Liquefaction Hazard Mapping – Liquefaction Vulnerability Mapping for a Given Return Period versus Return Period Mapping for a Given Severity of Liquefaction Vulnerability

V. Lacrosse, S. van Ballegooy and M. Ogden
Tonkin & Taylor Ltd., Auckland, New Zealand

ABSTRACT
Liquefaction hazard maps are typically developed by collating geotechnical investigation data and undertaking simplified liquefaction analyses. Liquefaction vulnerability parameters are commonly calculated using a simplified liquefaction triggering method, a given groundwater level and a given set of earthquake ground motions, corresponding to a particular return period of earthquake shaking. The results at each investigation location are then typically interpolated and subsequently, smoothing might be applied. A more robust methodology involves dividing a study area into smaller Similar Expected Ground Performance (SEGP) areas as a result of earthquake shaking. Liquefaction consequence parameter values for a wide range of earthquake scenarios are then calculated using the available geotechnical investigation data and grouped according to SEGP areas in which they are located. Each SEGP area then has its own unique liquefaction vulnerability distribution fitted to the data as a function of earthquake magnitude (M_w) and Peak Ground Acceleration (PGA). Using these functions, a variety of liquefaction hazard maps can be produced. A typical mapping approach is to present the median or mean liquefaction vulnerability for each SEGP area for a given level of earthquake shaking. A variant to this approach is to present the expected spatial variability of liquefaction. This approach provides greater insight into how a study area is expected to behave spatially, which is especially relevant for risk modelling. An alternative mapping approach is to determine the level of earthquake shaking required to attain a given level of liquefaction vulnerability. This approach identifies SEGP areas where more frequent, smaller levels of earthquake shaking are likely to result in liquefaction damage and other SEGP areas where less frequent, larger levels of earthquake shaking are required for liquefaction-related damage to occur. This alternative approach helps improve the communication of the liquefaction hazard to non-technical audiences and presents the results in a similar way to other natural hazards that are assessed for land-use planning and hazard management purposes.

1 INTRODUCTION

Liquefaction hazard maps are typically used to communicate the expected liquefaction vulnerability over a study area for a given level of earthquake shaking. Such maps are generally developed by collating geotechnical investigation data and undertaking simplified liquefaction analyses. Liquefaction vulnerability parameters are commonly calculated using a simplified liquefaction triggering method, a given groundwater level and a set of earthquake ground motions, corresponding to a particular return period of earthquake shaking. The results at each investigation location are then usually interpolated and subsequently, some smoothing might be applied.

Ahead of undertaking the liquefaction analyses, a more robust process, presented in Section 2, involves overlaying geomorphic, depth to groundwater and sub-surface geological maps in order to divide regions into smaller Similar Expected Ground Performance (SEGP) areas as a result of earthquake shaking. Geotechnical investigation data within an SEGP area is then grouped and liquefaction vulnerability distributions versus earthquake magnitude (M_w) and Peak Ground Acceleration (PGA) are developed for each SEGP area. These functions can be created regardless of the size of the SEGP area and amount of geotechnical data available.

The liquefaction vulnerability parameter functions are used to create liquefaction vulnerability maps that display the expected spatial variability of liquefaction-related land damage in each SEGP area (discussed in Section 3).

An alternative mapping approach is also discussed in this paper, referred to herein as liquefaction return period mapping. As discussed in Section 4, liquefaction return period mapping presents the level of earthquake shaking required to attain a given level of liquefaction-related consequence, which in turn can be related to an expected severity of land damage. It is an effective way to visually communicate the level of earthquake shaking required to trigger liquefaction.

While the study area presented in this paper focus on the eastern part of Christchurch, the concepts can be applied for liquefaction hazard mapping and risk modelling purposes wherever there are soil deposits susceptible to liquefaction. This paper also only considers Cone Penetration Test (CPT)-based liquefaction analyses, but this methodology is also applicable for liquefaction analyses using other geotechnical investigation types.

1.1 Liquefaction Assessment Parameters and Assumptions

The CPT and Standard Penetration Test (SPT) are the two most widely used tools for undertaking liquefaction assessments. While the case study presented in this paper only uses CPT data, the methodology can also be applied using SPT data.

For this case study, the Liquefaction Severity Number (LSN) liquefaction vulnerability parameter has been used in an area-wide liquefaction assessment approach using the Boulanger and Idriss (2014) simplified liquefaction triggering method and the Zhang et al. (2002) method to calculate the post-liquefaction volumetric consolidation strains. The area-wide liquefaction assessment and calculation of the LSN at each CPT location has been undertaken in accordance with the assumptions laid out in van Ballegooy et al. (2015). All of the CPT data used in this study was obtained from the New Zealand Geotechnical Database (MBIE, 2016).

It is important to note that the methodologies presented in this paper are only applicable for flat land free field liquefaction. This means that the mechanics of lateral spreading are not accounted for.

1.2 Liquefaction Severity Number (LSN)

The LSN liquefaction vulnerability parameter that was developed following the Canterbury Earthquake Sequence 2010-2011 to reflect the more damaging effects of shallow liquefaction on land and shallow foundations. It was formulated to provide a better fit to the observed liquefaction-related land damage in Christchurch than the existing vulnerability parameters, as described in van Ballegooy et al. (2014a).

The LSN parameter is defined in terms of the calculated post-liquefaction volumetric consolidation strain for each layer, integrated over the depth of the soil profile containing liquefying layers. As a result, LSN gives a larger weighting factor to liquefying soil layers closer to the ground surface compared to liquefying layers at depth. It considers the balance between crust thickness and severity of underlying liquefaction, allowing the analysis of more complex layered soil profiles such as those frequently encountered in New Zealand.

More information on how LSN values are computed from CPT investigations and the difference between LSN and other vulnerability parameters can be found in van Ballegooy et al. (2014a).

1.3 Risk Modelling

Liquefaction vulnerability maps used to inform design/urban planning are different to those used to inform risk modelling. For design and planning purposes, a conservative groundwater depth, accounting for seasonal highs, is more likely to be used (i.e. the 15th percentile depth to groundwater). Likewise, conservatism is incorporated in the liquefaction triggering assessment by using the 15th percentile probability of liquefaction (P_L) Cyclic Resistance Ratio (CRR) curve.

With risk modelling, it is important to use mean values to avoid compounding conservatism. The uncertainty may be captured and modelled by incorporating a standard deviation parameter. Given that this paper focuses on risk modelling, the median depth to groundwater model for the case study area (van Ballegooy et al., 2014b) and the 50th percentile CRR curve have been used.

1.4 Level of Earthquake Shaking

The return period level of earthquake shaking is directly linked to the PGA. For example, in Christchurch, the MBIE Guidelines (2014) state that for a M_w 6 earthquake, a PGA value of 0.19g is representative of 25-year return period levels of earthquake shaking. PGAs of 0.30g and 0.52g are representative of 100-year and 500-year return period levels of earthquake shaking respectively.

The example presented in this paper focuses on a M_w 6 earthquake, as it is the dominant hazard source in Christchurch (Bradley, 2014).

2 LIQUEFACTION HAZARD MAPPING METHODOLOGY

The flowchart in Figure 1 presents the methodology used to develop the liquefaction vulnerability maps and liquefaction return period maps presented in this paper. This methodology can be used for both less granular and granular detailed mapping. Each step is discussed in Sections 2 and 3.

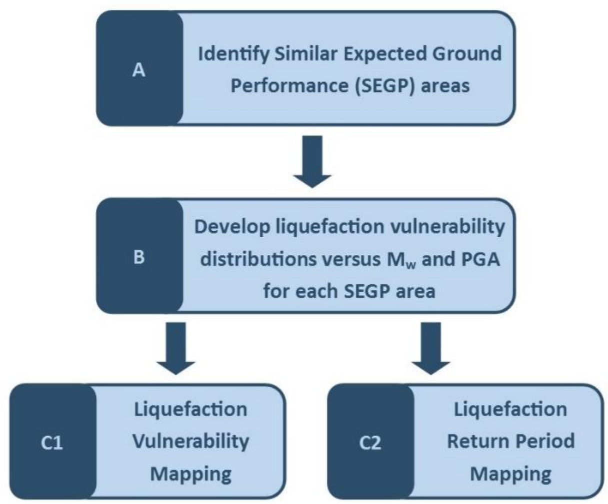

Figure 1. Liquefaction hazard mapping methodology flowchart.

2.1 Similar Expected Ground Performance (SEGP) Areas

Prior to undertaking any liquefaction assessments, SEGP areas are developed. These areas are based on similar geomorphology, similar sub-surface geology and similar depth to groundwater conditions. Adding this step to the liquefaction hazard mapping process means a liquefaction hazard map can be created regardless of the density of geotechnical investigation data. The amount of knowledge about a study area ultimately determines how coarse or refined the SEGP areas are. This step requires the consideration of the geological processes and history of the study area, requiring collaboration between the engineering and geology disciplines, ensuring the larger picture is carefully considered before site-specific liquefaction analyses are undertaken. This step is particularly important in study areas with limited geotechnical investigation information.

Interpolating single LSN values over an area does not capture all the potential land performance outcomes. Creating SEGP areas is an effective and more robust way to capture the potential spatial variability of the area as it incorporate uncertainty. A study by Russell et al. (2015) explains how it is common for suburbs to behave similarly by experiencing consistent liquefaction-related land damage, yet the CPT-based liquefaction vulnerability assessments indicate the land damage across these suburbs can in fact be highly variable.

2.2 Liquefaction Vulnerability Functions

The LSN is calculated for all the CPT investigations for different levels of earthquake shaking. These results are grouped together for each SEGP area and LSN distributions versus earthquake shaking intensity (represented by PGA) are developed. Figure 2 presents an example of this approach for an area in eastern Christchurch, New Zealand, assuming a M_w 6 earthquake event. Each grey line in the plots within Figure 2 represents the LSN versus PGA response of a single CPT investigation.

Developing the SEGP areas and grouping the CPT together within these areas enables the expected spatial variability to be captured. For example, a site could have a number of CPT in it, all with very different LSN values. Grouping these CPT is important to capture the fact that the subsurface conditions vary greatly over a short distance. Alternatively, another site may have CPT that compute very similar LSN values. Therefore, the spatial distribution of the LSN values for that SEGP area would be very consistent.

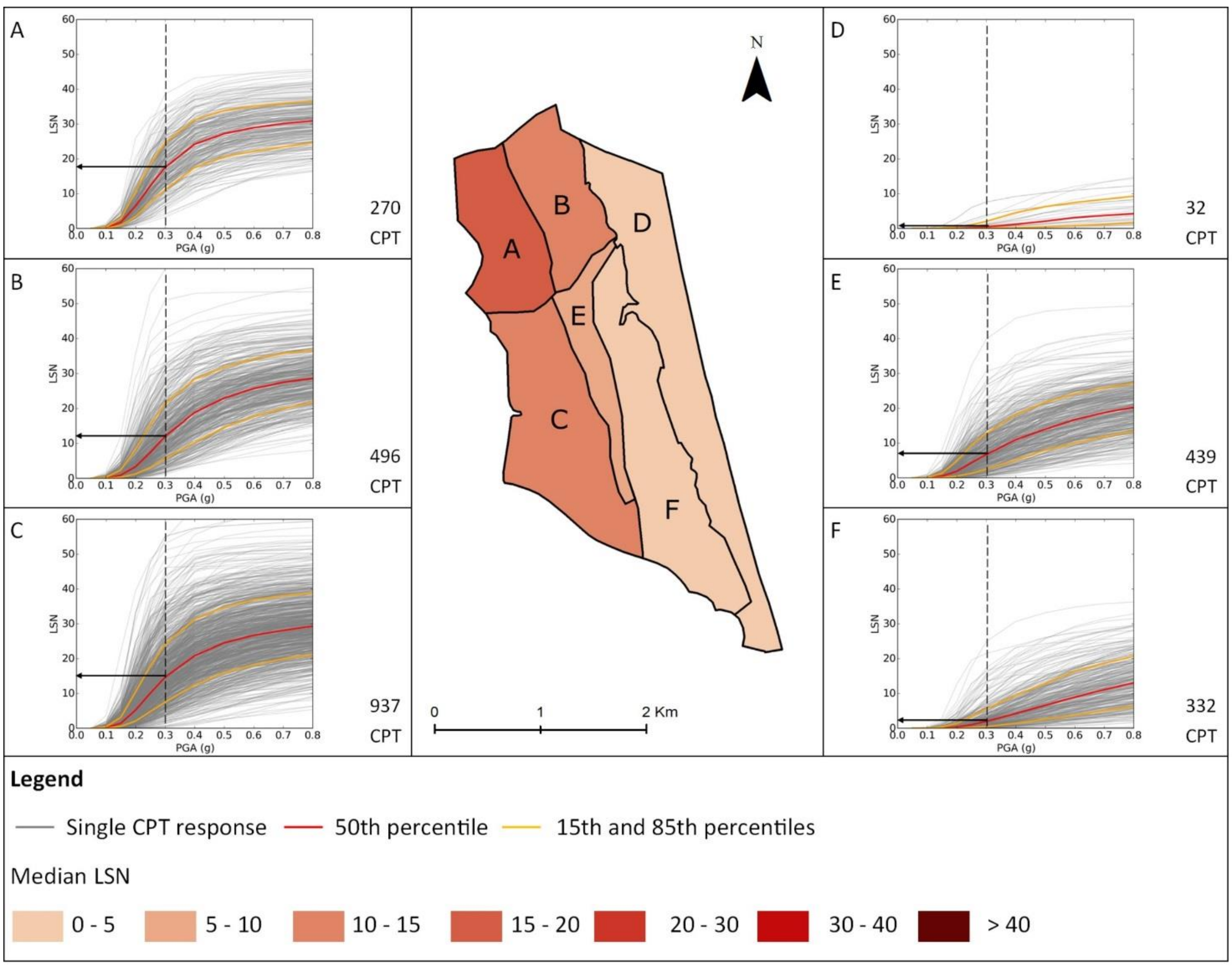

Figure 2. Plots showing the liquefaction vulnerability (i.e. LSN) versus earthquake shaking intensity (i.e. PGA) for a M_w 6 earthquake event for each of the six SEGP areas in eastern Christchurch. Each plot contains all the computed CPT investigations for that SEGP area (in grey) and 15th, 50th and 85th percentile values at the various PGA values are shown as red and yellow lines. The number of CPT within each SEGP area is captured in the bottom right hand corner of each plot. The liquefaction vulnerability map in the middle presents the median LSN value for each SEGP area for 100-year return period levels of earthquake shaking (i.e. M_w 6, 0.3g).

Figure 2 shows that in eastern Christchurch, at 0.3g (refer to the vertical dashed lines on each graph), Area A is the most vulnerable (i.e. it is the distribution with the highest LSN values) and Area D is the least vulnerable (i.e. it is the distribution with the lowest LSN values) to liquefaction-related land damage. While Area A, B and C have similar median LSN values at high levels of earthquake shaking, the median LSN value of Area A increases at a faster rate at lower levels of earthquake shaking than Area B and C. Another point to note is that while Area A, B and C all have similar median LSN values at high levels of earthquake shaking, the spatial distribution of LSN is different in all three SEGP areas. The spatial distribution of LSN in Area A is much lower than Areas B, let alone C as there is a smaller range between the 15th and 85th percentile LSN values (refer to the yellow curves on each graph in Figure 2).

The spatial distribution of LSN varies not only between the SEGP areas but also depending on the level of earthquake shaking. For example, the spatial distribution of LSN in Area A is similar at both 0.3g and 0.8g. Conversely, the spatial distribution of LSN in Area F is much greater at 0.8g than it is at 0.3g. Figure 3 presents the expected spatial distribution of LSN for each of the six SEGP areas at 0.3g levels of earthquake shaking in form of a frequency density plot.

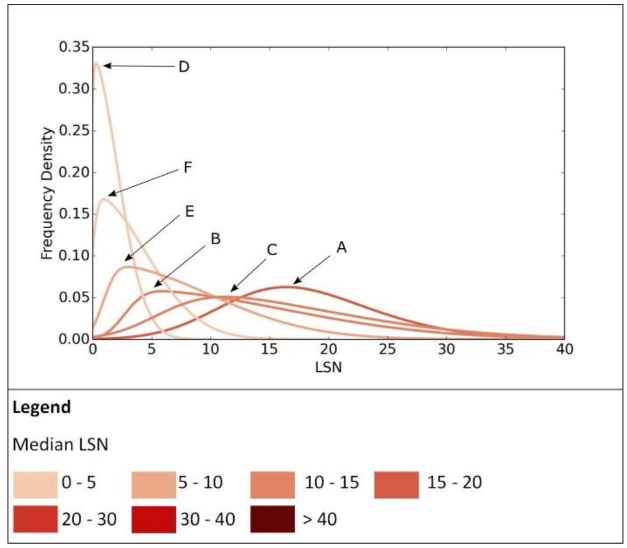

Figure 3. Frequency density plot showing the expected spatial distribution of liquefaction vulnerability (i.e. LSN) for each SEGP area for 100 year return period levels of earthquake shaking (i.e. M_w 6, 0.3g).

3 LIQUEFACTION VULNERABILITY MAPPING

Current liquefaction hazard mapping practice typically involves developing a map of the likely expected liquefaction vulnerability for a given level of earthquake shaking. This type of map can be derived from the liquefaction vulnerability versus earthquake shaking functions. An example is shown in Figure 2 for M_w 6 and 0.3g levels of earthquake shaking, corresponding to a 100-year return period level of earthquake shaking in eastern Christchurch (MBIE, 2014). The map visually demonstrates where liquefaction damage is expected to be most and least severe in the different SEGP areas for this given level of earthquake shaking. In this example, Area A has the highest liquefaction vulnerability and Area D, E and F all have the lowest liquefaction vulnerability.

The liquefaction vulnerability map that presents the median LSN for each SEGP area (Figure 2) is useful for indicating which SEGP areas are more vulnerable than others. However, this map does not provide any insight into the spatial variability of liquefaction vulnerability that can be expected in each SEGP area. Some SEGP areas have a higher spatial variability in liquefaction vulnerability compared to others, typically due to spatial variability in subsurface ground conditions in each SEGP area. Capturing this variability is important to better understand the expected performance of a study area.

Figure 3 shows the expected spatial distribution of LSN for each of the six polygons for M_w 6 and 0.3g levels of earthquake shaking. It demonstrates that while some of the SEGP areas have very similar median LSN values, the distribution around the median can differ significantly.

Figures 2 and 3 show that Area D and F have very similar median LSN values at 100-year levels of earthquake shaking. However, Figure 3 shows that the standard deviation (i.e. variability) of the LSN is very different for the two SEGP areas. Area D has a much smaller standard deviation than Area F representing less expected spatial distribution of liquefaction vulnerability in Area D than Area F. Conversely, the median LSN values of Area B and E are different (see Figure 2) but the spatial distributions of these two SEGP areas are similar (see Figure 3).

The liquefaction vulnerability variability within each area can also be captured visually. For example, each SEGP area can be broken down into a grid (in this instance a 250 x 250m grid). Each cell is randomly assigned a LSN value based on the LSN distribution at M_w 6 and 0.3g. The resultant map is shown in Figure 4.

Figure 4 is a visual representation of Figure 3. It shows that Area B and C have the greatest amount of expected spatial variability (i.e. there is a large assortment of different cell colours) and that Area D has the least amount of expected spatial variability (i.e. nearly all the cells have a similar colour). While the exact same information can be derived from the frequency distribution plot in Figure 3, it is easier to communicate the expected spatial variability of the liquefaction vulnerability on the liquefaction hazard map to a non-technical audience.

The application of this type of approach is relevant for risk modelling purposes because it means more accurate losses can be estimated. For example, using the median damage value may result in a prediction that half the houses in that SEGP area are damaged, requiring repairs worth 20% of the costs of the houses. However, when uncertainty is incorporated, this could predict that in fact, a large portion of the houses require minor cosmetic repairs, a small portion of the houses require repairs worth 50% of the cost of the house and another small portion of the houses are total losses. Being able to capture this information means not only can more accurate losses be calculated, but the risk model can also be used to estimate the number of builders required to repair the houses or the number of families that may need to be displaced.

It is important to note than the expected spatial distribution can vary significantly within a SEGP area for different levels of earthquake shaking and magnitude. For example, while the expected spatial distribution of Area F is low at 100-year levels of earthquake shaking, the expected spatial distribution for that SEGP area is much greater at 500-year levels of earthquake shaking. On the contrary, for Area A, the expected spatial distribution at 500-year levels of earthquake shaking is lower than that at 100-year levels of earthquake shaking.

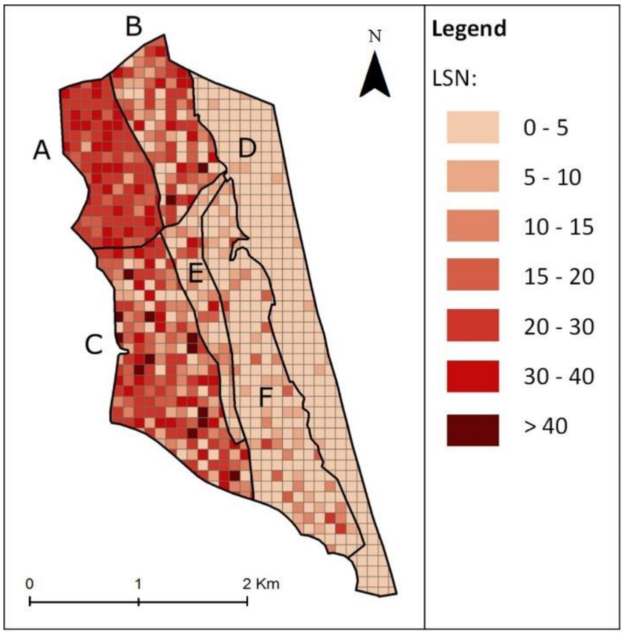

Figure 4. Liquefaction vulnerability map showing the expected spatial distribution of liquefaction vulnerability (i.e. LSN) for each SEGP area for 100-year return period levels of earthquake shaking (i.e. M_w 6, 0.3g).

4 LIQUEFACTION RETURN PERIOD MAPPING

An alternative mapping approach is to determine the level of earthquake shaking required to attain a given level of liquefaction-related land damage. This is referred to as liquefaction return period mapping. As with the liquefaction vulnerability mapping approach, the SEGP areas and the liquefaction vulnerability versus earthquake shaking functions (described in Sections 2.1 and 2.2) are used to develop the liquefaction return period map.

For this example, LSN = 10 has been used as a threshold to indicate the likelihood of minor to moderate liquefaction-related land damage. Figure 5 presents the level of earthquake shaking (i.e. PGA) required from a M_w 6 event to attain LSN = 10. While it is possible to simply present the liquefaction at the median level of earthquake shaking required for each SEGP area, the map in Figure 5 presents the expected spatial variability of the level of earthquake shaking required for each SEGP area. The same process is used as that described in Section 3 except in this case, it refers to the level of earthquake shaking rather than the liquefaction vulnerability.

Figure 5 shows that Area A requires a low return period earthquake event (i.e. a small amount of earthquake shaking) to attain a LSN = 10. For a M_w 6 event, liquefaction-related land damage could be expected at 0 – 0.2g (corresponding to 25-year return period levels of earthquake shaking or less). Conversely, Area D requires a very large return period earthquake event (i.e. a large amount of earthquake shaking) to attain a LSN = 10. For a M_w 6 event, liquefaction-related land damage would only be expected at more than 0.8g (corresponding to much greater than 500-year return period levels of earthquake shaking).

This mapping approach is not common but is similar to how other natural hazards are mapped and presented. For example, flood mapping is commonly presented as areas within a region that are inside the 10, 50 and 100-year flood plain. This helps local government authorities with land-use planning as it clearly identifies areas that are potentially affected by smaller, more regular flooding events and areas that are only affected by larger more infrequent flooding events. The same information can be derived for liquefaction vulnerability using liquefaction return period mapping. It can be used to identify areas where more frequent smaller levels of earthquake shaking are likely to result in liquefaction damage and other areas where less frequent larger levels of earthquake shaking are required for liquefaction-related damage to occur.

It is noted that the spatial variability is typically higher for liquefaction return period mapping compared to liquefaction vulnerability mapping (i.e. there is a wider distribution when a horizontal line is drawn across the liquefaction vulnerability functions than when a vertical line is drawn). The amount of spatial variability is also dependent on the desired liquefaction vulnerability level. There is less spatial variability in earthquake shaking at LSN = 5 than there is at LSN = 10. Generally, the greater the LSN, the greater the spatial variability in earthquake shaking.

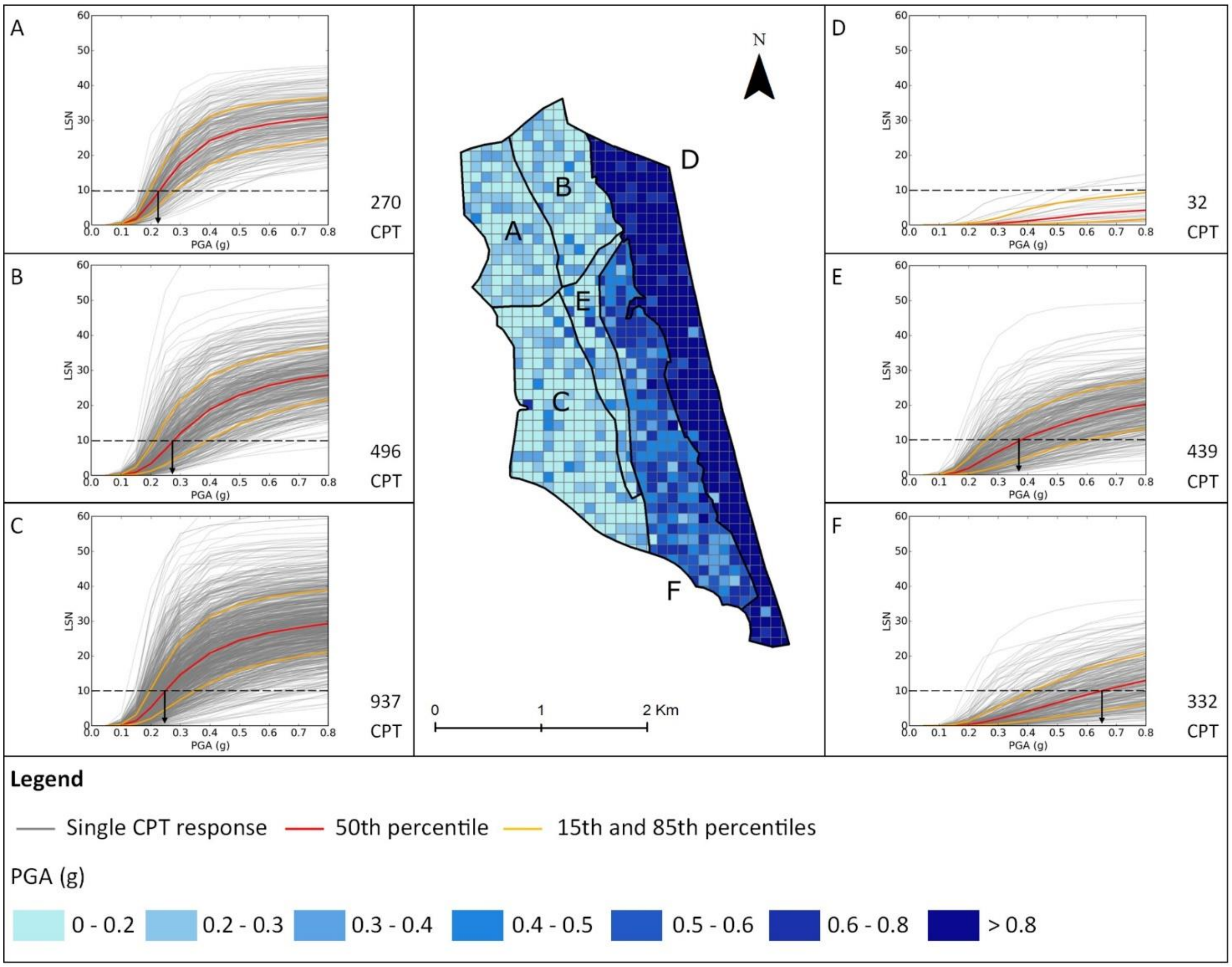

Figure 5. The liquefaction return period map in the middle presents the expected spatial distribution of the level of earthquake shaking required to attain minor to moderate liquefaction-related land damage (LSN = 10) for a M_w 6 earthquake event. The number of CPT within each SEGP area is captured in the bottom right hand corner of each plot.

5 FURTHER WORK

The current approach of calculating the LSN distributions for each SEGP area is to take all the data. However, within an area, in reality, the slightly denser pockets of soil do not behave better and the slightly looser pockets do not behave poorly. More uniform behaviour is generally observed than what the CPT-based liquefaction assessments suggest (as shown in Russell et al., 2015). This is probably because when there is heterogeneity in soil conditions, excess pore water pressures can also dissipate laterally, liquefying pockets of denser material that are surrounded by looser material and likewise reducing the build-up of excess pore water pressures by lateral dissipation from a loose pocket of material into the surrounding denser soils. Therefore, the extremes do not actually occur and the current process over-estimates the spatial variability.

Further work is being undertaken by examining actual liquefaction performance in case history SEGP areas to quantify how much the spatial variability standard deviation parameter can be reduced by. This research can then be incorporated into the methodologies discussed in this paper.

6 CONCLUSIONS

The following conclusions can be drawn from this paper:

- It is possible to capture the expected behaviour of a SEGP area by grouping CPT results within the area together. The expected spatial variability of liquefaction vulnerability can then be considered rather than a single median value. Being able to capture the spatial variability and account for uncertainty is particularly important for SEGP areas with limited geotechnical investigation data.
- It is recognised that this process can overestimate the spatial variability and further work being undertaken compares actual liquefaction observations and land performance against CPT-based liquefaction assessments to determine

whether the spatial variability standard deviation parameter can be reduced.

- Creating SEGP areas means the areas are being evaluated more robustly with careful consideration of the geology, geomorphology and depth to groundwater. Current practice involves interpolating CPT locations, in some cases over large distances, without considering the geology of the region. This approach can be undertaken regardless of the amount of geotechnical data available.
- Liquefaction vulnerability can be visually presented in multiple ways. The most common method is to present the median liquefaction vulnerability for a given level of earthquake shaking (see Figure 2). It is also possible to present the expected spatial distribution of the liquefaction vulnerability for a given level of earthquake shaking (see Figure 4). This is typically more useful as greater insight can be drawn from this type of map. Alternatively, the same data can be used to create a liquefaction return period map. This shows the expected spatial distribution of the level of earthquake shaking required to attain a given level of liquefaction vulnerability (see Figure 5).
- Liquefaction vulnerability maps are more commonly used than liquefaction return period maps but the latter is more aligned with how other hazards are usually mapped and presented. The different mapping approaches are useful in their own right and provide alternative insights. A liquefaction vulnerability map helps a community answer the question, “If we had an earthquake of this size, what might our liquefaction-related land damage look like?”, whereas a liquefaction return period map helps answer the question, “How big of an earthquake do we need for us to start worrying about having liquefaction-related land damage?”.

7 REFERENCES

Bradley, B. 2014. Seismic hazard analysis for urban Christchurch accounting for the 2010-2011 Canterbury earthquake sequence. Technical report prepared for the New Zealand Earthquake Commission (EQC) and Tonkin and Taylor Ltd by Bradley Seismic Ltd.

Boulanger, R. W. and 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, USA.

Ministry of Business, Innovation and Employment (MBIE) 2014. Clarifications and updates to the Guidance 'Repairing and rebuilding houses affected by the Canterbury earthquakes'. Issue 7. Ministry of Business, Innovation and Employment, Christchurch. Available from: https://www.building.govt.nz/building-code-compliance/canterbury-rebuild/repairing-and-rebuilding-houses-affected-by-the-canterbury-earthquakes/

Ministry of Business, Innovation and Employment (MBIE) 2016. New Zealand Geotechnical Database (NZGD). Available from: https://www.nzgd.org.nz

Russell, J., van Ballegooy, S., Torvelainen, E. & Gulley, R. 2015. Consideration of Ground Variability Over an Area of Geological Similarity as Part of Liquefaction Assessment for Foundation Design. *6th International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand.

van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M.E., Cubrinovski, M., Bray, J.D., O’Rourke, T., Crawford, S., Cowan, H. 2014a. Assessment of Liquefaction-Induced Land Damage for Residential Christchurch. *Earthquake Spectra, EERI*, 30(1), 31 – 55.

van Ballegooy, S., Cox, S.C., Thurlow, C., Rutter, H.K., Reynolds, T., Harrington, G., Fraser, J. & Smith, T. 2014b. 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, New Zealand.

van Ballegooy, S., Lacrosse, V., Simpson, J. & Malan, P. 2015. Comparison of CPT-based simplified liquefaction assessment methodologies based on Canterbury Geotechnical Dataset. *12th Australia New Zealand Conference on Geomechanics*, Wellington, New Zealand.

Zhang, G., Robertson, P. & Brachman, R. 2002. Estimating liquefaction-induced ground settlements from CPT for level ground. *Canadian Geotechnical Journal*, 39(5): 1168-1180.