JOINT REPORT OF
THE EXPERT PANEL

Peer Review of the Increased Liquefaction Vulnerability Assessment Methodology

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on behalf of the EQC

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Contents

EXECUTIVE SUMMARY

General Statement

The review of the Increased Liquefaction Vulnerability (ILV) Assessment Methodology by the independent Expert Panel was undertaken in three phases. The first phase involved evaluation of memos, reports, analytical results, and supporting documentation provided by Tonkin and Taylor (T+T) as the ILV methodology was developed and evolved in the period 2012 to 2014. In the second review phase, comments were given on draft sections of the ILV report with recommendations for improvement and further scrutiny of aspects of the ILV methodology. The third phase was to perform an independent review of the report entitled "Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology," dated September 2015 (herein referred to as ILV Report).

Consistent with the Terms of Reference, the Expert Panel has come to the following conclusions:

1. Both the concept of ILV as a form of insured land damage and the need for an ILV Assessment Methodology have no apparent precedents in history. The development of the ILV Assessment Methodology required overcoming numerous technical and administrative challenges with little or no prior experience to draw from, and as such, represents a significant original achievement. The Expert Panel commends the project team for their strategic thinking, comprehensive technical approach, and thorough evaluation process that employs an exceptional dataset with sound analysis platforms and engineering evaluations.

2. The ILV Report is a comprehensive document that describes the ILV Assessment Methodology and its development in sufficient detail to address all key aspects of the methodology and its application in the complex geological conditions of Christchurch. It provides appropriate descriptions of technical limitations in the available information and liquefaction evaluation procedures. It provides sufficient examples to illustrate how such limitations are addressed in evaluating the engineering criteria for ILV assessment specified by EQC. It provides a reasonably thorough summary of relevant scientific literature. The ILV Report is not, however, an easy document to digest given the depth to which interconnected and intricate issues are often covered. This characteristic of the report is understandable given the desire to emphasize comprehensive and transparent coverage of all aspects of the ILV Assessment Methodology and its development.

3. The information and assumptions used in the ILV assessment are technically sound, reasonable, and consistent with the objectives set for the assessment. The Expert Panel did not identify any technical limitations, aside from those identified and addressed in the ILV report, which could be reasonably expected to have a material effect on quantifying the extent of ILV damage.

4. Alternative forms for the ILV Assessment Methodology may have utilized the available information in different ways, but it is likely that an alternative, robust methodology meeting the general objectives specified by EQC, as discussed above, would have produced results reasonably consistent with those of the ILV Assessment Methodology for the large majority of residential properties.

5. The ILV Assessment Methodology meets the general objectives specified by EQC. It uses well-founded and current engineering procedures with the best available data and information. The data and information used are available to property owners. Moreover, the process allows any claimant to provide further information or alternative interpretation of existing information to support ILV damage for any residential property. It considers all reasonably relevant factors, allows for incorporation of engineering judgement through manual assessments and peer review

processes, and is applied in good faith with avenues for challenge and consideration of new information. The overall methodology provides for reasonably efficient processing of claims while also providing a comprehensive basis upon which to derive equitable decisions with the goal of not rejecting legitimate claims.

Findings

The agreed findings of the Expert Panel regarding the ILV Assessment Methodology support the previous conclusions and are as follows:

1. *Information Used for ILV Assessment*

i. The information used in the ILV Assessment Methodology is unsurpassed for its quantity, quality, and open accessibility. The Canterbury Geotechnical Database (CGD), which is the primary source of information, is a unique resource for accessing regional data. The ILV Assessment Methodology provides appropriate checks and allowances for known limitations in the various sources of data and information.

ii. The observed land performance information in the CGD is derived from widespread, multiple independent sources, which have been scrutinized and verified in numerous ways. The quality and comprehensiveness of the data provide a strong evidential basis for the ILV assessment.

iii. The observed performance of residential land and buildings in the 2010-2011 Canterbury Earthquake Sequence (CES) is the most important source of information, because it can be used to assess whether land is vulnerable to liquefaction damage at the 100 year return period levels of earthquake shaking and whether as a consequence of previous liquefaction-induced ground subsidence, land is more vulnerable to liquefaction damage in the future. Additionally, these observations provide for regional and site-specific validation of the engineering procedures employed to evaluate liquefaction triggering and its consequences.

iv. The LiDAR data in the CGD for ground surface elevation were found to be accurate generally within ±0.1 m for the majority of areas where the ILV assessments were performed. Nearly all of the affected area had a ground surface elevation accuracy of ±0.2 m. This level of accuracy is sufficient for evaluating the amount of subsidence at residential properties consistent with the ILV Assessment Methodology.

v. Using the total ground surface subsidence over the entire CES (as opposed to each event) increases the reliability of the ground subsidence estimates, and thus is a reasonable and appropriate basis for incorporating subsidence into the ILV Assessment Methodology.

2. *Assumptions Used for ILV Assessment*

i. The ILV Assessment Methodology combines the current, post-CES level of liquefaction vulnerability with the current seismic hazard and thus provides a consistent basis for assessing liquefaction vulnerability in alignment with appropriate seismological models.

ii. The adopted 100-year return period is consistent with the return period already used for natural hazards in New Zealand legislation and thus is a logical extension of the reference time that is already part of New Zealand law. It is also consistent with flood risk characterization in other countries, like the U.S., and advantageous as compared to the alternative 25-year and 500-year return periods levels of shaking.

iii. The adopted reference 100-year return period M6/0.3 g earthquake shaking level is consistent with current MBIE guidelines, which may overestimate earthquake ground shaking, thus weighting the ILV Assessment Methodology in favor of qualification of properties. Given the EQC direction (as stated in the ILV Report) that the process must not produce wrong answers in the rejection of claims, which are on the balance of probabilities well-founded, in combination with the uncertainties involved in defining a universally accepted seismic hazard, the earthquake shaking level adopted in the ILV Assessment Methodology is reasonable.

iv. The decision to not include the potential anthropogenic and climate influences on groundwater levels is reasonable and appropriately justified.

v. The use of post-CES cone penetration tests (CPTs) for soil characterization is reasonable and consistent with how a large majority of the CPT data were obtained in the empirically-based liquefaction triggering procedure. Analyses of pre- and post-CES CPT data obtained at the same sites shows no significant change in liquefaction resistance due to the effects of the CES.

vi. The assumption that the potential for lateral spreading in future earthquakes has not increased as a result of physical changes to the land caused by the CES is reasonable and appropriately justified by the observations of lateral spreading displacements in successive events of the CES.

vii. Observable damage from ground cracking induced by the CES is compensated separately by EQC by paying the cost of repairing cracks in accordance with readily available recommended procedures. Such repairs performed by a competent contractor according to those recommended procedures are a reasonable basis for reinstating pre-CES crust integrity, thus supporting the assumption that ground cracking, if present and repaired, is not a significant source of increased vulnerability.

viii. The ILV assessment areas for residential properties did not include long access ways. The assessment of long access ways is still under consideration and is not covered by the ILV report.

3. ILV Assessment Methodology

i. The two-stage ILV Assessment process is a reasonable approach for resolving ILV claims in an efficient manner, given the large number of properties that need assessment. Importantly, very few decisions made in Stage 1 were reversed during the Stage 2 assessment. Thus, Stage 2 assessments are consistent with Stage 1 assessments, and both are judged to be robust.

ii. The overall approach embodied in the ILV Assessment Methodology is comprehensive with respect to systematic use of the available databases and sufficiently detailed to resolve ILV at the level of individual residential properties.

iii. The LSN indicator was selected over alternative liquefaction vulnerability indices as a primary index in the ILV Assessment Methodology, because once calibrated, it was shown to provide the most consistent correlation with the observed land damage performance data over the primary CES events on a regional scale. This reconciliation of observations with computed LSN values is an essential and desirable component in the overall ILV Assessment Methodology.

iv. The LSN = 16 and ΔLSN = 5 criteria for identifying ILV damage in the automated models were developed through a process that is transparent and defensible. The adopted indicator values provide a consistent and reasonable basis for evaluating ILV land damage claims with the goal of not rejecting legitimate claims.

v. Conservative liquefaction triggering assessments are embodied in the LSN calculation, which leads to an ILV assessment process that is weighted in favor of property owners. Given the intention of EQC to minimize the rejection of well-founded claims under highly variable subsurface conditions and uncertainties regarding soil properties, the assumptions embodied in liquefaction triggering are not excessively conservative and on balance of the probabilities provide a reasonable and justifiable basis for LSN calculations.

vi. The manual components of the ILV assessments provide appropriate opportunities for engineering judgements regarding the balance of evidence. Engineering judgements are inherently subjective and hence best exercised in groups using iterative steps, multiple checks, and quality control procedures, all of which are integrated in the manual reviews of the ILV Assessment Methodology. The manual review process is reasonable and appropriate, considering the complexities and stated objectives of the ILV Assessment Methodology.

4. ILV Assessment Results

i. The conclusions in the ILV Report that 1) *the population of properties qualifying for ILV performed very differently compared to the population of properties which are not materially vulnerable to liquefaction*, and 2) *the ILV automated model at a regional level generally performed well in differentiating between properties with and without ILV* are substantiated by the data and evaluations presented in the report.

ii. The ILV Report includes a comprehensive identification of limitations and discrepancies in the ILV assessment process, all of which were subject to an independent case-by-case engineering evaluation and eventual engineering judgement as to whether a given property satisfies the ILV criteria. Thus, the ILV Assessment Methodology reflects a reasonable and appropriate audit of potential discrepancies and limitations that are addressed in a suitable and defensible manner when decisions are made regarding ILV qualification of individual residential properties.

iii. The Worked Examples confirm that, in accordance with the EQC direction, the ILV Assessment Methodology was applied in good faith; not applied mechanically; and did not exclude consideration of factors that are relevant to any particular case. Moreover, each Worked Example follows faithfully and in detail the procedures in the ILV Assessment Methodology and provides results that are reasonable and appropriate in terms of the Expert Panel's own judgement.

1. INTRODUCTION

1.1. Liquefaction in the Canterbury Earthquake Sequence

The City of Christchurch and surrounding areas were affected by a large number of earthquakes in the 2010-2011 Canterbury Earthquake Sequence (CES). The main earthquakes in the CES, including their moment magnitudes (M_w), were (e.g., Bradley et al. 2014):

- M_w = 7.1 on 4 September 2010 (known as the Darfield earthquake);
- M_w = 6.2 on 22 February 2011 (known as the Christchurch earthquake);
- M_w = 5.3 and 6.0 on 13 June 2011; and
- M_w = 5.8 and 5.9 on 23 December 2011.

The majority of the affected region is located on the Holocene deposits of the Canterbury Plains (Brown and Weeber 1992). The Canterbury Plains are a complex sequence of alluvial fans deposited by eastward-flowing rivers. The near surface sediments are composed of fluvial deposits of gravels, sands, and silts, which are intertwined with estuarine, lagoon, beach, dune, and coastal swamp deposits of sand, silt, clay, and peat. These young and often loose deposits are highly variable over short distances, both vertically and horizontally. The surface sediments are underlain by gravelly alluvial deposits that have artesian pressures throughout the eastern Christchurch area. The ground water table ranges from depths of about 5 m west side of the city to about 1 m east of the city centre.

Liquefaction and associated ground deformations were pervasive throughout the affected region and highly variable due to the rapidly changing geologic conditions and levels of strong shaking during the CES. Areas with severe liquefaction effects were characterized by large quantities of soil and water ejecta and ground surface subsidence exceeding hundreds of millimeters, along with lateral spreading displacements often exceeding 1 m in the vicinity of river channels. Areas with minor to moderate liquefaction effects were characterized by smaller ground surface subsidence or lateral displacements, but even these movements were often sufficient to damage homes and infrastructure.

The body of scientific and engineering data compiled regarding liquefaction and its effects in the CES is unsurpassed in history for its quantity, quality, and open accessibility. The documented data include: strong ground motion recordings; thousands of borehole and cone penetration test (CPT) soundings; multiple, high resolution LiDAR surveys; aerial photography; detailed field reconnaissance records; ground surveying records; and large numbers of well-documented case studies on the performance of buried pipelines, bridges, commercial buildings, and residential homes. The body of data provides an excellent basis for evaluating liquefaction and its effects on land and engineered structures. The database and documented case studies are expected to provide a continuing resource for studies that advance both the science and the engineering practices for protection against earthquakes, including the assessment and mitigation of liquefaction.

1.2. Impacts of Liquefaction on Residential Buildings and Infrastructure

Ground deformations and failure associated with liquefaction contributed to widespread damage to residential buildings, commercial buildings, buried pipelines, bridges, roads, and stop banks. The extent and nature of the liquefaction-related damages for each type of infrastructure have been well documented in various publications and databases and are the subject of ongoing research by researchers worldwide.

Damage to residential buildings depended on the magnitude and distribution of the ground surface subsidence and lateral spreading displacements across their foundations. Differential ground settlements or stretching (lateral extension) across a site were associated with cracking, tilting, or warping of building foundations, which were accompanied by architectural cracking and structural distress manifested as racking, hogging, twisting, or distortion of the building structure. Ground deformations also caused cracking and offsets in driveways, patios, and other landscaping features and damaged underground utility connections between the buildings and distribution mains. Building damage was generally repairable in areas of minor to moderate liquefaction effects, but was often too extensive for economical repair in areas of severe liquefaction effects. There were no cases of liquefaction-induced ground deformations causing collapse of a residential building. However, some buildings in the areas of extensive lateral spreading in the Red Zone (discussed below) were severely deformed and close to partial collapse.

The observed impacts of liquefaction on residential buildings in the CES were a primary consideration in the land zonation established by the New Zealand Government shown in Figure 1. The residential Red Zone is land identified by the New Zealand Government where the repair and rebuilding process is not judged to be practical, because the required land repair and improvement works would be difficult to implement, prolonged, and disruptive for landowners. The balance of the land was categorized into the three technical categories TC1-TC3 by the Ministry of Building, Innovation and Employment (MBIE). The TC1 area corresponds to areas where liquefaction damage is unlikely in future large earthquakes, and standard residential foundation assessment and construction is appropriate. The TC2 area corresponds to areas where liquefaction damage is possible in future large earthquakes and standard enhanced foundation repair and rebuild options per MBIE guidance (MBIE, 2012) are suitable for liquefaction mitigation. The TC3 area corresponds to areas where liquefaction damage is possible in future large earthquakes and individual engineering assessment with site specific geotechnical investigations is required to select appropriate foundation repair or rebuild options.

1.3. Increased Liquefaction Vulnerability

The Earthquake Commission Act of 1993 (EQC Act) provides statutory insurance for physical loss or damage to residential property caused by an earthquake. Physical loss or damage includes any physical change in the residential land which causes a loss of use or amenity as a result of that physical change. The High Court has concluded that "*residential land that is materially more prone to liquefaction damage in a future earthquake because of changes to its physical state as the direct result of one or more of the earthquakes in the CES, has sustained natural disaster damage in terms of the Act.*"

A residential site is considered vulnerable to liquefaction if the earthquake loading by an adopted reference level of earthquake shaking would likely trigger liquefaction that is materially damaging for residential land and buildings. Liquefaction-induced damage to land includes ground distortion and cracking, sand ejecta on the ground surface, subsidence, differential settlements, lateral movements, and consequent deformation and damage of structures.

A residential site may be considered to have "Increased Liquefaction Vulnerability (ILV)" if its uses and amenities are adversely affected by being materially vulnerable to liquefaction *and* by being materially more prone to liquefaction damage in a future earthquake as a result of the CES. Materiality refers to both the vulnerability and the increase in vulnerability of the land as being sufficient to affect its potential uses and amenities as a platform for a residential building and related purposes. Land materially vulnerable to liquefaction involves residential properties that are likely to sustain moderate to severe liquefaction-related damage in a future reference earthquake and thus, absent land repair, require enhanced building foundations. An increase in land vulnerability is material, for example, when ground surface subsidence reduces significantly the depth to the groundwater table and produces a thinner surface layer of competent soils (i.e., the non-liquefied crust). A thinner crust layer, which may be weakened by cracking and lateral deformation, will be prone to greater distortion and larger differential movements in a future earthquake, which translates into greater damage to overlying buildings. Note that the effects of cracking of the crust layer predominantly caused by lateral spreading have been addressed as part of the repair of other forms of land damage and are excluded for the purpose of assessing ILV.

The New Zealand Earthquake Commission (EQC) has specified three criteria for identifying ILV damage from the CES:

- Criterion 1 is that the residential land has a material vulnerability to liquefaction damage after the CES for levels of earthquake shaking with return period of up to 100 years.
- Criterion 2 is that the vulnerability to liquefaction damage of the residential land in future earthquakes has materially increased as a result of ground surface subsidence of the land caused by the CES, for levels of earthquake shaking with return period of up to 100 years.
- Criterion 3 is that 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 is evaluated in a separate study by EQC's valuers and hence is not a subject of this review.

1.4. Objectives of the ILV Assessments

EQC retained T+T through Chapman Tripp to develop an ILV Assessment Methodology that consistently assesses the criteria for ILV damage adopted by EQC, as described in the previous section. The objectives of the ILV Assessment Methodology are to:

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

EQC also instructed T+T to ensure that the ILV Assessment Methodology:

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

The subject report describes the ILV Assessment Methodology T+T developed to satisfy the above objectives.

As stated in the ILV Report, EQC also advised T+T that its *"policy for assessing claims for damage to residential land claims must not produce 'wrong answers' in the sense that it leads to rejection of claims which are on the balance of probabilities well-founded.*" Accordingly, T+T has implemented the ILV Assessment Methodology in a manner that favors qualification when significant uncertainties are involved.

The development of an ILV Assessment Methodology is a unique undertaking, with no apparent precedent in history. This development project had to overcome technical and administrative challenges for which there was little or no guidance or prior experiences to draw from. As such, its development represents a significant original achievement.

1.5. Purpose of this Report

This joint report was prepared by an independent peer review panel, referred to as the Expert Panel (see Appendix B for biographies of panel members), for Chapman Tripp on behalf of EQC to review and comment on the ILV Assessment Methodology developed by T+T for EQC and documented in the ILV Assessment Report. The Expert Panel was specifically asked to review and comment on:

- the technical limitations of the available information and liquefaction evaluation procedures described in the ILV Report and the appropriateness of their treatment in addressing the first two criteria specified by EQC for identifying ILV damage;
- the methodology for the assessment of ILV damage, including both assessment assumptions and processes;
- the completeness and accuracy of the scientific literature review contained in the ILV report; and
- any technical limitations which the panel considers could have a material effect on quantifying the extent of ILV damage.

The remainder of this report is organized in the following main sections:

- Section 2 provides commentary on our current understanding of liquefaction processes and the known limitations in currently available engineering evaluation procedures;
- Section 3 provides commentary on the information currently available and the key assumptions used in the ILV assessments;
- Section 4 provides commentary on the four-phase ILV Assessment Methodology (see Figure 3) that takes account of site-specific performance observations, engineering liquefaction evaluations, and engineering judgement; and
- Section 5 provides commentary on the evaluation of the ILV assessment results based on its comparison with regional observations of ground performance and their flexibility to accommodate local variations in ground performance.

The last section provides the Expert Panel's conclusions.

We acknowledge that we have read the High Court Code of Conduct for Expert Witnesses and have complied with it in preparing this report.

2. COMMENT ON LIQUEFACTION PROCESSES AND EVALUATION PROCEDURES

The profession's current understanding of liquefaction processes and the known limitations in currently available engineering evaluation procedures provide an important backdrop for reviewing any proposed ILV Assessment Methodology.

2.1. Liquefaction Processes

Liquefaction in saturated sands and other cohesionless soils is a common cause of ground deformation and damage to structures during earthquakes. Loose sands tend to contract, or decrease in volume, under the cyclic loading imposed by earthquake shaking. This contraction transfers normal stress from the sand matrix onto the pore water if the soil is saturated and largely unable to drain during shaking. By losing normal stress between its particles, the soil loses frictional resistance, which is essential for strength and stability of the soil mass. The result is a reduction in the effective confining stress within the soil and an associated loss of stiffness and strength that contributes to deformations of the soil deposit. The term "liquefaction" has been assigned various technical meanings in the literature, including criteria based on excess pore water pressure ratios, peak shear strains, flow deformations in laboratory tests, observations of sand boils, significant ground deformations, or slope instability in the field. Liquefaction, in the present context, is best viewed as a general term involving the loss of internal soil stiffness and strength because of elevated water pressure during shaking and encompassing the above general classes of behavior.

The mechanics of liquefaction triggering and associated ground deformations in natural deposits during earthquake shaking are more complex than current engineering procedures are able to address in a comprehensive way. Factors contributing to the complexity of the phenomena include the spatial variability of natural deposits, highly nonlinear stress-strain behavior of liquefying soils, characteristics of the earthquake ground motions, local dynamics of site response, diffusion of excess pore water pressures during and after shaking, formation of cracks and slip surfaces in the soil, and interactions with any embedded structures or deep foundations. The complexity of the phenomena is such that the accuracy of ground deformation estimates obtained using even the most sophisticated analyses may be limited by uncertainties in the initial ground conditions, earthquake loading, and soil behavior.

Spatial variability of natural deposits, like that encountered in the Christchurch area, is an important consideration in the assessment of liquefaction vulnerability. Significant variations in soil type and density over short vertical and horizontal distances can translate into similar local variations in excess pore pressure and shear strains during earthquake shaking. The magnitude and distribution of ground surface settlement, or subsidence, depends on the extent and continuity of the zones, lenses, or pockets in which liquefaction is triggered and on the thickness, strength, and stiffness of any overlying competent soil layers, which can bridge across liquefied pockets, thereby reducing the resulting ground surface damage or distortion. The magnitude of lateral spreading displacements similarly depends on the lateral extent and continuity of liquefied materials, but also depends on the slope and shape of the ground surface as well as the inclination and thickness of underlying deposits. Accordingly, the spatial variability of natural soils, like those encountered in the Christchurch area, means that (1) ground deformations can be expected to vary substantially over short distances, and (2) common site characterization practices with a limited number of in-situ soundings and borings can only provide an approximate understanding of subsurface conditions at a specific site. As a result, any analyses based on such data can only be expected to provide an approximate estimate of the actual deformations in a future earthquake. However, such estimates are sufficiently supported by a considerable amount of empirical data that appropriate engineering procedures can be used with confidence to render sound engineering assessments.

The effects of recent earthquake loading on the liquefaction vulnerability of a specific site may include contributions from several factors, some of which are better understood than others. Ground surface subsidence and its effect on water table depth are considered the primary factors, in that subsidence can reduce the thickness of the competent crust layer thickness that supports residential buildings.

Other factors can have competing secondary effects on liquefaction resistance in future earthquakes. For example, ground cracking and water venting processes may weaken a crust, making it easier to be distorted and more vulnerable to the expulsion of ejecta in a future earthquake. These effects would contribute to an increase in liquefaction vulnerability. Liquefaction can also lead to an overall or localized densification of the subsurface soils, which results in increased liquefaction resistance. Although such effects are not included or quantified explicitly in current engineering practice, aside from changes in water table depth and measured in-situ penetration resistance, they are typically considered less important relative to other more significant factors that are captured adequately in current liquefaction assessment procedures.

2.2. Engineering Evaluation Procedures

Engineering procedures for estimating liquefaction effects are limited by the complexity of the phenomena, incomplete definition of initial conditions (including the spatial variations in subsurface conditions), and uncertainty in the earthquake loading. Engineering procedures are therefore simplified to make the analyses tractable, while recognizing that the simplifications may contribute to an increase in the bias or dispersion in predictions.

Liquefaction evaluations in the Christchurch area have made extensive use of CPT-based liquefaction vulnerability parameters (or indices), including: one-dimensional (1D) post-liquefaction reconsolidation settlement (S_{V1D}) (e.g., Ishihara and Yoshimine 1992, Zhang et al. 2002), liquefaction potential index (LPI) (Iwasaki et al. 198, 1982), and liquefaction severity number (LSN) (T+T 2013). These liquefaction vulnerability parameters all use a liquefaction triggering analysis as one (principal) step in their calculation. The ability of the S_{V1D}, LPI, and LSN parameters, in combination with common liquefaction triggering correlations, to predict the observed liquefaction-induced damage on a regional scale was evaluated by T+T (2013), van Ballegooy et al. (2014), and van Ballegooy et al. (2015). They concluded that: (1) LSN provides a more consistent correlation with the observed liquefaction-induced damage than the LPI, and (2) use of liquefaction vulnerability parameters in regional studies can, at best, only provide general assessments of liquefaction-induced damage patterns. The Expert Panel concurs with this evaluation.

The large uncertainty or dispersion in the correlations between liquefaction vulnerability parameters and observed liquefaction-induced damage is partly attributed to the simplifying assumptions inherent in each parameter relative to the complexity of actual field behavior. Each of the liquefaction vulnerability parameters involves significant simplifications, which mean that certain physical mechanisms of settlement and lateral spreading are not explicitly accounted for (e.g., lateral discontinuity of strata, three dimensional effects, thickness and competency of the non-liquefiable crust layer, dynamic response, proximity of vertical or sloping ground surfaces, loss of soil ejected to the surface). These simplifications make the analyses more straightforward to perform, but also contribute to the uncertainty (bias and dispersion) in the correlation between these parameters and actual ground surface displacements. The utility of vulnerability parameters in site-specific or regional applications improves if the bias and dispersion in their correlation with actual liquefaction-induced damage can be reduced.

The ability to calibrate engineering models against known site performance at a local or regional scale is therefore of key importance whenever possible. This calibration includes everything from liquefaction triggering to the resulting ground deformation to consequences for structures founded on or embedded in the ground. Therefore, a sound engineering evaluation requires judgement guided by explicit and detailed observations of liquefaction-induced damage that can be correlated with in-situ soil properties, soil layering, accurate ground surface and groundwater levels, and reliable models for earthquake-induced transient ground motions at the site or sites of interest. Because some site conditions are time-dependent, such as groundwater tables with seasonal fluctuations, the dataset should allow for an assessment of time-variable factors. Such factors in Christchurch include seasonal high and low groundwater elevations as well as changes in ground surface elevations over time in response to subsidence and tectonic movements generated by successive earthquakes.

The regional evaluation of liquefaction effects across Christchurch is all the more demanding because of the challenges in combining observations of liquefaction-induced damage with comprehensive data collection, site characterization, and ground motion estimates. When the geographically distributed damage of scores of thousands of residential properties is evaluated, the geotechnical and seismic complexity and variability that applies to a single site is multiplied and spread spatially by the number of properties under consideration. In Christchurch there is an added complexity of multiple, successive earthquakes, the effects of which also require characterization and judgement in the evaluation of potential liquefaction-induced damage.

3. REVIEW AND COMMENT ON INFORMATION USED FOR ILV ASSESSMENT

3.1. Information Available for Assessing ILV

EQC has requested that the ILV Assessment Methodology consider all relevant factors and utilize the best available information. For this reason, the form of any ILV Assessment Methodology, as discussed later in the Section 4, necessarily depends on the nature of the information available for assessing both liquefaction vulnerability and changes to liquefaction vulnerability.

The body of information available for assessing ILV in the Christchurch area due to the CES is unsurpassed for its quantity, quality, and open accessibility. The documented data include: strong ground motion recordings; thousands of borehole and cone penetration test (CPT) soundings; multiple, high resolution LiDAR surveys; aerial photography; detailed field reconnaissance records after the major events in the CES; ground surveying records; and large numbers of well-documented case studies on the performance of buried pipelines, bridges, commercial buildings, and residential homes. The body of data provides an excellent basis for evaluating liquefaction and its effects on land and engineered structures.

Most of this information is in the publically available Canterbury Geotechnical Database (CGD). The only information that is not publically available is the EQC Land Damage Assessment Reports prepared following the inspection of each property.

Inevitably, assumptions are required to perform the ILV assessment. There are always limitations in the quantity and quality of the available subsurface information, and there are limitations in our understanding of liquefaction and the procedures for evaluating its effects. The reasonableness of the assumptions required in the ILV assessment are an important consideration in the evaluation of its results.

This section provides commentary on the information and assumptions used for assessing ILV. The commentary on available information is organized in the following subsections addressing: (1) observed performance of residential land and buildings in the CES, (2) LiDAR and subsidence data, (3) Canterbury Geotechnical Database, and (4) site specific information. The last subsection provides commentary on the key assumptions used in the ILV Assessment Methodology developed by T+T for EQC.

3.2. Observed Performance of Residential Land and Buildings in the CES

The observed performance of residential land and buildings in the CES at relevant levels of earthquake shaking is the most important information available, because this information addresses directly the primary issue of whether land is vulnerable to liquefaction and, whether as a consequence of previous liquefaction-induced ground subsidence, land is more vulnerable to liquefaction in the future. Additionally, these observations provide for regional and site-specific validation of the engineering procedures employed to evaluate liquefaction triggering and its consequences, which are key components of the ILV Assessment Methodology. Observations of land heavily damaged after earthquake shaking at the adopted reference level provide the most compelling evidence in support of an ILV land damage claim. Therefore, the ILV Assessment Methodology should assign the greatest weight to relevant land performance observations where possible. The ILV Assessment Methodology includes checks and systematic assessments of observed land damage in areas susceptible to liquefaction, and thus provides an approach that is reasonably grounded in land performance observations.

The observed land performance information is a product of the integration of post-event aerial photography, rapid inspections of liquefaction occurrence and effects, liquefaction-induced ground cracking maps, and the Land Damage Assessment Reports. This information is used to develop general land damage categories for regional and local assessment of liquefaction-induced land damage. Land damage observation categories are defined clearly in Appendix B of the ILV Report. Dwelling foundation damage observations are highly correlated to the liquefaction-induced land damage observations across Christchurch (e.g., van Ballegooy et al. 2014). Thus, a consistent picture is provided, which gives one confidence in the information.

The building damage ratio (BDR) is the cost to repair earthquake related damage divided by the greater of the replacement value or valuation of a specific residential building. High values of BDR (greater than 0.5) were shown to correlate well with moderate to severe land damage. This correlation supports the relationship between liquefaction land damage severity and building performance, which again provides a consistent picture of residential property behavior in response to mapped liquefaction severity.

The land damage observations are most useful in the ILV assessment process when the shaking level in the area being evaluated is at or near the adopted reference level of ground shaking for an event. Bradley and Hughes (2012) developed models for estimating the ground motions produced throughout the region by the CES major events. Their peak ground acceleration (PGA) models for the Darfield 2010, Christchurch 2011, June 2011, and December 2011 earthquakes were employed. The models provide a median estimate of PGA and the standard deviation of the dispersion. The Bradley and Hughes (2012) models represent the best available scientific information on this issue, so it is appropriate to use them in the ILV assessment of land damage.

It is pointed out in the ILV report that *"during the September (Darfield) 2010 earthquake most of urban Christchurch experienced approximately 100 year return period levels of earthquake shaking,"* which corresponds to the level of shaking adopted in the ILV assessment. Hence, one may argue that field observations showing moderate-to-severe land damage in this event (excluding the southwestern suburbs of Halswell, Hornby, and Oaklands) could be used as direct evidence that such land satisfies the ILV Criterion 1. This approach would use land damage observations for the initial ILV classification, and then additional analyses and engineering evaluations would be employed either to confirm or reject the ILV status. Instead, the approach actually adopted uses the automated ILV assessment based on the CPT data and LSN as the first screening tool, and then employs land damage observations, geotechnical evaluation and engineering judgement to scrutinize the automated ILV output and the agreement (or lack of it) between the 'computed' and 'observed' ILV. The Expert Panel believes that the approach adopted in the ILV Assessment Methodology would produce outcomes consistent with the alternative approach described above in which damage observations are first used as a yardstick in the ILV assessment, provided that an appropriate engineering evaluation and identical guidance supporting engineering judgement have been employed in both processes.

The observations of liquefaction occurrence and its effects on land and structures also enable a Christchurch region-specific evaluation and calibration of state-of-the-art liquefaction triggering procedures and consequence models. All procedures have their inherent biases and dispersion. The land damage observation information is critically important for one to gain confidence in the reliability of the methods employed in the ILV assessment process. The studies by van Ballegooy et al. (2014), van Ballegooy et al. (2015), as well as other studies by T+T used the land damage observation data to evaluate and to calibrate the proposed LSN parameter and the Boulanger and Idriss (2014, 2015) CPT-based liquefaction triggering procedures. This was a useful exercise and gives one confidence in the application of these tools in Christchurch.

3.3. LiDAR and Subsidence Data

The pre- and post-event airborne LiDAR data provides immensely useful, quantitative data to estimate the elevation of the ground surface following each major earthquake event. LiDAR surveys of the earth are revolutionizing geodesy, geology, and geotechnical engineering, among other fields. The quality and quantity of airborne LiDAR data are unparalleled. The local and national New Zealand government organizations that commissioned the LiDAR surveys should be commended for collecting data that are an integral element of the ILV Assessment Methodology. The LiDAR data give one increased confidence that an equitable ILV assessment decision can be made.

The processed “bare earth” LiDAR survey data, however, have limitations in resolution and accuracy that must be considered when using it. The LiDAR data was evaluated and found to provide generally an accuracy of ground surface elevation of ±0.1 m in a majority of the area where the ILV assessments were performed. Nearly all of the affected area had a ground surface elevation accuracy of ±0.2 m. The older pre-Darfield event LiDAR survey was the least accurate. This level of accuracy is sufficient for evaluating the amount of subsidence at residential properties consistent with the ILV Assessment Methodology.

The difference between pre- and post-event LiDAR survey ground surface elevation data produced ground subsidence data that are a primary component in the ILV Assessment Methodology. The total amount that the ground subsided during the CES relates directly to whether the land's performance during future earthquakes has been materially affected. The reliability of the ground subsidence data were increased by using the total ground surface subsidence over the entire CES, as opposed to over each event. This approach is reasonable.

3.4. Canterbury Geotechnical Database

CERA maintains the Canterbury Geotechnical Database (CGD) which provides public access to extensive subsurface geotechnical and groundwater data along with most of the other data available for assessing ILV. The CGD includes comprehensive records of liquefaction damage observations from the CES and the LiDAR and subsidence data discussed in the preceding subsections. The CGD also incorporates maps of strong ground motions from the CES, topography, surface geology, aerial photos, and other supporting data. The CGD can be accessed at: https://canterburygeotechnicaldatabase.projectorbit.com.

The geotechnical and groundwater data in the CGD provides broad coverage of the affected regions. At the time of the T+T ILV assessment study, the CGD included in-situ test data from more than 15,000 CPTs and 3,000 borings, and groundwater monitoring from a network of 1,000 shallow piezometers. The groundwater level data combined with the subsidence data provide the basis for evaluating potential reductions in the thickness of the non-liquefied ground above the groundwater table.

The CGD is unique and extremely valuable for conducting the ILV assessment. The development of the CGD was visionary and should be commended. The CGD provides the data in sufficient detail and accuracy to support the ILV assessment process.

3.5. Site Specific Information

Additional site specific information may be collected and considered for complex and marginal cases or when automated and manual assessment procedures produce inconsistent results. Site specific information can include visual inspection of the site and surrounding areas, local topography, local geologic features, photographs, additional CPTs or soil exploratory borings, additional documentation of ground and building damage, and known limitations in any of the regional data utilized in the ILV assessments (e.g., post-earthquake reconnaissance data, LiDAR data, in-situ test data). In some cases, owners may provide information that was not publically available at the time of the Stage 1 assessment. Site specific data are of great value in enabling the more detailed Stage 2 assessments to be performed to resolve complex and marginal cases with confidence.

3.6. Key Assumptions

The ILV Assessment Methodology needs to be based on several key assumptions due to the limitations in the available data and the simplified liquefaction evaluation procedures. The reasonableness of these assumptions is an important consideration in the evaluation of the results of the ILV assessment. The assumptions that underpin the ILV assessment are grouped according to earthquake seismicity, return period levels of seismicity, anthropogenic and climate change influence on groundwater levels, soil property characterization, potential changes in soil behavior, impact of lateral spreading, impact from other forms of land damage, and evaluation of long access ways. Each of these factors is discussed under the subheadings that follow.

3.6.1. Earthquake Seismicity

EQC requested T+T to assess ILV on the basis of the post-CES level of seismicity. The ILV Assessment Methodology uses a consistent level of seismicity before and after the CES. Thus, the assessment combines the current, post-CES level of liquefaction vulnerability with the current seismic hazard parameters provided in the MBIE (2012) guidelines. The Expert Panel agrees with this approach. It provides a consistent basis for assessing liquefaction vulnerability in conjunction with the current recommended hazard parameters. Relative to pre-CES seismicity, the adoption of higher post-CES seismicity results in a greater number of properties qualifying for ILV.

It can be argued that the post-CES increase in regional seismicity has increased the material vulnerability to liquefaction for residential land that otherwise would not have been vulnerable for pre-CES seismicity. However, as noted by T+T, that in accordance with the EQC Act 1993, EQC is only required to compensate for losses arising from a physical change to the structure or materials of the residential land. The Expert Panel agrees with the decision that an increase in vulnerability due to a change in seismicity does not result from a physical change in the land. Thus, such change does not qualify as a basis for compensation.

3.6.2. Return Period Levels of Seismicity

The ILV assessment is performed for return periods up to and including 100 years for an earthquake with $M_W = 6.0$ and PGA = 0.3 g (i.e., M6/0.3g earthquake shaking level). The 100-year return interval is justified as being consistent with existing New Zealand legislation for natural hazards, in particular Section 106 of the Resource Management Act (1991) and Section 71 of the Building Act (2004) that both specify a 100-year return period for other natural hazards.

The New Zealand Building Code is based on the expected performance of buildings at 25-year and 500-year return period earthquake ground motions. Thus, a 25-year or a 500-year return period might also be considered as a basis for ILV assessment. The performance expectation at the 25-year return period level is that building damage should be minor (i.e., non-structural damage only). The CES experience showed that most of the TC1, TC2, and TC3 land meets this 25-year performance expectation. The CES experience also shows that the performance expectation of life safety in residential houses at earthquake shaking equivalent to a 500-year return period was not compromised due to soil liquefaction. Thus, there is no intrinsic reason to select a 500-year return interval on the basis of the life safety performance of residential housing. Materiality with respect to residential land vulnerability is neither unique nor substantiated by life safety performance under these conditions. In contrast, the 100-year return period is consistent with the return period already used for natural hazards in NZ legislation and thus a logical extension of the reference time that is already part of New Zealand law. Thus, the Expert Panel concurs with the use of up to a 100-year return period for earthquake ground motion on the basis of precedence in New Zealand law for natural hazards. It is also consistent with flood risk characterization in other countries, like the U.S.

The reference 100-year return period ground shaking level (or less) of PGA = 0.3 g for a M6 event was adopted based on an interpolation of the MBIE (2012) ground motion values and consideration of the liquefaction triggering magnitude scaling factors developed by Idriss and Boulanger (2008). The adopted reference 100-year return period M6/0.3 g earthquake shaking level is consistent with current MBIE guidelines. However, a more recent and scientifically defensible probabilistic seismic hazard assessment (PSHA) by Bradley (2014) indicates that the 100-year return period level of earthquake ground shaking is overestimated by the current MBIE values. Considering the Bradley (2014) study, the Expert Panel believes that the adopted reference M6/0.3 g earthquake shaking level is high for the 100-year return period. Use of a lower PGA level at this return period would reduce the number of ILV claims. Thus, the policy decision by EQC to base the level of future earthquake shaking on the MBIE (2012) guidelines is favorable to qualification.

3.6.3. Anthropogenic and Climate Change Influence on Groundwater Levels

EQC requested T+T to not include the potential anthropogenic and climate influences on groundwater levels is reasonable and appropriately justified. Physical change to the structure or materials of the residential land as a result of the CES is not affected by such changes in groundwater level. Accordingly, they do not qualify as a basis for compensation as the result of earthquake effects. Furthermore, incorporating groundwater changes due to potential anthropogenic and climate influences is problematic, because such changes can occur in many different ways, some of which can increase as well as decrease material vulnerability to liquefaction. As such, there is no sound or established basis for selecting scenarios that represent accurately future anthropogenic and climate influences on groundwater levels over a large region like Christchurch.

3.6.4. Potential Changes in Soil Behavior

In the opinion of the Expert Panel, any change in soil behavior as a result of time effects (over relatively short period of time relevant for the ILV study) is likely to be inconsequential, given its effect relative to other important factors. As discussed in Section 2.1, the multiple occurrences of liquefaction throughout the CES would have highly variable and competing effects on liquefaction resistance in future earthquakes. It is not possible *a priori* to predict where and how significant changes in soil conditions affecting its behavior would occur in the diverse geological environment of Christchurch. Moreover, there is no evidence to support changes in soil behavior over time. To the contrary, there is compelling evidence provided in the report that indicates that there is no significant change in resistance to liquefaction where soil exploration data are available at nearly the same locations at different times (i.e., before and after major earthquake events). Data from closely spaced CPT soundings are provided in the report that show no bias in the measured tip resistance over time. The use of post-CES CPTs is thus reasonable and consistent with how a large majority of the CPT data were obtained (i.e., after major earthquakes) in the empirically-based Boulanger and Idriss (2014, 2015) CPT-based liquefaction triggering procedure.

3.6.5. Impact from Lateral Spreading

The assumption that the potential for lateral spreading in future earthquakes has not increased as a result of physical changes to the land caused by the CES is reasonable and appropriately justified by the empirical observations of lateral spreading displacements in successive events of the CES. To make this case, two types of evidence for lateral spreading displacements caused by the CES can be used: local measurements at particular locations using ground surveys, and global measurements based on aerial surveys, such as LiDAR and aerial photography. Lateral spreading displacements measured by ground surveys after the September 2010 and February 2011 earthquakes indicate that the magnitude of ground displacements at specific locations was often greater in the February 2011 event than in the September 2010 event (Cubrinovski et al. 2011). However, the seismic demand was also greater in the February 2011 event. When considered relative to seismic demand, the lateral spreading displacements caused by the February 2011 earthquake were either smaller or similar to those measured by ground surveys after the September 2010 earthquake. Hence, the evidence from repeated measurements at the same locations indicates no apparent increase in the potential for lateral spreading displacements (or vulnerability) in areas that were affected by previous CES events. LiDAR data generally support these findings and show on a global scale that the average lateral spreading displacements relative to seismic demand did not increase during the CES.

The observed reductions or similarities in lateral spreading displacements relative to seismic demand with each successive CES event may be partly explained by the fact that a common manifestation of lateral spreading is a reduction in the average ground surface slope and free-face height due to settlement on the landward side and heaving in the area just beyond the free-face. This reduction in the average ground surface slope and free-face height can be expected to reduce the potential for lateral spreading displacements in future earthquakes. The potential for lateral spreading in future earthquakes may also be affected by potential changes in soil behaviors (as discussed in the previous section) or the impacts of associated forms of land damage (e.g., cracking and ejecta vents in the crust layer, as discussed in the following section). The relative influence of these different factors is difficult to quantify, but the empirical observations of lateral spreading displacements during the CES suggest that the net effect was not a progressive increase in lateral spreading potential with each successive earthquake event.

Any component of lateral spreading would likely be associated with some amount of ground surface subsidence that would affect computed LSN and ΔLSN values. The specific causes of ground surface subsidence cannot be neatly separated and compartmentalized in many cases, as they may include contributions from lateral spreading, dynamic ground lurch, post-liquefaction settlement, soil ejecta induced settlement, or shear distortion under building loads. Nevertheless, the empirical calibration of the LSN and ΔLSN indicator values against performance observations provides a reasonable allowance for the various factors that may affect ground surface subsidence, including possible contributions from lateral spreading.

In summary, there are fundamental reasons associated with the mechanics of ground deformation that support a reduced potential for lateral spreading in future earthquakes. A key effect of lateral spreading on ground conditions is the reduction of the free-face height, which in turn promotes a reduction of the lateral spreading potential. Current models that account for the mechanics of ground deformation show clearly that the magnitude of lateral movement will decrease as the vertical elevation difference across the area of spreading is reduced. Both ground survey data from successive CES earthquakes and the statistical trends in global LiDAR measurements show that lateral spreading displacements, when considered relative to seismic demand, did not increase during the CES.

3.6.6. Impact from Other Forms of Land Damage

The report points out that crust disturbance, such as cracking, could provide pathways for venting ejecta in a future earthquake, thereby causing volume loss in the soil underlying residential structures, and increasing their vulnerability to damage. The report also points out that crack repair methods are described in the Guide to the Settlement of Canterbury Flat Land Claims (EQC 2013) and that observable damage is compensated separately by EQC by paying the cost of repairing cracks in accordance with these recommended procedures.

Repair of cracks in accordance with recommended procedures is expected to re-establish crust integrity. It is understood that cracks in the crust are sometimes discovered during excavation for the foundation of a new building, in which case the owner can make a separate claim to EQC for additional compensation to repair the cracks. The Expert Panel notes there is no way to substantiate or to quantify the extent of cracking that is likely to be missed and that geotechnical remediation frequently relies on good workmanship that follows recommended practice.

Crack repair has the distinct advantage of being tailored to block pathways for ejecta that are specific for each site. Given that recommended crack repair procedures are readily available, are compensated by EQC, and are flexible and adaptable for site-specific conditions, the practical means are at hand for the restoration of a disturbed crust to conditions consistent with its pre-earthquake seismic performance. The Expert Panel regards such repairs performed by a competent contractor according to recommended procedures as a reasonable basis for reinstating pre-CES crust integrity.

3.6.7. Consideration of Long Access Ways

The ILV assessment areas for residential properties did not include long access ways. The assessment of long access ways is still under consideration and is not covered by this report.

4. REVIEW AND COMMENT ON THE ILV ASSESSMENT METHODOLOGY

4.1. Methodology for ILV Assessment

An ILV Assessment Methodology needed to be developed to provide a basis for the settlement of ILV land damage claims in a manner consistent with EQC's obligations under the EQC Act and through the utilization of the best available engineering procedures and data. The ILV Assessment Methodology needed to be structured such that it could be applied in good faith, incorporate sound engineering judgement, and consider all relevant factors. It needed to evaluate the change in liquefaction vulnerability across the entire CES and consider the uncertainties inherent to the data and evaluation procedures. Accordingly, the ILV Assessment Methodology needed to lead to an equitable determination of whether or not a property materially satisfies the criteria for ILV land damage with the stated intent of not rejecting claims that are on the balance of probabilities well founded. Key property considerations embodied in the engineering criteria of the ILV Assessment Methodology ILV are presented in Figure 2.

The ILV methodology developed by T+T for EQC was implemented within a four-phase process, as depicted in Figure 3. Phase 1 defined the geographic extent of properties under consideration for ILV. Phase 2 evaluated the sufficiency of the information available for assessing ILV and gathered additional information wherever it was required for providing a sufficient basis to assess ILV. Phase 3 assessed each property for ILV. Phase 4 reached a decision regarding ILV for each property.

The Phase 3 assessment of ILV for each property involved two stages of assessment, as also shown in Figure 3. The Stage 1 assessment was applied to all properties to determine if the geotechnical information and liquefaction vulnerability assessments reconciled with the land damage observations relative to the levels of estimated shaking for the main CES events. If the decisions regarding ILV were considered straightforward, the property moved to a decision under Phase 4. If the decision regarding ILV was considered not to be straightforward, the property moved to a more rigorous and detailed Stage 2 assessment. The Stage 2 assessment was therefore only applied to properties classified as either complex or marginal (i.e., in a transition zone between 'yes' and 'no' cases). It incorporated more detailed specific analyses in seeking to answer the same question. This two-stage process is a reasonable approach for the efficient resolution of ILV claims for the large number of residential properties that need assessment (i.e., nearly 140,000 properties).

The Stage 1 and Stage 2 assessments of ILV in Phase 3 both included use of an automated ILV model followed by a manual ILV assessment. The automated ILV model involved the mapping of LSN values and the change in LSN values caused by the CES (i.e., ΔLSN) based on the CPT, groundwater elevation, and ground surface subsidence data in the CGD. The manual ILV assessment involved the examination of local data packs covering neighboring properties.

The manual ILV assessment in Stage 1 sought to identify geologic features, spatial trends in the LSN values, spatial trends in land damage patterns from the CES, and known limitations in the data underpinning the automated model. A key consideration was whether the mapped LSN and ΔLSN values were consistent with the land damage observations relative to the levels of shaking for the main CES events.

The manual ILV assessment in Stage 2 involved the additional steps of further assessing local geologic and topographic features, visiting the site in some instances, examining laboratory and borehole data, updating the liquefaction vulnerability analyses, performing sensitivity analyses focused on understanding and reconciling computed LSN values with damage observations, and systematically examining several other factors that could influence judgements. The ILV Report includes detailed descriptions of how a large number of different scenarios are to be handled, including variations in the quality of information available and potential inconsistencies between different sources of information.

The Phase 4 decisions regarding ILV for each property were made by the project director and senior technical review team based on their technical and administrative review of the Phase 3 assessments. An appeal process was established for property owners who disagreed with the ILV decisions.

The Expert Panel finds that the ILV Assessment Methodology meets the general objectives specified by EQC. It uses well-founded and current engineering procedures with the best available data and information. The data and information used are available to property owners. The methodology considers all reasonably relevant factors, allows for incorporation of engineering judgement through manual assessments and peer review processes, and is applied in good faith with avenues for challenges and consideration of new information. The overall methodology provides for a relatively efficient processing of claims while also providing a reasonable basis upon which to derive equitable decisions.

The Expert Panel believes the ILV Assessment Methodology has the flexibility to account reasonably for local variations in ground conditions and observed ground performance during the CES. This flexibility is built into the manual steps of the Stage 1 and Stage 2 assessments of ILV, and are supplemented by the opportunity for additional information to be considered as part of a challenge by a property owner. This allows for site-specific calibration of the analysis methods, which as discussed earlier, is appropriate given the known limitations in the application of these methods.

Alternative forms for the ILV Assessment Methodology may have utilized the available information in different ways, but any reasonable methodology would be expected to have the ability to reconcile the ILV assessments with land damage observations from the CES at both the local and regional scale. For this reason, it is likely that alternative methodologies could be calibrated to produce, on average, reasonably consistent decisions for large majority of properties. Decisions for properties having ILV assessments near the boundaries of the applicable criteria would undoubtedly be more affected by the differences between alternative ILV assessment methodologies. The sensitivity of decisions for such cases is unavoidable given: (1) uncertainty in the engineering evaluations of liquefaction vulnerability and increases in liquefaction vulnerability, (2) reasonable differences of opinion are possible as to what would be considered a material increase in vulnerability, and (3) reasonable differences of opinion are possible as to when damage would be considered established on the balance of probabilities, at least in marginal cases.

The following subsections provide additional commentary regarding the roles of four key components of the ILV Assessment Methodology developed by T+T: (1) the site specific performance observations, (2) LSN and its reconciliation with land damage observations, (3) LSN criteria for ILV assessment, and (4) engineering judgement and the two-stage assessment process.

4.2. Site Specific Performance Observations

In view of the complexities of liquefaction phenomena, pronounced variations in soil characteristics over short vertical and horizontal distances in the Christchurch area, and limitations in currently available engineering evaluation procedures, observations of site performance in the CES are the most important and convincing information for an ILV assessment. Properties that have been shaken at the reference ground motion level with no visible land damage (that is significant from an engineering perspective) or significant subsidence could not satisfy the ILV criteria for material vulnerability or increased vulnerability to liquefaction damage after the CES (Criteria 1 and 2, respectively). Conversely, residential land that was badly damaged and exhibited significant subsidence would indicate that the vulnerability to liquefaction damage might have changed due to the CES.

As many residential properties in Christchurch were shaken two or three times at levels of ground shaking relevant for the ILV assessment, such observations provide direct observational evidence supporting or denying a claim for increased liquefaction vulnerability through comparisons of the performance of a property in an earthquake relative to its performance in a previous significant CES event. In such comparative evaluations it is important to account for the difference in the seismic demand (levels of ground shaking) produced by different earthquakes, which has been undertaken in the manual ILV assessment. Given the different location of the earthquake sources and differing source-to-site distances for the CES events, each suburb or area in Christchurch has experienced a unique sequence of earthquake shaking levels. Although field observations may be variable, the observed performance of residential land and buildings during the CES is nonetheless the most important information that was used in the ILV classification, and was also essential for calibration of the analytical models and LSN-criteria described below.

4.3. LSN and its Calibration to Observations

The ILV assessment process requires a liquefaction vulnerability parameter to help evaluate cases when relevant field observations are not available. Such an indicator should also provide an independent measure of land performance, both in absolute and relative terms, which can be applied systematically throughout Christchurch over a wide range of relevant earthquake shaking levels. The parameter should capture the governing liquefaction-induced ground failure mechanisms and track the principal trends in the observed land damage following major CES events. Moreover, it should be able to be calibrated with the CES land damage data to capture the observed land performance, so it can be used with confidence in cases when direct field evidence at the adopted reference level of shaking level does not exist.

Several liquefaction vulnerability parameters were considered by T+T, including thickness of the nonliquefiable crust (H_1), 1D post-liquefaction reconsolidation settlement (S_{V1D}), liquefaction potential index (LPI), modified liquefaction potential index (LPI_{ISH}), and liquefaction severity number (LSN). Of these parameters, LSN was able to best capture the governing mechanisms, shown to provide the most consistent correlation with the observed liquefaction-induced ground damage, and once calibrated, captured best the observational land damage performance data over the primary CES events on a regional scale (i.e., T+T 2013, van Ballegooy et al. 2014, and van Ballegooy et al. 2015). LPI, an older liquefaction vulnerability parameter, does not consider all of the key factors that LSN considers and did not correlate as well with the trends in the observed data. Thus, LSN was adopted as a tool in the ILV assessment process.

Recognizing the limitations of any liquefaction vulnerability parameter, T+T performed an exhaustive study of several parameters before concluding that LSN worked best. Moreover, T+T then performed a comprehensive calibration process of the LSN to the land damage observations at a macro-scale across Christchurch. The calculated values of LSN correlated well to areas of observed land damage (T+T 2013). There is strong support for the use of LSN in the ILV assessment process.

Although LSN is judged to be the preferred liquefaction vulnerability parameter for use in the ILV assessment methodology, it has limitations. For example, LSN is very sensitive to groundwater depth when the groundwater is shallow (e.g., less than about 1 m below the ground surface), subject to the inherent vulnerability of subsurface conditions, and affected by uncertainties with regard to the liquefaction resistance of certain mixtures of sands and silts of varying plasticity. Thus, LSN should be viewed as a necessary tool to assist in the ILV assessment process, and not as the primary means for categorizing properties.

The Expert Panel agrees that LSN provides a sound and consistent scientific basis for assisting in the ILV assessment. It considers relevant key factors and can be applied in a fair and consistent manner. LSN incorporates the well-established empirically based simplified liquefaction triggering calculation (i.e., Factor of Safety against liquefaction triggering, FS) and the widely accepted Ishihara & Yoshimine (1992) post-liquefaction volumetric strain relationships as implemented in the CPT-based procedure by Zhang et al. (2002) for estimating liquefaction-induced ground settlements. As such, LSN captures the primary role that soil relative density plays in terms of the resulting ground damage. Loose sand deposits that liquefy have the propensity to cause more damage than medium dense sand deposits that liquefy. Also, once ground shaking is sufficient to cause extensive liquefaction in a deposit, an increased level of shaking does not produce a corresponding (proportional) increase in damage. With LSN the calculated strain value is used as a damage index that includes the effects of strength loss and the potential for soil ejecta rather than as an index purely for settlement calculation. Importantly for the CES events, LSN places greater importance on the thickness of the non-liquefied crust (Ishihara, 1985) when the groundwater table is close to the ground surface. Thus, LSN is better able to discriminate between cases when the crust is thin and significant ejecta results, and when the crust is thicker and substantially less ejecta occurs.

The LSN calculation requires the specification of several input parameters (some of which are summarized in Table A3.1 of the ILV Report). Default values for these input parameters have been selected which tend to provide a conservative assessment of liquefaction triggering (e.g., a lower bound relationship for estimating the soil's fines content, the I_c cutoff of 2.6, a probability of triggering of 15%, and full saturation of soil below the groundwater surface). Most of these assumptions are consistent with standard practice. Coupled with the conservatively adopted reference M6/0.3 g earthquake level of shaking, these assumptions result in a conservative calculation of liquefaction triggering. This in turn results in higher LSN values being calculated. These higher LSN values are then correlated with the observed land performance and used in the selection of the LSN and ΔLSN indicator values. Thus, conservatisms in the default input parameters are not expected to substantially affect the outcomes of the ILV assessments on average, because they conceptually have comparable effects on both the computed LSN values and the selected LSN and ΔLSN indicator values.

EQC has requested that the ILV assessment should not produce ‘wrong answers’ in the sense that it leads to rejection of claims which are well-founded. Given the intention of EQC to minimize the rejection of well-founded claims under highly variable subsurface conditions and uncertainties regarding soil properties, the Expert Panel finds that the assumptions underpinning liquefaction triggering are not excessively conservative and on balance of the probabilities provide a reasonable and justifiable basis for LSN calculations.

4.4. LSN Criteria for ILV Assessment

A primary objective in establishing the indicator values for LSN and ∆LSN which demonstrate material liquefaction vulnerability and a material change in vulnerability is that these values should be considered to be reasonable and developed through a process that is transparent and defensible. The ILV Report summarizes the process employed by T+T and the reasoning and observational data that support the selected indicator values of LSN = 16 and ∆LSN = 5. A LSN value of 16 is about at the midpoint of the transition of land that is materially vulnerable to liquefaction and land that is not based on observations of land damage and building performance in the major CES events. A value of ∆LSN of 5 is about the minimum LSN difference that can be considered meaningful given the uncertainty of the input parameters and the requirement that the resulting change in land vulnerability be material. The Expert Panel finds the process of selecting the indicator values of LSN and ∆LSN to be transparent and defensible, with the acknowledgment that the characterization of the earthquake shaking and ground conditions used to calculate LSN are likely to favor qualification. With that acknowledgment, the adopted indicator values of LSN = 16 and ∆LSN = 5 are thus judged to provide a consistent, scientifically defensible basis for evaluating ILV land damage claims with the goal of not rejecting legitimate claims.

It is important to remember that LSN is only an indicator of the likelihood of particular levels of liquefaction related damage occurring in a future earthquake. Liquefaction analysis cannot provide a precise prediction of the exact level of land damage that will occur. Hence, the application of engineering judgement is required when considering estimated LSN values against an indicator value of LSN, for example, as part of a liquefaction vulnerability assessment. The Expert Panel has always emphasized the importance of utilizing field observations of liquefaction-induced ground damage and exercising engineering judgement in the application of the LSN and ∆LSN parameters. We believe that T+T has performed the ILV assessment in a careful, deliberate, and fair-minded manner. When there are significant uncertainties, T+T employs generally conservative assumptions that are favorable to qualification. Thus, we find no issue with them using the adopted LSN and ∆LSN values in the manner described in the report.

4.5. Engineering Judgement and the Two-Stage Assessment Process

The Expert Panel believes a key component of the ILV Assessment Methodology is the manual review by experienced engineering staff. The LSN and ∆LSN criteria serve as proxies to assess whether a property is likely or unlikely to be assessed as having ILV land damage, after which the manual review is intended to catch false-positive or false-negative assessments.

In the Stage 1 assessment, the likely ILV status was first evaluated using the automated ILV model (LSN methodology). In these analyses, key model parameters have been varied within the relevant range of values to evaluate effects of uncertainties on the computed LSN value. For example, uncertainties associated with the depth to groundwater table, I_c cutoff value of 2.6, I_c-FC relationship, and effects of the adopted probability of liquefaction in the triggering assessment have been scrutinized using the automated ILV model and sensitivity analyses. The subsequent manual step of the Stage 1 Assessment involved geotechnical engineering evaluation of borehole logs, then classification, grouping and scrutiny of CPT data based on geological features and spatial land damage distributions, and also consideration of complex issues such as identification and interpolation across geological boundaries, variable ground conditions, and other issues arising from the limitations of the LSN methodology. This manual assessment relied on engineering judgement in the assessment of all available relevant information to determine the ILV status of each property. In cases when the automated ILV outcome (LSN value) reconciled with the ILV status based on the engineering evaluation (judgement) in the manual assessment, a straightforward decision was made and the ILV status of the property was determined. In the remaining cases where such consistent outcomes were not obtained, the property was designated as needing a Stage 2 assessment.

In the Stage 2 assessment, the manual step involved further in-depth scrutiny considering geological and topographic issues, geospatial patterns of ILV in the neighborhood of the property, site performance, analyses, and other factors to guide engineers towards an informed decision based on engineering judgement. The T+T report provides worked example packages illustrating the details of this assessment process for several characteristic scenarios requiring Stage 2 assessment (e.g., marginal, complex, and insufficient LiDAR data cases). Importantly, very few decisions made in Stage 1 were reversed during the Stage 2 assessment. Thus, Stage 2 assessments are consistent with Stage 1 assessments, and both are judged to be robust.

The ILV assessment methodology by T+T is comprehensive and addresses a large number of details and factors that could potentially influence the ILV status of land. Despite this complexity, there are three key elements to the ILV assessment: (1) observations of physical land damage in the CES; (2) computed ILV status of land using the LSN methodology, and (3) engineering evaluation followed by decision-making based on engineering judgement. The latter element is key to synthesizing information from the damage observations, automated ILV model calculations and any other relevant information for the ILV assessment. In this final step, the engineer can consider the observations and the analytical results with full recognition of their overall and local limitations in making a judgement. Greater weight should be given in this process to the land damage observations if there is no convincing reason or evidence to the contrary. The ILV assessment employed by T+T has all key elements mentioned above.

Engineering judgements are inherently open to reasonable differences of opinion, and hence are best exercised in groups using iterative steps, multiple checks, and quality control processes. The ILV Assessment Methodology employed by T+T involves three levels of scrutiny and engineering judgement by engineers, senior engineers, and project director. It is an open and transparent process that engages feedback, but also allows for an independent scrutiny of decisions based on engineering judgement. The Panel finds this process reasonable.

5. REVIEW AND COMMENT ON THE ILV ASSESSMENT RESULTS

5.1. Consistency with Regional Observations of Ground Performance

The output of the ILV assessment process identified two classes of properties: properties that qualify for ILV (which satisfy both Criteria 1 and 2), and properties that do not qualify for ILV (which do not satisfy either Criterion 1 or Criterion 2). T+T evaluated the consistency of the ILV Assessment results using summary maps and statistics in which properties that do not qualify for ILV were further subdivided into NV – not materially vulnerable to liquefaction (i.e.,. do not satisfy Criterion 1), and LV – vulnerable to liquefaction but with no material change in vulnerability due to CES (i.e., do not satisfy Criterion 2). The spatial distribution of ILV, LV, and NV properties was then compared with the spatial distribution of the observed land damage, liquefaction-induced land subsidence, building damage costs, and computed LSN and ΔLSN values. Generally, the areas qualifying for ILV coincide with areas in which moderate-to-severe liquefaction was observed, land subsidence exceeded 0.3 m, and computed LSN and ΔLSN values exceeded the indicator values of 16 and 5, respectively. T+T concluded that *the population of properties qualifying for ILV characteristically performed very differently compared to the population of properties which are not materially vulnerable to liquefaction (NV)*, and that *the ILV automated model at a regional level was generally doing a good job in differentiating between properties with and without ILV*. The Expert Panel agrees with this interpretation of the ILV assessment results.

Certain limitations in the ILV assessment results were also identified, and some of these are apparent anomalies in the presented summary plots and statistics. For example, properties that have *minor-to-moderate* worst observed land damage during CES or *total liquefaction-related ground subsidence of less than 100 mm* have qualified for ILV. A large number of properties along the Avon River that were seriously affected by lateral spreading have also qualified for ILV. Also, properties with total building damage cost of less than $10,000 qualified for ILV. Conversely, properties with *moderate-to-severe* worst observed land damage during the CES or *total liquefaction-related ground subsidence greater than 400 mm* have not qualified for ILV. These counterintuitive outcomes and apparent anomalies have been the subject of a detailed review by the T+T engineers to resolve the discrepancies. T+T identify in the report some issues that produced such anomalies in the summary maps and statistics, such as: erroneous record of land damage observations (e.g., none-to-minor due to removal of ejecta prior to field inspections), erroneous record of ground subsidence due to errors in the DEM differences, and incorrect input parameters in the LSN analyses. A few more challenging cases for explanation included properties affected by lateral spreading only, properties where the liquefaction damage was a result of high levels of earthquake shaking, or the composition of the crust being the principal reason for not satisfying the Criterion 2 required for the ILV qualification. All these discrepancies were subject to an independent case-by-case engineering evaluation and engineering judgement as to whether a given property satisfies the ILV criteria based on the balance of probabilities and all available information. Further examples regarding particular engineering evaluation decisions and judgement calls were provided by the six worked examples accompanying the ILV Report.

5.2. Worked Examples

Six worked examples were provided with the ILV Assessment Methodology Report to demonstrate in detail how the methodology is applied in the manual review of both Stage 1 and Stage 2 assessments under Phase 3 in Figure 3. A decision regarding ILV was able to be reached for the residential property in Worked Example 1 by using either Stage 1 or Stage 2 manual reviews. This is not always the case, because other properties require a more detailed Stage 2 manual review to resolve issues identified in the Stage 1 assessment. Given that a decision can be reached for the property in Worked Example 1 by either Stage 1 or Stage 2 manual reviews, it was chosen to show the consistency in the qualification process. In other words, it illustrates that both stages of manual review lead to the same answer when a property is amenable to both Stage 1 and Stage 2 qualification. Worked Examples 1 through 3 illustrate how qualification decisions are made for complex or marginal cases, and Worked Example 4 illustrates how a qualification decision is made where insufficient LiDAR data are available. Worked Example 5 illustrates the determination of ILV status for marginal cases and cases with variable prediction of land performance. Manual review at the Stage 2 assessment level was required for a decision in Worked Examples 2 through 5.

The Expert Panel reviewed the Worked Examples to confirm that, in accordance with the EQC direction, the ILV Assessment Methodology was applied in good faith; not applied mechanically; and did not exclude consideration of factors that are relevant to any particular case. The Worked Examples were then examined in detail to confirm that they followed the procedures described in the ILV Assessment Methodology Report and summarized schematically in Figure 3. In particular, each Worked Example was checked carefully to confirm that both Stage 1 and Stage 2 procedures were applied in an appropriate way. Finally, the decision taken for each property in the Worked Examples was evaluated according to the Expert Panel's own judgement. This final check was made so that, to the extent possible, the decision taken by following the ILV Assessment Methodology was verified by independent evaluation outside the proposed methodology.

For each Worked Example, the Expert Panel finds that ILV Assessment Methodology conforms to the EQC direction summarized above, follows faithfully and in detail the procedures described in the ILV

Assessment Methodology Report, and provides results that are reasonable and appropriate in terms of the Expert Panel's own judgement.

6. CONCLUSIONS

6.1. General Comments

The review of the Increased Liquefaction Vulnerability (ILV) Assessment Methodology by the independent Expert Panel was undertaken in three phases. The first phase involved evaluation of memos, reports, analytical results, and supporting documentation provided by Tonkin and Taylor (T+T) as the ILV methodology was developed and evolved in the period 2012 to 2014. In the second review phase, comments were given on draft sections of the ILV report with recommendations for improvement and further scrutiny of aspects of the ILV methodology. The third phase of the review was to perform an independent review of the final ILV report entitled "Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology," dated September 2015. Consistent with the Terms of Reference, in this report the Expert Panel summarizes their review comments and findings on the final ILV report.

The City of Christchurch and surrounding areas were affected by a large number of earthquakes in the 2010-2011 Canterbury Earthquake Sequence (CES). Liquefaction caused widespread damage to residential buildings and infrastructure during the CES. The extensive Christchurch liquefaction is attributable to the characteristics of the near-surface sediments, the shallow groundwater levels, and the intensity of strong ground motions. The damaging effects of liquefaction-induced ground deformations are attributable to the fact that most foundations and infrastructure were not designed to withstand the amount of ground deformations that occurred in many of the affected areas.

The Earthquake Commission Act of 1993 (EQC Act) provides statutory insurance for physical loss or damage to residential property caused by an earthquake. A residential site may be considered to have "Increased Liquefaction Vulnerability (ILV)" damage if its uses and amenities are adversely affected by being materially vulnerable to liquefaction *and* by being materially more prone to liquefaction damage in a future earthquake as a result of the CES.

The New Zealand Earthquake Commission (EQC) retained T+T through Chapman Tripp to develop an ILV Assessment Methodology that provides the basis for settlement of ILV land damage claims. The ILV Assessment Methodology was developed with the best available scientific and engineering understanding of liquefaction and best available information on subsurface conditions, subsidence, earthquake ground motions, and liquefaction effects throughout Christchurch to provide consistent treatment of the large number of residential properties affected by the CES.

6.2. Findings

The findings of the Expert Panel regarding the information used and ILV methodology presented in the subject report are summarized below.

6.2.1. Information Used for ILV Assessment

The information used in the ILV Assessment Methodology is unsurpassed for its quantity, quality, and open accessibility. The Canterbury Geotechnical Database (CGD), which is the primary source of information, is unique resource for accessing regional data on strong ground motion recordings from the CES; thousands of cone penetration test (CPT) soundings and soil boreholes; multiple, high resolution LiDAR surveys; aerial photography; detailed field reconnaissance records after the major CES events; and land surveying records. The ILV Assessment Methodology provides appropriate checks and allowances for known limitations in the various sources of data and information.

The observed land performance information in the CGD is extensive. It is derived from widespread, multiple independent sources, and is the product of the integration of post-event aerial photography, rapid inspections of liquefaction occurrence and effects, liquefaction-induced ground cracking maps, and the Land Damage Assessment Reports. This information has been scrutinized and verified. Observations of foundation damage in residential structures are highly correlated to the liquefaction-induced land damage observations throughout Christchurch. The quality and comprehensiveness of the data provide a strong evidential basis for ILV assessment.

The observed performance of residential land and buildings in the CES is the most important source of information, because it addresses directly whether land is vulnerable to liquefaction damage, and as a consequence of liquefaction-induced ground subsidence in the CES, more vulnerable to liquefaction damage in the future. Additionally, these observations provide for regional and site-specific validation of the engineering procedures to evaluate liquefaction triggering and its consequences.

The LiDAR data for ground surface elevation in the CGD were found to be accurate generally within ±0.1 m for the majority of areas where the ILV assessments were performed. Nearly all of the affected area had a ground surface elevation accuracy of ±0.2 m. This level of accuracy is sufficient for evaluating the amount of subsidence at residential properties consistent with the ILV Assessment Methodology.

The difference between pre- and post-event LiDAR survey ground surface elevation data produced ground subsidence data that are a primary component in the ILV Assessment Methodology. The total amount that the ground subsided during the CES relates directly to whether the land's performance during future earthquakes has been materially affected. The Expert Panel concurs with using the total ground surface subsidence over the entire CES (as opposed to over each event). This approach increases the reliability of the ground subsidence data, and thus is a reasonable and appropriate basis incorporating subsidence into the ILV Assessment Methodology.

The CGD is unique and extremely valuable for conducting the ILV assessment. It also incorporates maps of strong ground motions from the CES, topography, surface geology, aerial photos, thousands of CPTs and borehole data, and other supporting data. The geotechnical and groundwater data in the CGD provide broad coverage of the affected regions to a level of detail required for the ILV assessment. The groundwater level and subsidence data provide the basis for evaluating reductions in the thickness of the non-liquefied ground above the groundwater table. It would have been impossible to perform the ILV assessment at such level of detail and scrutiny without this database.

6.2.2. Assumptions Used for ILV Assessment

The assumptions that underpin the ILV assessment are grouped according to earthquake seismicity, return period levels of seismicity, anthropogenic and climate change influence on groundwater levels, potential changes in soil behavior, impact of lateral spreading, impact from other forms of land damage, and consideration of long access ways, with comments summarized below:

- The ILV assessment combines the current, post-CES level of liquefaction vulnerability with the current seismic hazard. The Expert Panel agrees with this approach. It provides a consistent basis for assessing liquefaction vulnerability in conjunction with the current hazard.
- The adopted 100-year return period is consistent with the return period already used for natural hazards in NZ legislation and thus is a logical extension of this reference time. It is also consistent with flood risk characterization in other countries, like the U.S., and advantageous as compared to the alternative 25-year and 500-year return periods levels of shaking. Thus, the Expert Panel concurs with the use of up to a 100-year return period for earthquake ground motion as a basis for the ILV assessment.

- The adopted reference 100-year return period M6/0.3 g earthquake shaking level is consistent with current MBIE guidelines. However, a more recent and scientifically defensible probabilistic seismic hazard assessment (PSHA) indicates that the 100-year return period level of earthquake ground shaking is overestimated by the current MBIE values. Thus, based on our current understanding of the hazard, the policy decision by EQC to base the level of future earthquake shaking on the MBIE (2012) guidelines is weighted in favor of qualification. Given the EQC direction that the process must not produce wrong answers in the rejection of claims, which are on the balance of probabilities well-founded, in combination with the uncertainties involved in defining a universally accepted seismic hazard, the Expert Panel regards the earthquake shaking level adopted in the ILV Assessment Methodology to be reasonable.
- The instruction by EQC to T+T to not include the potential anthropogenic and climate influences on groundwater levels is reasonable and appropriately justified.
- The use of post-CES CPTs for soil characterization is reasonable and consistent with how a large majority of the CPT data were obtained in the empirically-based liquefaction triggering procedure and with the evidence provided in the report that no significant change in CPT and hence liquefaction resistance was observed due to the effects of the CES.
- The assumption that the potential for lateral spreading in future earthquakes has not increased as a result of physical changes to the land caused by the CES is reasonable and appropriately justified by the observations of lateral spreading displacements in successive events of the CES.
- Observable damage from ground cracking induced by the CES is compensated separately by EQC by paying the cost of repairing cracks in accordance with readily available recommended procedures. Such repairs performed by a competent contractor according to those recommended procedures are a reasonable basis for reinstating pre-CES crust integrity, thus supporting the assumption that ground cracking, if present and repaired, is not a significant source of increased vulnerability.
- The ILV assessment areas for residential properties did not include long access ways. The assessment of long access ways is still under consideration.

6.2.3. ILV Assessment Methodology

The ILV Assessment Methodology was implemented with a four-phase process, with the ILV assessment Phase 3 involving two Stages. The Stage 1 assessment was applied to all properties and sought to determine if the geotechnical information and liquefaction vulnerability assessments from the automated model reconciled with the land damage observations relative to the levels of estimated shaking for the main CES events. If the decision regarding ILV was considered not to be straightforward, the property was moved to a more rigorous and detailed Stage 2 assessment. The Panel finds that this two-stage process is a reasonable approach for resolving ILV claims in an efficient manner, given the large number of properties that need assessment. Importantly, very few decisions made in Stage 1 were reversed during the Stage 2 assessment. Thus, Stage 2 assessments are consistent with Stage 1 assessments, and both are judged to be robust.

The Stage 1 and Stage 2 assessments of ILV both include the use of an automated ILV model followed by a manual ILV assessment. The automated ILV model involved the mapping of Liquefaction Severity Number (LSN) values and the change in LSN values caused by the CES (i.e., ΔLSN) based on the CPT, groundwater elevation, and ground surface subsidence data in the CGD. The comprehensive calibration of the automated model with respect to the CES data and observations validates its relevance and use in the ILV assessment. The manual ILV assessment, applied to a set of neighboring properties, identified geologic features, spatial trends in the LSN values, spatial trends in land damage patterns from the CES, and known limitations in the data underpinning the automated model. The manual ILV assessment in Stage 2 was expanded to include additional steps for assessing local geologic and topographic features, visiting the site in some instances, examining laboratory and borehole data, updating the liquefaction vulnerability analyses, performing sensitivity analyses focused on understanding and reconciling computed LSN values with damage observations, and systematically examining several other factors which could influence judgements. A key consideration in either stage was whether the mapped LSN and ΔLSN values were consistent with the land damage observations relative to the levels of estimated shaking for the main CES events. The ILV Report includes detailed descriptions of how a large number of different scenarios are to be handled, including variations in the quality of information available and potential inconsistencies between different sources of information. The Expert Panel finds this overall approach is comprehensive with respect to systematic use of the available databases and sufficiently detailed to resolve ILV at the level of individual residential properties.

The LSN parameter was selected over alternative liquefaction vulnerability indices as a primary index in the ILV Assessment Methodology, because once calibrated, it was shown to provide the most consistent correlation with the observed land damage performance data over the primary CES events on a regional scale. The LSN parameter places greater weighting on liquefaction at shallow depths, which has been shown to improve its ability to track the effect of non-liquefied crust layer thickness on the performance of residential building foundations. The LSN parameter, like all simplified liquefaction vulnerability parameters, has limitations which are appropriately described and addressed in the ILV report. Thus, a key attribute of the manual steps in the ILV assessment is the effort toward reconciling the mapped LSN values with the land damage observations relative to the levels of estimated shaking for the main CES events. The Expert Panel believes this reconciling of observations with computed LSN values is an essential component in the overall ILV Assessment Methodology, and concurs with the application of LSN combined with its reconciliation with observed land damage, as embodied in the ILV Assessment Methodology.

The LSN = 16 and ΔLSN = 5 criteria for identifying ILV damage in the automated models were developed through a process that is transparent and defensible. These criteria were selected based on examination of observational data regarding land damage and building performance in the major CES events. A value of ΔLSN of 5 is about the minimum LSN difference that can be considered meaningful given the uncertainty of the input parameters and the requirement that the resulting change in land vulnerability be material. The Expert Panel believes the adopted indicator values provide a consistent and reasonable basis for evaluating ILV land damage claims with the goal of not rejecting legitimate claims.

The manual components of the ILV assessments provide appropriate opportunities for engineering judgements regarding the balance of evidence. Engineering judgements are inherently open to reasonable differences of opinion and hence best done in groups using iterative steps, multiple checks and quality assurance processes. The ILV Assessment Methodology employed by T+T involves three levels of scrutiny and engineering judgement by engineers, senior engineers, and project director. It is an open and transparent process that engages feedback, but also allows for an independent scrutiny of decisions based on engineering judgement. The Panel finds this process reasonable and appropriate, considering the complexities and stated objectives.

6.2.4. ILV Assessment Results

The conclusions in the ILV Report that: (1) the population of properties qualifying for ILV performed very differently compared to the population of properties which are not materially vulnerable to liquefaction, and (2) the ILV automated model at a regional level generally performed well in differentiating between properties with and without ILV are substantiated by the data and evaluations presented in the report.

The Worked Examples confirm that, in accordance with the EQC direction, the ILV Assessment Methodology was applied in good faith; not applied mechanically; and did not exclude consideration of factors that are relevant to any particular case. Moreover, each Worked Example follows faithfully and in detail the procedures in the ILV Assessment Methodology and provides results that are reasonable and appropriate in terms of the Expert Panel's own judgement.

6.2.5. Concluding Remarks

The concept of ILV as a form of insured land damage and the associated need for an ILV Assessment Methodology have no apparent precedents in history. The development of the ILV Assessment Methodology required overcoming numerous technical and administrative challenges with little or no prior experience to draw from, and as such, represents a significant original achievement. The Expert Panel commends the project team for their strategic thinking, comprehensive technical approach, and thorough evaluation process that employs an exceptional dataset with sound analysis platforms and engineering evaluations.

The Expert Panel finds the ILV Report to be a comprehensive document that describes the ILV Assessment Methodology and its development in sufficient detail to address the various aspects of the methodology and its application in the complex geological conditions of Christchurch. It provides appropriate descriptions of technical limitations in the available information and liquefaction evaluation procedures. It provides sufficient examples to illustrate how such limitations are addressed in evaluating the engineering criteria for ILV assessment specified by EQC. It provides a reasonably thorough summary of relevant scientific literature. The ILV Report is not, however, an easy document to digest given the depth to which interconnected and intricate issues are covered. This characteristic of the report is understandable given the desire to emphasize comprehensive and transparent coverage of all aspects of the ILV Assessment Methodology and its development.

The information and methodology of the assessment including both assumptions and processes used to identify Increased Liquefaction Vulnerability (ILV) are technically sound, reasonable and consistent with the objectives set for the assessment. The Expert Panel did not identify any technical limitations, aside from those identified and addressed in the ILV report, which could be reasonably expected to have a material effect on quantifying the extent of ILV damage.

Alternative forms for the ILV Assessment Methodology may have utilized the available information in different ways, but it is likely that an alternative, robust methodology meeting the general objectives specified by EQC, as discussed above, would have produced results reasonably consistent with those of the ILV Assessment Methodology for the large majority of residential properties.

The Expert Panel concludes that the ILV Assessment Methodology meets the general objectives specified by EQC. It uses well-founded and current engineering procedures with the best available data and information. The data and information used are available to property owners. Moreover, the process allows any claimant to provide further information or alternative interpretation of existing information to support ILV damage for any residential property. It considers all reasonably relevant factors, allows for incorporation of engineering judgement through manual assessments and peer review processes, and is applied in good faith with avenues for challenges and consideration of new information. The overall methodology provides for a reasonably efficient processing of claims while also providing a comprehensive basis upon which to derive equitable decisions.

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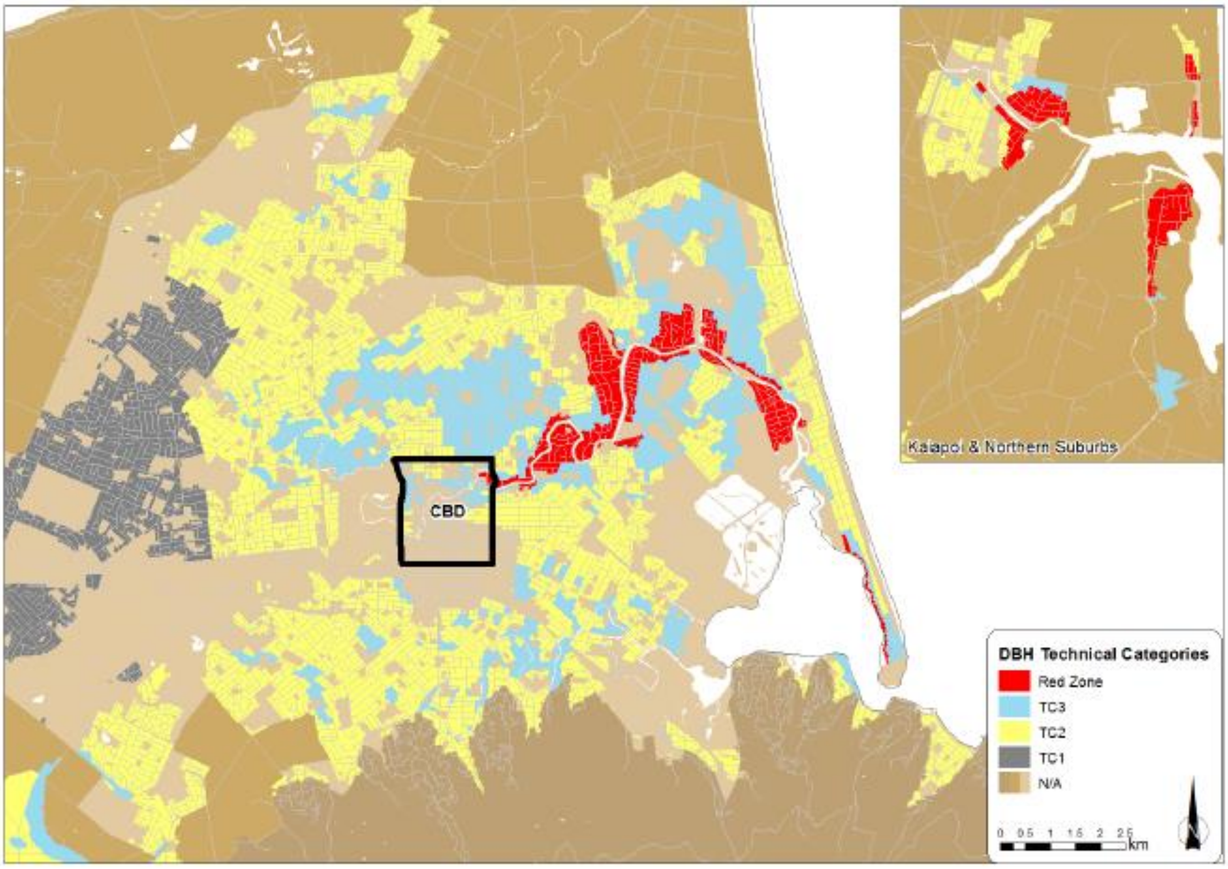


Figure 1. The Red Zone and Technical Categories zones established by the New Zealand government

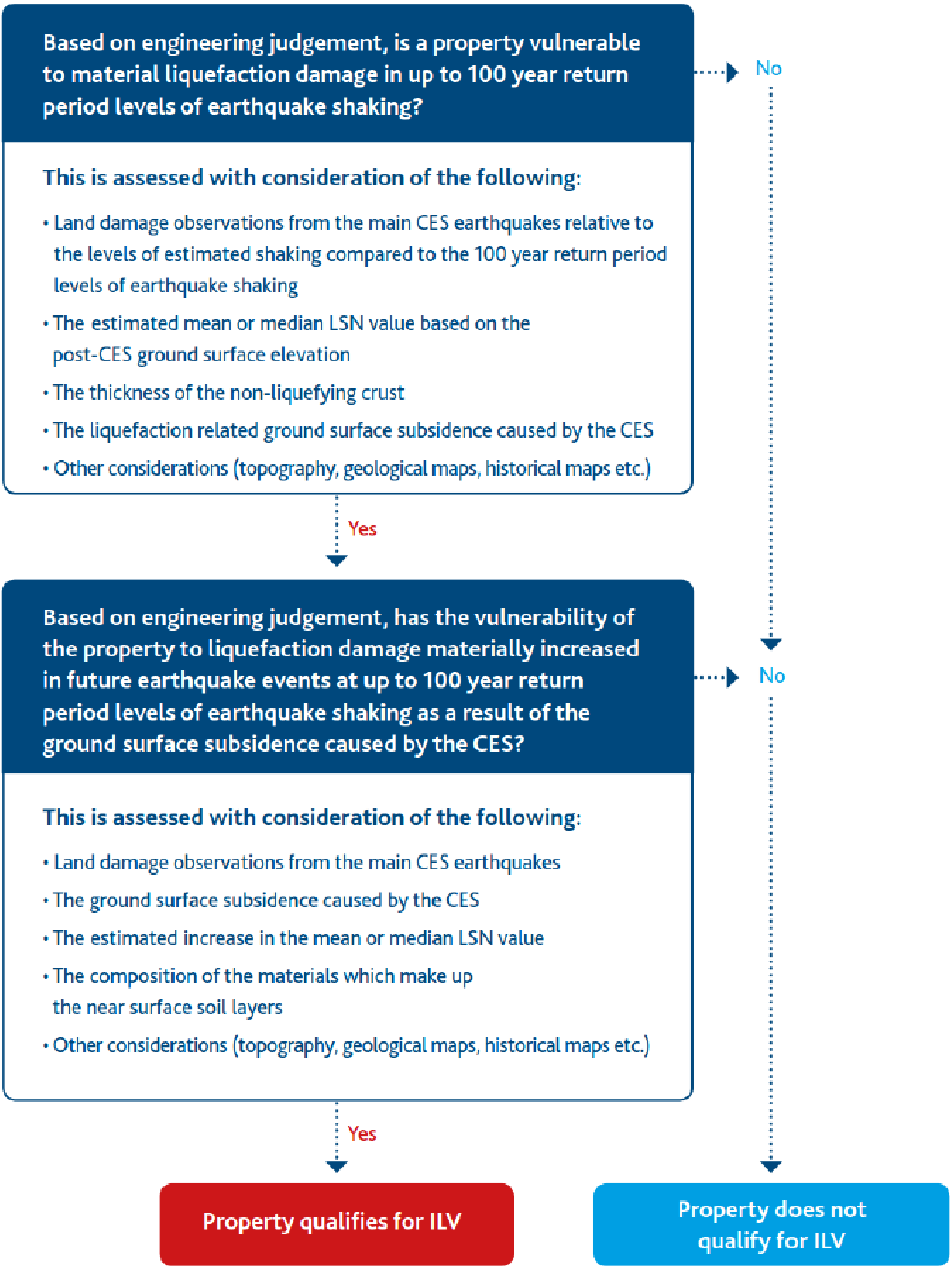
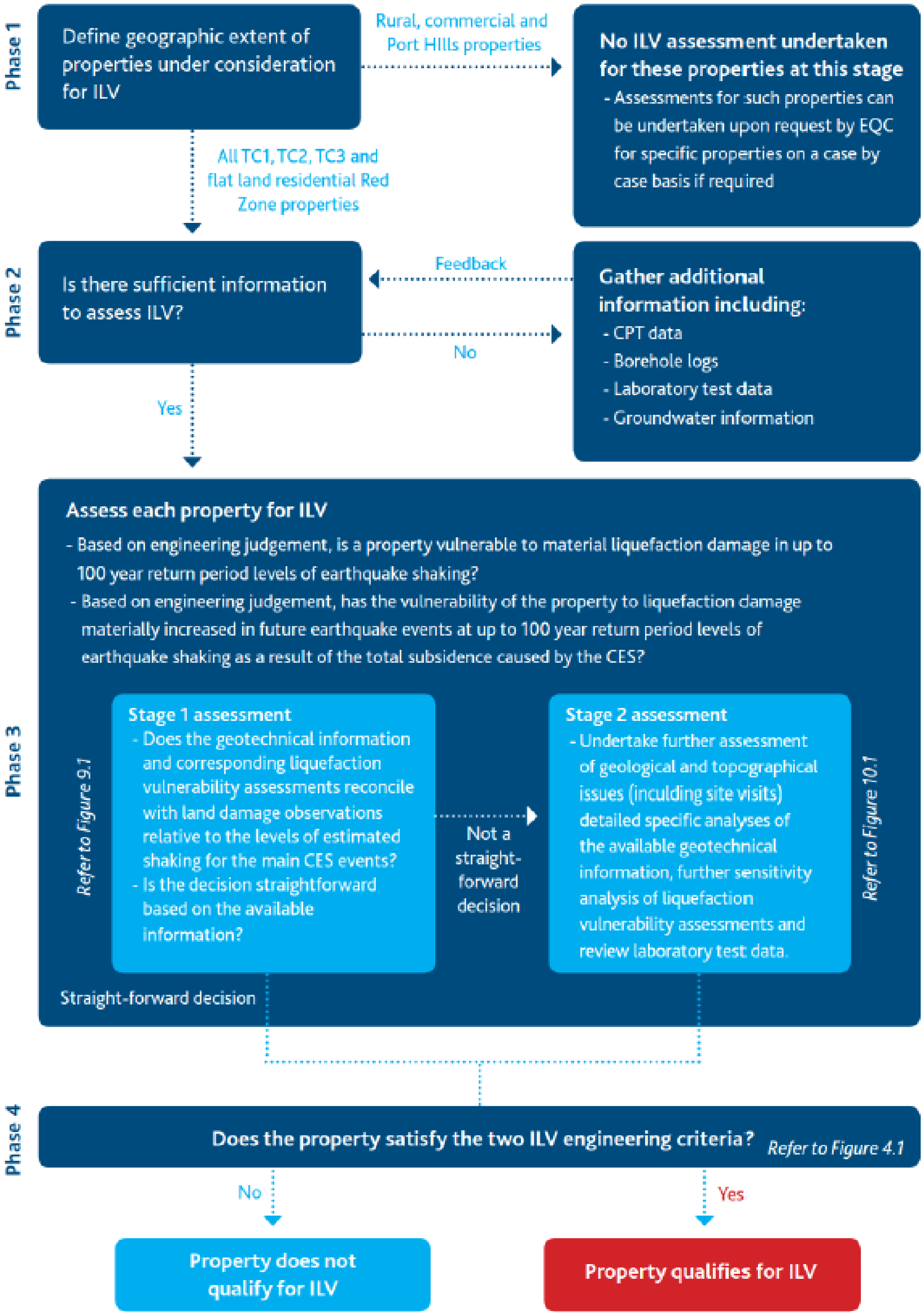


Figure 2. Typical property attribute considerations incorporated in the ILV Assessment Methodology



Define geographic extent of properties under consideration for ILV

No ILV assessment undertaken for these properties at this stage

- Assessments for such properties can be undertaken upon request by EQC for specific properties on a case by case basis if required

Is there sufficient information to assess ILV?

Gather additional information including:

- CPT data
- Borehole logs
- Laboratory test data
- Groundwater information

Assess each property for ILV

- Based on engineering judgement, is a property vulnerable to material liquefaction damage in up to 100 year return period levels of earthquake shaking?
- Based on engineering judgement, has the vulnerability of the property to liquefaction damage materially increased in future earthquake events at up to 100 year return period levels of earthquake shaking as a result of the total subsidence caused by the CES?

Stage 1 assessment

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

Stage 2 assessment

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

Does the property satisfy the two ILV engineering criteria?

Property does not qualify for ILV

Property qualifies for ILV

Figure 3. ILV Assessment Methodology

APPENDIX A: PREVIOUS REVIEWS BY EXPERT PANEL MEMBERS

A.1. Increased Liquefaction Vulnerability Reviews

Members of the Expert Panel have been engaged in numerous peer reviews following the Canterbury Earthquake Sequence. At all stages in the development of the ILV methodology and application process, the Expert Panel reviewed the scientific and engineering basis for assessing how liquefaction vulnerability has increased for residential properties in Christchurch.

Bray, Cubrinovski, and O'Rourke provided peer reviews for EQC of a series of reports prepared by Tonkin & Taylor to evaluate liquefaction land damage in Christchurch and develop a methodology for increased vulnerability to liquefaction.

Following this work, the Expert Panel evaluated memos, reports, and supporting documentation provided by Tonkin &Taylor as the ILV process was developed. The Expert Panel assessments were undertaken in two stages, associated with what was referred to during development as ILV Stages 1 and 2.

The major reports and the dates of the peer review response are set out in the table below.

The T+T report submitted to review	Expert Panel report / comments in response	Brief description of the topics covered in the review
Initial Reports in the ILV Assessment Process		
T+T report entitled "*Data Analysis of Increased Vulnerability to Liquefaction: Canterbury Earthquake Sequence*" dated May 2012 (Report and Appendices A-M).	Reports by Bray, Cubrinovski, and O'Rourke dated 2 May 2012, 16 June 2012, 28 June 2012 and 28 July 2012.	The review focused on whether LSN was an appropriate basis for liquefaction land damage assessment in the Christchurch area, and also considered the T+T report's evaluation of liquefaction land damage observations, subsurface characteristics, and earthquake ground motion areal distribution.
T+T report entitled "*Report for Chapman Tripp Acting on Behalf of the Earthquake Commission"* dated August 2012.	Report by Bray, Cubrinovski, and O'Rourke dated 10 September 2012	The Expert Panel provided comments on representative case study areas and the assessment framework, including the use of LSN and the materiality indicator.
T+T report entitled *"Canterbury Earthquake Series: Category 8 Land Damage – Exacerbated Vulnerability to Liquefaction*" dated September 2012 (Report and Appendices A-H).	Report by Bray, Cubrinovski, and O'Rourke dated 12 November 2012	The Expert Panel provided further comments on LSN as a parameter for assessing land vulnerability to liquefaction, and commented on the proposed assessment methodology.
ILV Stage One		
T+T memorandum entitled "*Increased Liquefaction Vulnerability – Idriss and Boulanger 2008 versus Boulanger and Idriss 2014"* dated 23 June 2014 and updated version dated 9 September 2014	Preliminary comments on 16 July 2015 Meetings at 10th US National Conference on Earthquake Engineering in Anchorage, Alaska	The review concerned the reasonableness and justifiability of a proposed implementation of the Boulanger and Idriss (2014) simplified liquefaction triggering methodology into the ILV framework, including as against the Idriss and Boulanger (2008) method.
Report by technical advisory group composed of private insurers' geotechnical engineers entitled "*Review of LSN and its use in Category*	Memorandum dated 22 October 2014	

8 land damage eligibility assessments” dated 2 April 2014		
T+T report entitled “*Overview of Increased Liquefaction Vulnerability Eligibility Assessment”.*		
ILV Stage Two		
T+T report to EQC Executive Leadership Team entitled “*Stage 2 ILV Qualification Methodology Report*”.	Memorandum dated 23 January 2015.	The review focused on the validity of the adopted approaches and whether they produced consistent, defensible results. In particular, the Expert Panel commented on the treatment of marginal and complex cases, and the importance of land damage observations in evaluating land performance in future earthquakes at the 100-year return period level.
Interim Reviews of Increased Liquefaction Vulnerability Assessment Report		
Preliminary draft “*ILV Assessment Report – Draft of Sections 1 to 6”* (T+T Ref. 52010.140 Draft May 2015), provided on 21 May 2015	Review Comments on May 2015	The Expert Panel provided comments in particular on the organization, presentation and focus of the ILV Assessment Methodology.
Sections of the “*Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology”* draft report: • Master draft copy dated 17 June 2015; • Draft section 5.5 dated 24 June 2015; and • Draft section 10 dated 24 June 2015, with some draft sections being incomplete and excluding appendices.	Email entitled “*Expert Panel review comments on sections of the draft T+T ILV Report circulated in June 2015*” dated 16 July 2015.	The Expert Panel provided comments on the further draft of the ILV Assessment Methodology report.

A.2. Reviewer Contributions to Other Canterbury Projects

Bray, Boulanger, Cubrinovski, and O’Rourke helped EQC and Tonkin & Taylor plan for the shallow ground improvement field trials that were performed during 2013-2014 and prepared a peer review for the final report “Christchurch Ground Improvement Trials Report” prepared by Tonkin and & Taylor, 19 December 2014**.**

Expert Panel members have also assisted with peer reviews for the Ministry of Business, Innovation and Employment (MBIE). Bray, Cubrinovski, and O’Rourke provided peer review for “Guidance for Repairing and Rebuilding Foundations in Technical Category 3 (TC3)” issued in May, 2012. Bray, Boulanger, Cubrinovski, and O’Rourke provided peer reviews of 1) Section 15.3, and (2) Appendix C4: Method statements for site ground improvement, both of which are part of the updated and expanded MBIE guidance document, "Part C: Assessing, Repairing and Rebuilding Foundations in Technical Category 3 (TC3)", issued in April, 2015.

APPENDIX B: BIOGRAPHIES OF EXPERT PANEL MEMBERS

Ross W. Boulanger, Ph.D., P.E., is the Director of the Center for Geotechnical Modeling and professor in the Department of Civil and Environmental Engineering at the University of California, Davis. He received his Ph.D. and M.S. degrees in Civil Engineering from the University of California at Berkeley in 1990 and 1987, respectively, and his B.A.Sc. degree in Civil Engineering from the University of British Columbia in 1986. He was a senior staff engineer at Woodward-Clyde Consultants from 1990-92 before joining the faculty at UC Davis in 1992.

His research and professional practice are primarily related to liquefaction and its remediation, seismic soil-pile-structure interaction, and seismic performance of dams and levees. His research over the past 25 years has produced over 230 publications, including co-authoring with I. M. Idriss the EERI Monograph MNO-12 on Soil Liquefaction during Earthquakes. He has served as a technical specialist on over 40 seismic remediation and dam safety projects for private, state, and federal organizations. His honors include the TK Hsieh Award from the Institution of Civil Engineers, and the Ralph B. Peck Award, Norman Medal, Walter L. Huber Civil Engineering Research Prize, and Arthur Casagrande Professional Development Award from the American Society of Civil Engineers (ASCE).

Jonathan D. Bray, Ph.D., P.E., NAE, is the Faculty Chair of Earthquake Engineering Excellence at the University of California, Berkeley. He was elected into U.S. National Academy of Engineering in 2015. He earned engineering degrees from West Point (B.S., 1980), Stanford University (M.S. in Structural Engineering, 1981), and the University of California, Berkeley (Ph.D. in Geotechnical Engineering, 1990). His expertise includes liquefaction and its effects on structures, the seismic performance of earth structures and waste fills, earthquake fault rupture propagation, earthquake ground motions, seismic site response, and post-event reconnaissance.

Dr. Bray has been a registered professional civil engineer since 1985 in Virginia and 1990 in California. He has served as a consultant on several engineering projects and peer review panels, and he has served as an expert geotechnical engineer in several legal cases. Consultancies include the California High-Speed Train Project Technical Advisory Panel, Advisor to the New Zealand Earthquake Commission, Transbay Tower Structural Design Review Team, and the BART Earthquake Safety Program Peer Review Panel. Dr. Bray is the creator and Chair of the NSF-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Association. Additionally, he has served as the Vice-President of the Earthquake Engineering Research Institute and as a member of the Advisory Committee on Earthquake Hazards Reduction.

Professor Bray has authored over 300 research publications. He has received several honors, including the ASCE Peck Lecture Award, SSA-EERI Joyner Lecture Award, ASCE Middlebrooks Award, ASCE Huber Research Prize, Shamsher Prakash Research Award, Packard Foundation Fellowship, and NSF Presidential Young Investigator Award.

Misko Cubrinovski, Ph.D., is a Professor of Geotechnical and Earthquake Engineering in the Department of Civil and Natural Resources Engineering at the University of Canterbury, Christchurch. He holds a BSc degree in Civil Engineering (1982) and MSc degree in Earthquake Engineering (1989) from UCM Skopje, Macedonia, and a PhD degree in Geotechnical Engineering from the University of Tokyo (1993). He was a research engineer at Taisei Corporation, Tokyo, from 1993-97 and principal researcher at Kiso-Jiban Consultants, Tokyo, from 1997-2005 before joining the University of Canterbury in 2005.

His research interests and expertise are in geotechnical earthquake engineering and in particular problems associated with liquefaction, seismic response of earth structures and soil-structure interaction. Misko has authored or co-authored over 300 technical publications, and has worked as a geotechnical specialist and advisor on a number of significant engineering projects. He had a leadership role in the research efforts following the 2010-2011 Christchurch earthquakes including providing expert opinion and advice to government and regional authorities, and the profession at large. In recognition of his scholarly work and research he has received several prestigious fellowships and awards including the Ivan Skinner Award, NZGS Geomechanics Award, ANZ Joint Societies Award, Director’s Award of Taisei Corporation, and several outstanding paper awards of journals and international conferences. He is a Faculty Member of the Rose School, University of Pavia, IUSS, Italy, and Fellow of the University of Tokyo.

Thomas D. O'Rourke, Ph.D., Dist.M.ASCE, NAE, FREng, is the Thomas R. Briggs Professor of Engineering in the School of Civil and Environmental Engineering at Cornell University. He holds a Ph.D. and M.S. degree in Geotechnical Engineering from the University of Illinois at Urbana-Champaign. He is a member of the US National Academy of Engineering, International Fellow of the Royal Academy of Engineering, Distinguished Member of American Society of Civil Engineers (ASCE), and Fellow of the American Association for the Advancement of Science. He received numerous awards from professional societies, including ASCE, Institution of Civil Engineers, and the American Society for Testing and Materials.

Tom served as President of the Earthquake Engineering Research Institute and as a member of numerous advisory committees for the National Science Foundation, National Institute of Standards and Technology, and National Research Council. He worked as a Fulbright Senior Specialist in 2007 with the Office of the Prime Minister and Cabinet on New Zealand national policy for hazards and critical infrastructure.

He authored or co-authored over 360 technical publications. He served as chair or member of the consulting boards of many large infrastructure projects, as well as the peer reviews for projects associated with highway, rapid transit, water supply, and energy distribution systems. His research interests cover geotechnical engineering, earthquake engineering, underground construction technologies, engineering for large, geographically distributed systems, and geographic information technologies and database management.