building Code and is consistent with the ILV criteria (i.e. assessment at up to 100 year return period levels of earthquake shaking).

The New Zealand Building Code has a performance based component whereby the expected performance of buildings is prescribed at 25 year and 500 year return period levels of earthquake shaking. At 25 year return period levels of earthquake shaking the performance expectation is that building damage should only be minor and non-structural. At 500 year return period levels of earthquake shaking the performance expectation is that buildings should not collapse, thereby preventing loss of life.

During the CES, there were no residential buildings in flat land areas that collapsed or posed a risk to human life as a result of liquefaction despite shaking in excess of 500 year return period levels in the CES. Accordingly, ultimate limit state foundation requirements at 500 year return period levels of shaking are not specifically considered in this report as land performance was demonstrated to achieve the residential building performance expectations to a satisfactory level throughout the CES at this level of shaking and it is not expected to govern future foundation design.
6 Practical implications: Properties with new residential buildings constructed using TC2 or TC3 foundations without ground improvement

This section considers the practical implications of ILV land damage for new residential buildings constructed using TC2, TC3 or TC3/TC2 Hybrid surface foundation solutions (MBIE surface foundation solutions)\(^{24}\), without ground improvement works to repair the ILV land damage\(^{25}\).

6.1 Expected land damage on properties with new residential buildings with no ground improvement

For properties with new residential buildings constructed using MBIE surface foundation solutions without ground improvement works to repair the ILV land damage, the expected liquefaction vulnerability severity classification and the increased likelihood of moderate-to-severe land damage for each property is the same as presented in Section 3 and Section 4.1 respectively.

On properties where the new residential building has been constructed using an MBIE TC2 Option 2 or 4, TC3 Type 2A or 2B, or a Firth RibRaft concrete slab, then the potential for liquefaction ejecta (sand boils) to come up directly beneath the building footprint is expected to be substantially reduced when compared to pre-CES residential buildings and the new MBIE TC3 Type 1, Type 3A or Type 3B surface foundation solutions. This is because the new concrete slabs provide an impenetrable barrier with sufficient strength and stiffness to limit heaving and prevent sand boils coming up beneath the residential building\(^{26}\). However, in most cases this is expected to shift the location of the surface manifestation of liquefaction ejecta to the edges of the building footprint and to the land surrounding the residential building. The total amount of liquefaction ejecta on most properties is not expected to change.

6.2 Effect of differential ground surface subsidence on residential buildings

Next to lateral spreading land damage (the vulnerability to which has not increased due to ground surface subsidence during the CES or ILV land damage\(^{27}\)), the type of liquefaction related land damage that has most potential to cause significant damage to residential buildings is differential ground surface subsidence. Differential ground surface subsidence occurs where land subsides unevenly due to liquefaction of the underlying soil layers, which results in non-uniform volumetric consolidation caused by spatially varying ground conditions and localised volume loss due to sand boils. Figure 6.1a shows an example of typical differential ground surface subsidence.

Over the area of a building footprint, ground surface subsidence can be either uniform or non-uniform. For the cases where the ground surface subsidence is non-uniform, the subsidence could be planar or non-planar. These types of ground surface subsidence patterns in relation to a building footprint are illustrated in Figure 6.1a.

Differential ground surface subsidence can cause significant damage to residential buildings if the foundations have not been designed to resist or tolerate it. Figure 6.1b illustrates the typical response of houses with low stiffness and low strength foundations and Figure 6.1c illustrates the

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\(^{24}\) MBIE surface foundations as defined in Section 5.3 and 15.4 of the MBIE Guidance (MBIE, 2015)

\(^{25}\) Ground improvement works as defined in Section 15.3 of the MBIE Guidance (MBIE, 2015)

\(^{26}\) It is acknowledged that pre-CES Type C concrete slab foundations may also limit heaving and prevent sand boils coming up beneath the residential building but this is expected not to be to the same extent as the new MBIE surface foundation solutions.

\(^{27}\) Refer to Section 6.6 of the ILV Assessment Methodology Report (T+T, 2015).
typical response of houses with stiff and strong foundations when subjected to the differential ground surface subsidence patterns beneath the building footprints.

In the case where the differential ground surface subsidence is relatively planar beneath the residential building, planar settlement of the residential building is expected. Planar differential building settlement is not expected to cause significant structural damage but it may cause damage to connected services and affect the amenity of the building by making it difficult to access and utilise (e.g. bath does not drain, benches are not level, etc.).

![Figure 6.1: Types of ground surface subsidence and resulting residential building damage.](image)

In the case where the differential ground surface subsidence beneath the residential building is non-planar and the surface foundations have low stiffness and low strength, then significant structural damage to the foundations and superstructure can occur due to out-of-plane distortions in the foundations (hogging, dishing, cracking) (see Figure 6.1b). Out-of-plane distortions occur when the building foundation and superstructure are not sufficiently stiff or strong enough to remain planar when uneven ground surface subsidence occurs beneath the residential building. Non-planar differential ground surface subsidence may also cause damage to connected services and affect amenity by making it difficult to access and utilise the building.

In the case where the differential ground surface subsidence beneath the residential building is non-planar and the surface foundations have high stiffness and high strength, the surface foundations are more likely to remain planar or have much less out-of-plane distortions when compared to surface foundations with low stiffness and low strength (see Figure 6.1c).
6.3 New MBIE surface foundation solutions

The MBIE Guidance (MBIE, 2015) provides a set of principles to assist engineers in the interpretation and implementation of the proposed MBIE foundation solutions. One of the key principles of the MBIE Guidance that relates directly to foundations for new residential buildings states:

“The [MBIE] guidance provides design solutions and methods that aim to substantially improve the performance of house foundations in future seismic events, while recognising that the land performance may still induce deformations and loads that could cause some damage.” (refer to Section 11.2 of the MBIE Guidance, 2015)

As discussed in Section 5.3, residential buildings in New Zealand must be designed in accordance with the New Zealand Building Code, whereby the expected performance of buildings is prescribed at 25 year (serviceability limit state (SLS)) and 500 year (ultimate limit state (ULS)) return period levels of earthquake shaking. The performance objectives are that the building remain serviceable at 25 year return period levels of earthquake shaking and that there is no loss of life at 500 year return period levels of earthquake shaking. The New Zealand Building Code does not include performance requirements for residential buildings at 100 year return period levels of earthquake shaking.

The surface foundation solutions in the MBIE Guidance have been developed to meet the performance requirements of the New Zealand Building Code and to provide improved residential building performance and resilience when compared to typical pre-CES residential buildings. The surface foundation solutions in the MBIE Guidance (MBIE, 2015) aim to provide robust foundations to comply with life safety requirements at ULS levels of earthquake shaking and also provide a level of habitability and potential reparability at that design level of shaking. These solutions also aim to minimise damage and repair costs at SLS levels of earthquake shaking. Some damage may result in either of these design events, however any damage under SLS seismic loading is expected to be ‘readily repairable’ (refer to Section 11.2 of the MBIE Guidance, 2015).

In providing robust surface foundation solutions for new residential buildings at ULS levels of earthquake shaking, substantial improvement in the performance and resilience of surface foundation solutions at both SLS and 100 year return period levels of earthquake shaking is expected when compared to typical pre-CES residential buildings. The resilience of MBIE surface foundation solutions allows them to be relevelled and repaired in the event of differential ground surface subsidence across the building footprint.

MBIE surface foundation solutions are expected to substantially reduce the amount of structural damage caused by out-of-plane distortions as a result of differential ground surface subsidence beneath the foundation compared to typical pre-CES residential buildings. The MBIE TC2 Option 4, TC3 Type 2A and TC3 Type 2B surface foundation solutions and the Firth RibRaft proprietary foundation are expected to provide the highest level of performance. The TC3 Type 1 and Type 3A surface foundation solutions are not expected to perform as well as the other TC3 foundations because they are not as stiff. In particular, these foundations are less likely to remain planar when non-planar differential ground surface subsidence occurs. However, while the increase in resilience of the TC3 Type 1 and Type 3A foundation solutions are less than for the TC2 Option 4 and TC3 Type 2 foundations, this lower resilience is compensated for by the lower cost of remediation (i.e. they are relatively easy and more economical to relevel compared to pre-CES Type B and Type C

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28 In the design of residential buildings prior to the CES, it was not common to consider liquefaction induced differential ground surface subsidence and consequential loss of support to isolated areas of the building foundation at 25 year return period levels of shaking.
foundation systems). The performance of the MBIE Type 3B foundations is expected to lie somewhere between these two extremes.

6.4 Expected performance of new residential buildings constructed using MBIE surface foundation solutions

T+T does not hold quantitative data that can be used to assess the seismic performance of new residential buildings that have been constructed using MBIE surface foundation solutions (for example, T+T is unable to determine BDR values for new residential buildings constructed using MBIE surface foundation solutions). However, MBIE have measured and assessed differential building settlements that occurred on approximately 400 pre-CES residential buildings as a result of the CES. While the results of this study will not be published until late 2016, preliminary results indicate that there is a weak but measurable correlation between liquefaction severity classification and the increased chance of differential building settlement.

While the study does not include new residential buildings constructed using MBIE surface foundation solutions, it can be reasonably assumed, that due to the relatively low stiffness and low strength of the pre-CES residential building foundations constructed using either 100mm thick concrete slabs or suspended timber floors, the measured differential building settlement is likely to be similar to the differential ground surface subsidence over length of the building footprint (i.e. the 100mm thick concrete slab or suspended timber floor pre-CES residential building undergoes differential settlement due to uneven subsidence at the ground surface).

On the basis that the chance of moderate-to-severe land damage is not affected by MBIE surface foundation solutions, the chance of liquefaction induced differential ground surface subsidence (obtained from the MBIE study of pre-CES residential buildings described above) is considered to be the same for properties that have new residential buildings. The chance of moderate-to-severe liquefaction related land damage and the chance of differential ground surface subsidence for each liquefaction severity classification for residential Green Zone properties is presented in Tables E3A and E3B in Appendix E.

Tables E3A and E3B also include expected structural performance of MBIE surface foundation solutions. The foundation groups shown on Table E3A and E3B (Groups I – IV) contain foundations that are expected to have similar levels of performance with regard to the ability of the foundations to mitigate the effects of liquefaction induced differential ground surface subsidence beneath the residential buildings. The foundation groups are arranged by increasing performance and resilience (i.e. Group I contains pre-CES surface foundations with low resilience that are expected to perform poorly on properties with high to very high liquefaction vulnerability, and Group IV contains new MBIE surface foundation solutions with high stiffness and high strength that are more resilient and are expected to perform well on all residential Green Zone properties).

The structural damage classifications within the coloured boxes on Table E3A and E3B are an estimate, based on engineering judgement, of the most likely structural outcomes for residential buildings for each combination of foundation group and severity classification. In reality however, a number of structural outcomes are possible for a given combination of foundation group and liquefaction severity. For example, the structural damage classification for a residential building in foundation group III with a severity classification of Medium is Not Significant, meaning that most residential buildings are expected to sustain only planar settlement that does not require levelling (a description of each structural damage classification is provided in Table 6.1). While this is the

29 Refer to Spencer Holmes Report titled Preliminary assessment of foundation reparability of new residential dwellings on residential green zoned land with liquefaction vulnerability (Spencer Holmes, 2016).

30 It is acknowledged that higher or lower angular distortions may occur within the building foundation due to differential ground surface subsidence beneath the building footprint.
most likely structural outcome, there is a chance that the residential building sustains some out-of-plane distortions that require relevelling or repair of structural damage. However, it is not possible to quantify the chance that a particular residential building will sustain planar or out-of-plane distortions due to differential ground surface subsidence and how much structural damage will occur as there is no data on which to base this.

Also shown on Table E3B are the percentages of new residential buildings that have been constructed using new MBIE surface foundation solutions for each foundation group and severity classification combination. These percentage values have been derived from building consent information obtained from Christchurch City Council and T+T’s ILV severity mapping results (refer to Section 3)\(^{31}\). The black numbers show the percentage of residential buildings for 25 year return period levels of earthquake shaking and the purple numbers show the percentage of residential buildings for 100 year return period levels of earthquake shaking.

Table 6.1: Structural Damage Classifications in Table E3A and E3B

<table>
<thead>
<tr>
<th>Structural Damage Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Not Significant</strong></td>
<td>Most residential buildings likely to sustain only planar settlement that does not require relevelling.</td>
</tr>
<tr>
<td></td>
<td>Very few residential buildings likely to sustain planar or out-of-plane distortions that require relevelling and/or repair of minor structural damage.</td>
</tr>
<tr>
<td><strong>Minor</strong></td>
<td>Some residential buildings likely to sustain planar settlement that may require relevelling but unlikely to sustain structural damage.</td>
</tr>
<tr>
<td></td>
<td>Some residential buildings likely to sustain out-of-plane distortions that may require relevelling and repair of minor structural damage.</td>
</tr>
<tr>
<td><strong>Moderate</strong></td>
<td>Most residential buildings likely to sustain out-of-plane distortions that requires relevelling and repair of moderate structural damage.</td>
</tr>
<tr>
<td></td>
<td>Few residential buildings likely to sustain only planar settlement that requires relevelling and repair of minor structural damage.</td>
</tr>
<tr>
<td><strong>Major</strong></td>
<td>Most residential buildings likely to sustain out-of-plane distortions that require relevelling and repair of major structural damage. For some residential buildings repairs may not be economical and a full rebuild may be required.</td>
</tr>
<tr>
<td></td>
<td>Few residential buildings likely to sustain planar settlement that requires relevelling and repair of moderate structural damage.</td>
</tr>
</tbody>
</table>

6.5 Conclusions in regards to properties with MBIE surface foundation solutions

Based on the above analysis and assumptions made with regard to differential building settlement, and by applying engineering judgement, the following conclusions have been made.

\(^{31}\) At the time of writing, the total number of ILV properties that T+T have determined from Christchurch City Council records to have been consented or built using new MBIE surface foundation solutions is 381.
At SLS (25 year return period) levels of earthquake shaking, approximately 90% of the residential buildings in the residential Green Zone that have been designed and constructed using MBIE surface foundation solutions have structural damage classifications of Not Significant, are expected to sustain planar settlement that does not require relevelling and are not expected to result in any structural damage. Approximately 10% of the residential buildings in the residential Green Zone have structural damage classifications of Not Significant OR Minor and are expected to sustain planar settlement or out-of-plane distortions that are able to be releved with only minor structural damage.

These results are consistent with observations from the 14 February 2016 Mw 5.7 earthquake, which for parts of eastern Christchurch was equivalent to 25 year return period levels of shaking. Anecdotal evidence from engineers that visited areas of eastern Christchurch in the days following this earthquake noted that there were areas in eastern Christchurch where there had been Minor-to-Moderate liquefaction related land damage causing differential ground surface subsidence. In these areas, where new residential buildings had been constructed using MBIE surface foundation solutions, the corresponding foundation damage generally comprised occasional planar distortions that did not require relevelling with only minor cosmetic damage. There were a very small number of residential buildings that appear to have sustained planar distortions that would have required relevelling and may have resulted in minor structural damage.

At 25 year return period levels of earthquake shaking, the chance of structural damage to residential buildings in the residential Green Zone constructed using MBIE surface foundation solutions, due to liquefaction related land damage in a future earthquake, is not expected to have materially increased as a result of the ground surface subsidence due to the CES. This is because the change in severity for these properties does not, for most cases, change the expected structural damage classification (i.e. properties stay within the Not Significant structural damage classification on Table E3B). There are however a very small number (< 1%) of properties in Group II that move to a worse structural damage classification and therefore have an increased chance of building damage (i.e. move from Not Significant to Minor). This conclusion is also consistent with the observations of the 14 February 2016 earthquake, and the objectives of the MBIE Guidance (MBIE, 2015) that some damage may occur at 25 year return period levels of earthquake shaking but this damage can be easily repaired.

At 100 year return period levels of earthquake shaking, approximately 45% the residential buildings in the residential Green Zone that have been designed using MBIE surface foundation solutions have a structural damage classification of Not Significant. Most of these residential buildings are expected to sustain only planar settlement that does not require relevelling while very few may sustain out-of-plane distortions that require relevelling or repair of any structural damage. Approximately 40% the residential buildings in the residential Green Zone that have been designed using MBIE surface foundation solutions have a structural damage classification of Not Significant OR Minor and Minor. Approximately 15% of the residential buildings in residential Green Zone that have been designed using MBIE surface foundation solutions have a structural damage classification of Minor OR Moderate and Moderate. Refer to Table 6.1 for descriptions of each of the structural damage classifications.

As a result of the change in liquefaction severity at 100 year return period levels of earthquake shaking, approximately 50% of the residential buildings in the residential Green Zone have remained within the same structural damage classification (and approximately half of these lie within the Not Signification structural damage classification post-CES). The other 50% have moved to a worse structural damage classification\(^{32}\). Most of those that have moved to a worse structural damage
classification (approximately 90% of the 50%) have had only a Minor change in severity meaning that in reality they have moved from the top of one structural damage classification to the bottom of the next structural damage classification. The other residential buildings (approximately 10% of the 50%) have had a Minor OR Major change in severity, meaning that they may have had a more significant change in the chance of planar or out-of-plane differential settlement and associated structural damage.

While there are four structural damage classifications shown in Table E3A and E3B that appear to indicate that a step change in structural damage occurs between each classification, in reality beyond the point at which differential settlement requires a residential building to be releveled, the foundation is expected to sustain increasing planar and out-of-plane distortions up to the point at which the foundation fails and a complete foundation rebuild is required (i.e. distortions occur along a continuum and not in step changes)\(^33\).

It is reasonable to conclude that for properties that have increased liquefaction vulnerability at 25 year and 100 year return period levels of earthquake shaking, new residential buildings that have been constructed using MBIE surface foundation solutions are less likely to sustain material building damage and be more resilient (i.e. be able to be releveled and repaired) when compared to pre-CES residential buildings.

6.6 Estimate of costs to repair new residential building foundations

The costs to repair new residential buildings constructed using MBIE surface foundation solutions will depend on whether the building has sustained planar or out-of-plane distortions. The expected approximate costs for repairing planar and out-of-plane distortions for each foundation are provided in Table 6.2 below.
### Table 6.2: Estimate of costs to repair new residential building foundations (provided by Spencer Holmes, 2016)

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>Foundation Description</th>
<th>Planar Distortion Repair Costs</th>
<th>Out-of-plane Distortion Repair Costs</th>
<th>Combined out-of-plane and planar Distortion Repair Costs¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC2 Option 4</td>
<td>Waffle Slab</td>
<td>$30,000</td>
<td>$41,000</td>
<td>$41,000</td>
</tr>
<tr>
<td>TC3 Type 1</td>
<td>Enhanced NZS3604</td>
<td>$16,000</td>
<td>$26,000</td>
<td>$26,000</td>
</tr>
<tr>
<td>TC3 Type 2A</td>
<td>150mm reinforced concrete slab</td>
<td>$16,000</td>
<td>$28,000</td>
<td>$28,000</td>
</tr>
<tr>
<td>TC3 Type 2B</td>
<td>300mm thick reinforced concrete slab</td>
<td>$16,000</td>
<td>$33,000</td>
<td>$33,000</td>
</tr>
<tr>
<td>TC3 Type 3A</td>
<td>Isolated concrete pads beneath stiff continuous bearers</td>
<td>$25,000</td>
<td>$35,000</td>
<td>$35,000</td>
</tr>
<tr>
<td>TC3 Type 3B</td>
<td>Steel beams over pre-stressed concrete beams</td>
<td>$25,000</td>
<td>$38,000</td>
<td>$38,000</td>
</tr>
<tr>
<td>Firth RibRaft</td>
<td>Re-levelable concrete slab (Firth proprietary system)</td>
<td>$15,000</td>
<td>$26,000</td>
<td>$26,000</td>
</tr>
</tbody>
</table>

1. In the event of combined planar tilt as well as out-of-plane distortions, the combined cost of remediation is expected to be the same as reinstatement costs of the out-of-plane distortions.
7 Practical Implications: ILV properties with IFV

The practical implications of ILV land damage presented in the preceding sections are, in so far as the scope of this report is concerned, independent of whether a property has IFV land damage or not. That is, the practical implications of:

- increased likelihood of moderate-to-severe land damage;
- increased likelihood of significant building damage for existing residential buildings;
- increased ground improvement and building foundation requirements for new residential buildings,

which are presented in this report and summarised in Tables E1, E2, E3A and E3B in Appendix E, are the same (both for land with a pre-CES residential building or land where the building has or will be rebuilt using an MBIE surface foundation solution) whether a property with ILV land damage has IFV land damage or not.

However, where properties with ILV land damage have a minimum floor level requirement due to flooding as defined by Waimakariri District Council and Christchurch City Council, this may be a relevant consideration for whether there are any building foundation requirements for new residential buildings.
8 Additional engineering information for selected assessment areas

As part of the iterative development of the methodology for assessing DoV caused by ILV land damage, as discussed in Section 2.3, EQC’s valuation advisors requested more detailed engineering information in relation to selected assessment areas. This information was primarily compiled to enable EQC’s valuation advisors to understand the basis of the severity classifications and change in severity classifications for groups of assessment areas where there was a significant difference between the assessed DoV values of adjacent areas.

The location of the eight groups of assessment areas is presented in Figure 8.1. Each of the areas were split into a number of sub-areas to explain the differences in assessed DoV values utilising additional engineering information. Appendix D details the groups of assessment areas, the sub-areas, severity and change in severity classifications of the sub-areas and the additional engineering information provided to the valuation advisors. This additional information includes:

- Estimated total change in ground surface elevation as a result of the CES;
- Ground surface elevation;
- Subsurface ground strength and soil behaviour profiles;
- Groundwater depth;
- Liquefaction Severity Number (LSN) relative to levels of earthquake shaking; and
- Liquefaction observations from the February 2016 earthquake event.

Figure 8.1: Location of the groups of selected assessment areas where additional engineering information was provided to EQC’s valuation advisors.
9 Conclusions

This report has been prepared to assist the Earthquake Commission (EQC) and its valuation advisors understand the practical implications of a property having increased liquefaction vulnerability (ILV) land damage due to the Canterbury Earthquake Sequence (CES). It presents the advice that a geotechnical engineer would be expected to give a buyer or seller of a property about the practical implications that result from land having experienced a material increase in liquefaction vulnerability due to the CES.

Liquefaction vulnerability severity classification

Properties with ILV land damage have been assigned pre-CES and post-CES liquefaction vulnerability severity classifications for both 100 year and 25 year return period levels of earthquake shaking. The change in liquefaction vulnerability severity across the CES for both 100 year and 25 year return period levels of earthquake shaking has also been determined. The primary severity classifications, in increasing extent of severity, are:

- Not Vulnerable (NV);
- Medium (M);
- High (H); and
- Very High (VH).

The primary change in severity classifications, in increasing extent of change, are:

- No Change (NC);
- Minor (Min); and
- Major (Maj).

All properties with ILV land damage have been assessed using an area/neighbourhood approach. In this way, the severity and change in severity classifications were assigned to groups of properties that had similar observed land performance through the CES, ground surface subsidence over the CES, and topographical characteristics. Full details and the reasons for an area/neighbourhood assessment methodology are set out in Section 3.1.2 and Appendix A.

For many of the assessment areas in Canterbury, it was not possible to determine a primary severity classification or change in severity classification. The severity classifications for these properties were identified as:

- Not Vulnerable OR Medium (NV or M);
- Medium OR High (M or H); and
- High OR Very High (H or VH).

For the change in severity classifications these were identified as:

- No Change OR Minor (NC or Min); and
- Minor OR Major (Min or Maj).

The results of severity and change in severity classifications for all properties with ILV land damage are presented in a series of six maps in Section 3.2 and as tabulated results in Section 3.3, with further details of results presented in Appendix B.

Increased likelihood of moderate-to-severe liquefaction related land damage

As a result of the ground surface subsidence caused by the CES, properties with ILV land damage are now more likely to suffer moderate-to-severe land damage in a future earthquake event than they
would have before the CES. Moderate-to-Severe land damage includes sand ejecta, differential ground surface subsidence, greater levels of undulation and ponding. Additionally, material liquefaction related land damage is now likely to occur at more frequent intervals (shorter return periods) than before the CES.

**Increased likelihood of significant liquefaction related residential building damage**

As a result of the ground surface subsidence caused by the CES, pre-CES residential buildings on land with ILV land damage are now more likely to suffer from increased building damage in future earthquakes. This includes planar and out-of-plane distortions and overall settlement of the residential building, lateral extension or ‘stretch’ of the floor and foundations, and damage to specific foundation elements. Additionally, material liquefaction related building damage is now expected to occur at more frequent intervals (shorter return periods) than before the CES.

The performance of pre-CES residential buildings on land with ILV damage is dependent on many factors and some pre-CES residential buildings are likely to deal with changes in vulnerability to liquefaction better than others. Heavier and more complex shaped pre-CES residential buildings are considered to have an increased likelihood of building damage in future earthquake events and may have an increased chance of being uneconomical to repair as a result of ILV land damage. Lightweight and simpler shaped pre-CES residential buildings are considered to have a lower increased likelihood of damage and are potentially more suitable for repair following future earthquake events. The MBIE Guidance (MBIE, 2015) recognises the effect that building weight has on the performance of the structure and recommends the removal of heavy materials for properties in TC3 areas.

**Increased ground improvement and building foundation requirements**

To assess whether ILV land damage has resulted in an increase in the ground improvement and building surface foundation requirements for any future residential building works on properties with ILV land damage, a 25 year return period level of shaking has been adopted in accordance with the New Zealand Building Code and MBIE Guidance (MBIE, 2015).

For the Design Method that is most commonly employed in Canterbury (simplified liquefaction evaluation assessment and standard ground improvement and foundation solutions), ILV land damage is unlikely to have an effect on ground improvement and foundation design solutions and costs.

However, if a specific engineering assessment is undertaken, and the ground surface subsidence caused by the CES has resulted in a property going from one severity classification to a higher classification at 25 year return period levels of earthquake shaking, more resilient ground improvement solutions or stiffer and stronger surface foundation solutions may be needed to meet the Building Code requirements than would have been required if the ground surface subsidence had not occurred. This may result in higher construction costs for new residential buildings, but is dependent on whether a number of other potential constraints are present, including the type of house to be constructed, floor level requirements (flooding levels), and lateral spreading hazard.

Where ground surface subsidence caused by the CES is minor and has not changed the severity classification of a property at 25 year return period levels of earthquake shaking, ground improvement and surface foundation solutions are not expected to be different to what would have been required if no ground surface subsidence had occurred.

**Properties with new residential buildings constructed using MBIE surface foundations without ground improvement**

MBIE surface foundation solutions are expected to substantially reduce the amount of structural damage to new residential buildings as a result of differential ground surface subsidence when
compared to typical pre-CES residential buildings. However, differential ground surface subsidence may cause damage to connected services and affect the amenity of the building by making it difficult to access and utilise (e.g. bath does not drain, benches are not level, etc.)

At 25 year return period levels of shaking, the chance of structural damage to new residential buildings constructed using MBIE surface foundation solutions is not expected to have materially increased as a result of the change in severity caused by the CES. This is because the change in severity for these properties does not, for most cases, change the expected structural damage classification (i.e. properties remain within the Not Significant structural damage classification on Table E3B).

At 100 year return period levels of shaking, approximately 50% of the residential buildings in the residential Green Zone have remained within the same structural damage classification as a result of the change in severity caused by the CES. The other 50% have moved to a more severe structural damage classification as a result of the change in severity caused by the CES. Of those that have moved:

- Approximately 90% have had only a Minor change in severity, meaning that they have moved from the top of one structural damage classification to the bottom of the next structural damage classification; and
- Approximately 10% have had a Minor OR Major change in severity, meaning that they may have had a more significant change in the chance of planar or out-of-plane differential settlement and associated structural damage.

**ILV Properties with IFV**

The practical implications of ILV land damage presented in the preceding sections, in so far as the scope of this report is concerned, are independent of whether a property has IFV land damage or not. That is, the practical implications of:

- increased likelihood of moderate-to-severe land damage;
- increased likelihood of significant building damage for existing residential buildings; and
- increased ground improvement and building foundation requirements for new residential buildings,

which are presented in this report and summarised in Tables E1, E2, E3A and E3B in Appendix E, are the same (both for land with a pre-CES residential building or land where the building has or will be built using an MBIE surface foundation solution) whether a property with ILV land damage has IFV land damage or not.
References


Earthquake Commission (EQC). 2016b. *DoV Methodology for ILV (for properties with residential building in place)*. Available at [www.eqc.govt.nz/ilv](http://www.eqc.govt.nz/ilv);

Earthquake Commission (EQC). 2016c. *DoV Methodology for ILV (for where the residential building has been or will be rebuilt)*. Available at [www.eqc.govt.nz/ilv](http://www.eqc.govt.nz/ilv);


# 11 Glossary

This glossary defines the specific meaning of certain words and phrases used in this report. Note that some words and phrases used in this report have different definitions and meanings in other literature.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building Damage Ratio (BDR)</strong></td>
<td>The ratio between the cost to repair earthquake related damage to a residential building and the greater of the replacement value or valuation of that building.</td>
</tr>
<tr>
<td><strong>Canterbury Earthquake Sequence (CES)</strong></td>
<td>The sequence of earthquakes and aftershocks in the Canterbury area from 4 September 2010 to the end of 2011. This included four main earthquakes on 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011.</td>
</tr>
<tr>
<td><strong>New Zealand Geotechnical Database (NZGD) (formally Canterbury Geotechnical Database (CGD))</strong></td>
<td>An online database established by CERA and now managed by MBIE. The NZGD was set up to promote sharing of existing and new geotechnical and Christchurch recovery related information between professional engineers, EQC, insurers and local territorial authorities. Prior to 1 June 2016, this was the Canterbury Geotechnical Database (CGD).</td>
</tr>
<tr>
<td><strong>Change in LSN (ΔLSN)</strong></td>
<td>A measure of the change in liquefaction vulnerability due to ground surface subsidence caused by the CES.</td>
</tr>
<tr>
<td><strong>Christchurch City Council (CCC)</strong></td>
<td>The local council for the Christchurch City area.</td>
</tr>
<tr>
<td><strong>Cone Penetration Test (CPT)</strong></td>
<td>A geotechnical in-situ ground investigation test which involves pushing an instrumented steel cone into the ground at a controlled rate measuring the cone tip resistance, sleeve friction and pore water pressure.</td>
</tr>
<tr>
<td><strong>CPT Tip Resistance (qc)</strong></td>
<td>A measure of the force required to push the tip of a CPT probe through a given soil layer.</td>
</tr>
<tr>
<td><strong>Criterion</strong></td>
<td>A principle or standard by which something may be judged or decided.</td>
</tr>
<tr>
<td><strong>Crust</strong></td>
<td>The non-liquefying soil layers from the ground surface to the first liquefied soil layer.</td>
</tr>
<tr>
<td><strong>Department of Building and Housing (DBH)</strong></td>
<td>Previously the government agency of the New Zealand government responsible for developing and implementing building legislation in New Zealand. In March 2012 the DBH was integrated into MBIE.</td>
</tr>
<tr>
<td><strong>Digital Elevation Model (DEM)</strong></td>
<td>A model of the ground surface elevation derived from a LiDAR survey that consists of a regular grid of equal size cells (i.e. 1m x 1m, 5m x 5m, 25m x 25m, etc.). The elevation at the centre of each</td>
</tr>
</tbody>
</table>
cell is derived by taking the median elevation of all of the LiDAR ground classified point elevations within that cell.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition/description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Earthquake Commission (EQC)</strong></td>
<td>A government owned entity responsible for carrying out the statutory functions set out in the Earthquake Commission Act 1993. This includes natural disaster insurance for residential property, administration of the natural disaster fund and funding research and education into natural disasters and ways of reducing their impact.</td>
</tr>
<tr>
<td><strong>EQC Act</strong></td>
<td>The Act of parliament that details the provisions of a home owners entitlements for EQC insurance cover.</td>
</tr>
<tr>
<td><strong>Free Face</strong></td>
<td>A steep slope such as a river bank, road cutting or old river channel towards which lateral spreading could occur.</td>
</tr>
<tr>
<td><strong>Geological and Nuclear Sciences (GNS)</strong></td>
<td>A government owned entity which provides Earth, geoscience and isotope research and consultancy services.</td>
</tr>
<tr>
<td><strong>Groundwater</strong></td>
<td>Water present beneath the ground surface in soil pore spaces and in the fractures of rock formations.</td>
</tr>
<tr>
<td><strong>Groundwater Depth (GWD)</strong></td>
<td>The depth from the ground surface to the groundwater surface. For the purposes of this report, this is estimated by calculating the difference between the post-CES DEM and the median groundwater surface.</td>
</tr>
<tr>
<td><strong>Increased Liquefaction Vulnerability (ILV)</strong></td>
<td>An increase in vulnerability of the land to liquefaction related damage. For the purposes of this report this is due to ground surface subsidence.</td>
</tr>
<tr>
<td><strong>Lateral Spread</strong></td>
<td>A consequence of liquefaction where horizontal movement of upper soil layers occurs relative to soil layers at greater depth. It is measured as the global horizontal movement of a block of land.</td>
</tr>
<tr>
<td><strong>Lateral Stretch</strong></td>
<td>A consequence of liquefaction where the magnitude of horizontal movement of upper soil layers occurs non-uniformly. It is measured as the difference between the horizontal displacement of two observation points over a given length.</td>
</tr>
<tr>
<td><strong>Levels of earthquake shaking</strong></td>
<td>The PGA and $M_w$ of an earthquake event.</td>
</tr>
<tr>
<td><strong>Light Detection and Ranging (LiDAR)</strong></td>
<td>A method used to survey large areas using laser range-finding technology. LiDAR can be undertaken from an aeroplane (an aerial survey) or on the ground.</td>
</tr>
<tr>
<td><strong>LiDAR Survey Point Cloud</strong></td>
<td>The complete set of data supplied for a LiDAR survey. Specifically, the $x$, $y$, $z$ location that each laser impulse which was captured during the survey. The points are also classified to indicate the type</td>
</tr>
</tbody>
</table>
of surface that they were reflected from, with the most LiDAR returns classified as either ground or non-ground classified points.

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

Liquefaction Consequence
The effects of liquefaction e.g. liquefaction ejecta, ground surface subsidence, differential ground surface subsidence, lateral spread, buoyancy of underground structures and ground cracking.

Liquefaction Ejecta
Where water and liquefied soil material is ejected to the ground surface. Commonly observed as cone shaped piles of soil on the ground surface.

Liquefaction Related Ground Surface Subsidence
The ground surface subsidence attributable to the consequences of liquefaction. For the purposes of this report this is estimated by calculating the difference between the Total Ground Surface Subsidence and the estimated vertical tectonic movement as a result of the CES.

Liquefaction Severity Number (LSN)
A liquefaction vulnerability parameter developed by Tonkin + Taylor Ltd.

Liquefaction Triggering
The initiation of liquefaction from shaking, commonly caused by earthquakes. Shaking must be sufficiently intense to trigger or initiate liquefaction. The shaking level that triggers liquefaction varies for different soils.

Liquefaction Vulnerability
The exposure of the land to damage at the ground surface from soil layers liquefying.

Liquefaction Vulnerability Severity
The relative extent of liquefaction vulnerability. It describes how severe the liquefaction vulnerability of a property is relative to other properties.

Liquefiable
Soil that is able to liquefy (i.e. is susceptible to liquefaction).

Liquefying
Soil that is subjected to the seismic demand necessary to trigger liquefaction.

Magnitude ($M_w$)
A measure of earthquake energy. For the purposes of this report it is estimated using the Richter magnitude scale.
<p>| <strong>Ministry of Business Innovation and Employment (MBIE)</strong> | The government department that administers the Building Act. It includes what was previously the Department of Building and Housing (DBH). |
| <strong>Non-liquefiable</strong> | Soil that are not able to liquefy (i.e. are not susceptible to liquefaction). |
| <strong>Non-liquefying</strong> | Soil that is able to liquefy but has not been subjected to the seismic demand necessary to trigger liquefaction. |
| <strong>Non-liquefying Crust</strong> | The non-liquefying soil layers from the ground surface to the first liquefied soil layer. |
| <strong>New Zealand Geotechnical Society (NZGS)</strong> | The affiliated organization in New Zealand of the International Societies representing practitioners in Soil mechanics, Rock mechanics and Engineering geology. |
| <strong>One Dimensional Volumetric Consolidation Settlement (SV1D)</strong> | A calculated settlement liquefaction vulnerability parameter recommended by MBIE using a method proposed by Zhang et al. (2002). |
| <strong>Peak Ground Acceleration (PGA)</strong> | The maximum acceleration of the ground during an earthquake. |
| <strong>Residential Green Zone</strong> | Land in the Christchurch area that is suitable for residential occupation, though some land may require geotechnical investigation and/or particular types of foundations to minimise any future liquefaction damage. |
| <strong>Residential Red Zone</strong> | Land in the Christchurch area where the land has been so badly damaged by the earthquakes that it is unlikely it can be rebuilt on for a prolonged period. |
| <strong>Return Period</strong> | The estimated average period between natural hazard events (in this case earthquake shaking levels) of the same size or intensity. |
| <strong>Seismic</strong> | Relating to earthquakes or other vibrations of the earth and its crust. |
| <strong>Seismicity</strong> | The occurrence or frequency of earthquakes in a region. |
| <strong>Soil Behaviour Type Index (Il)</strong> | A CPT-based soil behaviour classification method developed by Robertson and Wride (1998). |
| <strong>Technical Category (TC)</strong> | A classification of land developed by the Department of Building and Housing (now part of Ministry of Business, Innovation and Employment) for geotechnical investigation purposes for repairing and rebuilding residential buildings (up to two storeys) in the Christchurch area. TC’s are exclusively within Green Zone Land. |</p>
<table>
<thead>
<tr>
<th>Technical Category 1 (TC1)</th>
<th>Land in the residential green zone where liquefaction damage is unlikely in future large earthquakes. Standard residential foundation assessment and construction is appropriate.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Category 2 (TC2)</td>
<td>Land in the residential green zone where liquefaction damage is possible in future large earthquakes. Standard enhanced foundation repair and rebuild options in accordance with MBIE Guidance are suitable to mitigate against this possibility.</td>
</tr>
<tr>
<td>Technical Category 3 (TC3)</td>
<td>Land in the residential green zone where liquefaction damage is possible in future large earthquakes. Individual engineering assessment is required to select the appropriate foundation repair or rebuild option.</td>
</tr>
<tr>
<td><strong>Total Ground Surface Subsidence</strong></td>
<td>The ground surface subsidence sustained. This is estimated with difference DEMs derived from LiDAR surveys. This includes both the tectonic vertical movement and any liquefaction related subsidence.</td>
</tr>
<tr>
<td><strong>Waimakariri District Council (WDC)</strong></td>
<td>The local council for the Waimakariri district.</td>
</tr>
</tbody>
</table>
12 Applicability

This report has been prepared for the benefit of Chapman Tripp acting on behalf of the Earthquake Commission (EQC), with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.