Comparison of CPT-based simplified liquefaction assessment methodologies based on the Canterbury dataset

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ABSTRACT

The four most commonly used simplified Cone Penetration Test (CPT) based liquefaction triggering methods in engineering practice are Robertson and Wride (1998) as set out in Youd et al. (2001), Seed et al. (2003) as set out in Moss et al. (2006a), Idriss and Boulanger (2008) and Boulanger and Idriss (2014). This paper compares these four liquefaction triggering methods on a regional basis by calculating the associated Liquefaction Severity Number (LSN) for around 15,000 CPTs across Christchurch and correlating these calculated values with the liquefaction-induced land damage observations throughout the 2010 to 2011 Canterbury Earthquake Sequence (CES). The results show that all four methods provide reasonable correlations between observed land damage and the LSN liquefaction vulnerability parameter. Areas with none-to-minor observed liquefaction-induced land damage generally have low calculated LSN values and areas with moderate-to-severe liquefaction-induced land damage generally have high calculated LSN values. More detailed examination of the results shows that the Boulanger and Idriss (2014) liquefaction triggering method provides the best overall fit to the observed land damage for each of the main events across the CES and also provides the best differentiation between sites with no observed liquefaction-induced land damage at the ground surface and sites with observed liquefaction-induced land damage.

Keywords: Earthquakes, Liquefaction, Vulnerability, Liquefaction Severity Number, LSN, Triggering

1 INTRODUCTION

The CPT and Standard Penetration Test (SPT) are the two most widely used tools for undertaking liquefaction assessments. The development of CPT-based and SPT-based liquefaction triggering methods has progressed over the years through the efforts of countless researchers. Development of SPT-based correlations began in Japan and progressed into the landmark work of Seed et al. (1984 & 1985) which set the overall liquefaction assessment framework which has been used by engineering practice for nearly three decades. Development of CPT-based methods began with the work of Zhou (1980) based on the observations from the 1978 Tangshan earthquake followed by Seed and Idriss (1981) who developed correlations between SPT and CPT penetration resistance to cover the available SPT-based liquefaction triggering methods for use with CPT. Other contributors to the evolution of the CPT-based liquefaction triggering methods include Shibata and Teparaksa (1988), Stark and Olson (1995), Suzuki et al. (1997), Robertson and Wride (1998), Olsen (1997), Youd et al. (2001), Seed et al. (2003), Moss et al. (2006), Idriss and Boulanger (2008) and Boulanger and Idriss (2014). The quantity and quality of CPT case histories has continued to increase since the first assessment methods were developed with recent earthquake events. Data obtained from the 2010 to 2011 CES (van Ballegooy et al., 2014 and Green et al., 2014) and the 2011 Tohoku earthquake (Tokimatsu et al., 2012 and Cox et al., 2013) is included in the latest liquefaction assessment method.

As part of the recovery programme following the CES, an extensive geotechnical investigation programme was undertaken including 15,000 CPT and 3,000 boreholes. These have been used to better understand the subsurface conditions beneath the residential suburbs in Christchurch and assess the liquefaction vulnerability to inform repair of existing foundations and design of new foundations when repairing and rebuilding on this land. Using this extensive amount of data (available through the Canterbury Geotechnical Database https://canterburygeotechnicaldatabase.projectorbit.com), as well as the detailed land damage mapping undertaken after each main earthquake event, a comparative regional evaluation has been carried out to evaluate the difference between the four most commonly applied liquefaction triggering methods used in engineering practice. These four methods are Robertson and Wride (1998) as set out in Youd et al. (2001), Seed et al. (2003) as set out in Moss et al. (2006a), Idriss and Boulanger (2008) and Boulanger and Idriss (2014). Hereafter, these methods are referred to as RW, MS, IB-2008 and BI-2014 respectively.

The regional evaluation of liquefaction effects requires automated analyses that can process data from thousands of CPT soundings and compute the liquefaction vulnerability parameters. Automated analyses do not allow for the detailed examination of site-specific conditions which can influence the evaluation of potential ground deformations (such as geologic details, horizontal or vertical continuity of liquefiable layers, thin-layer effects, information from site-specific laboratory test data, or site geometry). Nonetheless, the automated analyses provide the ability to broadly correlate analysis results with site performance on a regional basis.

There is much discussion in the literature about the merits and shortcomings of each method. However, they are all based on similar case history databases, although each method has its own approach and empirical equations. The empirical equations and iterative processes derived from the case history data vary between methods. The results from the liquefaction triggering assessments cannot be directly compared on a regional basis with the observed land damage mapping throughout the CES because they only assess which soil layers are likely to liquefy, whereas the mapped land damage is based on ground surface expression of liquefaction. Not all soil layers which liquefy result in ground surface expression as demonstrated by Ishihara (1985) and hence, absence of surface expression of liquefaction ejecta does not mean liquefaction triggering in particular soil layers did not occur. Therefore, in order to evaluate and compare the effectiveness of the various liquefaction triggering methods on a regional basis, they need to be analysed in conjunction with a liquefaction vulnerability index parameter. The effectiveness and suitability of several CPT-based liquefaction vulnerability parameters including one dimensional volumetric densification settlement developed by Zhang et al. (2002) and the Liquefaction Potential Index (LPI) developed by Iwasaki et al. (1982) were assessed by T&T (2013) and van Ballegooy et al. (2014 & 2015b). These regional studies indicated that while these parameters were predicting higher vulnerability in areas of observed severe liquefaction related damage in some parts of Canterbury, the parameters were also predicting higher vulnerability in areas where little to no damage observations were recorded. The studies by Tonkin and Taylor (2013) and van Ballegooy et al. (2014, 2015a & 2015b), have shown that a new liquefaction vulnerability parameter, LSN, provides a better correlation with the land and residential house foundation damage observations recorded in Canterbury. Likely ranges of LSN values for none-to-minor liquefaction-induced damage ranges between 0 to 16, minor-to-moderate liquefaction-induced damage ranges between 16 to 25 and moderate-to-severe liquefaction-induced damage is greater than 25.

This paper presents a back analysis using the event based peak ground acceleration models (Bradley and Hughes 2012) shown in the first row of Figure 1 and the respective event-specific depth to groundwater surfaces given in Tonkin & Taylor (2013) for the 4 September 2010, 22 February and 13 June 2011 earthquakes and compares it to the mapped land damage (Tonkin & Taylor 2013 and van Ballegooy et al. 2014 & 2015b). A series of data analyses have been undertaken to determine which triggering method best fits the observed land damage for all the main earthquake events for which land damage mapping has been undertaken.

2 LIQUEFACTION TRIGGERING

In the 1990's, the CPT began to be used as a tool to assess the potential for soils to liquefy. A series of National Center for Earthquake Engineering Research (NCEER) workshops on liquefaction culminated in the Robertson and Wride (1998) paper being adopted in Youd et al. (2001) as a preferred liquefaction analysis method. The method corrects for the soil Fines Content (FC) using relationships with the soil behaviour type index, I_c, derived from the CPT data. Normalisation of the CPT was deterministic, as iterative normalisation was not in widespread use. Seed et al. (2003) adopted an extended body of field case history data to develop revised triggering relationships. Critical layers from that database were used by Moss et al. (2006) to develop a CPT-based relationship, which included probabilistic assessments of critical layers. The fines was inherently considered by the use of the friction ratio measurement. The CPT data was normalised with an iterative procedure.

A new method was then developed and presented by Idriss and Boulanger in their 2008 Earthquake Engineering Research Institute (EERI) monograph. That monograph contained equivalent CPT and SPT methods for assessing liquefaction triggering. Corrections for siltier materials were based on FC that were to be manually input based on laboratory data. For this paper, FC were estimated based on the apparent FC correlations with I_c presented in Robertson and Wride (1998), as recommended by MBIE (2012). The IB-2008 method was updated in a 2014 publication by Boulanger and Idriss. The

2014 method considered additional case histories from the Christchurch earthquakes, along with a revised FC-I_c correlation and introduced material-specific magnitude scaling factors (MSF). The MSF variability is a feature which was included based on analyses of strong ground motion records and cyclic laboratory test for a broad range of soil types. The method-specific correlation for FC from I_c assuming a fitting parameter (C_{FC}) of zero generally estimates higher FC compared to the Robertson and Wride (1998) correlation at values greater than 1.7.

3 REGIONAL LIQUEFACTION ASSESSMENT METHODOLOGY

For the purposes of this study as well as the study presented in van Ballegooy et al. (2014 & 2015b) and Russell et al. (2015), the June 2011 (M_w 5.6 & 6.0) events were analysed as a single equivalent event with M_w 6.2 to account for the effects of the initial, smaller event on liquefaction responses during the second, larger event. In-situ pore pressure recordings at five instrumented sites that were affected by liquefaction damage showed that the excess pore pressures induced by the first M_w 5.6 event had only partially dissipated when the second M_w 6.0 event occurred 80 minutes later. Therefore, the number of equivalent uniform loading cycles for the single equivalent event was estimated at these sites as the number of equivalent uniform cycles from the M_w 6.0 event plus 25% of the number of equivalent uniform cycles from the M_w 5.6 event. The resulting number of equivalent uniform cycles was then used to estimate the equivalent M_w of 6.2 for all sites throughout Christchurch. However, for other sites, the effects of the smaller first earthquake on the responses to the second larger earthquake will depend on that site's subsurface conditions. For this reason, the use of M_w 6.2 rather than 6.0 is an approximate means for representing the second larger event of June 2011 and is a simplification for this regional scale evaluation of liquefaction analysis methods.

The LSN parameter was computed based only on the top 10m of any CPT sounding. This cut-off depth was found to usually have negligible effect on the computed vulnerability parameter because the liquefiable sediments are generally at shallower depths and the depth-weighting function in the LSN parameter reduces the impact of loose soils at larger depths. In order to apply the four methods to a regional study of thousands of CPT, assumptions have been made to provide consistency. The main assumptions are:

1. **Probability of Liquefaction:** The probability of liquefaction is adopted as 15% in MS and BI-2014. RW and IB-2008 typically represent a 15% probability of liquefaction.
2. **Non-liquefying properties where I_c exceeds 2.6:** For this regional analysis, it was assumed that no liquefaction occurs where I_c > 2.6 for all four triggering methods. RW states that above an I_c of 2.6, the soil is considered too clay-rich to liquefy so non-liquefying properties have been applied when this is the case.
3. **FC calculation:** For IB-2008, the FC has been calculated in accordance with the Robertson and Wride (1998) apparent FC correlations as recommended in MBIE (2012). The FC in BI-2014 has been calculated in accordance with a method-specific FC-I_c correlation assuming a default C_{FC} fitting parameter of zero. RW and MS do not require explicit FC to be input.

The calculated LSN values at each CPT location have been interpolated between CPT investigation locations (based on a natural neighbour method which calculates Thiessen polygons and weights them with proximity to CPT locations). It is noted that the LSN liquefaction vulnerability parameter involves significant simplifications to capture potential for liquefaction-induced damage away from lateral spreading areas, which means that the mechanisms of lateral spreading are not explicitly accounted for (such as lateral discontinuity of strata, three dimensional effects, dynamic response, proximity of free faces and loss of soil ejected to the surface). These simplifications make the analyses easier to perform, but they 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 damages can be reduced, which is the objective of the present study. Nonetheless, there are likely lower limits on the dispersion that can be achieved using these types of simplified methods and single CPT soundings as a predictor of liquefaction-induced ground displacements or damages.

4 RESULTS AND ANALYSES

Maps of liquefaction severity observations during the September 2010 (M_w 7.1), February 2011 (M_w 6.2), and June 2011 (M_w 5.6 & 6.0) events are shown in the top row of Figure 1. Areas are separated into those with none-to-minor visible liquefaction effects, minor-to-moderate liquefaction effects and moderate-to-severe liquefaction effects. Comparing these maps, the regional effects of liquefaction were greatest for the February 2011 event, slightly less for the June 2011 events, and least for the September 2010 event. The spatial variation of the calculated LSN maps for each is shown in the maps presented in the second row of Figure 2 for the BI-2014 liquefaction triggering method.

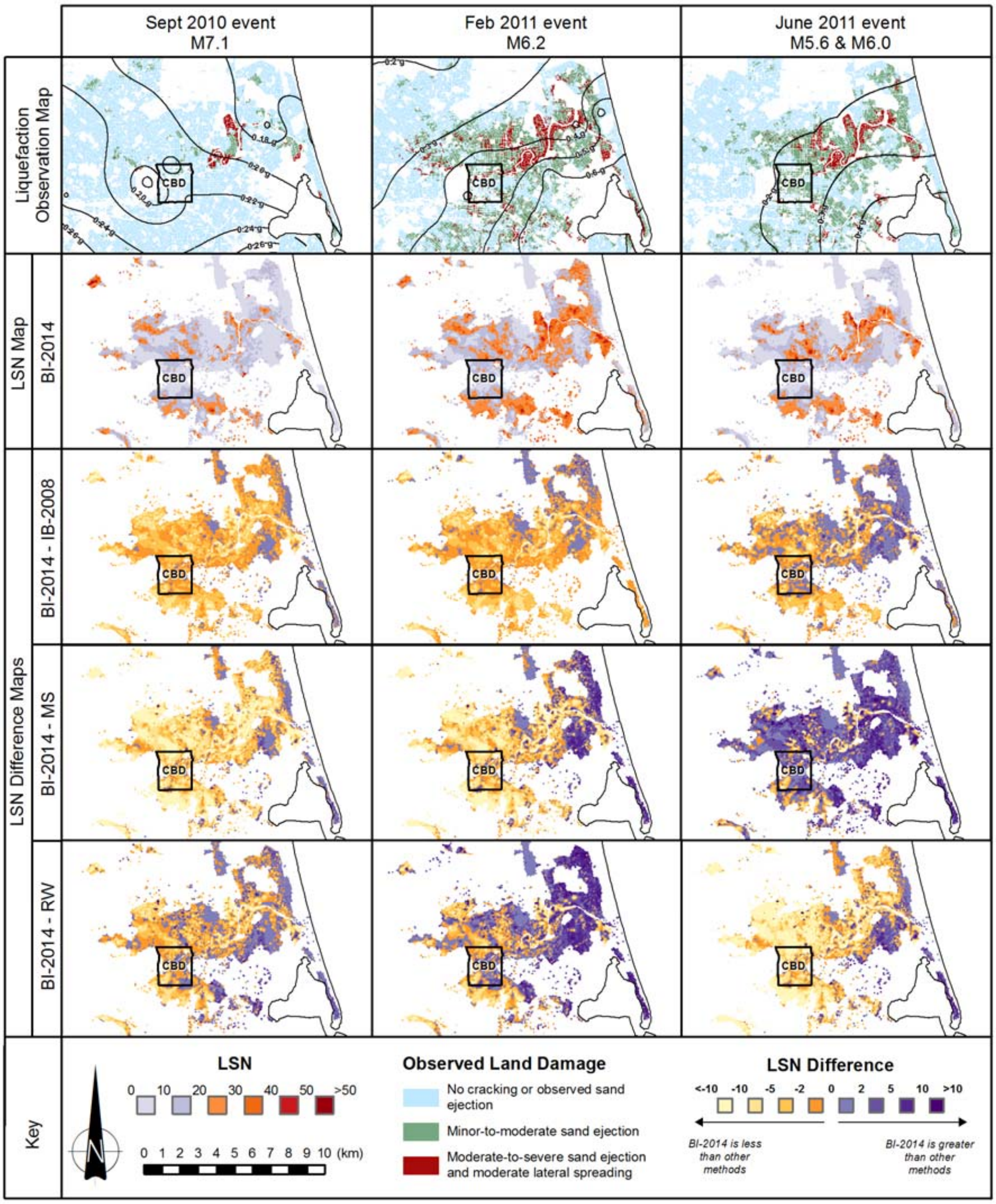

Figure 1. Map series of liquefaction severity observations and calculated LSN for each CPT using the BI-2014, IB-2008, MS and RW simplified liquefaction evaluation methods for the September 2010, February 2011 and June 2011 earthquake events. PGA contours (Bradley and Hughes 2012) are overlaid on the liquefaction severity observation maps. Difference maps are shown between BI-2014 and the other three methods (IB-2008, MS and RW) to accentuate the differences between the LSN maps. Positive values on the difference maps indicate areas where BI-2014 predicts higher values and negative values indicate areas where BI-2014 predicts lower values.

The maps show that the areas with high LSN values generally correlate with areas where there was moderate-to-severe liquefaction effects, whereas areas with low LSN values generally correlate with areas where there was none-to-minor observed liquefaction-induced land damage. This observation also applies to the LSN maps for the other liquefaction triggering methods. Therefore, LSN difference maps have been made between the BI-2014 and other liquefaction triggering methods (IB-2008, MS and RW) shown in the third, fourth and bottom rows in Figure 1 respectively. The difference maps have been presented instead of the actual LSN maps to accentuate the differences between the LSN maps for the different liquefaction triggering methods.

The difference maps for the BI-2014 versus IB-2008 liquefaction triggering method show that for the September 2010 event, the BI-2014 triggering method gives mostly smaller LSN values towards the west, which is more aligned with the limited extent of observed liquefaction-induced damage in these areas compared with the results of the IB-2008 method. For the June 2011 event, use of the BI-2014 triggering method gives greater LSN values in the areas to the east of the Central Business District (CBD), which is more aligned with observations of the affected areas compared with the IB-2008 method. The difference maps for the BI-2014 versus MS liquefaction triggering method show that for all events the MS triggering method gives much higher LSN values for all events compared to the BI-2014 liquefaction triggering method apart from eastern Christchurch where the MS liquefaction triggering method gives lower LSN values compared with the BI-2014 liquefaction triggering method. The results for the MS method are least aligned with the land damage observations compared to the other methods.

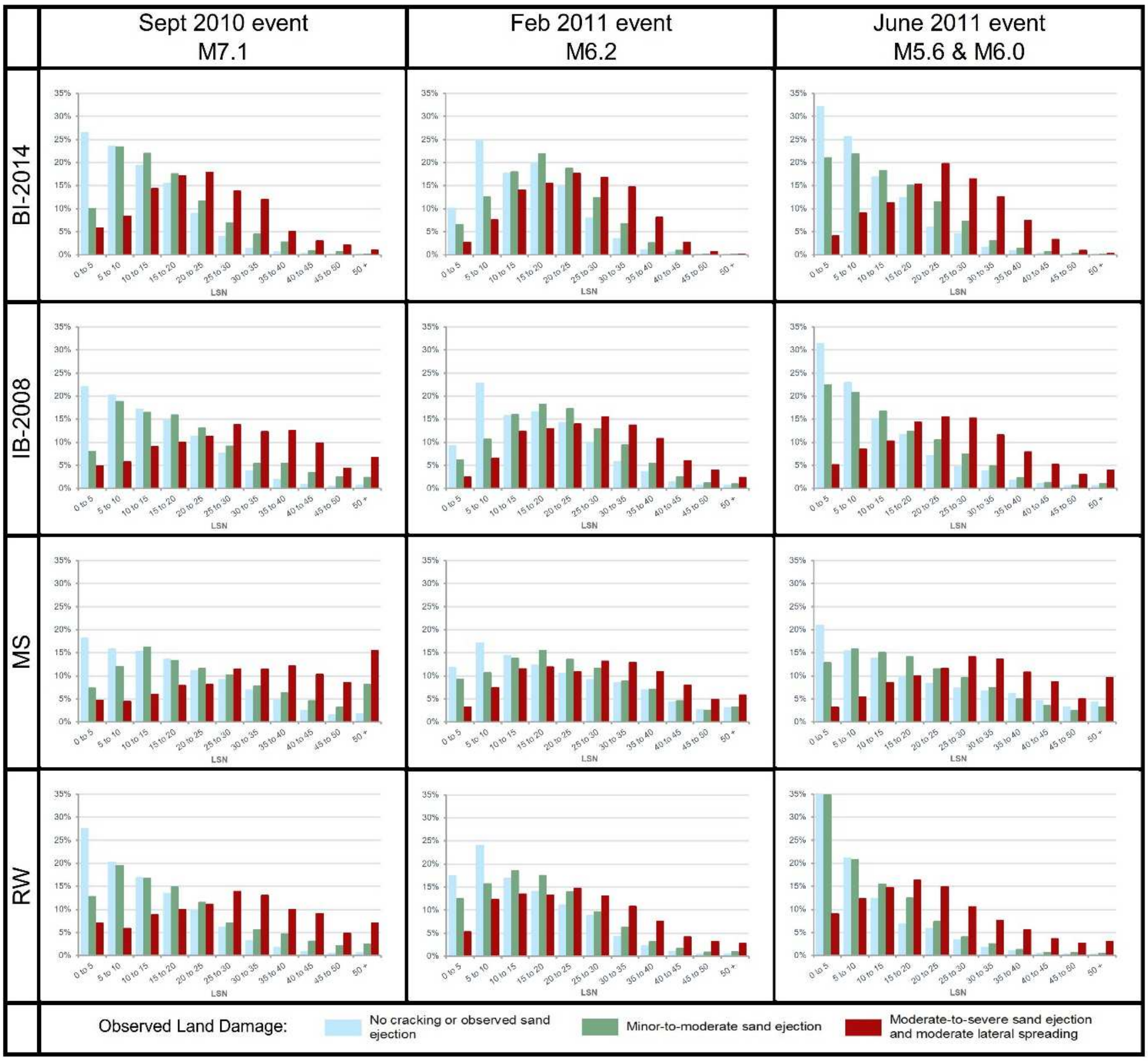

Figure 2. Frequency histograms of the calculated LSN values throughout Christchurch for the BI-2014, IB-2008, MS and RW simplified liquefaction triggering methods for the September 2010, February 2011 and June 2011 earthquake events, for observation categories of none-to-minor liquefaction damage, minor-to-moderate liquefaction damage and moderate-to-severe liquefaction damage based on the land damage maps in Figure 1. The horizontal axis represents LSN from 0 to 50+ in increments of 5, and the vertical axis represents frequency percentage from 0 to 35%.

The difference maps for the BI-2014 versus RW liquefaction triggering method show that for the September 2010 event the RW triggering method generally gives much higher LSN values compared to the BI-2014 liquefaction triggering method and the opposite for the June 2011 event. For the February 2011 event the RW liquefaction triggering method has higher calculated LSN values in western Christchurch and lower calculated LSN values in eastern Christchurch compared with the BI-2014 liquefaction triggering method. These results for the RW method are not as well aligned with the land damage observations for all the main events compared to the BI-2014 liquefaction triggering method, in particular for the February 2011 event.

Frequency histograms of the calculated regional based LSN values throughout Christchurch for each of the four liquefaction triggering methods for the September 2010, February 2011 and June 2011 events are given in Figure 2. These are categorised into three liquefaction land damage observation categories; none-to-minor liquefaction damage, minor-to-moderate liquefaction damage and moderate-to-severe, as shown on the liquefaction land damage maps shown in the top row of Figure 1. It is clear that all four methods generally correlate similarly with the observed liquefaction-induced land damage, although some of the methods show better consistency of calculated ranges between events and also better separation of calculated regional based LSN distributions between the observation categories of none-to-minor observed liquefaction damage and moderate-to-severe liquefaction-induced land damage. Despite the MS method calculating larger LSN values than BI-2104, whether or not the land damage observation categories are distinctly separated relative to each other is what needs to be considered. Therefore, it is important to focus on the comparison between the categories of none-to-minor observed liquefaction-induced land damage and moderate-to-severe liquefaction-induced land damage. 15th, 50th and 85th percentile statistics for the calculated regional based LSN distributions for these two land damage observation categories are summarised in Table 1 and can be used to help identify the subtle differences between the four different liquefaction triggering methods.

Table 1: Summary of the statistics for the calculated regional based LSN distributions (i.e. 15th, 50th and 85th percentiles) for the BI-2014, IB-2008, MS and RW simplified liquefaction evaluation methods for the observation categories of none-to-minor liquefaction-induced land damage and moderate-to-severe liquefaction-induced land damage.

		Average of the Sept 2010, Feb 2011 and June 2011 events		Range for the Sept 2010, Feb 2011 and June 2011 events	
		No observed land damage	Moderate to severe land damage	No observed land damage	Moderate to severe land damage
BI-2014	15th %ile	3.9	11.1	4.0	1.5
	50th %ile	12.0	23.5	6.3	1.9
	85th %ile	21.1	33.4	5.1	0.5
	overlap	59%		N/A	
IB-2008	15th %ile	4.2	11.9	4.7	2.0
	50th %ile	13.7	27.7	7.0	4.9
	85th %ile	25.3	39.7	5.4	3.9
	overlap	60%		N/A	
MS	15th %ile	4.4	13.7	3.5	2.8
	50th %ile	18.2	31.8	2.7	6.7
	85th %ile	35.0	45.7	5.7	8.4
	overlap	68%		N/A	
RW	15th %ile	2.6	9.3	3.3	3.6
	50th %ile	10.9	24.7	7.5	8.9
	85th %ile	22.4	38.1	7.9	8.4
	overlap	59%		N/A	

For BI-2014, IB-2008, and MS liquefaction triggering methods, the 85th percentile LSN value of the none-to-minor observed land damage category has a lower LSN value than the 50th percentile LSN value of the moderate-to-severe liquefaction induced land damage category. On the contrary, for MS liquefaction triggering method, the 85th percentile LSN value of the none-to-minor observed land damage category is higher than the 50th percentile LSN value of the moderate-to-severe liquefaction induced land damage category. This suggests that BI-2014, IB-2008 and RW liquefaction triggering methods have a more distinct separation between their populations of land damage as is visually apparent in the maps in Figure 1 and the histograms in Figure 2. The percentage of overlap between the none-to-minor observed land damage and moderate-to-severe liquefaction-induced land damage categories also confirms this, where the BI-2014, IB-2008 and RW liquefaction triggering methods have around 60% of overlap whereas the MS liquefaction triggering method has nearly 70% of overlap. Another key factor to consider is consistency between events, because the distributions of calculated LSN should be similar regardless of earthquake magnitude and/or shaking intensity as discussed in Russell et al. (2015). Table 1 shows the maximum range across the three events for the 15th, 50th and 85th percentiles for the observation categories of none-to-minor liquefaction-induced land damage and moderate-to-severe liquefaction-induced land damage. The RW liquefaction triggering method appears to be the least consistent with an average range of over 6 LSN points for both the none-to-minor observed liquefaction damage and moderate-to-severe observed liquefaction damage categories. The MS and IB-2008 liquefaction triggering methods both have an average range across the three events of 5 LSN points, whereas the BI-2014 liquefaction triggering method is most consistent with an average range of 3 LSN points. The consistency of the moderate-to-severe liquefaction observation category is particularly noteworthy with a range of 1 LSN point.

Therefore, when considering the separation of the land damage populations as well as consistency between the events, the BI-2014 liquefaction triggering method appears to be the one which is the best fit to the mapped liquefaction-induced land damage for the regional prediction of liquefaction vulnerability for the Christchurch soils. This should be expected given that the liquefaction case history database used to develop this method included 50 Christchurch-based case history data points.

5 CONCLUSION

This paper has shown that all four simplified liquefaction triggering methods provide reasonable correlations between land damage observations and the LSN liquefaction vulnerability parameter. However, detailed examination of the results shows that the BI-2014 method gives the most consistent distribution of calculated LSN values between events for the observation categories of none-to-minor liquefaction-induced land damage and moderate-to-severe liquefaction-induced land damage. The BI-2014 method also provides the best differentiation between sites with no observed liquefaction-induced land damage and sites with observed liquefaction-induced land damage, and is therefore the liquefaction triggering method best suited to the Christchurch soils.

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