

Appendix I: The LSN Calculation and Interpolation Process

I1. Introduction

Cone Penetration Tests (**CPTs**) can be used in the assessment of the liquefaction vulnerability. The CPTs available from the Canterbury Geotechnical Database (**CGD**) can vary in length (some long, some short, some with predrill) and hence need to be standardised before corresponding Liquefaction Severity Number (LSN) values can be interpolated to estimate, on a regional basis, an LSN value for each property for given levels of shaking.

As of the end of 2015, approximately 18,000 CPT investigations have been undertaken across Christchurch. Of these 18,000 CPT approximately 15,000 have been undertaken in a manner that provides a sufficient length of soil profile for the purposes of estimating LSN values at the test location, illustrated by green dots in Figure I1.1. The remaining 3,000 CPT illustrated by yellow and red dots in Figure I1.1 are missing portions of information, generally as a result of predrilling at the surface to avoid services or termination of the test prior to reaching the required depth.

In order for the estimated LSN values from a CPT to be used, a sufficient length of soil profile is required. A process of the LSN slicing has been developed to make use of the estimated vertical LSN slice increments (hereinafter referred to as LSN slices) available in the 3,000 CPT that have insufficient length of soil profile, without reducing the accuracy of the estimated LSN values by introducing arbitrary from nearby CPT for the missing portions of the CPT profiles.

A number of limitations are applied to the slicing process to ensure only relevant LSN slices from nearby CPT investigations is used to fill in incomplete portions of the CPT Profiles. These limitations are addressed in Section I3 below.

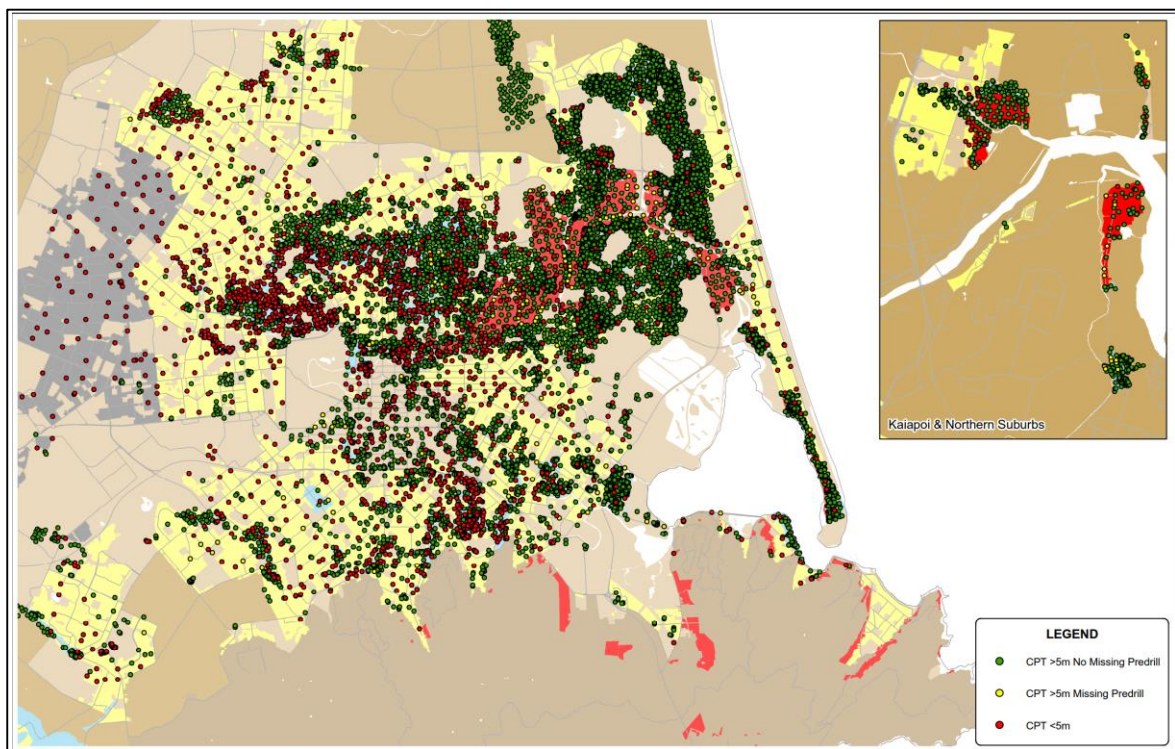


Figure I1.1: CPT test locations

I1.1 Purpose and Outline

This appendix presents a brief summary of the estimation of LSN values, CPT slicing and the interpolation process used to assess on a regional basis the liquefaction vulnerability of each

property in Canterbury for both the pre-CES and post-CES ground surface elevations for the purposes of building an automated IVL assessment model.

This appendix is laid out in the following sections:

- Section I2 outlines the method used to estimate the Liquefaction Vulnerability parameter at specific CPT test locations;
- Section I3 outlines the process used to slice LSN values from nearby CPT pairs which are missing portions of information on the soil profile to obtain complete CPT profiles for use in the LSN analysis;
- Section I4 outlines the interpolation process used to estimate property specific LSN values from the CPT LSN values; and
- Section I5 outlines the minor extrapolation process used at the boundary of the interpolation grid.

I2. Overview of the Estimation of LSN

CPT investigations provide measurements of cone tip resistance (q_c) and skin friction (f_s) recorded at regular intervals below the ground surface (z) within the CPT profile. These soil parameters are used to estimate the resistance to liquefaction (CRR) throughout the soil profile and comparing it to the seismic demand (CSR) to determine whether liquefaction is likely to trigger under specific levels of ground shaking. Further detail about these terms is provided in **Appendix A**.

The soil layers are then assessed to estimate the LSN value for that CPT location. Section I2.1 outlines the liquefaction triggering procedure and lists the assumptions used to undertake the liquefaction triggering procedures on an automated basis for regional assessment purposes. Section I2.2 outlines the LSN estimation procedure and similarly lists the assumptions used to undertake the assessment on an automated basis for regional assessment purposes.

I2.1 Assessment of Liquefaction Triggering

Liquefaction triggering, expressed as a factor of safety (FS) is assessed using the Boulanger and Idriss (2014) method summarised in Figure I2.1 below. Descriptions of the parameters illustrated in Figure I2.1 and a more in depth description of the estimation methodology can be found in Boulanger and Idriss (2014) *CPT and SPT based liquefaction triggering procedures*.

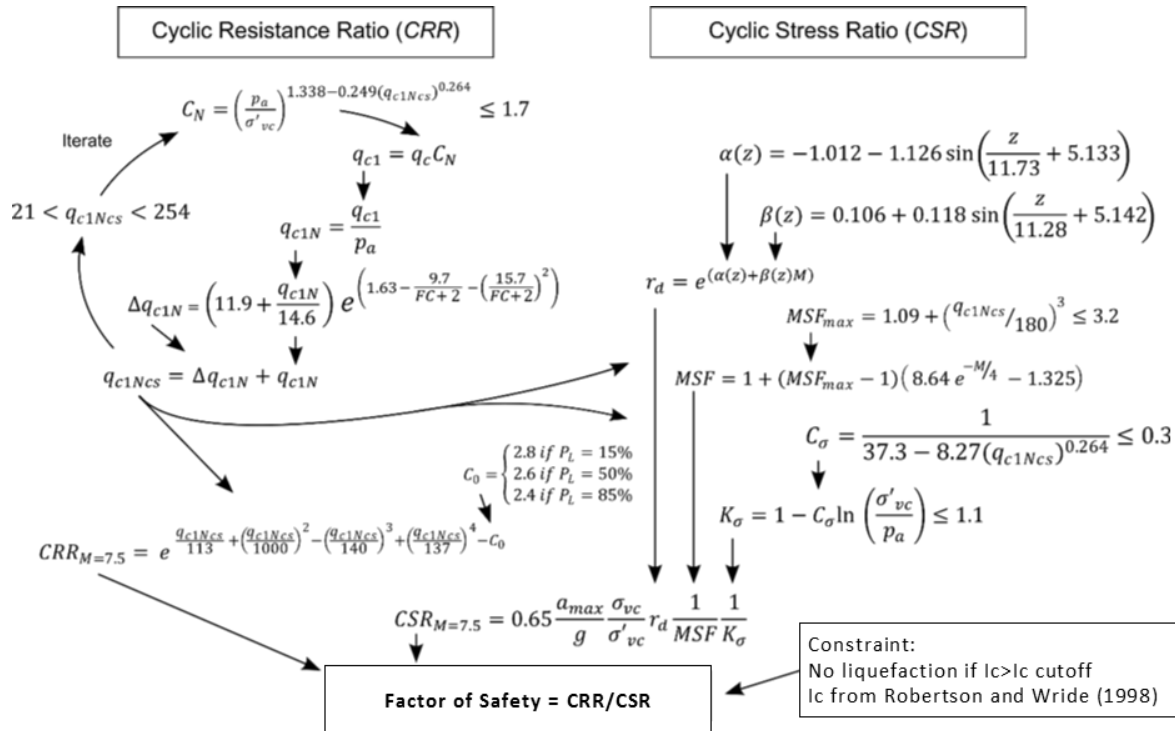


Figure 12.1: Boulanger and Idriss (2014) CPT-based liquefaction triggering procedures.

The Boulanger and Idriss (2014) liquefaction triggering method requires the Fines Content (FC) for the soil profile at each CPT location. For these regional-scale analyses, the FC is inferred from the CPT profile using the empirical function of the Soil Behaviour Type Index (I_c) and a fitting parameter (C_{FC}) using the expression:

$$FC \% = \begin{cases} 0 & \text{if } I_c + C_{FC} < 1.71 \\ 80(I_c + C_{FC}) - 137 & \text{if } 1.71 \leq I_c + C_{FC} < 2.96 \\ 100 & \text{if } 2.96 \leq I_c + C_{FC} \end{cases}$$

I_c is based on the normalised CPT tip resistance (Q) and normalized friction ratio (F) as recommended by Robertson and Wride (1998) and Youd et al. (2001). The I_c is also used as a limit where, if I_c exceeds the specified I_c cut-off value, the soil is not considered susceptible and the liquefaction triggering assessment for these soil layers is not undertaken.

The Boulanger and Idriss (2014) liquefaction triggering procedure has a Cyclic Resistance Ratio (CRR) fitting parameter (C_0) that was used to fit CRR predictions to experimental results with probabilities of liquefaction of, $P_L = 15\%$, $P_L = 50\%$, and $P_L = 85\%$

The total vertical stress (σ_{vc}) and effective vertical stress parameters (σ'_{vc}) are given by the expressions:

$$\sigma_{vc} = \gamma z \text{ and } \sigma'_{vc} = \sigma_{vc} - u.$$

where γ is the soil density and u is the static porewater pressure defined by:

$$u = \begin{cases} 0 & \text{if } z < GWD \\ (z - GWD) \times 9.81 & \text{if } z > GWD \end{cases}$$

where GWD is the depth to the ground water below the ground surface.

The γ , C_{FC} , I_c cut-off, earthquake magnitude (M_w), Peak Ground Acceleration (**PGA**), P_L and GWD parameters used for the automated LSN assessment in Christchurch for ILV assessment purposes are summarised in Table I2.1.

Each of the input parameters listed in Table I2.1 and the reason for why the associated values have been adopted are discussed in **Appendix A**.

Table I2.1: Input Parameters used for the automated regional liquefaction triggering assessment for ILV assessment purposes

Input parameter	Default value adopted	Comments
Soil Density (γ)	18 kN/m ³	Not sensitive to the typical variability in soil density in Christchurch (Tonkin & Taylor, 2013)
Fitting parameter C_{FC}	$C_{FC} = 0.0$	Appropriate upper bound value for Christchurch soils (Lees, et al., 2015)
I_c - cutoff	I_c cutoff = 2.6	Appropriate value for Christchurch soils (Lees, et al., 2015)
Level of earthquake shaking	$M_w = 6.0$, $PGA = 0.3g$	Critical case for 100 year return period levels of earthquake shaking using the BI 2014 methodology
Probability of Liquefaction (P_L)	$P_L = 15\%$	Based on standard engineering design practice
Depth to Groundwater (GWD)	Surrogate median groundwater surface for the post-CES ground surface elevation and offsets from the surrogate median groundwater surface for the pre-CES ground surface elevation	Based on the GNS groundwater model (van Ballegooy, et al., 2014a) Two key assumptions associated with GWD are: <ul style="list-style-type: none"> The groundwater profile is hydrostatic below the ground water surface; and The soils are fully saturated below the groundwater surface.

I2.2 Assessment of Liquefaction Vulnerability

The LSN parameter was developed to assess the liquefaction vulnerability of residential land in Canterbury in future earthquakes and was validated against the CES land damage observations. The LSN is defined as:

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

where $\varepsilon_v(z)$ = the volumetric densification strain at depth, z , based on Zhang et al. (2002), which is a function of the FS (described in Section I2.1) and the normalised clean sand CPT tip resistance (q_{c1Ncs})

Extensive studies have been undertaken on assessing the vulnerability of land to liquefaction damage (summarised in **Appendix A**). These studies show that liquefaction triggering of soil layers more than 10m below the ground surface provides a negligible contribution to liquefaction damage at the ground surface. Therefore, the regional LSN models are based on the top 10m of the soil profile only.

I3. LSN Slicing Methodology

In order for the information from a CPT to be used, a sufficient soil profile is required. A process of the LSN slicing has been developed to make use of the data available in the 3,000 CPT on the CGD

that do not contain a sufficient length of profile, without reducing the accuracy of the estimated LSN values by introducing arbitrary LSN slices from neighbouring CPT for the missing portions of the CPT profiles.

The general LSN slicing methodology applied is as follows:

1. The LSN value is estimated for each CPT as described in Section I2 and is then broken down into 16 contributing slices in the upper 10m of the soil profile. The contribution from slices below 10m is not considered;
2. All CPT data is taken into account and the LSN slices are estimated for each of the slices.
3. LSN slices which are in the pre-drill part of the CPT and extend deeper than the GWD or which stop short of 10m are replaced with "NULL" values;
4. All LSN slices above the median groundwater table are assigned an LSN value of 0 (regardless of whether they are in the pre-drill part of the CPT) as they are unlikely to liquefy;
5. CPT containing any NULL values are identified. The LSN slice layers from surrounding CPT in a geologically similar area (based on the areas shown in Figure I3.1) and within 50m are used to replace the NULL value with a LSN slice;
6. A proportional distance weighting is used if more than one CPT in a geologically similar area are within 50m and able to contribute to the LSN slice value (i.e. the LSN slice values from nearby CPT have a higher weighting compared to those from CPT that are further away);
7. CPT which are shorter than a depth of 5m are not extended using the LSN slice methodology (i.e. all CPT are used to contribute towards LSN slice values but only CPT greater than 5m deep are extended to a 10m depth if neighbouring CPT LSN slices are available); and
8. The LSN slice values of each slice down the CPT profile are summed to give a single overall adjusted LSN value at each CPT location with missing data from the soil profile.

The LSN slicing methodology is demonstrated using the schematic drawing in Figure I3.2.

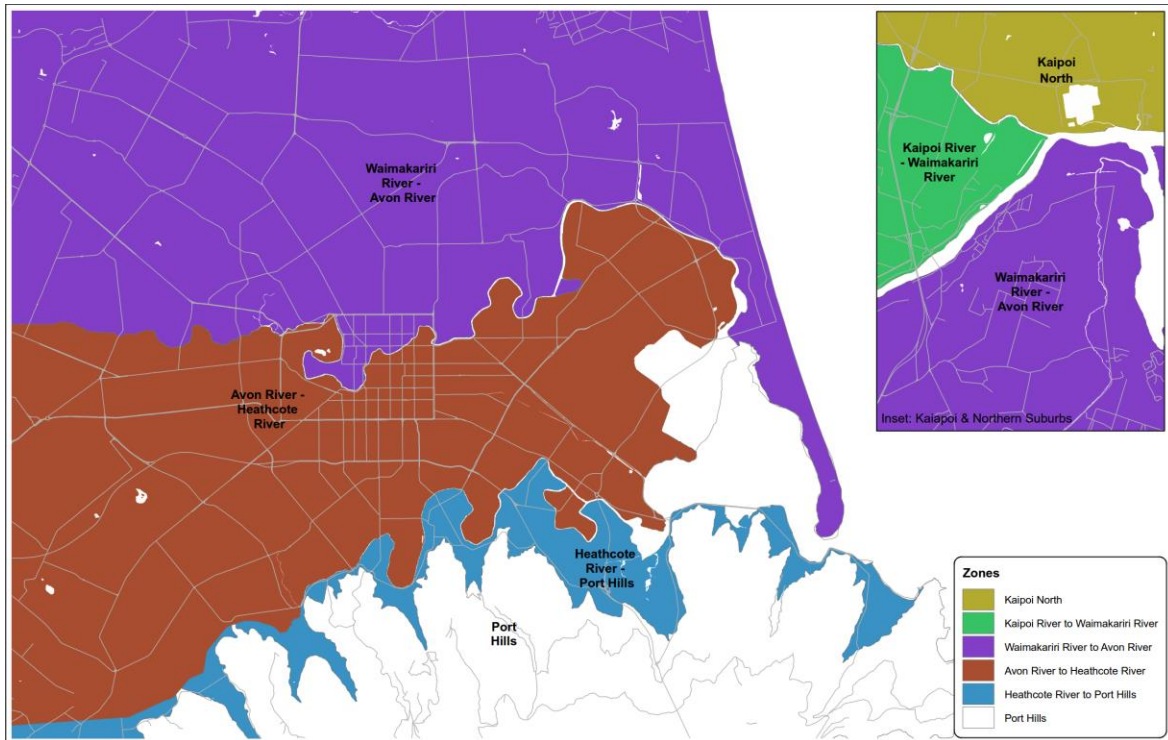


Figure I3.1: Geological areas used as slice interpolation zones.

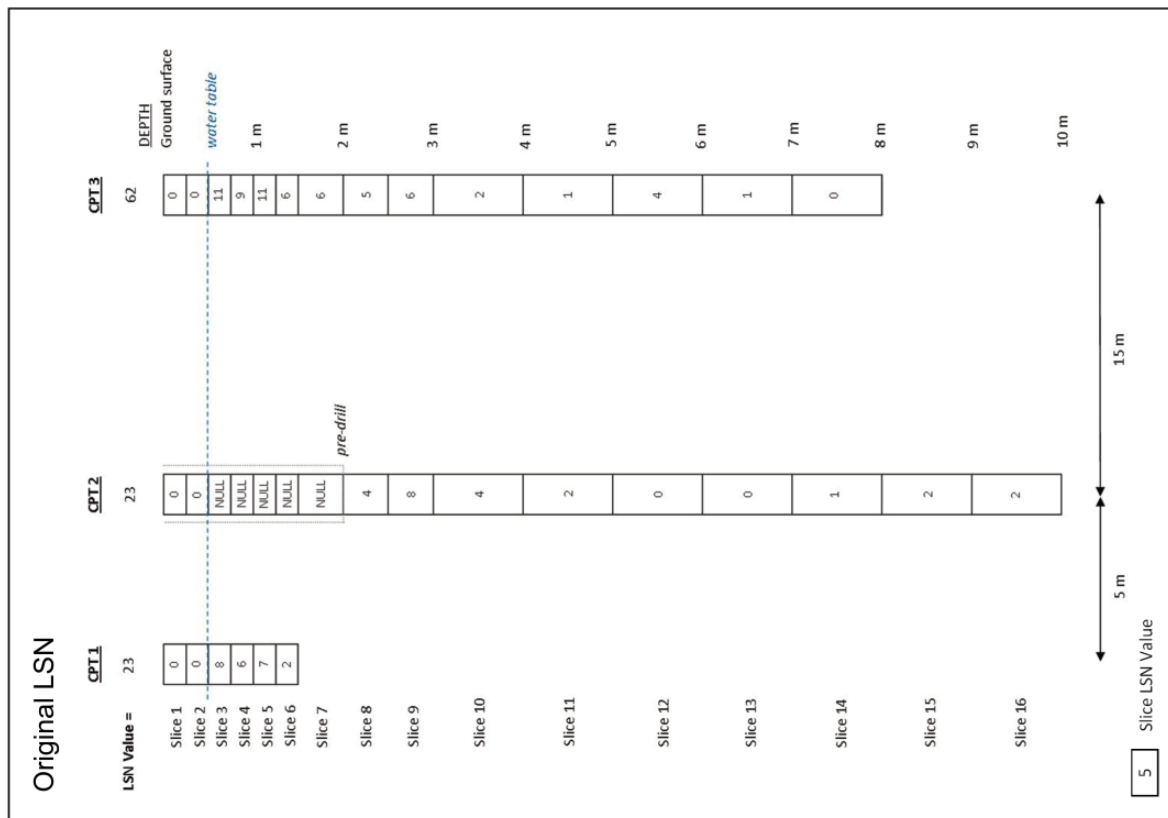
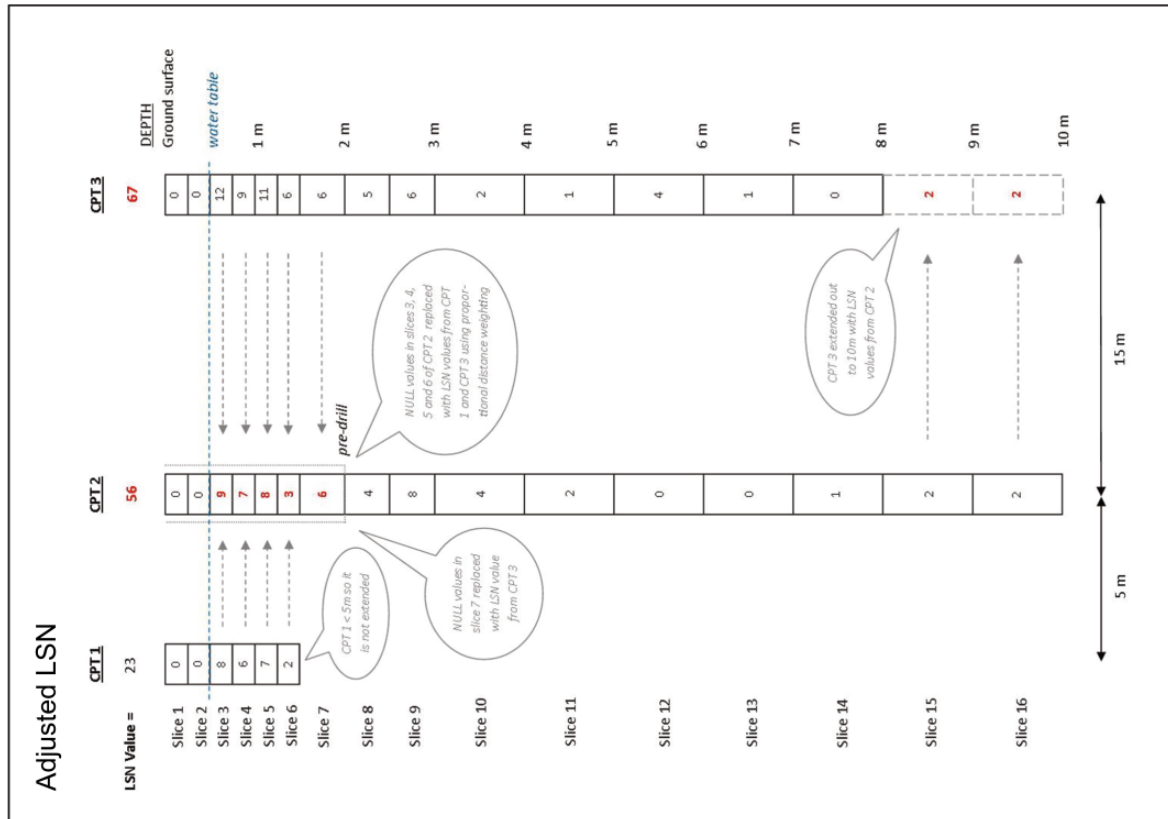


Figure 13.2: Schematic example of the LSN slicing method

I4. LSN Interpolation Process

The estimated LSN values at each CPT location need to be interpolated in order to obtain, on a regional basis, LSN values specific to each property. The LSN interpolation is based on the Natural Neighbour (NN) method with inverse distance weighting (Shepard's basic formulae). The general methodology used to apply these methods is as follows.

- 1 The location of the complete set of CPT and their corresponding LSN values are plotted. Interpolation boundaries are then applied along major watercourses, geological units and other obvious locations as shown on Figure I4.1;
- 2 Each of the sub-areas that is produced is interpolated separately using natural neighbours and the result is clipped back to its' defined boundary;
- 3 The results are then mosaicked to create a single continuous raster of continuous LSN values.

CPT profiles less than 5m deep or with a pre-drill depth greater than 2m are excluded from the analyses.

Following the interpolation process, a minor extrapolation at the perimeter of the grid is carried out. This is described in Section I5 below.

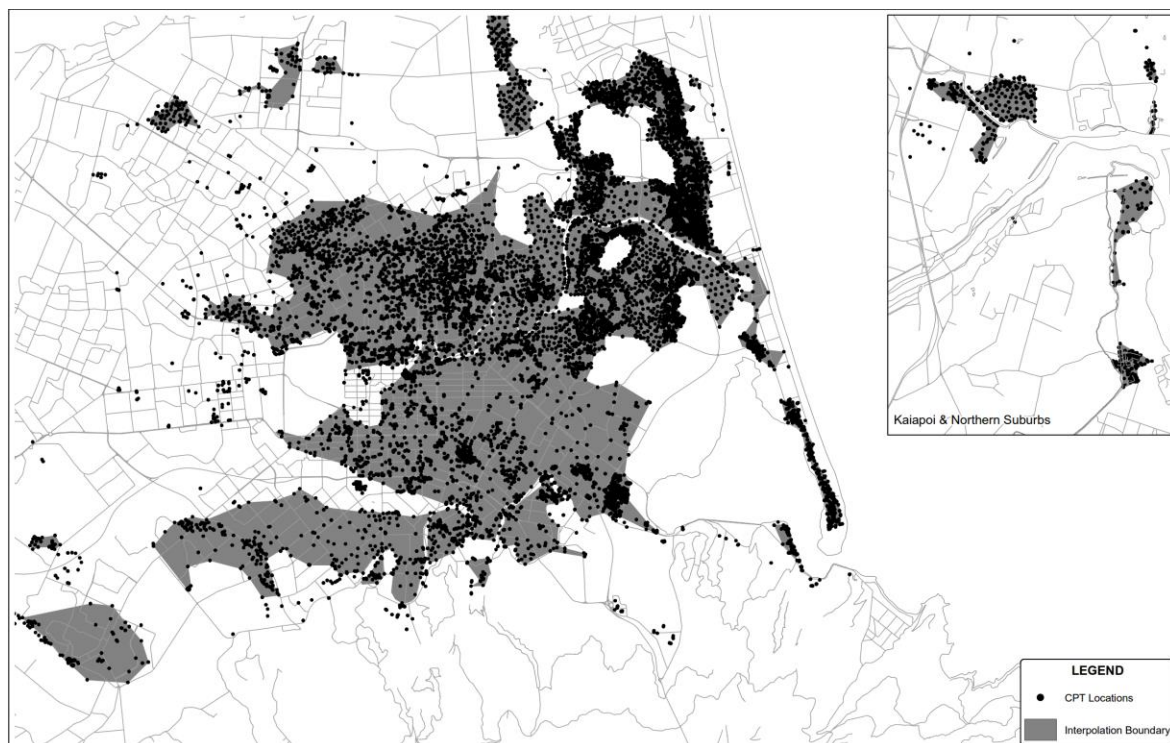


Figure I4.1: Spatial distribution of CPTs and interpolation extents.

I5. LSN Extrapolation Process

The extrapolation process is used around the perimeter of the site investigation regions to include areas that are within 50m of a site investigation location.

- 1 All CPT that are less than 50m from the boundary are selected.

- 2 The estimated LSN values of each CPT are extrapolated for each grid cell up to 50m beyond the boundary as shown in Figure I5.1 below. No extrapolation is carried out across any defined break line.
- 3 Where more than one CPT fall within 50m of each other, Inverse Distance Weighting (IDW) is applied to estimate the LSN value at that point.
- 4 The interpolated raster is then overlaid on the extrapolated raster to produce the final raster.

A series of figures showing the extrapolation process is set out in Figure I5.1.

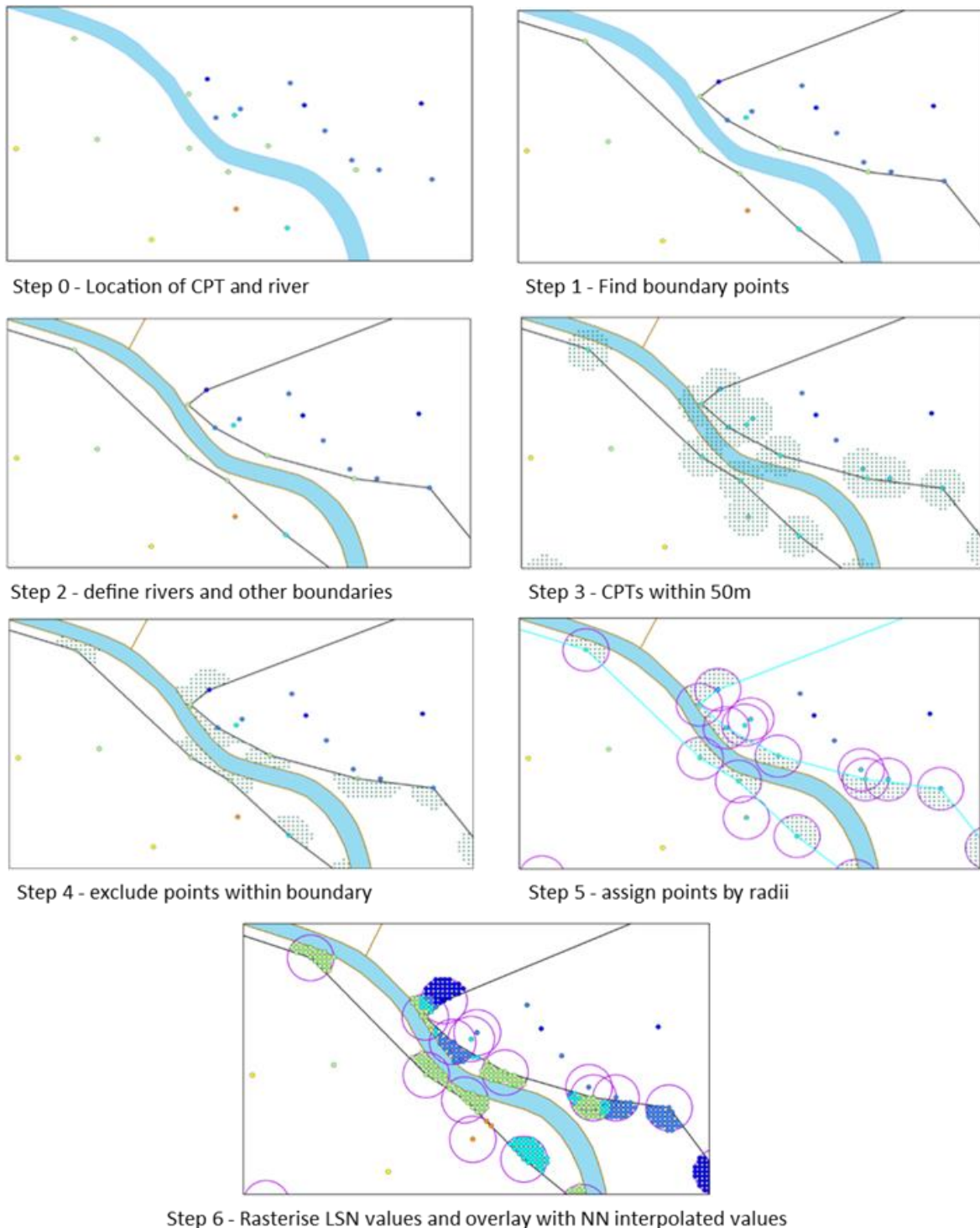


Figure I5.1: Extrapolation process schematic

I6. References

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

Lees, J., van Ballegooy, S. & Wentz, F. J. 2015. Liquefaction Susceptibility and Fines Content Correlations of the Christchurch Soils. *6th International Conference on Earthquake Geotechnical Engineering, Christchurch*.

Tonkin & Taylor Ltd. 2013. *Liquefaction vulnerability study - Report to Earthquake Commission*. (Report 52020.0200) February 2013.

van Ballegooy, S., Cox, S.C., Thurlow, C., Rutter, H.K., Reynolds, T., Harrington, G., Fraser, J. & Smith, T. 2014a. *Median water table elevation in Christchurch and surrounding areas after the 4 September 2010 Darfield Earthquake Version 2*. (GNS Science report 2014/18). Institute of Geological and Nuclear Sciences, Lower Hutt.