Technical Specification 01

Liquefaction Evaluation of CPT Investigations

Summary

This technical specification outlines how the liquefaction evaluation tool classifies liquefaction vulnerability for each of the Cone Penetration Test (CPT) profiles stored in the Canterbury Geotechnical Database (CGD). The liquefaction vulnerability indicators used in the Tonkin and Taylor (2013) Liquefaction vulnerability study are calculated for each CPT profile in the database, for a range of earthquake and groundwater scenarios. A regional-scale map is displayed for each scenario and indicator in the "Liquefaction Evaluation of CPT Investigations" (Map Layer CGD0050). This specification summarises these scenarios and gives the detailed evaluation method for each indicator, supplementing the overview descriptions in Tonkin and Taylor (2013).

Introduction

This analysis tool calculates a series of liquefaction vulnerability indicators for each CPT profile stored in the Canterbury Geotechnical Database (CGD) for two general forms of earthquake and groundwater scenario:

- **Investigative (forward) analysis** for magnitude-weighted peak ground accelerations (PGA) of 0.08 to 0.40 g occurring when the depth to groundwater is given by the GNS Science Median Groundwater Surface Elevations (Map Layer CGD5160); and
- **Event-specific (back) analysis** with the Conditional PGA for Liquefaction Assessment (Map Layer CGD5110), Spatially Interpolated PGA (Map Layer CGD5170) and the estimated depth to groundwater at the time from the corresponding Event Specific Groundwater Surface Elevations (Map Layer CGD0800)

The first general scenario provides forward analysis to predict the possible future foundation behaviour, for designers to investigate the local variation of each vulnerability indicator at a regional scale. Map Layer CGD0050 (Liquefaction Evaluation of CPT Investigations) maps classify indicator values for earthquake magnitudes of Mw=6.0 and 7.5 and for a uniform spatial distribution of selectable PGA increments between 0.08 and 0.40 g. The median depth to groundwater, based on the Feb 2012 ground surface levels, is used for these regional scale maps as this considered to be consistent with the probabilistic nature of seismic hazard modelling.

The back analysis is provided to estimate the expected responses during a selection of significant historic earthquakes. The earthquake PGA and depth to groundwater are both spatially distributed and represent the best estimates for each at the time of the earthquake. These allow the vulnerability indicators to be compared with other observations in the vicinity of a specific site, at a regional scale.

The liquefaction vulnerability indicators calculated for each scenario and CPT profile are given in Table 1. These were used for the Tonkin and Taylor Liquefaction vulnerability study (2013), but some are only defined in the nominated sections within this specification.

Table 1. Liquefaction vulnerability indicators

Indicator name and symbol		Description or Reference
Crust Thickness	CT	Based on PGA and depth to groundwater (see Section 7)
Cumulative Thickness of Liquefied Layers	CTL	Total thickness for whole CPT profile (see Section 8)
Liquefaction Potential Index	LPI	Using the Iwasaki et al. (1982) method
Calculated Settlement	S	Using the Zhang, Robertson and Brachman (2002) method
Liquefaction Severity Number	LSN	As defined in Tonkin & Taylor (2013)

This specification outlines the earthquake and groundwater scenarios and gives the assumptions and calculation methods for each of the Table 1 liquefaction vulnerability indicators. The indicators are calculated and classified for display in the regional scale maps in Map Layer CGD0050. Site specific analyses should consider aspects that were not explicitly incorporated in the probabilistic and regional scale analysis.

The vulnerability indicators are calculated at each CPT location within the database using the Figure 1 flowchart. This also provides a visual table of contents for the sections in the remainder of this specification, with the white on blue numbers giving the section numbers in this specification. Each CPT profile is analysed using the Idriss & Boulanger (2008) liquefaction triggering method to develop profiles that are then in turn used for calculation of the individual indicators before being classified and mapped.

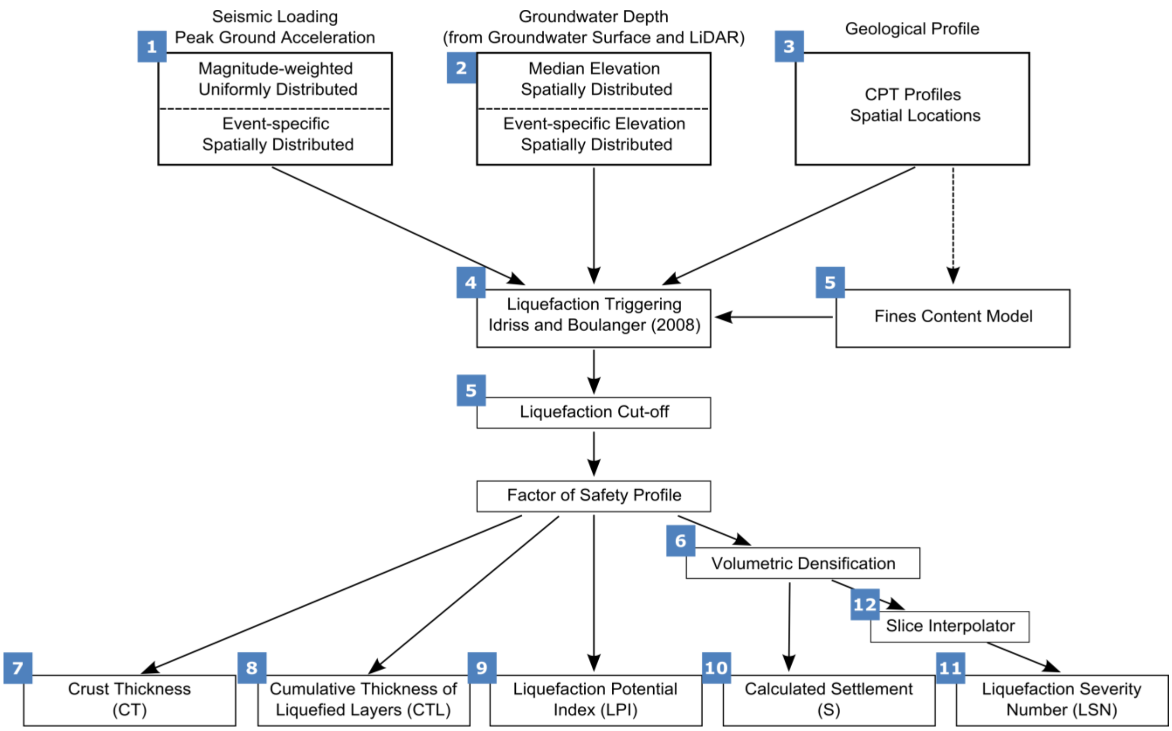

Figure 1. Calculation Flowchart for the Liquefaction Vulnerability Indicators

1. Seismic loading

Investigative Analysis

The seismic loading for the investigative (forward) analysis uses earthquake magnitudes of Mw=6.0 and 7.5. The uniform spatial distribution of Peak Ground Acceleration (PGA) can be selected as 0.08, 0.10, 0.13, 0.15, 0.18, 0.22, 0.27, 0.35 or 0.40 g, with 0.13 g corresponding to the Service Limit State PGA recommended by MBIE (2012) for Canterbury (with Mw= 7.5) and 0.35 g for the Ultimate Limit State.

Event-specific Analysis

The event-specific (back) analyses were carried out using two spatially distributed PGA models developed by Bradley and Hughes (2012a and 2012b) and by O'Rourke et al. (2012).

For each earthquake, Bradley and Hughes calculated the PGA at each location within the region by adjusting the predictions from an empirical ground motion model of the fault ruptures to match the PGA values recorded at the strong motion stations. The spatial distribution of PGA was therefore mostly from the empirical model at large distances from any strong motion station and mostly the recorded values nearer the stations. These PGA distributions are in Map Layer CGD5110.

The O'Rourke et al. PGA models interpolated the spatial variation of the geometric mean ground accelerations for each earthquake using a Kriging interpolation method. These PGA distributions are in Map Layer CGD5170.

Event-specific Earthquake Magnitudes

Table 2 summarises the earthquake magnitudes used for modelling, based on the individual event magnitudes published on GeoNet and supplied by Berryman (2012). The June and December earthquakes were both preceded by a smaller foreshock, approximately 80 minutes earlier. The foreshocks would have increased the excess pore water pressure within the ground, so this increase was used to derive an equivalent magnitude for use in the model as described below.

Table 2. Earthquake magnitudes used for seismic loading

Earthquake	Date	Magnitude		
		Foreshock	Earthquake	As Modelled
Darfield Earthquake	04 September 2010	-	M7.1	7.1
Christchurch 1 Earthquake	22 February 2011	-	M6.2	6.2
Christchurch 1 Aftershock	16 April 2011	-	M5.3	5.3
Christchurch 2 Earthquake	13 June 2011	M5.6	M6.0	6.2
Christchurch 3 Earthquake	23 December 2011	M5.8	M5.9	6.1

Note

Elevated pore water pressures generated by a foreshock are expected to make the material more susceptible to liquefaction during subsequent shaking if the additional pressure is unable to dissipate before the earthquake.

Records from five, 5 m deep piezometers that were grouted into the ground and recorded at 5 second intervals during the June 2011 earthquakes were used to quantify the dissipation. Records from these piezometers (Tonkin and Taylor, 2013) show that more than 75% of the excess pore pressure generated during the M5.6 foreshock had dissipated in the 80 minutes before the M6.0 earthquake. The pore pressures were assumed to reduce by the same percentage between the December foreshock and earthquake because, while no pore pressure records were recorded, the dissipation period was similar.

For the purposes of the liquefaction assessment, the foreshock and earthquake were combined into a single earthquake magnitude by assuming the 25% excess pore water pressure remaining from the foreshock is equivalent to 25% of the equivalent stress cycles from the foreshock. The relationship between earthquake moment magnitude and the number of equivalent stress cycles was assumed to follow Figure 62 of Idriss and Boulanger (2008), based on work by Seed and Idriss (1982) and by Idris(1999). The equivalent earthquake magnitude was calculated using the Idriss and Boulanger relationship, first to convert the two magnitudes to equivalent numbers of stress cycles, and then to convert the total number of effective cycles (i.e. adding the 25% of the cycles remaining from the foreshock to those generated by the earthquake) back to an equivalent magnitude.

2. Depth to Groundwater

Investigative Analysis

The investigative (forward) analyses use a depth to groundwater based on a seasonal median groundwater elevation around Canterbury. The median groundwater elevation from the regional-scale "GNS Science Median Water Table Elevations" (Map Layer CGD5160) is considered to be consistent with the probabilistic nature of seismic hazard modelling.

The median groundwater elevations were subtracted from the ground surface elevations from the most recent LiDAR surveys (Map Layer CGD0500) to estimate the spatial distribution of the depth to groundwater. The regional-scale depth to median groundwater is also mapped in Map Layer CGD5160.

The depth to groundwater at an individual site may vary from that estimated using the median groundwater model, and will need to be considered for an individual site assessment. Aspects that may require further investigation include extreme or seasonal fluctuations, localised perturbations (e.g. changes in topography or permeability), and the distance from the wells where elevations were recorded.

Event-specific Analysis

Event-specific (back) analyses use the "Event Specific Groundwater Surface Elevations" (Map Layer CGD0800) for each earthquake. These 'depth to groundwater' models are based on the LiDAR acquired after each earthquake and the estimated groundwater elevation at the time of the earthquake. The June 2011 groundwater elevation was used with the 16 April 2011 aftershock.

3. Geological profile

The geological profile is provided by the CPT profiles (with depth) stored in the Canterbury Geotechnical Database (CGD). The tip resistance, q_c, and skin friction, f_s, recorded for each depth, z, within the CPT profile was used to infer the resistance to liquefaction throughout the soil profile, by making the following assumptions:

1. The material is a standard material that is consistent with the empirical liquefaction databases and methods. Specifically, it is not welded, cemented or pumiceous to the extent that the mechanical soil behaviour affects the penetration test results.
2. The ground is effectively flat or has a uniform surcharge (i.e. there are no shear stresses locked in the soil by embankments, retaining walls or sloping ground)
3. The pore water pressure profile is hydrostatic below the groundwater surface
4. The total vertical stress, σ_{vc}, and effective vertical stress, σ'_{vc}, can be reasonably well approximated using an average soil density of 18 kN/m^3
5. The soils are assessed as being susceptible to liquefaction (i.e. have the potential to liquefy and are not too fine-grained)

4. Idriss and Boulanger triggering

Liquefaction triggering is calculated at each depth, *z*, recorded within the CPT profile for the scenario earthquake and groundwater profile using the Idriss and Boulanger (2008) method shown in the Figure 2 flowchart.

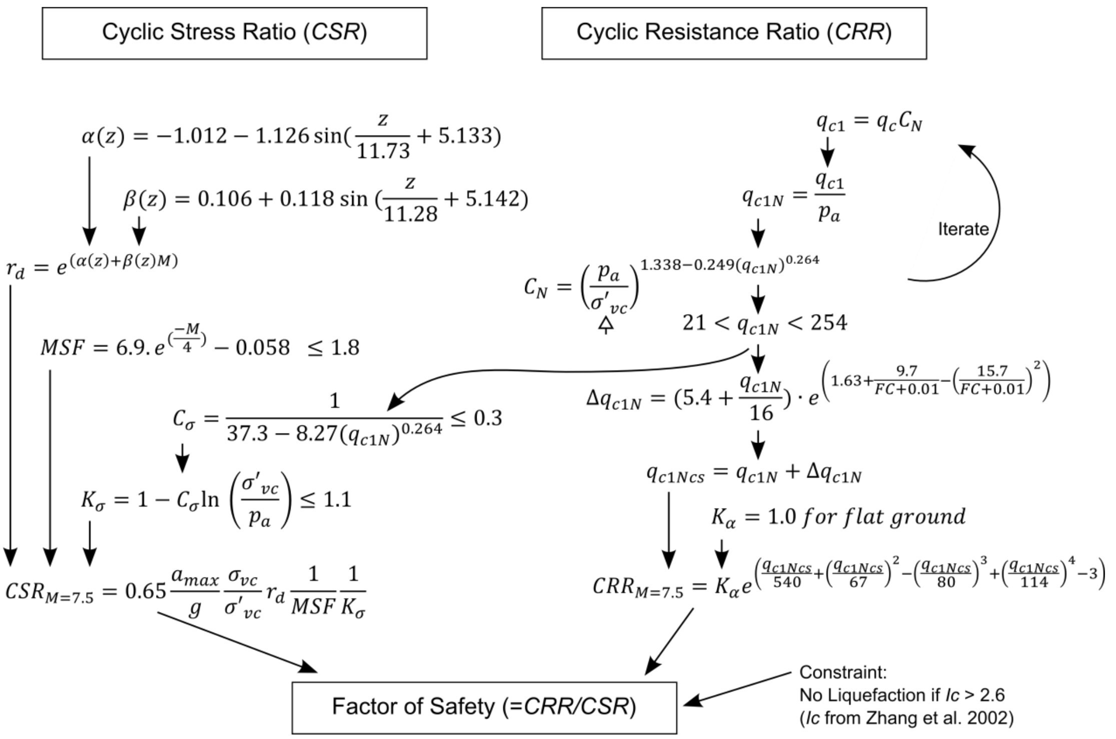

Figure 2. Calculation of the Factor of Safety using the Idriss and Boulanger (2008) method (symbols are defined within the text).

The Idriss and Boulanger (2008) method calculates the Cyclic Resistance Ratio (CRR) from the measured CPT tip resistance, q_c, the CPT sleeve friction, f_s, and the effective vertical stress, σ'_{vc}, in the soil. These are used to estimate an overburden correction factor, C_N, and correct the tip resistance to account for the overburden stress, q_{c1}, which is calculated using the Section 3 assumptions. The normalized overburden stress, q_{c1N}, is q_{c1} divided by the atmospheric pressure, p_a=100 kPa. During the iteration (usually about 3 cycles), q_{c1} is always based on the measured tip resistance, q_c, while C_N is based on the iteratively updated value for q_{c1N}. A second correction is made for the fines content, *FC*, percentage as described in Section 5. With the assumed flat ground or uniform surcharge for the regional-scale analysis, the correction for the effects of an initial static shear stress ratio is $K_\alpha = 1.0$.

For the Cyclic Stress Ratio (CSR), a shear stress reduction coefficient, r_d, is calculated using two functions of the depth, *z*, within the soil profile, namely *α(z)* and *β(z)*, and the earthquake magnitude, *M*. The CSR includes contributions from an empirical magnitude scaling factor, *MSF*, horizontal Peak Ground Acceleration at the surface, a_{max}, and gravitational acceleration (*g*, with the same units as a_{max}). The final contribution to the CSR is the ratio of total to effective vertical stress, σ_{vc}/σ'_{vc}, and an overburden correction factor K_σ that uses an intermediate coefficient, C_σ, which is a function of q_{c1N}.

The Factor of Safety at depth z, *FoS*(*z*), is then calculated from the normalised $CRR_{M=7.5}$ and $CSR_{M=7.5}$. This is constrained when the Soil Behaviour Type Index (*Ic*) is large, as described in Section 5.

The following additional constraints are applied to the factor of safety calculations:

Calculation issue	Description or Reference
Limits on values	$C_n \leq 1.7$ $K_\sigma \leq 1.1$ $FoS \leq 2$ $21 < q_{c1N} < 254$
Ic > 2.6	FoS=2 (see Section 5 below)

5. Fines content calculation and cut-offs

The Idriss and Boulanger liquefaction triggering method requires the percentage of fines content, *FC*, for the soil. For these regional-scale analyses, the fines content is inferred from the CPT profile using the empirical Robertson and Wride (1998) equations and the Soil Behaviour Type Index (*Ic*) using the expression:

$$FC = \begin{cases} 0 & if\ I_c < 1.26 \\ 1.75 \times {I_c}^{3.25} - 3.7 & if\ 1.26 \leq I_c < 3.5 \\ 100 & if\ 3.5 \leq I_c \end{cases}$$

The Soil Behaviour Type Index (*Ic*) is based on the dimensionless CPT tip resistance, *Q*, and normalized friction ratio, *F*, as recommended by Robertson and Wride (1998) and Youd et al. (2001):

$$I_c = \sqrt{(3.47 - \log Q)^2 + (1.22 + \log F)^2}$$

where

$$Q = \frac{q_c - \sigma_{vc}}{P_a} \cdot \left[\frac{P_a}{\sigma'_{vc}}\right]^n$$

$$F = \frac{f_s}{q_c - \sigma_{vc}} \cdot 100\%$$

and

q_c = the CPT tip resistance
f_s = the CPT sleeve friction
σ_{vc} = the total stress, based on an average density of 18 kN/m^3 (as per Section 3)
σ'_{vc}= the effective stress, based on σ_{vc} and a hydrostatic pressure profile
P_a = atmospheric pressure, nominally 100 kPa
n = in the range of 0.5 to 1.0 as calculated using the Robertson and Wride (1998) method

The soil is assumed to be too fine grained to liquefy when the calculated *Ic* exceeds 2.6. The validity of this assumption for the regional-scale analyses must be considered when undertaking an individual site assessment.

6. Volumetric Densification (Zhang et al. (2002) calculated volumetric strain)

At each layer, the Factor of Safety (FoS) described in Section 4 and the normalised tip resistance, q_{c1N}, are used to calculate the post-liquefaction volumetric densification strain, $\mathcal{E}_v$. These strains are interpolated from the Figure 3 curves proposed by Zhang et al. (2002), except the CPT tip resistance is corrected to remove the effect of overburden stress using the iterative Idriss and Boulanger (2008) method (shown in the Figure 2 flowchart above).

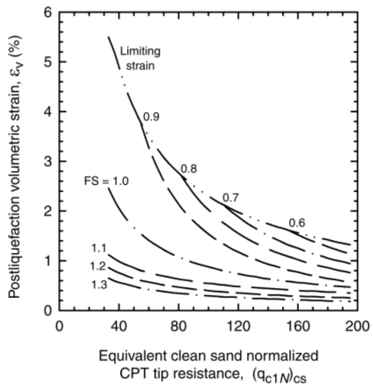

Figure 3. Relationship between post-liquefaction volumetric densification strains, $\mathcal{E}_v$, and the normalized CPT tip resistance, q_{c1N}, for selected factors of safety, FS, (Zhang et al., 2002)

The following additional constraints are applied to the volumetric densification calculations using the piecewise equations given in Appendix A of Zhang et al. (2002) and plotted in Figure 3 above:

Calculation issue	Description or Reference
Strain equations are only provided for $q_{c1}/q_{c1ncs} \geq 33$	For $q_{c1Ncs} < 33$, the strain is bounded by the limiting strain, calculated using $q_{c1Ncs} = 33$
Strain equations are only provided for specific Factors of Safety	Linear interpolation is used between the published equations
Limits on values	Maximum strain = 102 $q_{c1ncs}^{-0.82}$

7. Crust Thickness (CT) Indicator

This indicator represents the thickness of the upper, non liquefying layer of material. To avoid very thin layers of potentially liquefiable material being interpreted as the base of the crust, the crust thickness includes the top 100 mm of any layer of liquefied material (i.e. with FoS < 1.0 calculated by the triggering method) that is itself more than 100 mm thick. Where the pre-drill depth extends below the water table, the base of the crust is assumed to be 100 mm below the depth to the groundwater when the material directly beneath the pre-drill is assessed as liquefying.

8. Cumulative Thickness of Liquefied Layers (CTL) Indicator

The Cumulative Thickness of Liquefied Layers (CTL) is calculated by summing the thickness of all layers of material with a calculated FoS < 1.0 for the entire CPT profile using:

$$CTL = \int_{0\,m}^{Z} F_0(z)dz$$

where

$$F_0(z) = \begin{cases} 1 & FoS(z) < 1.0 \\ 0 & FoS(z) \geq 1.0 \end{cases}$$

z = the depth below the ground surface in metres

Z = the total depth of the CPT profile

FoS(*z*) = the Factor of Safety at depth z (see Section 4)

The CTL for CPT profiles that have material missing due to pre-drill were calculated using nominally liquefying material properties q_c = 2MPa and f_s = 0.01MPa through the pre-drill depth.

Deeper CPT profiles typically produce larger CTL values than shallower CPT profiles if there are deep liquefying soil layers. Therefore, the CTL indicator values are not strictly comparable between CPT locations.

9. Liquefaction Potential Index (LPI) Indicator

Iwasaki et al. (1982) defined the Liquefaction Potential Index (LPI) of a 20 m deep soil profile as:

$$LPI = \int_{0\,m}^{20\,m} F_1(z)W(z)dz$$

where

W(z) = 10 – 0.5*z*,

$$F_1(z) = \begin{cases} 1 - FoS(z) & FoS(z) < 1.0 \\ 0 & FoS(z) \geq 1.0 \end{cases}$$

z = the depth below the ground surface in metres

FoS(*z*) = the Factor of Safety at depth z (see Section 4)

The LPI for CPT profiles that have material missing due to pre-drill were calculated using nominally liquefying material properties q_c = 2MPa and f_s = 0.01MPa through the pre-drill depth.

There are no LPI adjustments when the CPT profile is less than 20 m deep, so the CTL indicator values are not strictly comparable between CPT locations.

Iwasaki observed that LPI values can range from 0 to 100, with the following indicators of liquefaction induced damage:

LPI range	Liquefaction risk
LPI = 0	very low
0 < LPI ≤ 5	low
5 < LPI ≤ 15	high
LPI >15	very high

10.Settlement (S) Indicator

The Settlement indicator integrates the volumetric densification strains, $\mathcal{E}_v$, calculated using the Zhang et al. (2002) method described in Section 6, over the total depth of the CPT profile, Z, using:

$$S = \int_{0\,m}^{Z} \mathcal{E}_v(z)dz$$

where

$\varepsilon_v(z)$ = the volumetric densification strain at depth, z, based on Zhang et al. (2002), described in Section 6

Z = the total depth of the CPT profile

z = the depth in metres below the ground surface.

There are always volumetric densification strains when the excess pore pressure rises during shaking, so strains are included for all factors of safety up to *FoS* = 2.0 (i.e. including non-liquefied layers).

Settlements calculated using this method for Deeper CPT profiles are typically greater than settlements calculated for shallower CPT profiles. The calculated values are therefore not strictly comparable between CPT profiles.

Note

The calculated settlement uses empirical equations (Zheng et al., 2002) that are based on a volumetric densification mechanism. There was little correlation between the calculated and observed settlements for Christchurch CPT profiles (Tonkin and Taylor, 2013), which is most likely because there were more significant settlement mechanisms such as loss of soil material from sand ejection at the ground surface (and its subsequent removal), lateral spreading and vertical tectonic movement. However, MBIE (2012) suggests that the calculated settlement is best only considered to be a proxy for the likelihood of liquefaction related damage at the ground surface, rather than method of quantifying settlement. Tonkin & Taylor (2013) also note that the risk of severe effects at the ground surface increases as the calculated settlement increases.

11.Liquefaction Severity Number (LSN) Indicator

The LSN indicator was developed to assess the performance (vulnerability) of residential land in Canterbury in future earthquakes and was validated against the residential land damage observed in Canterbury. The LSN depends on the seismic load, depth to groundwater and geological profile. The LSN is defined as:

$$LSN = 1000 \int_{0\,m}^{10\,m} \frac{\varepsilon_v(z)}{z} dz$$

where

$\varepsilon_v(z)$ = the volumetric densification strain at depth, z, based on Zhang et al. (2002), described in Section 6

z = the depth in metres below the ground surface.

The LSN presented here is based on the top 10 m of material only. A slice interpolation method (see Section 12 below) was used where there was less than 10 m of material. CPT profiles with more than 2 m pre-drill missing and/or less than 5 m total depth were not included in the analysis and are not mapped.

12. LSN Slice interpolation

The LSN indicator is not able to be calculated when CPT sites are either pre-drilled prior to the test or are less than 10 m deep. A slice interpolation method is used to estimate the LSN for each slice missing from the top 10 m of these CPT profiles (i.e. from the pre-drill zone and from the base of the CPT down to the required 10 m depth). The LSN for each missing slice is a weighted average of the LSN values of slices at the same depth from other profiles within 50 m of the incomplete profile. The weighted average is only calculated using slices from CPT profiles within a similar geological area, where the geological areas are bounded by the significant waterways, namely the Kaiapoi, Waimakariri, Avon and Heathcote rivers.

While CPT with more than 2 m pre-drill and/or less than 5 m total depth are not included in the analysis as indicated in Section 11, their profiles are used for LSN slice interpolation of any nearby CPT that are not excluded for the same reasons.

The LSN slice interpolation divides each 10 m deep CPT profile into sixteen slices, with six in the upper 1.5 m, three in the next 1.5 m and the remaining seven over the remaining 7.0 m as shown in the Figure 4 worked example. Thinner slices are used at the top of the profile because these influence the LSN more significantly than the deeper slices.

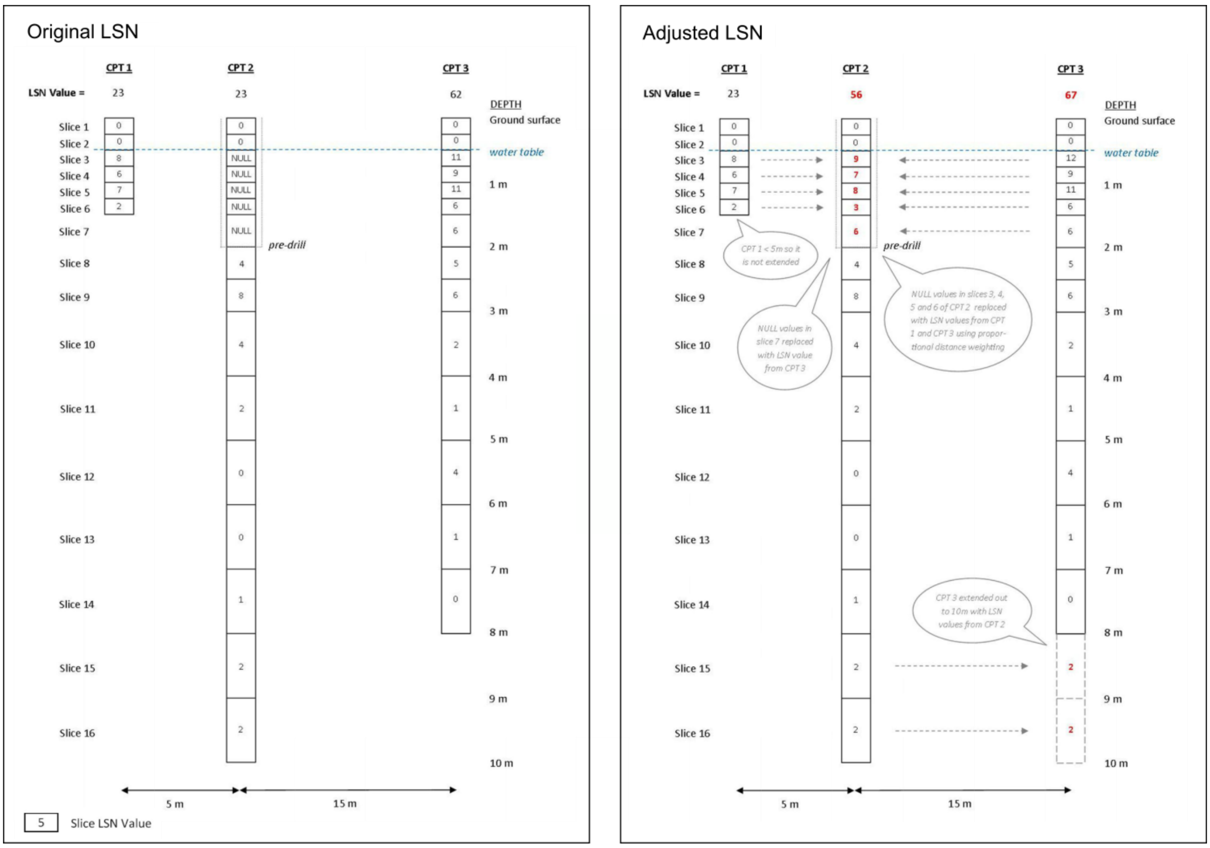

Figure 4. Worked example of the LSN Slice Interpolator algorithm with CPT 2 slices being interpolated from slice LSN values in the two neighbouring CPT profiles

The interpolator algorithm has the following steps:

1. Calculate the LSN for each slice within each CPT using:
    a. LSN=0 for slices with more than half of their thickness above the groundwater surface and are not therefore potentially liquefiable;
    b. LSN= calculated value where there is a more than half of the CPT profile available for that slice; or
    c. LSN=NULL for all remaining slices (i.e. slices below the groundwater surface that are either less than the pre-drill depth or deeper than the bottom of the CPT profile);
2. For each CPT profile that has slices with one or more NULL values and that have either up to 2 m pre-drill or a total depth greater than 5 m:
    a. Identify all CPT profiles that are within 50 m and within the same geological area
    b. For each slice within the CPT profile, replace any NULL values with:
        i. LSN = inverse distance weighted average of the raw LSN for the same slice number within each of the neighbouring CPT profiles (i.e. those at the same depth below surface and with a raw value that is neither NULL nor interpolated).
           Use the slice value when there is only one valid neighbouring slice.
    c. When slices 1 to 7 (i.e. those less than 2.0 m deep) still have any value NULL, replace that NULL with:
        i. LSN = value for a slice at that depth that is expected to liquefy, calculated using a CPT profile with q_c = 2MPa and f_s = 0.01MPa.
    d. Remove the CPT if slices 8 to 11 (i.e. 2.0 to 5.0 m deep) still have a NULL value
3. Calculate the LSN for the remaining CPT that have LSN values for all sixteen slices that are not NULL (i.e. sum the LSN values for the slices)

13.References

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