Appendix C: The Evolution of the ILV Methodology

C1 Purpose and Outline

The purpose of this appendix is to summarise key aspects of the history of the development of the Increased Liquefaction Vulnerability (**ILV**) Assessment Methodology and in particular:

- The background to the recognition of the phenomenon of increased liquefaction vulnerability as a result of ground surface subsidence in the Christchurch area (Section C2);
- The recognition of ILV as a form of land damage covered under the EQC Act and the development of the ILV Assessment Framework (Section C3); and
- The implementation of the ILV Assessment Framework with the ILV Assessment Methodology (Section C4).

C2 Background to Increased Liquefaction Vulnerability in the Christchurch Area

The earthquake shaking from the Canterbury Earthquake Sequence 2010-2011 (**CES**) triggered minor-to-severe liquefaction induced ground surface deformations resulting in land damage throughout the Christchurch area. The land damage included liquefaction ejecta, liquefaction-induced differential settlement, and lateral spreading resulting in extensive residential building damage.

It was observed that the majority of the areas affected by severe liquefaction induced land damage coincided with lower lying areas near the Avon River where the groundwater surface is close to the ground surface. Conversely, areas with less liquefaction-induced land damage were typically areas with higher elevation and deeper groundwater levels, indicating a correlation between liquefaction damage and the depth to the groundwater surface and hence the non-liquefying crust thickness.

Comparison of LiDAR survey information taken before and after the CES showed significant ground subsidence occurred as a result of the CES due to liquefaction-induced volumetric densification, liquefaction ejecta, lateral spreading and tectonic subsidence. Of the 140,000 flat land residential properties in Christchurch, approximately 85% have subsided following the CES (Rogers et al., 2015). Of these:

- 60,000 have estimated total ground surface subsidence of more than 0.2m;
- 12,000 have estimated total ground surface subsidence of more than 0.5m; and
- 500 have estimated total ground surface subsidence of more than 1m.

Following the September 2010 and February 2011 events, residents in low lying suburbs were reporting that their land was performing differently during smaller aftershocks relative to the pre-CES performance. However, there was no evidence that the earthquakes were having an effect on the soil strength and stiffness in Christchurch (as discussed in Section 6.5).

It was following the April 2011 aftershock and subsequently the June 2011 event that it became apparent that land performance was deteriorating. The shaking intensity from these events was lower than the September and February events yet the land damage was more severe in certain parts of Christchurch. In the most affected parts of Christchurch, the land was less able to support the weight of buildings than it was prior to the CES. This allowed the houses to partially sink into the ground in subsequent CES earthquakes (Russell et al. 2015). This was particularly noticeable in low lying areas where the greatest amount of subsidence had occurred. It was at this time that the concept of “crust thinning” was first proposed.

Due to the ground subsidence and seasonal increases in groundwater levels, the depth to groundwater during the April 2011 aftershock and June 2011 event was closer to the ground surface than it had been in both the September 2010 and February 2011 events. This formed the basis of a hypothesis that, in areas where the upper soil layers are susceptible to liquefaction, reduced depth to the groundwater surface due to ground surface subsidence was effectively reducing the thickness of the non-liquefying crust – i.e. "crust thinning" (Russell et al., 2015). In turn this "crust thinning" resulted in increased vulnerability to liquefaction-induced land damage.

In the low lying areas of Christchurch with the most significant levels of ground surface subsidence this hypothesis was consistent with land damage observations. However in areas away from the rivers and less affected by ground surface subsidence, a more complex picture emerged. In these areas, ground surface subsidence did not always correlate with deteriorating land performance through the CES. That is, "crust thinning" was not always directly correlated to change in depth to groundwater.

It became apparent that the complex ground conditions encountered in the Christchurch area were contributing to this complex picture. This is because the thickness of the non-liquefying crust and the thickness of the underlying liquefying soil layers is also dependent on the geological composition of the upper soil layers. The complexity of these ground conditions is demonstrated in Table C2.1 which summarises the geological units encountered in the Christchurch urban area. Areas where the near surface soils below the groundwater table are not susceptible to liquefaction have not experienced "crust thinning" despite having subsided as a result of the CES.

Table C2.1: Summary of Geological Units in the Christchurch Urban Area

Time period and location	Relevant Geological Formation	Description	Liquefaction Implications
>10,000 years before present (BP). WEST to EAST.	Riccarton Gravel	The top of the Riccarton Gravel formed the land surface when the sea level was approximately 30m lower than today. The old land surface is 10m above sea level near Christchurch Airport and 35m below sea level at New Brighton, an overall slope of about 1 in 300 towards the east. The Riccarton Gravel formed as an alluvial fan of the braided Waimakariri River.	'Hard' base to the Christchurch geology. Extremely low potential for liquefaction.
10,000 to 6,500 years BP. CENTRAL and EAST.	Base of Christchurch Formation	Sea level rose to the current level and the coast line regressed from east of New Brighton to an arc through Cashmere, Riccarton and Belfast. Fine grained forested coastal soils and estuarine deposits form the capping layer that confines the present day Riccarton Gravel aquifer.	Soils are generally soft and loose; some layers have potential for liquefaction.

Time period and location	Relevant Geological Formation	Description	Liquefaction Implications
6,500 to 2,500 years BP. CENTRAL and EAST.	Christchurch Formation	The coast line moved eastward from Riccarton to Wainoni due to the build-up of sand and silt supplied by the Waimakariri River and trapped in coastal currents between Pegasus Bay and Banks Peninsula. Dense to very dense sands are indicative of offshore sand bank and surf beach deposits (as per present day New Brighton), while silt and sand layers with minor organics indicate estuarine and back beach environments similar to the present day estuary. Narrow lenses of gravel deposited by deltas of the prehistoric Avon and Heathcote Rivers persist through the Christchurch Formation in places (e.g. Waltham/St Martins).	Dense to very dense sands often have a low potential for liquefaction and are 5 to 10m thick, commencing a few meters below sea level. Interbedded silt and sand layers and very low plasticity silts can create problems with the assessment of liquefaction and therefore appropriate engineering responses to mitigate liquefaction triggering and consequence are required.
10,000 years BP to present. WEST.	Yaldhurst Member of the Springston Formation	The alluvial fan of the Waimakariri River has steadily built out onto the old Riccarton Gravel land surface, and then onto the coastal deposits of the Christchurch Formation. Gravel with minor layers of sand and silt form the fan, which slopes at about 1 in 250 towards the east from the airport to Hagley Park. The boundary between Riccarton Gravel and overlying Yaldhurst Member gravel is generally indistinct and the aquifer is unconfined.	Low potential for liquefaction because of the predominantly gravel materials and groundwater some 3 to 10m below surface due to the relatively steeply sloping fan surface.
2,500 years BP to present. CENTRAL.	Yaldhurst Member of the Springston Formation	The alluvial fan has built out across the coastal plain as ‘fingers’ of medium dense gravel and sand forming flood channels, and flood plains formed by loose overbank silt and sand layers. The channels are self-levee forming and tend to sit above the overall flood plain level. Several low lying areas have been surrounded by flood plain and channel deposits to form wetlands, or historic wetlands, since in-filled, e.g. Hendersons Basin, Spreydon, Riccarton, Papanui/Cranford, St Albans, Marshlands. The combined alluvial and coastal plain from Hagley Park to New Brighton slopes eastward at about 1 in 1500.	High potential for liquefaction in near surface sand and silts. Actual risk of surface damage varies from area to area depending on groundwater depth, which is controlled by relative ground surface elevation (e.g. higher level flood channels and lower lying plains or wetlands). Lenses and layers of gravel deposited in layers a few metres either side of sea level have a generally low risk of liquefaction. Caution is required in assessing rapid changes in gravel thickness across individual development sites. Relatively low liquefaction potential may be present in some low lying areas due to the predominance of plastic fine grained soils through the profile.

Time period and location	Relevant Geological Formation	Description	Liquefaction Implications
2,500 years BP to present. EAST.	Christchurch Formation	Eastward pro-gradation of the coast line has continued, depositing dense beach sands, medium dense dunes and loose estuarine deposits Dune deposits from Shirley to Linwood have been eroded by the Avon and Heathcote Rivers and thin layers of sandy alluvium re-deposited in river channels and on flood plains within a few metres of sea level.	High potential for liquefaction in recent near surface coastal and alluvial sand and silt. Groundwater is generally 1 to 2m below surface due to the very flat slope of the coastal plain (e.g. tidal influence on the Avon River extends to Manchester Street). Low potential for liquefaction in dense beach sand, typically 5m below surface.

In various documentation, "crust thinning" was initially referred to as Category 8 (or Cat 8) land damage. The terminology was later amended to Increased Liquefaction Vulnerability (**ILV**). From this point forward in this appendix it will be referred to as ILV.

C3 Recognition of ILV Land Damage and the Development of the ILV Assessment Framework

In early 2012, EQC recognised ILV as a form of natural disaster damage for the purposes of the EQC Act 1993, where it was having a material effect on the use and amenity of the land. The primary challenge arising from the recognition of this form of land damage was how to define and assess the material effects of ILV. The reason for this is that, unlike most other forms of land damage recognised by the EQC (listed in **Appendix B**), the effects of ILV are not immediately apparent. This is because this form of land damage is dependent upon the occurrence of a future earthquake event in order for the change in vulnerability to be realised.

At this time, it was recognised that there was insufficient information available in order to undertake an assessment of ILV throughout the Christchurch area. As a result of this, EQC commissioned and collated one of the most extensive databases of geotechnical investigation information and land and dwelling performance observations ever assembled. This database and other relevant information has been made publicly available on the Canterbury Geotechnical Database (**CGD**), which was launched in April 2012. The information sources used in the assessment of ILV are discussed in Section 5.

Concurrently with the collation of the geotechnical investigations and land and building performance information, a detailed literature review of the widely used CPT-based liquefaction vulnerability parameters was undertaken. As a result of this literature review and the analysis of the available geotechnical information, it was recognised that none of these tools were appropriate for the assessment of ILV in the Christchurch area. Therefore, a new liquefaction vulnerability parameter called the Liquefaction Severity Number (**LSN**) was developed for the assessment of ILV. Refer to Section 7 and **Appendix A** for further detail about the assessment of liquefaction vulnerability using CPT-based parameters.

Based on the information gathered during 2012 and legal and engineering advice, an initial ILV land damage assessment framework presented in Figure C3.1 was approved by EQC in January 2013. The purpose of this framework was to provide a consistent approach for the assessment of ILV.

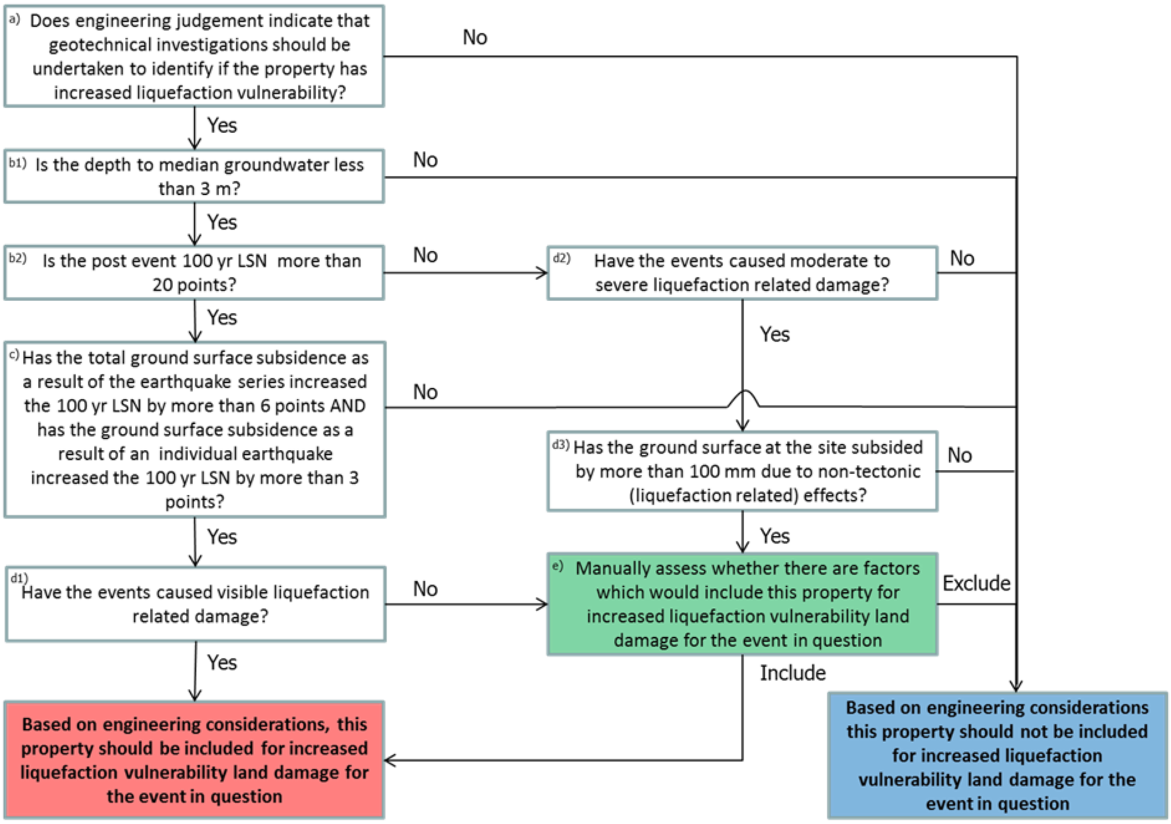

Figure C3.1: ILV land damage assessment framework approved by the EQC in January 2013

The ILV assessment framework was established to consider the engineering considerations associated with the assessment of ILV. Therefore, it can only be used to assess the *engineering criteria* as discussed in Section 2.4. The *engineering criteria* are as follows:

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

The ILV land damage assessment framework shown in Figure C3.1 did not provide the mechanism to assess *criterion 3* – namely that "…any 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."

C4 Refinement and Development of the ILV Assessment Framework with the ILV Assessment Methodology

Following the approval of the ILV land damage assessment framework by the EQC, the assessment of ILV was operationalised. As the undertaking of an assessment of this nature and scale had never been attempted before, the ILV Assessment process has developed in an iterative manner as assessments were undertaken and understanding of ILV land damage increased. Where this occurred all properties previously assessed were reviewed to ensure consistency with the updated understanding. The ILV Assessment Methodology described in the Report is the final methodology applied to all residential properties in Christchurch.

Initially it was envisioned that an automated approach could be adopted to ILV assessment. The automated ILV model was developed for this purpose. The intention was that the automated model would be used to confirm approximately 90% of the ILV qualifications with the remaining 10% requiring manual review (i.e. the green box in Figure C3.1). However, it became apparent that the automated ILV model was unable to account for the full complexity of ground conditions requiring assessment for ILV (Table C2.1 demonstrates the complexity of the ground conditions in Christchurch).

Accordingly, in July 2013 it was determined that a manual ILV assessment would be required for each of the 139,390 urban residential properties in the Christchurch area with the level of manual engineering assessment on each property being proportional to the complexity of the assessment. The automated ILV model was used as an input into the manual ILV assessment process. Refer to Section 8.2 for more information about the automated ILV model.

The manual assessment of ILV was undertaken using a two stage process. Stage 1 was used to assess straightforward cases and Stage 2 was used to assess more complex cases. The Stage 1 ILV assessments started in June 2013 and were completed by September 2014. The Stage 2 ILV assessments started in February 2015 and were completed by April 2015. Further discussion about the ILV assessment process is provided in Sections 8, 9 and 10.

As discussed in Section 1.4, the ILV Assessment Methodology has been developed in collaboration with a number of other parties with an interest in the ground surface subsidence caused by the CES. A key outcome of this collaborative process was the incorporation of the mean LSN value into the automated ILV model in February 2014. As shown in Figure C3.1, previously the automated ILV model used only the median LSN value. Refer to **Appendix H** for further discussion about the mean and median LSN.

Another significant change to the ILV Assessment Methodology was the adoption of the Boulanger and Idriss (2014) liquefaction triggering methodology in July 2014. Previously the Idriss and Boulanger (2008) liquefaction triggering methodology was applied, however the April 2014 update to this methodology incorporated 50 case histories from the CES and provided an improved correlation with land damage observations.

Adopting this revision to the liquefaction triggering methodology meant that the indicator LSN and ΔLSN values for the two ILV engineering criteria (refer to Section 2.4) required revision. Originally, using the Idriss and Boulanger (2008) liquefaction triggering methodology, the LSN and ΔLSN indicator values were 20 and 6 respectively. Due to the changes in the Boulanger and Idriss (2014) liquefaction triggering methodology the LSN and ΔLSN values were revised to 16 and 5 respectively. As a result of these revisions the Stage 1 ILV assessment process effectively needed to be started again. Further detail about the differences between the various liquefaction triggering methodologies can be found in **Appendix A**.

The final refinement relates to the EQC Act's requirement that EQC must determine whether an insured property has suffered natural disaster damage in each natural disaster event. EQC must therefore be satisfied that a physical change has occurred resulting in a material increase in vulnerability to liquefaction that has affected the amenity and value of the insured property in one or more of the main earthquake events. However, for the reasons listed in Section 2.7.3, the manual assessment methodology developed for the CES can only practically be undertaken by considering ground surface subsidence-induced changes to liquefaction vulnerability across the CES, and then (after the assessment process is completed) considering which individual events are likely to have contributed to that change. Accordingly, the assessment of the effects of a particular event was removed from Step c in Figure C3.1.

For completeness, it is noted that Step b1 (assessment of depth to median groundwater) in Figure C3.1 was not directly applied in final ILV assessment methodology. This is because low LSN values and low ΔLSN values are estimated when the depth to groundwater is greater than 3m, which in practice makes Step b1 superfluous. Similarly, the 100mm threshold for non-tectonic subsidence in Step d3 in Figure C3.1 was intended as a filter to determine which properties would require manual review. However, when the decision was made to complete a manual assessment for all ILV properties this step also became superfluous.

The main refinements to the implementation of the ILV eligibility assessment process are summarised in Table C4.1 below.

Table C4.1: Main refinements to the ILV eligibility assessment process

Feature	**Initial framework** **(Figure C3.1)**	**Updated assessment process** **(Figure 4.2 in the Report)**
Assessing ILV for a 1 in 100 year earthquake event.	Assess ILV at exactly a 1 in 100 year event (refer to Figure C3.1).	Assess ILV at a 1 in 100 year event, or any more frequent event where a greater change in vulnerability occurs (refer to Figure 4.2 in the Report).
Manual review process.	90% of ILV eligibility decisions expected to be made via an automated model, with 10% of properties assessed individually by engineers (refer to Figure C3.1).	Every ILV eligibility assessment includes manual review by experienced engineering staff (refer to Figure 4.2 in the Report).
Interpolation of LSN values between geotechnical investigation locations.	Calculate LSN at single point location on the property only (refer to Figure C3.1).	Calculate LSN over entire ILV assessed area (refer to Figure 8.1 in the Report).
	Interpolate change in LSN based on change in ground elevation at investigation locations (refer to Figure C3.1).	Impose measured subsidence of property being assessed on to surrounding investigations before interpolating (refer to Figure 8.1 in the Report).
	Where investigation included pre-drill (to clear services), incomplete soil profile data skews interpolated LSN values (refer to Figure C3.1).	Overwrite pre-drill layers with known LSN data from surrounding investigations (refer to Figure 8.1 in the Report).
Natural seasonal and year-to-year variations in the groundwater level.	Assess thresholds using the median LSN value, calculated based on the long-term median groundwater level (refer to Figure C3.1).	Assess both median and mean LSN values, calculated across a wide range of groundwater levels (refer to Section 7.5 in the Report).
Liquefaction triggering methodology for the automated ILV model.	Automated ILV model applied using Idriss and Boulanger (2008) liquefaction triggering methodology. The original indicator values were as follows: • LSN = 20 for the assessment of Criterion 1; and • ΔLSN = 6 for the assessment of Criterion 2. (refer to Figure C3.1)	Automated ILV model applied using Boulanger and Idriss (2014) liquefaction triggering methodology. The revised indicator values are as follows: • LSN = 16 for the assessment of Criterion 1; and • ΔLSN = 5 for the assessment of Criterion 2. (refer to **Appendix A**)
Ground surface subsidence assessment case	Assess ILV based on the change in ground surface elevation over the CES and for each individual event (refer to Figure C3.1).	Assess ILV based on the change in ground surface elevation over the entire CES (refer to Section 2.7.3 in the Report).

C5 References

Boulanger, R. W. & Idriss, I. M. 2014. *CPT and SPT based liquefaction triggering procedures*. (Report No. UCD/CGM-14/01). Center for Geotechnical Modelling, Department of Civil and Environmental Engineering, University of California, Davis, CA.

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