Assessment of liquefaction evaluation procedures and severity index frameworks at Christchurch strong motion stations

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ABSTRACT

The objective of the study presented herein is to assess three commonly used CPT-based liquefaction evaluation procedures and three liquefaction severity index frameworks using data from the 2010-2011 Canterbury earthquake sequence. Specifically, post-event field observations, ground motion recordings, and results from a recently completed extensive geotechnical site investigation program at selected strong motion stations (SMSs) in the city of Christchurch and surrounding towns are used herein. Unlike similar studies that used data from free-field sites, accelerogram characteristics at the SMS locations can be used to assess the performance of liquefaction evaluation procedures prior to their use in the computation of surficial manifestation severity indices. Results from this study indicate that for cases with evidence of liquefaction triggering in the accelerograms, the majority of liquefaction evaluation procedures yielded correct predictions, regardless of whether surficial manifestation of liquefaction was evident or not. For cases with no evidence of liquefaction in the accelerograms (and no observed surficial evidence of liquefaction triggering), the majority of liquefaction evaluation procedures predicted liquefaction was triggered. When all cases are used to assess the performance of liquefaction severity index frameworks, a poor correlation is shown between the observed severity of liquefaction surface manifestation and the calculated severity indices. However, only using those cases where the liquefaction evaluation procedures yielded correct predictions, there is an improvement in the correlation, with the Liquefaction Severity Number (*LSN*) being the best performing of the frameworks investigated herein. However scatter in the relationship between the observed and calculated surficial manifestation still remains for all liquefaction severity index frameworks.

Keywords: Liquefaction, Canterbury earthquake sequence, CPT, strong motion stations

1 INTRODUCTION

The city of Christchurch and some surrounding towns experienced widespread damage due to seismically induced liquefaction during the 2010-2011 Canterbury Earthquake Sequence (CES), beginning in 4 September 2010 with the M_w 7.1 Darfield earthquake. Other notable earthquakes in this sequence were the 22 February 2011 M_w 6.2 Christchurch earthquake, and the 13 June 2011 and 23 December 2011 events. Each resulted in widespread liquefaction, with the most severe damage occurring during the Christchurch earthquake (Cubrinovski et al. 2010, 2011).

Prior to the CES, assessments had shown that there was a high potential for liquefaction across most of the city (Elder et al. 1991, Beca 2004). This work used the simplified liquefaction evaluation procedures, first proposed by Seed and Idriss (1971) and Whitman (1971). This procedure is largely based on empirical observations of laboratory and field data and has been continually refined as a result of newer studies and the increase in the number of field case histories (e.g., Youd et al. 2001, Cetin 2000, Idriss and Boulanger 2008). Although the early versions of this procedure only proposed correlations relating standard penetration test (SPT) blow count to liquefaction resistance, subsequent studies have also proposed correlations that are based on cone penetration test (CPT) results (e.g., Robertson and Wride 1998, Moss 2006, Idriss and Boulanger 2008). In developing these correlations, the field case histories were categorized as “liquefaction” and “no liquefaction,” almost exclusively based on surficial evidence of liquefaction or the lack thereof. Surficial evidence of liquefaction includes presence of sand ejecta, ground cracking and fissures, and lateral spreading at the ground surface in close vicinity to site investigation locations. The proposed boundaries separating the liquefaction and no liquefaction cases were often conservatively defined, providing a lower bound for the estimated liquefaction resistance (Youd et al. 2001). This paper focusses on CPT-based simplified liquefaction evaluation procedures proposed by Robertson and Wride (1998), Moss et al. (2006), and Idriss and Boulanger (2008).

The simplified procedures indicate whether or not liquefaction is predicted to occur at a given depth in the soil profile, but it does not provide an indication of the cumulative effect of liquefaction triggering throughout the soil column and the severity of manifestation at the ground surface. Results from the simplified procedures can be used as inputs in liquefaction severity index frameworks to predict the severity of surficial liquefaction manifestation. One of the earliest

proposed and most widely used liquefaction severity index frameworks is the Liquefaction Potential Index (*LPI*) proposed by Iwasaki et al. (1978), equal to:

$$LPI = \int_0^{20\text{ m}} F_1 W(z) dz$$

where $F_1 = 1 - FOS$ for $FOS \leq 1.0$, and $F_1 = 0$ for $FOS > 1.0$. $W(z) = 10 - 0.5z$, where FOS is the factor of safety against liquefaction and z is depth in meters. Computed *LPI* values were correlated to severity of surficial liquefaction manifestations using a borehole database and observations from Japanese earthquakes, where the *FOS* were computed using the SPT-based liquefaction evaluation procedure specified in the Japanese Specifications for Highway Bridges (JRA 1980). Using this approach liquefaction severity was defined as: minor for $0 < LPI \leq 5$, moderate for $5 < LPI \leq 15$, and major for $LPI > 15$. A number of studies have presented modified versions of these classifications (e.g. Sonmez 2003, Papathanassiou 2008). Work by Toprak & Holzer (2003) following the 1989 Loma Prieta earthquake suggested that there is unlikely to be any surface manifestations for an *LPI* less than 5. Using a database from Taiwan and the Robertson and Wride (1998) CPT-based liquefaction evaluation procedure, Lee et al. (2003) showed that the surface manifestation severity is low if $LPI < 13$, and extremely high if $LPI > 21$. Maurer et al. (2014) analysed a database of almost 1200 CPT soundings from Christchurch using the Robertson and Wride (1998) procedure, finding that the original *LPI* framework was generally able to predict moderate-severe surficial manifestation severity, but less able to predict cases with lesser severity.

The magnitude of post-liquefaction consolidation settlement (*S*) has also been proposed as a proxy for the severity of surficial liquefaction manifestation. Zhang et al. (2002) proposed the following relation for computing *S*:

$$S = \sum_{i=1}^j \varepsilon_{vi} \Delta z_i$$

where ε_v is the volumetric strain due to post-liquefaction consolidation of soil layer i , Δz_i is the thickness of layer i , and j is the number of soil layers. The Zhang et al. model has been modified by Juang et al. (2013) to account for the likelihood of liquefaction in each soil layer.

A recently proposed liquefaction severity index framework is the Liquefaction Severity Number (*LSN*) (van Ballegooy et al. 2012). The *LSN* was developed using the a database of approximately 5,500 CPTs across the city of Christchurch and observations of severity of surficial liquefaction

manifestations in residential areas following the Darfield, Christchurch, and 13 June 2011 earthquakes. The *LSN* is defined as:

$$LSN = 1000 \int_0^{10m} \frac{\varepsilon_v}{z} dz$$

where ε_v is defined as above and is a function of *FOS*. *FOS* used in the development of the *LSN* were computed using the Idriss & Boulanger (2008) CPT-based liquefaction evaluation procedure, and the volumetric strains were computed using Zhang et al. (2002). *LSN* is calculated using the top 10 m of the soil profile only. Using this approach liquefaction severity was defined as: minor for $0 < LSN \leq 20$, moderate for $20 < LSN \leq 50$, and major for $LSN > 50$. From the analysis of the Christchurch dataset, the *LSN* showed a better correlation with the observed severity of surficial manifestations than *LPI* and post-liquefaction consolidation settlement.

Prior to the start of the CES, the city and surrounding towns had a large network of strong motion stations (SMSs) installed, which recorded a vast database of strong ground motions (Bradley & Cubrinovski 2011, Bradley 2012, GNS Science 2013). This paper focuses on the SMSs installed prior to the Darfield earthquake, with the locations of the SMS study sites in Christchurch presented in Figure 1. Apart from one location (Hulverstone Drive Pumping Station, HPSC), all SMS locations are outside the red zone regions of Christchurch and Kaiapoi that suffered the most severe land damage due to soil liquefaction (Rogers et al. 2014).

The study presented herein assesses three commonly used CPT-based liquefaction evaluation procedures (i.e., Robertson and Wride 1998, Moss et al. 2006, and Idriss and Boulanger 2008) and three liquefaction severity index frameworks (i.e., *LPI*, post-liquefaction consolidation settlement, and *LSN*) using data from the 2010-2011 Canterbury earthquake sequence. Specifically, post-event field observations, ground motion recordings, and results from a recently completed extensive geotechnical site investigation program at selected strong motion stations (SMSs) in the city of Christchurch and surrounding towns are used herein. Unlike similar studies that used data from free-field sites, accelerogram characteristics at the SMS locations are used to assess the performance of liquefaction evaluation procedures prior to their use in the computation of surficial manifestation severity indices. This allows the exclusion of erroneously predicted liquefaction triggering cases from being used in the assessment of the liquefaction severity index frameworks.

2 REGIONAL GEOLOGY AND GEOTECHNICAL DATA

The city of Christchurch is located on the east coast of the South Island of New Zealand, on the edge of the Canterbury Plains, a large area (approximately 160 km long and up to 60 km wide) formed by the overlapping alluvial fans of glacier-fed rivers. The surface geology within the city consists primarily of the Springston Formation (Holocene alluvial gravels, sands and silts) and the Christchurch Formation (dune and beach sands) (Brown & Weeber 1992).

The SMSs within Christchurch and the near surface stratigraphy, as outlined in Brown & Weeber (1992), is presented in Figure 1. In this figure, the locations of different soil deposits and shallow gravel layers are presented. The sub-surface geology profiles for the SMSs vary significantly across the city, with gravel layers dominating the stratigraphy in the west of the city, while in the east there are no contiguous shallow gravel layers present. Hulverstone Drive Pumping Station (HPSC), New Brighton Library (NBLC), and North New Brighton School (NNBS) are located on the Christchurch Formation (The yellow zone in Figure 1). Heathcote Valley Primary School (HVSC) is situated on loess and volcanic colluvium deposits of the Banks Peninsula loess formation. Outside of the range of Figure 1, the Lyttelton Port (LPCC) SMS is founded on basalt that is part of the Lyttelton Group Volcanics. The remainder of the SMSs are located on the Springston Formation (including Kaiapoi North School (KPOC)).

2.1 Site specific geotechnical investigation

Prior to 2010, little information regarding the subsurface geotechnical characteristics of the SMS sites in and around Christchurch was available. As noted by Cousins & McVerry (2010), the soil profiles and seismic site classification at each SMS were assumed from well logs and regional geological knowledge. Therefore, as part of this study CPT, SPT and borehole data, shear wave velocity (V_s) profiles, and horizontal-to-vertical spectral ratio measurements (H/V) in close vicinity to the SMS were used to develop detailed soil profiles at each site (CERA 2012, Wood et al. 2011, Wotherspoon et al. 2013, 2014). At each location where borehole cores were available, samples from all sand and silty sand layers were collected to determine grain size distribution and fines content (FC). Regional geotechnical investigations have shown little change in CPT sounding characteristics before and after major events in the Canterbury earthquake sequence (Orense et al. 2011). Therefore, these site investigations carried out during and following the earthquake sequence can be reasonably assumed to provide a good representation of the pre- and post-sequence soil profile characteristics. A complete summary of the site investigation data is provided in Wotherspoon et al. (2014).

2.2 SMSs excluded from study

A number of SMS were not included in the assessment of liquefaction evaluation procedures (indicated by the asterisks in Table 1). The main reason for this was detailed geotechnical investigations showed that the soil profiles at these locations did not contain soils susceptible to liquefaction (Wotherspoon et al. 2014). LPCC is located directly on volcanic rock deposits, and therefore, there is no soil present to liquefy. CACS has stiff gravel deposits at the ground surface and a water table depth of greater than 10 m. At KPOC the soil profile was dominated by gravels at depths greater than 4.5 m. Above this were interbedded layers of sand and silts, with N_{60} values of greater than 30 (blws/ft) in the sands, indicating that liquefaction is unlikely to occur in these materials. At SMTC the profile consisted of interbedded gravels, sands, plastic silts and peat. Again the sand layers were not likely to liquefy, as all had N_{60} values greater than 35. At HVSC the soil profile consists of stiff volcanic colluvium and loess deposits that are not expected to liquefy ($V_s > 300$ m/s). At RHSC the profile consisted of interbedded sands and silts to 6.5 m (the depth of the water table), below which the profile was dominated by gravels. RHSC is located in the western part of the city, on the edge of the Inland Groundwater protection zone (Weeber 2008), where the water table is in the Springston Formation gravel deposits, below the surface layers.

3 OBSERVATIONS OF LIQUEFACTION

Two physical indicators of liquefaction were collected at each SMS site: 1) the observed severity of surficial liquefaction manifestation following the Darfield and Christchurch earthquakes; 2) the characteristics of the accelerograms recorded at the SMSs. A summary of these physical indicators is provided in Table 1, and a more detailed description of each is given in the following sections.

3.1 Surface manifestations

The severity of observed surficial liquefaction manifestation at each SMS was determined from both post-event site visits by the authors and high resolution aerial and satellite imagery taken soon after each earthquake (CGD 2012). Four levels of liquefaction severity (i.e., none, minor, moderate, and severe) were used, with visual examples of these surface manifestation severities at SMS sites summarised in Figure 2 (following the classification methodology of Green et al. (2014)). These levels can be summarised as follows:

None: no evidence of surface manifestation

Minor: limited ground cracking, small patches of surface ejecta (< 5% of ground surface), and/or limited seeping of water on the ground surface.

Moderate: moderate sized ground cracking (> 200 mm width) and/or moderate sized sand boils on the ground surface (5-40% of ground surface).

Severe: extensive ground cracking (> 200 m width) and/or massive sand boils on the ground surface (> 40% of ground surface).

3.2 Accelerogram characteristics

Visual interpretation of the earthquake accelerograms was used to determine whether liquefaction triggered during the Darfield and Christchurch earthquakes. Liquefaction is characterised in these accelerograms by acceleration spikes characteristic of cyclic mobility/soil dilation, and reduced high frequency content in the latter part of the record (Ishihara and Towhata 1982, Iai et al. 1995, Towhata et al. 1996). However, care must be taken to account for the effects of the long period motion from surface waves in later parts of the record, as this can have a similar effect on the accelerogram characteristics. Characteristics of the accelerograms recorded during the Darfield and Christchurch earthquake are discussed in more detail in Bradley (2012) and Bradley & Cubrinovski (2011).

Examples of accelerograms from the NNBS SMS during the Darfield and Christchurch earthquakes are presented in Figure 3. The NNBS record during the Darfield earthquake in Figure 3a shows no clear indication of liquefaction. However, surface waves are evident in this record after approximately 30 seconds, and even though no liquefaction was inferred to have occurred, there is some reduction in the high frequency content later in this record. During the Darfield earthquake, the distance from the fault (40 km or greater) meant that many accelerograms in the Christchurch region had reduced high frequency content later in the records due to the difference in the propagation velocities of the higher frequency primary and secondary waves and the lower frequency surface waves. This was evident both in sites with potentially liquefiable material and sites where no liquefiable material was present. The only SMS location with clear evidence of liquefaction in accelerograms during the Darfield earthquake was HPSC.

The NNBS accelerogram from the Christchurch earthquake is a good example of the effect of liquefaction, with cyclic mobility in the liquefied layers resulting in significant acceleration spikes, well in excess of the peak accelerations prior to the onset of liquefaction indicated in the figure. This severe liquefaction also resulted in a drastic reduction in the motion after 5 seconds, as shown in Figure 3b. During the Christchurch earthquake there was no clear reduction in high frequency content in the accelerograms at KPOC, SMTC or CACS, which were the most distant SMSs (used in this study) from the earthquake epicentre and their subsurface profiles contained no soils

susceptible to liquefaction (discussed in Section 2.2). Therefore any clear reduction in frequency content in accelerograms in the region during the Christchurch earthquake can reasonably be attributed to liquefaction in the subsurface.

4 LIQUEFACTION EVALUATION PROCEDURES

Three existing deterministic CPT-based simplified liquefaction evaluation procedures (referred to as evaluation procedures in the remainder of this paper) were studied herein:

- Robertson & Wride (1998)/Youd et al. (2001) – (R&W procedure)
- Moss et al. (2006) – (Moss procedure)
- Idriss & Boulanger (2008) – (I&B procedure)

Calculations were performed using the geometric mean of the horizontal components of peak ground acceleration (PGA) recorded at each SMS for the $M_w 7.1$ 2010 Darfield and the $M_w 6.2$ 2011 Christchurch earthquakes summarised in Table 2. Two approaches were used to compute the PGA for each component of horizontal ground motion. First, the overall PGA in each horizontal component was used to define the geometric mean. Second, the PGA in each component prior to any manifestation of liquefaction in the accelerograms was used to define the geometric mean. The motivation behind the use of these two approaches is shown in Figure 3b, where it is suggested that the overall PGA of this record is a result of cyclic mobility effects after liquefaction was triggered. The reduced PGA (for this record) is shown by the horizontal dashed line in the figure, which does not appear to be affected by cyclic mobility, and occurs prior to the sharp reduction in high frequency ground motion content. In total, four cases had a reduced PGA using this approach (CBGS, CCCC, NNBS, REHS). Because the NBLC SMS was not operational during these earthquakes, the PGA for the NNBS SMS prior to any manifestation of liquefaction was used in the calculations. Because these sites were only 1.6 km apart, and both located on Christchurch formation soils, this was considered a reasonable representation of the PGA at this location.

Ground water levels for each event were obtained using the water tables given in the Canterbury Geotechnical Database (CERA 2012). Soil unit weight was assumed to be 17 kN/m^3 above the water table, and 19.5 kN/m^3 below the water table. Fines content for potentially liquefiable layers were determined using lab testing data where available. At sites and/or depths where this data was not available, the fines content for the I&B procedure was estimated using the generic correlation between FC and soil behaviour type index (I_c) proposed by Robertson & Wride (1998). Only layers

having $I_c < 2.6$ were assumed to be potentially liquefiable in this analysis. The sensitivity of this assumption and the water table depths were investigated at each SMS location, with both shown to have little impact on the analysis results.

A probability of liquefaction (P_L) of 15% was used to represent a deterministic liquefaction evaluation for the Moss procedure. Each procedure used the magnitude scaling factor MSF (or Duration Weighting Factor, DWF) detailed in the respective references. The relative densities (D_r) were estimated using the relationship given by Robertson and Cabal (2012) for use in determining K_σ for the R&W procedure, with K_σ defined by Hynes and Olsen (1999):

$$K_\sigma = \left(\frac{\sigma'_{vo}}{P_a} \right)^{(f-1)}$$

where σ'_{vo} is the vertical effective stress, P_a is the atmospheric pressure, and f is function of relative density, with $f = 0.7-0.8$ for $D_r = 40-60\%$, and $f = 0.6-0.7$ for $D_r = 60-80\%$.

4.1 Indicators of liquefaction triggering

The performance of each evaluation procedure was assessed using both the evidence of surface manifestation and the observed accelerogram characteristics at the SMS for the Darfield and Christchurch earthquakes. A qualitative approach was used for the accelerogram performance assessment because a lack of clear evidence of liquefaction in the accelerogram is not definitive proof of an absence of liquefaction in the underlying soils. The following classifications were made:

- If there was no clear indication of liquefaction in the accelerogram and the evaluation procedure had factors of safety (FOS) above one, or if there was clear indication of liquefaction and the factor of safety was below one, the procedure was deemed satisfactory.
- If there was clear indication of liquefaction in the accelerogram and the evaluation procedure had factors of safety above one then the procedure was deemed unconservative.
- If there was no clear evidence of liquefaction in the accelerogram and the evaluation procedure had factors of safety below FS_{limit} then the method was deemed over-conservative, where FS_{limit} corresponds to a FOS below which the soil is predicted very likely to liquefy (additional information provided below).
- If there was no clear evidence of liquefaction in the accelerogram and the evaluation procedure had factors of safety between FS_{limit} and one then the method was deemed

conservative. As these deterministic models are inherently conservative, this is an acceptable result for each liquefaction evaluation procedure.

The factor of safety limit (FS_{limit}) between conservative and over-conservative cases was based on the likelihood of liquefaction classes defined by Chen & Juang (2000), with a probability of liquefaction (P_L) greater than 65% very likely to liquefy. Sites with $P_L < 15\%$ were deemed almost certain not to liquefy according to Chen & Juang. Using the P_L -FOS mapping function from Ku et al. (2012) for the R&W procedure, a 65% P_L corresponds to a factor of safety (FS_{limit}) of 0.81. Taylor (2014) developed a P_L – FOS mapping function for the I&B procedure, defining the FS_{limit} as 0.76 for this procedure. For the Moss procedure, each case was assessed using a deterministic limit corresponding to 15% P_L , and then a 65% P_L was used to identify cases that were deemed over-conservative.

4.2 Liquefaction Severity Index Frameworks

Data from each of the CPT-based evaluation procedures described in the previous section were used in conjunction with liquefaction severity index frameworks to compute indices for severity of surficial liquefaction manifestation (referred to as severity indices in the remainder of this paper). Because these represent the cumulative effect of the soil deposit, the computed severity indices were assessed using the severity of the observed surface manifestations following the Darfield and Christchurch earthquakes. This paper focusses on the Liquefaction Potential Index (LPI), predicted post-liquefaction consolidation settlement (S), and the Liquefaction Severity Number (LSN). The relationship between surficial manifestation severity and the LPI and LSN values based on the original LPI and LSN classifications is summarized in Table 3. The original framework and thresholds for liquefaction severity for LPI were used herein because they were validated by Maurer et al. (2014) using sites from the same region as the sites assessed herein. Similarly, LSN was developed using data from Christchurch, so the original LSN framework was used and assessed herein.

5. SMS CASE STUDIES

5.1 Christchurch Botanical Gardens (CBGS)

The CBGS SMS is located in the Christchurch Botanical Gardens (Figure 1) on the western edge of the Christchurch Central Business District (CBD). Investigations indicate approximately 9 m of gravels at the surface, overlying interbedded layers of sands, sandy silts and silts down to 21 m. The fines content for the sand and silty sand layers from lab testing ranged from 1 to 15%. Below 21 m the dense Riccarton Gravel deposits were encountered (Wotherspoon et al. 2014).

1 There was no clear manifestation of liquefaction effects at the ground surface in the immediate
2 vicinity of the SMS or evidence of liquefaction in the accelerogram from the Darfield earthquake
3 (Figure 4a). In addition, there was no clear manifestation of liquefaction effects near the CBGS SMS
4 following the Christchurch earthquake. Lighter spots in the grass surrounding the SMS were
5 confirmed as dry grass areas and not surface ejecta by ground reconnaissance following the
6 Christchurch earthquake. However, a few hundred metres to the north of the SMS, significant
7 volumes of ejecta were observed at the ground surface in North Hagley Park following the
8 Christchurch earthquake. Also, the accelerogram from the Christchurch earthquake in Figure 4b
9 showed a clear indication of liquefaction of the underlying soils, with characteristic acceleration
10 spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski
11 2011). This indicates that liquefaction likely triggered during the Christchurch earthquake, but the
12 thick gravel layer near the surface inhibited surficial manifestation of liquefaction near the SMS.

13 The geometric mean of the horizontal PGAs used in the evaluation procedures were equal to 0.16g
14 and 0.50g for the Darfield and Christchurch earthquakes, respectively (a reduced PGA prior to the
15 onset of liquefaction of 0.33g was also used, as indicated for one horizontal direction in Figure 4b).

16 For the Darfield earthquake only a small number of very thin layers were shown to have a factor of
17 safety slightly less than one in the soil profile. However, for the Christchurch earthquake multiple
18 layers up to 40 cm in thickness were predicted to liquefy in the soil profile, with the factors of safety
19 of these layers being as low as 0.5 (Figure 5). These results correlate well with the accelerogram
20 characteristics for each event, and using the classifications in Section 4.1 leads to a conservative
21 representation for the Darfield earthquake and a satisfactory representation for the Christchurch
22 earthquake.

23 Severity indices for each evaluation procedure for the Christchurch earthquake are summarized in
24 Figure 5. *LPI* values suggest nil-minor surface manifestation, which has a reasonable correlation with
25 what was observed. The *LSN* values were essentially zero for the Christchurch earthquake, which
26 signifies no surface effects and compares well with the lack of surficial manifestation at this location.
27 Clearly the crust thickness is important because it has an influence on the presence of any surficial
28 manifestation, and if the *LPI* was computed using only the top 10 m of the soil profile, as is the case
29 for *LSN*, the calculated surficial manifestation severity would be similar to those suggested by the
30 other severity indices. A settlement of approximately 10 cm is predicted, which is again all
31 constrained to the layers below the surface gravels, with the characteristics of the settlement with
32 depth similar to the *LPI*.

33 5.2 Cashmere High School

1 The CMHS SMS is located at the southern edge of Christchurch near the Port Hills (Figure 1). The
2 SMS is located on the edge of a thin surface gravel layer (less than 5 m thick), overlying interbedded
3 sands, sandy silts and silts down to 13.8 m. The fines content for the sand and silty sand layers from
4 lab testing ranged from 5 to 21% (Wotherspoon et al. 2014).

5 There was no clear manifestation of liquefaction at the ground surface across the entire school site
6 (Figure 6a) and there was no evidence of liquefaction in the accelerogram from the Darfield
7 earthquake. The acceleration record from the Christchurch earthquake showed a clear indication of
8 liquefaction, with characteristic acceleration spikes and reduced high frequency content in the latter
9 part of the record. However, following the Christchurch earthquake there was no surface evidence
10 of liquefaction directly adjacent to the SMS, but there was a distinct boundary between severe
11 surficial manifestation and no manifestation evident in the school grounds directly to the east and
12 south of the SMS (Figure 6b). The lack of surficial manifestation directly adjacent to the SMS was
13 likely due to the presence of a surface gravel layer at the site. Calculations here focus on the region
14 directly to the east and south of the SMS with no surface gravel layer present that was characterised
15 by CPT soundings.

16 The geometric mean of the horizontal PGAs were equal to 0.24g and 0.37g for the Darfield and
17 Christchurch earthquakes, respectively. For the Christchurch earthquake multiple layers with a
18 cumulative thickness greater than 6 m were predicted to liquefy in the soil profile, with the factors
19 of safety of these layers between 0.5 and 0.75 (Figure 7). Therefore, the Christchurch earthquake
20 results correlate well with the accelerogram characteristics for the event. However, similar factors of
21 safety were computed for the Darfield earthquake, and as there was no evidence of liquefaction in
22 the accelerogram for the Darfield earthquake these results can be deemed over-conservative
23 according to Section 4.1.

24 Severity indices for each evaluation procedure for the Christchurch earthquake are summarized in
25 Figure 7. The *LPI* and *LSN* values all suggest moderate – severe surficial manifestation, which shows a
26 good correlation with what was observed at the site. A settlement of 15-20 cm is predicted at this
27 location, with the majority of this occurring in the top 5 m of the profile, a characteristic also shown
28 by the other severity indices. Similar severity index values were computed for the Darfield
29 earthquake, and as there was no surficial manifestation the effect of the earthquake was
30 overestimated by all the severity indices. This outcome stems from the over-conservative results of
31 the evaluation procedures.

6. SUMMARY OF LIQUEFACTION ASSESSMENT

6.1 Indicators of liquefaction triggering

Table 4 summarises the performance of each evaluation procedure that were assessed using the accelerogram characteristics, with asterisks indicating the cases where liquefaction effects were evident in the accelerogram. In general, for cases where liquefaction effects were evident in the accelerogram, the evaluation procedures correlated well with the recorded accelerogram characteristics at each SMS. Depending on evaluation procedure, 80-100% of cases had a satisfactory performance, with the I&B procedure having a 100% agreement. However, for cases with no evidence of liquefaction in the accelerograms, 80-100% of evaluation procedures were conservative or over-conservative. Here the I&B procedure had no satisfactory cases, with 50% conservative and 50% over-conservative. These results tend to suggest that overall each of the deterministic evaluation procedures are conservative, a result that is expected given that these methods provide a lower bound for liquefaction triggering. This characteristic has been identified in other research (Ku et al. 2012). The use of the PGA prior to the onset of liquefaction only affected the R&W procedure at NNBS, shifting the performance from satisfactory to unconservative.

Each evaluation procedure was also assessed the evidence of surficial manifestation outlined in Table 1. For cases with evidence of surficial manifestation, 85-100% also predicted triggering of liquefaction. When there was no evidence of surficial manifestation, 77-85% of cases predicted triggering of liquefaction. This poor correlation between evaluation procedure and surface manifestation is not surprising, given that the evaluation produces do not provide a direct indication of the cumulative effect of liquefied soil on the ground surface.

Two of the R&W and Moss cases (NNBS & SHLC) for the Christchurch earthquake had unconservative results, with liquefaction not predicted for these cases but with clear evidence of liquefaction in the accelerograms (moderate surficial manifestation was evident at SHLC, and no surficial manifestation at NNBS). The same cases for the Darfield earthquake had satisfactory results, with factors of safety well above one and no accelerogram evidence of liquefaction. These were the only cases for the Darfield earthquake with no evidence of liquefaction in the accelerograms that were not classified as conservative or over-conservative.

6.2 Liquefaction severity index frameworks

6.2.1 LPI and LSN

Figure 8 compares the observed severity of surficial manifestation with the calculated severity index (*LPI* and *LSN*) values, and these are presented separately for each liquefaction evaluation procedure (R&W, Moss, I&B). The evaluation procedure performance based on evidence of liquefaction in accelerograms summarised in Table 4 is represented for each data point in Figure 8. Because the performance of the evaluation procedures directly influences the performance of the severity indices, evaluation procedure cases with a conservative or a satisfactory result were of the most interest. If all cases were included, regardless of the performance of the liquefaction evaluation procedure, there is clearly a poor correlation between both the *LPI* and *LSN* and surface manifestation severity.

Over-conservative evaluation procedure cases, where liquefaction factors of safety of less than FS_{limit} were computed for cases with no clear evidence of liquefaction in accelerograms, are likely to result in severity index values that correspond to higher liquefaction severity than was observed. Severity indices for these cases in Figure 8 highlight the large range in values for cases with no surficial manifestations. *LPI* and *LSN* values predict liquefaction surficial manifestation severity from minor to moderate, values that are too high for cases where no surficial manifestations were identified. In this situation the severity indices are controlled by the over-conservative input from the evaluation procedures, and without knowledge of the accelerogram characteristics at these locations, the performance of the severity indices would have been considered poor. Unconservative evaluation procedure cases, where liquefaction factors of safety above one were computed for cases with a clear indication of liquefaction in accelerograms, will lead to low computed severity index values. This may or may not correlate well with the observed surficial manifestation severity, as is shown in Figure 8. For cases with no surficial manifestations, the severity indices are controlled by the input from the evaluation procedures, and without knowledge of the accelerograms characteristics at this location, the performance of the severity indices would be considered acceptable.

Focussing only on satisfactory and conservative cases, Figure 8 shows that there was a reasonable correlation between the observed surficial manifestation severity, and the severity predicted using *LSN*. The removal of over-conservative cases reduced the range of *LSN* values for cases with no surface manifestation, however there is clearly still scatter in the general trend of an increase in *LSN* with observed surficial manifestation severity. There is a weaker correlation between *LPI* and the observed surficial manifestation severity, with similar maximum *LPI* values for the nil, minor and moderate observed manifestation severity cases. For each conservative evaluation procedure case, where no surficial manifestation was evident, low *LPI* and *LSN* values were calculated that predict

1 nil-minor surficial manifestation severity. This suggests that even though the evaluation procedures
2 were conservative in these cases, reasonable severity index ranges were calculated.

3 There was no observed surficial manifestation at REHS during the Christchurch earthquake
4 (indicated by R in Figure 8), however the severity indices predicted minor-moderate surficial
5 manifestation severity. A possible reason for the lack of observed surficial manifestations was the
6 presence of competent crust layer with a CPT tip resistance of approximately 25 MPa. This layer may
7 have prevented the passage of ejecta from the source layer to the ground surface. The HPSC SMS
8 (indicated by H in Figure 8) was the only SMS location where lateral spreading was evident, which
9 may have been the reason for the poor correlation between *LPI* and the observed manifestation
10 severity for these data points. A similar poor correlation between *LPI* and cases with lateral
11 spreading was highlighted in the study of Maurer et al. (2014).

12 Figure 9 summarises the changes in *LPI* when it was calculated using the output from liquefaction
13 evaluation procedures where the reduced PGA prior to the onset of liquefaction was used (from
14 Table 2). In this figure the blank symbols indicate cases where *LPI* was calculated from the output
15 from evaluation procedures using the overall PGA, with the dashed lines linking them to a filled
16 symbol corresponding to the same case using the reduced PGA. Cases where this does not result in
17 significant changes in the calculated *LPI* are shown as a single filled symbol, along with cases where
18 the overall PGA and the PGA prior to the onset of liquefaction was the same. These shifts clearly
19 improve the correlation between *LPI* and the observed surface manifestation severity for the nil and
20 minor cases, but scatter still remains. The use of the reduced PGA values did not result in any
21 significant changes to the *LSN* values, as the major changes to the output from the liquefaction
22 evaluation procedures were in soil layers deeper than 10 m that provided no contribution to *LSN*.

23 6.2.2 Calculated settlement

24 Figure 10 provides a comparison between the observed severity of surficial manifestation and the
25 calculated settlement for all liquefaction evaluation procedures. The over-conservative and
26 unconservative evaluation procedure cases are indicated by the smaller circle symbols in Figure 10.
27 Compared to *LPI* and *LSN*, there was a weaker correlation between calculated settlement and the
28 observed manifestation severity, with a similar range of calculated settlements for the no observed
29 manifestation and minor manifestation severity, and no clear delineation between the moderate
30 and major observed surface manifestation categories. There was also a much larger range in the
31 calculated settlements for cases where no surface manifestation was evident. These characteristics

are likely a result of the lack of any dependence on depth in the calculation of settlement, which is controlled by post-liquefaction volumetric strain estimates.

7. CONCLUSIONS

Using the database of strong ground motion recordings from the Canterbury earthquake sequence, the observations of liquefaction manifestation at the ground surface, and data from a recently completed extensive geotechnical site investigation program at each SMS, three CPT-based liquefaction evaluation procedures were assessed. For cases with evidence of liquefaction in the accelerograms the majority of liquefaction evaluation procedures performed satisfactorily, correctly predicting the triggering of liquefaction. This was evident for cases both with and without any surficial manifestation of liquefaction. For cases with no evidence of liquefaction in the accelerograms the majority of liquefaction evaluation procedures still predicted liquefaction, therefore under predicting the factors of safety against liquefaction (i.e., conservative). All these cases also had no surficial manifestation of liquefaction. The cases that suggest no liquefaction in a situation with clear evidence of liquefaction in accelerograms (i.e., unconservative) are significant misinterpretations, while over-conservative cases are shown to control severity index calculations and lead to overestimation of the predicted surficial liquefaction severity.

Unlike similar studies at general free-field sites, accelerogram data at the SMS locations allows assessment of the liquefaction evaluation procedures prior to their use in the computation of surficial manifestation severity indices. If all cases were used to assess the severity indices, a poor correlation was evident between the observed and predicted surficial manifestation for *LPI*, *LSN* and post-liquefaction consolidation settlement. However, in situations where the severity indices are computed from erroneous predictions from the evaluation procedures, these cases can be removed from those used to assess severity index performance. Taking this approach, a slightly improved correlation is shown between the observed severity of surficial liquefaction manifestations and the predictive capabilities of the severity indices, especially for cases with nil-minor observed manifestation severity. *LSN* had a reasonable correlation between predicted and observed surficial manifestation severity, but there is still scatter in the results. The *LPI* correlation was weaker than the *LSN*, however this improved for the nil and minor observed surface manifestation severity cases if *LPI* was based on the output from liquefaction evaluation procedures where the PGA prior to the onset of liquefaction was used. Post-liquefaction consolidation settlement showed the weakest correlation of all, with poor delineation between each surface manifestation severity categories.

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Figure Captions

Figure 1. Overview of Christchurch SMS locations with surface and near surface stratigraphy (after Brown & Weeber 1992). Outside the boundaries of this figure are the KPOC and LPCC SMSs.

Figure 2. Examples of liquefaction surface manifestation severity: a) None – RHSC following the Christchurch earthquake; b) Minor - CCCC following the Christchurch earthquake, with circled area highlighting small sand boils near the station ; c) Moderate – CHHC following the Christchurch earthquake, with moderate volumes of ejecta in the area; d) Severe – HPSC following the Christchurch earthquake, with entire area affected by large volumes of ejecta and lateral spreading. Small double circles indicate location of SMS in each image (CGD 2012).

Figure 3. Example of ground motions: a) NNBS during the Darfield earthquake; b) NNBS during the Christchurch earthquake, with large cyclic mobility spikes and a sharp reduction in ground motion amplitude and frequency due to liquefaction of the underlying soils. The pre-liquefaction PGA shown here was used in the liquefaction evaluation procedures for this SMS.

Figure 4. CBGS accelerogram for the: a) Darfield earthquake that shows no evidence of liquefaction; b) Christchurch earthquake with clear evidence of liquefaction. The pre-liquefaction PGA shown here was used in the liquefaction evaluation procedures for this SMS.

Figure 5. Assessment of CPT-based liquefaction evaluation procedures for the CBGS SMS during the Christchurch earthquake. Liquefaction factors of safety are presented individually for each procedure, with the resulting LPI, LSN and settlement values presented in three combined plots.

Figure 6. Aerial views of the CMHS SMS following the: a) Darfield earthquake, where no surficial manifestation was evident; b) Christchurch earthquake, with clear evidence of surficial manifestation in the form of large volumes of ejecta. The boundary between severe and no manifestation is identified by the dashed line in this figure (CGD 2012).

Figure 7. Assessment of CPT-based liquefaction evaluation procedures for the CMHS SMS during the Christchurch earthquake. Liquefaction factors of safety are presented individually for each procedure, with the resulting LPI, LSN and settlement values presented in three combined plots.

Figure 8. Comparison of observed surficial manifestation severity with calculated LPI and LSN severity indicators for each liquefaction evaluation procedure. Symbols identify the performance of the liquefaction evaluation procedure for each case.

Figure 9. Comparison of observed surficial manifestation severity and calculated LPI for each liquefaction evaluation procedure. Blank symbols indicate cases where the LPI values calculated using the output from the liquefaction evaluation procedures using the overall PGA, with the dashed lines linking them to the corresponding case study point using the reduced PGA prior to the onset of liquefaction.

Figure 10. Comparison of observed surficial manifestation severity with the calculated settlement for each liquefaction evaluation procedure. Over-conservative and unconservative liquefaction evaluation procedure cases are indicated by the smaller circle symbols.

Table 1. Summary of physical indicators of liquefaction at each SMS for the Darfield and Christchurch earthquakes. SMS sites with asterisks were not included in the analysis due to absence of soils susceptible to liquefaction.

SMS ID	Station Name	Severity of surface manifestation		Indicators of liquefaction in accelerograms	
		Darfield ^a	ChCh ^b	Darfield ^a	ChCh ^b
CACS	Canterbury Aero Club*	N	N	N	N
CBGS	Christchurch Botanical Gardens	N	N	N	Y
CCCC	Christchurch Cathedral College	N	Minor	N	Y
CHHC	Christchurch Hospital	N	Moderate	N	Y
CMHS	Cashmere High School	N	Severe	N	Y
HPSC	Hulverstone Dr Pumping Station	Severe	Severe	Y	Y
HVSC	Heathcote Valley School*	N	N	N	N
KPOC	Kaiapoi North School*	N	N	N	N
LPCC	Lyttelton Port*	N	N	N	N
NBLC	New Brighton Library	N	N	NA ^c	NA ^c
NNBS	North New Brighton School	N	N	N	Y
PPHS	Papanui High School	N	N	N	N
PRPC	Pages Rd Pumping Station	N	Minor	N	Y
REHS	Christchurch Resthaven	N	N	N	Y
RHSC	Riccarton High School*	N	N	N	N
SHLC	Shirley Library	N	Moderate	N	Y
SMTC	Styx Mill Transfer Station*	N	N	N	N

^a 4 September 2010 Darfield earthquake

^b 22 February 2011 Christchurch earthquake

^c No accelerogram recordings at this location

Table 2. Summary of CPT soundings at each SMS and geometric mean of the horizontal components of peak ground acceleration used in liquefaction evaluation procedures. Values in brackets indicate the PGA prior to the onset of liquefaction

SMS ID	CPT ID	PGA (g)	
		Darfield	ChCh
CBGS	CBGS_CPT1	0.16	0.50 (0.32)
CCCC	CCCC_CPT1	0.22	0.43 (0.35)
CHHC	CHHC_CPT1	0.17	0.37
CMHS	CMHS_CPT1	0.24	0.37
HPSC	HPSC_CPT1	0.15	0.22
NBLC	NBLC_CPT1	0.21	0.32
NNBS	NNBS_CPT1	0.21	0.67 (0.32)
PPHS	PPHS_CPT1	0.22	0.21
PRPC	PRPC_CPT3	0.21	0.63
REHS	REHS_CPT1	0.25	0.52 (0.36)
SHLC	SHLC_CPT1	0.18	0.33

Table 3. Categories of severity of liquefaction surficial manifestation as a function of LPI and LSN used in this study. Examples of each surficial manifestation severity are presented in Figure 2.

Indicator	Surficial manifestation severity			
	None	Minor	Moderate	Severe
LPI	0	0-5	5-15	15+
LSN	0	0-20	20-50	50+

Table 4. Performance of liquefaction evaluation procedures at each SMS for the Darfield and Christchurch earthquake. Asterisks indicate cases with evidence of liquefaction in accelerograms. Brackets indicate cases where the PGA prior to the onset of liquefaction was used.

Darfield Earthquake				Christchurch Earthquake			
SMS ID	Evaluation procedure			SMS ID	Evaluation procedure		
	R&W	Moss	I&B		R&W	Moss	I&B
CBGS	C	C	C	CBGS*	S (S)	S (S)	S (S)
CCCC	OC	OC	OC	CCCC*	S (S)	S (S)	S (S)
CHHC	OC	OC	OC	CHHC*	S	S	S
CMHS	OC	OC	OC	CMHS*	S	S	S
HPSC*	S	S	S	HPSC*	S	S	S
NNBS	S	S	C	NNBS*	S (UC)	UC (UC)	S (S)
PPHS	OC	OC	OC	PPHS	C	OC	C
PRPC	C	OC	C	PRPC*	S	S	S
REHS	OC	OC	OC	REHS*	S (S)	S (S)	S (S)
SHLC	S	S	C	SHLC*	UC	UC	S

where S=satisfactory, C=conservative, OC=over-conservative, UC=unconservative

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10