

Effect of Fines Content Correlations and Liquefaction Susceptibility Thresholds on Liquefaction Consequence

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ABSTRACT

The influence soil plasticity is one the main criteria for assessing the susceptibility of fine grained soils to liquefaction. In addition, the soil Fines Content (FC) increases the liquefaction triggering resistance of soils and is incorporated into liquefaction triggering assessment procedures. The soil behaviour type index (I_c), is a parameter calculated from Cone Penetration Test (CPT) tip resistance (q_c) and sleeve friction (f_s). I_c is typically used to indicate whether soils are susceptible to liquefaction (typically when $I_c < 2.6$). I_c has also been correlated to FC and these correlations are often used in the simplified CPT-based liquefaction triggering assessments. Lees et al. (2015) used the results of an extensive geotechnical investigation dataset collected following the 2010 – 2011 Canterbury Earthquake Sequence (CES) to examine the correlation of the liquefaction susceptibility and FC with I_c for the Christchurch soils. This paper assesses the sensitivity of liquefaction consequence assessments across Christchurch, using the extensive CPT dataset, at different levels of seismic hazard, by comparing the assessment results using typical default FC- I_c correlations with the Christchurch-specific FC- I_c correlation from Lees et al. (2015). The results show that liquefaction consequence assessments are particularly sensitive to the 25 and 100 year design ground motions and demonstrates the importance of undertaking laboratory testing and developing site-specific FC- I_c correlations for liquefaction assessment purposes.

Introduction and Background

The influence of Fines Content (FC) on increasing the liquefaction triggering resistance of soils is incorporated into the Boulanger and Idriss (2014) liquefaction triggering methodology. The soil behaviour type index (I_c), is a parameter calculated from Cone Penetration Test (CPT) tip resistance (q_c) and sleeve friction (f_s). The inability of the CPT to obtain soil samples requires that I_c correlations be relied on to estimate the FC of the soil when using only the CPT for site characterisation. Since the I_c parameter has been developed based on correlation to characteristic mechanical behaviour of different soil types, and because there is inherent soil variability, it is considered best practice to develop site-specific I_c -FC correlations by obtaining laboratory-derived FC values from representative samples collected adjacent to CPT soundings at the same depth. The FC- I_c correlation developed by Boulanger and Idriss (2014) includes a site specific fitting parameter, C_{FC} , which can be adjusted to calibrate the FC- I_c correlations.

Lees et al. (2015) used the results of an extensive geotechnical investigation dataset collected following the CES to examine the correlation of liquefaction susceptibility and FC with I_c for the Christchurch soils. Using the Bray and Sancio (2006) liquefaction susceptibility criteria, Lees et al. (2015) concluded that at a regional scale, an I_c cutoff value of 2.6 (above which the soils are

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not considered susceptible to liquefaction) for liquefaction triggering assessment is appropriate for the Christchurch soils. However, there are localised areas, particularly in the upper 0 to 5 m soil layers, where a slightly higher or lower I_c cutoff may be more appropriate. Lees et al. (2015) also show that the Boulanger and Idriss (2014) $FC-I_c$ correlation with a C_{FC} parameter of 0.2 is a better fit for Christchurch soils compared to the recommended default value (in the absence of laboratory testing) of 0. However, Lees et al. (2015) showed that there are localised areas in Christchurch, where higher or lower values (above and below 0.2) would be more appropriate.

This paper comprises three parts. The first part examines the sensitivity of the Cyclic Resistance Ratio (CRR) curves to the I_c parameter assuming the Boulanger and Idriss (2014) $FC-I_c$ correlation with C_{FC} values of 0 and 0.2 (Figure 1). The second part of the paper analysis the predicted extent and severity of liquefaction in Christchurch for C_{FC} values of 0 and 0.2 for the September 2010, 22 February and 13 June 2011 events in the 2010 – 2011 Canterbury Earthquake Sequence (CES) using the extensive Christchurch Cone Penetration test (CPT) dataset. The back analysis methodology, including the reasons for using the Boulanger and Idriss (2014) liquefaction triggering method coupled with the CPT-based Liquefaction Severity Number (LSN) consequence parameter are discussed in Lacrosse et al. (2015). The back analyses results are then compared to the respective mapped land damage observations across Christchurch for the three respective events (shown in the top row of Figure 2) to examine whether the incorporation of a Christchurch specific I_c-FC relationship improves the prediction of liquefaction extent and severity.

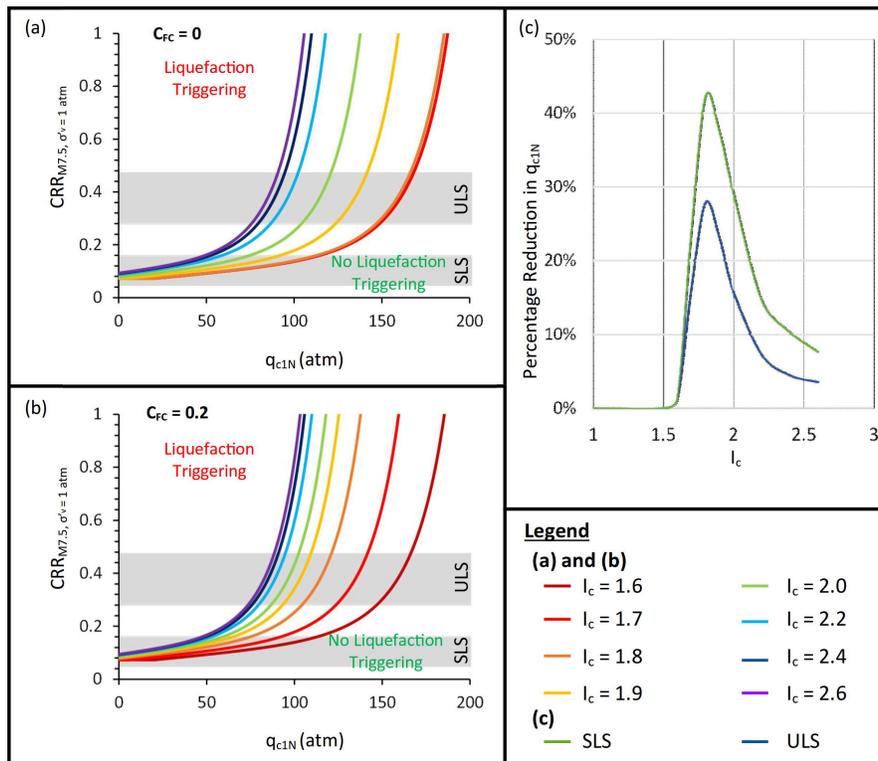


Figure 1. (a & b) The Boulanger and Idriss (2014) CRR lines for I_c between 1.6 and 2.6 for $C_{FC} = 0$ and 0.2 respectively. (c) Percentage reduction in q_{c1N} at the SLS and ULS ground motion CRR values, when comparing calculated q_{c1N} at $C_{FC} = 0.2$ with calculated q_{c1N} at $C_{FC} = 0$.

The third part of this paper examines the sensitivity of the calculated LSN liquefaction vulnerability parameter across Christchurch for C_{FC} values of 0 and 0.2 at 25, 100 and 500 year return period ground motions using the same methodology as described in Lacrosse et al. (2015). These three return periods are commonly referred to in New Zealand as the Serviceability Limit State (SLS), Intermediate Limit State (ILS) and the Ultimate Limit State (ULS) respectively. The SLS, ILS, and ULS ground motions for the Christchurch area have been based on a reference Magnitude (M) 6 earthquake with corresponding Peak Ground Acceleration (PGA) values of 0.19g, 0.30g, and 0.52g, respectively as discussed in Lacrosse et al. (2015). Sensitivity of the I_c cutoff value (ranging between 2.4 and 2.8) is also examined.

Sensitivity Liquefaction Triggering to the C_{FC} Parameter

Standardised M7.5 CRR ($CRR_{M7.5, \sigma'_v = 1atm}$) curves are shown in Figure 1a and 1b for I_c values ranging from 1.6 and 2.6 for $C_{FC} = 0$ and 0.2. They show that as I_c increases, the CRR curves shift to the left (i.e. liquefaction resistance increases). When C_{FC} increases from 0 to 0.2 (i.e. comparing Figures 1a and 1b), the CRR curves for $I_c > 1.6$ move to the left. The percentage reduction in normalised q_c (q_{cIN}) at the SLS and ULS ground motion CRR values when comparing the values calculated using $C_{FC} = 0.2$ with those calculated using $C_{FC} = 0$, is shown in Figure 1c. It can be seen that the percentage reduction in CRR is greater for the SLS ground motions compared to the ULS ground motions, and that the biggest changes occur when I_c is between about 1.7 and 2.2 (i.e. the sensitivity of liquefaction triggering to the FC- I_c correlation is greatest for this range of I_c). The largest percentage reduction in CRR occurs when $I_c \approx 1.8$ and is approximately 28% and 42% for the SLS and ULS ground motions respectively.

Sensitivity of the C_{FC} Parameter on Assessment of Liquefaction Consequence

The LSN parameter was computed at each CPT location for the top 10 m of all CPT soundings using the Boulanger and Idriss (2014) probability of liquefaction, $P_L = 15\%$ CRR equations for the September 2010, 22 February and 13 June 2011 CES events using the same methodology as described in Lacrosse et al. (2015). The second and third rows of Figure 2 present regional maps of the calculated LSN and frequency histograms, assuming $C_{FC} = 0$ (the typical default FC- I_c correlation) showing the distributions of calculated LSN for the none-to-minor, minor-to-moderate and moderate-to-severe land damage categories shown in the top row of Figure 2. The LSN values generally correlate with the observations of land damage within each event, i.e., areas with moderate-to-severe observations of land damage generally have higher LSN values.

The frequency histograms exhibit similar trends with none-to-minor land damage typically characterised by LSN values less than 15 to 20 and moderate-to severe land damage typically characterised by LSN values greater than 15 to 20. The fourth and fifth rows of Figure 2 present the corresponding maps and histograms for the same analyses, but with $C_{FC} = 0.2$ (the best fit C_{FC} value for the Christchurch specific FC- I_c correlation as described in Lees et al., 2015). In these maps, it is evident that the calculated values of LSN are noticeably reduced compared to the $C_{FC} = 0$ cases (due to the higher estimated FC and corresponding increase in liquefaction triggering resistance). As with the base case, the calculated LSN values generally correlate with the observations of land damage within each event.

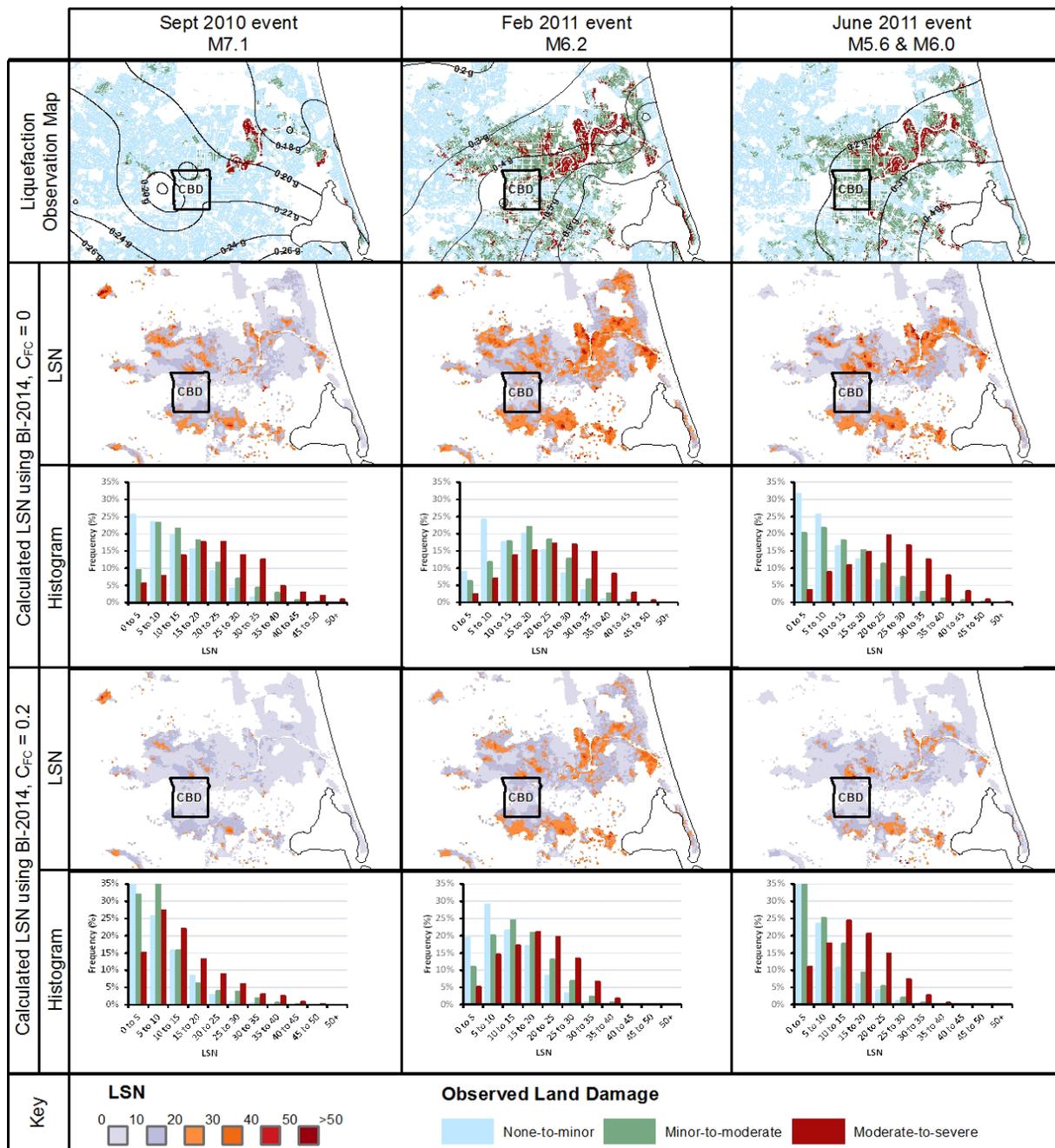


Figure 2. Maps of liquefaction severity observations across the CES overlaid with PGA contours (top row) and LSN using the $C_{FC} = 0$ (2nd row) and $C_{FC} = 0.2$ (4th row) for the September 2010, February 2011 and June 2011 earthquake events. Frequency histograms of LSN for the three land damage observation groupings are shown for $C_{FC} = 0$ (3rd row) and $C_{FC} = 0.2$ (5th row).

Closer examination of Figure 2 shows that when a FC- I_c correlation with $C_{FC} = 0.2$ is used, there is a noticeable reduction in LSN; particularly for the September 2010 and June 2011 events. The largest reduction occurs to the east and south of the Christchurch Central Business District (CBD) where the highest LSN values were calculated for the base case analyses ($C_{FC} = 0$). The

results show that while on a regional basis, changing the C_{FC} parameter from 0 to 0.2 reduces the calculated LSN values, it does not increase the separation between the distributions of the calculated LSN values, for the areas with none-to-minor observed land damage and the areas with moderate-to-severe observed land damage. This is probably because at a $C_{FC} = 0.2$, on a regional basis, for 50% of the properties the FC is underestimated and for the other 50% the FC is overestimated. The way to further improve the regional analyses would be to incorporate a spatially varying C_{FC} parameter to allow for areas where the C_{FC} is locally higher or lower than the median 0.2 value. Lees et al. (2015) did not find any regional spatial trends in the C_{FC} values across Christchurch, but instead found that there were localised areas where the C_{FC} values were higher or lower than the median 0.2 value. In addition, C_{FC} varies between soil layers at each CPT location. Therefore, the regional liquefaction consequence analyses cannot be practically improved using a spatially varying C_{FC} parameter because there is insufficient spatial coverage of CPT data pair with laboratory FC test results.

A similar analysis for the SLS, ILS and ULS design ground motions was also undertaken. Maps of calculated LSN at $C_{FC} = 0$ and 0.2 are presented in rows 1 and 2 of Figure 3, respectively. Difference maps of the calculated LSN for $LSN_{C_{FC}=0} - LSN_{C_{FC}=0.2}$ are shown in row 3. As expected, the difference maps show that the calculated LSN at $C_{FC} = 0$ is smaller throughout the analysis area for all three ground motions. The difference is much more significant at the SLS and ILS levels of shaking compared to the ULS level.

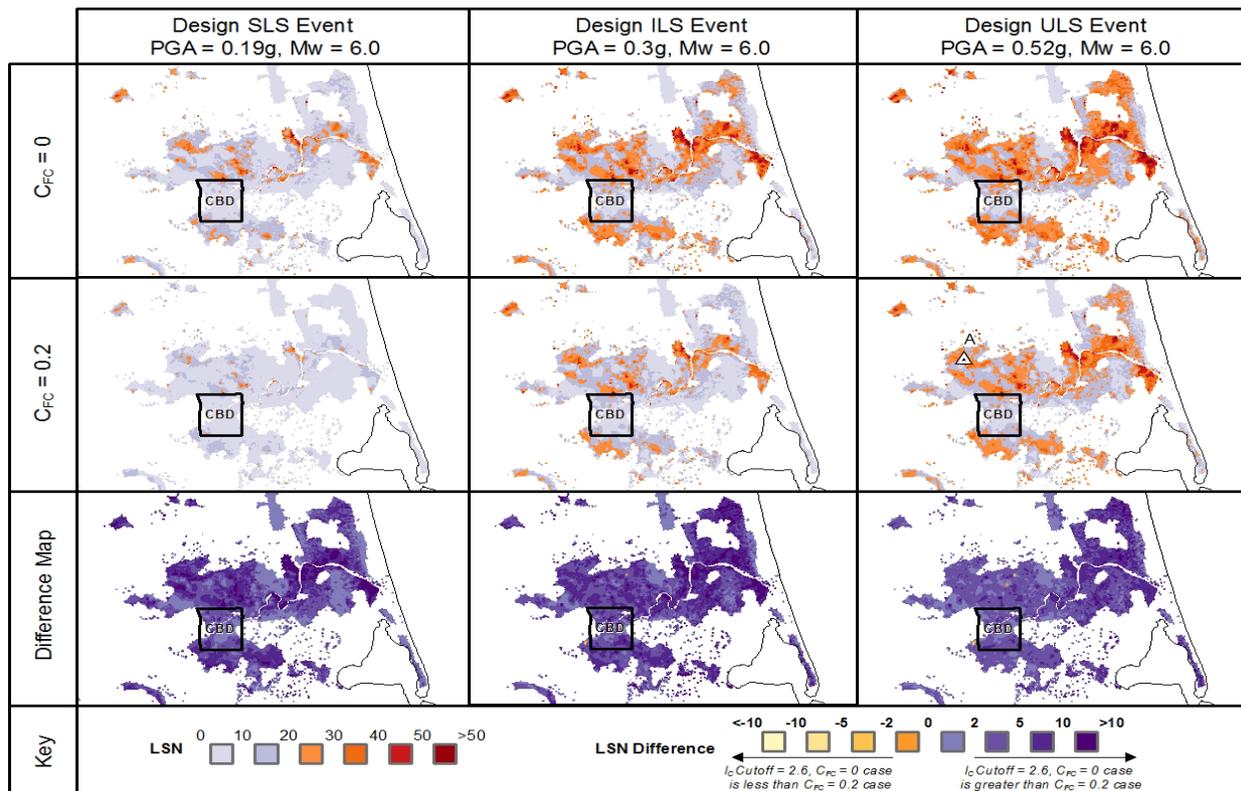


Figure 3. Calculated LSN maps at $C_{FC} = 0$ and 0.2 (rows 1 and 2 respectively) for the design SLS, ILS and ULS ground motions (left, center and right hand columns respectively). Row 4 shows difference maps of the calculated LSN for $LSN_{C_{FC}=0} - LSN_{C_{FC}=0.2}$.

In large parts of the city, the LSN difference for the $C_{FC} = 0.2$ case at SLS and ILS is in the order of 5 to 10 LSN points. At ULS, the difference is in the order of 2 to 5 points in the central and western parts of Christchurch and 5 to 10 points in the eastern suburbs. Given that the absolute LSN values at SLS are lower than at ULS, the percentage reduction in LSN when using $C_{FC} = 0$ is even more significant at the SLS ground motions compared to the ULS ground motions. The sensitivity of the liquefaction vulnerability parameters to the FC correlation as illustrated in Figure 3, highlights the importance of undertaking laboratory testing to develop site-specific FC- I_c correlations for liquefaction assessment purposes.

The sensitivity of LSN to I_c at two different C_{FC} values for the SLS, ILS and ULS ground motions is also demonstrated by LSN vs M6 PGA sensitivity curves shown in Figure 4 for three simplified soil profiles (with q_{c1N} values of 40, 80 and 120 atm respectively) with groundwater 1m below the ground surface. These sensitivity curves help explain some of the observed differences in LSN for the two C_{FC} cases presented in Figure 3. As the PGA increases, the LSN values increase up to a limiting value. An increase in I_c decreases the calculated LSN. Similarly, when the C_{FC} increases from 0 to 0.2, the CRR curves for $I_c > 1.6$ move to the left (Figures 1a and 1b). The biggest changes in calculated LSN values at the two C_{FC} values occur when I_c is between 1.7 and 2.2 (similar to the observations of the sensitivity of the CRR curves to I_c shown in Figure 1).

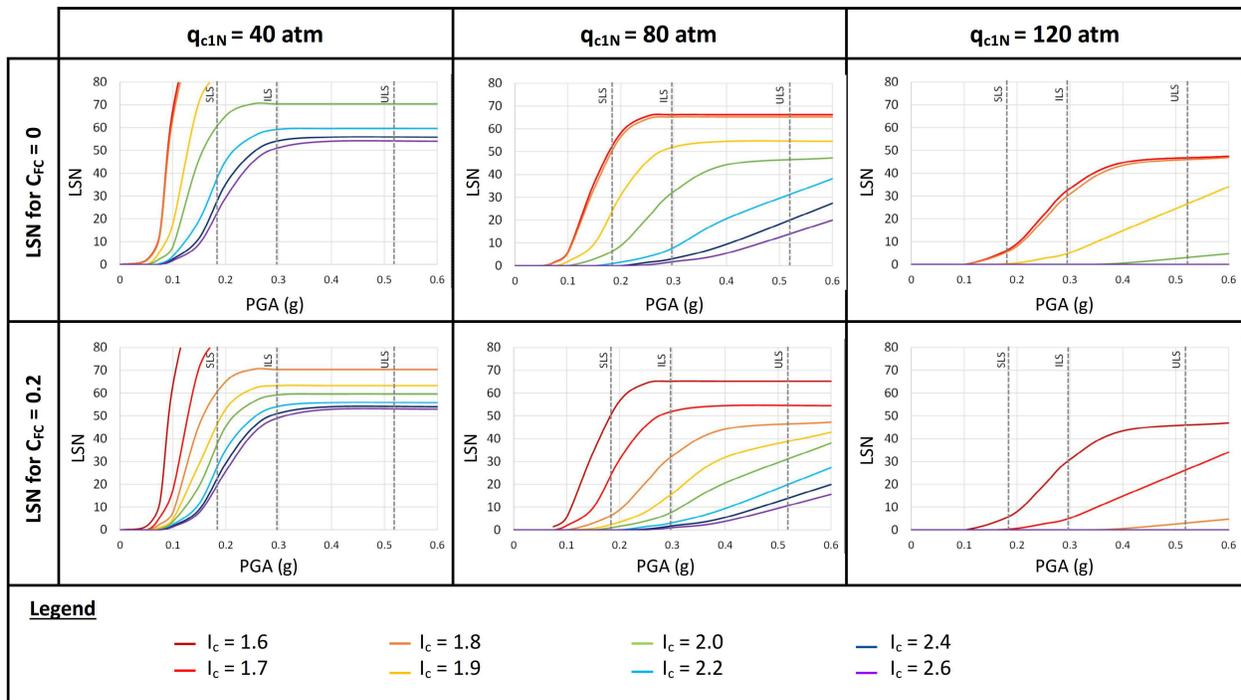


Figure 4. LSN vs M6 PGA sensitivity curves for I_c ranging between 1.6 and 2.6 for $C_{FC} = 0$ and 0.2 (top and bottom rows respectively) for soils with a q_{c1N} of 40, 80 and 120 atm.

The largest reduction in LSN occurs when $I_c \approx 1.8$. For soils with a $q_{c1N} = 80 \text{ atm}$ and $I_c = 1.8$, the calculated values of LSN at $C_{FC} = 0$ are 50, 65 and 65, and at $C_{FC} = 0.2$ are 5, 30 and 55 for SLS ILS and ULS ground motions respectively. This equates to a 90%, 50% and 15% reduction

in LSN at the SLS ILS and ULS ground motions, respectively. For soils with a $q_{c1N} = 120$ atm and $I_c = 1.8$, the calculated values of LSN at $C_{FC} = 0$ are 5, 30 and 45 and at $C_{FC} = 0.2$ are 0, 0 and < 5 for SLS ILS and ULS ground motions respectively. This equates to close to a 100% reduction in LSN. The percentage reduction in calculated LSN is significantly greater than the percentage reduction in the liquefaction triggering potential shown in Figure 1c. This is because the Christchurch specific FC- I_c correction for $C_{FC} = 0.2$ not only increases the assessed liquefaction triggering safety factor (FS), but also decreases the volumetric strain (ϵ_v) component incorporated into the LSN parameter which is both a function of FS and the clean sand equivalent q_{c1N} (q_{c1Ncs}).

Figure 5 shows the sensitivity of LSN to the I_c cutoff in conjunction with C_{FC} at the ILS level of ground shaking. The base case $C_{FC} = 0$ and a best fit $C_{FC} = 0.2$ were analysed with three I_c cutoff values – 2.4, 2.6 (typically used default) and 2.8. These values allow the relative influence of each parameter on liquefaction vulnerability in various areas of Christchurch to be assessed.

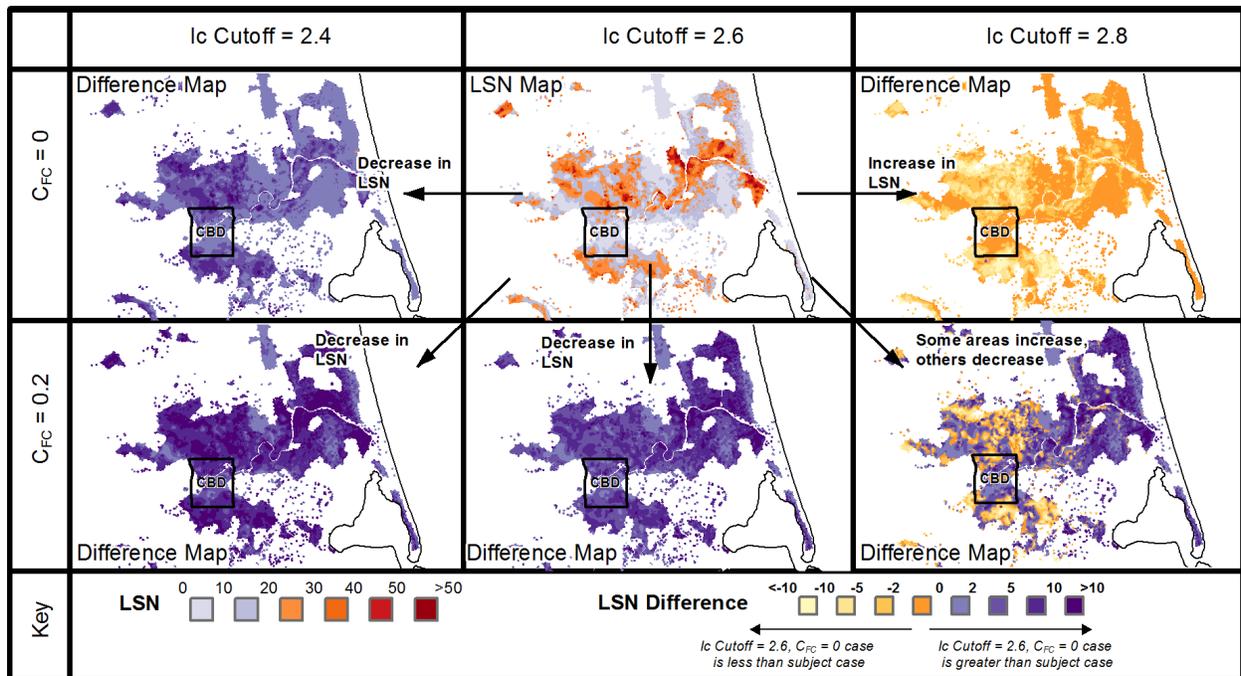


Figure 5. Calculated LSN map at $C_{FC} = 0$ and I_c cutoff = 2.6 for the ILS ground motion (the central map in the top row). The other maps show the differences of the calculated LSN for $LSN_{C_{FC}=0, I_c \text{ cutoff}=2.6}$ and LSN at $C_{FC} = 0$ and 0.2 (top and bottom rows respectively) and a I_c cutoff = 2.4, 2.6 and 2.8 (left, center and right hand columns respectively).

The base case ($C_{FC} = 0$, I_c cutoff = 2.6) is presented as the central map in Figure 5. Increasing the C_{FC} to 0.2 in isolation appears to have a slightly greater effect (by reducing LSN) than decreasing the I_c cutoff; particularly in eastern areas. Reducing the I_c cutoff and increasing the C_{FC} simultaneously compounds the overall reduction in LSN by approximately 10 points over most of Christchurch. In contrast, increasing the I_c cutoff in isolation results in a region-wide increase in LSN by 0 to 2 points in eastern Christchurch and 2 to 10 points in the central areas of Christchurch to the north and south of the CBD. When the I_c cutoff value is increased to 2.8 and

the best-fit $C_{FC} = 0.2$ is applied simultaneously, some areas increase and some decrease (predominantly a decrease due to the greater influence of the C_{FC} modification).

Discussions and Conclusions

The extensive CPT dataset collated following the CES, has provided a unique opportunity to carry out a regional study on two of the key components of a liquefaction vulnerability assessment including liquefaction susceptibility and liquefaction triggering. Using a best-fit FC- I_c correlation ($C_{FC} = 0.2$ for the Christchurch soils), regional scale liquefaction consequence analyses are compared to analyses based on the typical default FC- I_c correlation used in the Boulanger and Idriss (2014) liquefaction triggering assessment (i.e. $C_{FC} = 0$). The comparison include back analysis of the CES events and a forward analysis at design SLS, ILS and ULS ground motions to evaluate the influence of the Christchurch specific FC- I_c correlation relative to the default correlation. While there is a general reduction in the calculated LSN for each land damage category, the degree of overlap between the distributions of calculated LSN values for the none-to-minor and moderate-to-severe land damage categories do not reduce. This is probably because at a $C_{FC} = 0.2$, on a regional basis, for 50% of the properties the FC is underestimated and for the other 50% the FC is overestimated. Examination of individual CPT with laboratory FC test data from samples in an adjacent borehole on a case by cases basis would improve the calculation of the LSN parameter relative to the observed land damage after each main event in the CES.

The forward analysis indicated that the LSN parameter is very sensitive to the variation in C_{FC} ; particularly when I_c is between 1.7 and 2.2. This is because the FC correction for $C_{FC} = 0.2$ not only increases the FS, it decreases ε_v which is both a function of FS and q_{c1Ncs} . The interaction between modifying the I_c cutoff as well as the C_{FC} parameter indicates that modifying the C_{FC} appears to have the greatest effect on the predicted liquefaction, with the exception of the case where $C_{FC} = 0.2$ and I_c cutoff = 2.8, where the predicted liquefaction vulnerability appears to reduce in the west and increase in the east. The sensitivity of the liquefaction vulnerability to the FC- I_c correlation and I_c cutoff demonstrates the importance of undertaking laboratory testing and developing site-specific FC- I_c correlations and I_c cutoff thresholds for liquefaction assessment purposes, particularly when the assessments are undertaken at SLS and ILS ground motions.

Acknowledgments

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