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IN-SITU INVESTIGATION OF FALSE-POSITIVE LIQUEFACTION SITES IN CHRISTCHURCH, NEW ZEALAND: St. Teresa’s School Case History

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ABSTRACT
Over 22,000 cone penetration test (CPT) soundings collected in Christchurch, New Zealand, in the aftermath of the 2010-2011 Canterbury earthquake sequence are available on the New Zealand Geotechnical Database (NZGD). This incredible dataset has allowed for detailed comparisons between observed land performance and CPT-based retrospective predictions of liquefaction triggering on an unprecedented spatial scale. Results from these comparisons indicate a significant number of “false positive” CPT-based liquefaction triggering predictions across Christchurch. Meaning, there are some fairly large areas of the city in which severe liquefaction was predicted based on simplified analyses of CPT soundings but no, or very minor, surface manifestations of liquefaction were observed. In August of 2015 an in-situ site characterization study was initiated to further investigate the false positive liquefaction sites in Christchurch. Specifically, 31 sites were identified for a testing program consisting of: (a) seismic CPT (SCPT), (b) high-resolution compression and shear wave velocity ($V_p$ and $V_s$, respectively) measurements made via direct-push crosshole (DPCH) testing, and (c) continuous soil sampling via sonic drilling. This paper presents in-situ test results from one of these case history sites (St. Teresa’s School) and investigates the impact of considering additional refined analyses to both the "standard" Boulanger and Idriss (2015) deterministic CPT-based liquefaction triggering procedure and the Kayen et al. (2013) deterministic $V_s$-based liquefaction triggering procedure as a means to reconcile the over-prediction of liquefaction severity. The additional factors considered in these refined analyses include: (1) site-specific soil plasticity and fines content data, (2) partial saturation (as indicated by $V_p$), (3) coarse-to-fine-grained soil interlayering, (4) non-liquefying crust thickness and (5) microstructure. Adjustments made to basic liquefaction triggering procedures based on these factors significantly lowered the liquefaction severity parameters at this site, reconciling the over-prediction of liquefaction severity for the 2010 Darfield earthquake and reducing the over-prediction in the 2011 Christchurch earthquake from “severe” to “slight.”

1 INTRODUCTION
The city of Christchurch, New Zealand experienced a powerful series of earthquakes in 2010-2011, the most destructive of which were the 4 September 2010 moment magnitude (M$_W$) 7.1 Darfield Earthquake and the 22 February 2011 M$_W$ 6.2 Christchurch Earthquake. As discussed by Cubrinovski et al. (2012), this series of earthquakes caused extensive liquefaction damage throughout the greater Christchurch area, with nearly one third of the city experiencing liquefaction damage in one or several of the events.

An unprecedented, open-access geotechnical database, the Canterbury Geotechnical Database, was created in the aftermath of the earthquakes. This database was subsequently combined with data from other regions to create the New Zealand Geotechnical Database (NZGD). The NZGD (https://www.nzgd.org.nz/) contains over 22,000 cone penetration test (CPT) soundings from the greater Christchurch area as well as documentation of liquefaction manifestation after each earthquake. This information has been used to compare observed post-earthquake land performance with CPT-based retrospective predictions of liquefaction severity on a large spatial scale. After examining results from these comparisons, two broad observations were made: (1) CPT-based simplified methods correctly predicted the occurrence of liquefaction triggering at most sites in which
surface manifestations of liquefaction (sand boils, excessive settlement, lateral spreading, etc.) were observed during the earthquakes; and (2) CPT-based methods have resulted in a significant number of false positive assessments across the city, for which liquefaction triggering was predicted but no liquefaction damage was observed. This over-prediction of liquefaction severity has costly consequences for rebuilding efforts and insurance claims throughout Christchurch, and is potentially driving overly conservative liquefaction design in similar soils worldwide.

In order to attempt to reconcile some of the false positive liquefaction predictions, 31 case history sites throughout the greater Christchurch area were identified for a comprehensive in-situ testing program, including: (1) seismic cone penetration tests (SCPT); (2) high-resolution shear wave velocity ($V_s$) and compression wave velocity ($V_p$) measurements made via direct-push crosshole (DPCH) tests; (3) disturbed soil sampling and detailed borehole logging using continuous core from sonic drilling; and (4) laboratory index testing (i.e., Atterberg limits) and grain size analyses. At each case history site, the three in-situ tests (i.e., SCPT, DPCH, and sonic drilling) were performed within 2 m of one another and extended to a depth of 10-20 m below grade (depending on subsurface conditions). The sonic drilling was always performed after the SCPT and DPCH measurements. The in-situ test results were first used to perform standard liquefaction triggering analyses using both the Boulanger and Idriss (2015) deterministic CPT-based and the Kayen et al. (2013) deterministic $V_S$-based simplified procedures. Then, retrospective predictions of liquefaction surface manifestation based on several liquefaction severity parameters were compared with the observations of liquefaction/no-liquefaction at the sites for the 2010 Darfield and 2011 Christchurch earthquakes.

While data and analysis results are interesting at many sites in our study, we have chosen a single site for presentation in this paper. As discussed below, the liquefaction severity at St. Teresa’s School was “severely over-predicted” for both the 2010 Darfield and 2011 Christchurch earthquakes based on standard liquefaction triggering evaluations. In an attempt to reconcile the over-prediction of liquefaction severity at this site, several additional factors were considered, including: (1) site-specific soil plasticity and fines content (FC) data, (2) partial saturation (as indicated by $V_p$), (3) coarse-to-fine-grained soil interlayering, (4) non-liquefying crust thickness and (5) microstructure. Results obtained from these additional considerations are described below.

2 QUANTIFYING OBSERVED VS. PREDICTED LIQUEFACTION SEVERITY

The observed liquefaction severity at each study site was quantified using the six categories discussed in the Tonkin & Taylor (2013) Liquefaction Vulnerability Report: (1) none observed, (2) minor, (3) moderate, (4) major, (5) severe, and (6) very severe. Category assignments were made based on observations of liquefaction/no-liquefaction following both the September 2010 Darfield and February 2011 Christchurch earthquakes. The observations were made by engineers undertaking rapid site inspections and through review of high resolution aerial imagery which was collected immediately after each earthquake. This imagery is archived on the NZGD and most of our study sites are within the bounds of its coverage.

The first step in back-estimating liquefaction severity at each site was to apply the “standard” Boulanger and Idriss (2015) CPT-based simplified liquefaction triggering procedure using a deterministic analysis based on the 15th percentile probability of liquefaction ($P_L$) cyclic resistance ratio (CRR) curves. By “standard”, we mean a simplified triggering analysis based on CPT-data alone (i.e., without soil plasticity and FC information from laboratory testing of borehole core samples) and without refinements made for other potentially important factors like thin layers and partial saturation. We also mean that uncertainties in ground motions, depth to groundwater and triggering (reflected by different $P_L$, CRR curves) were not robustly accounted for. However, ground motions and groundwater levels were reasonably well-constrained by measurements across the city. Furthermore, in these standard analyses, the FC estimated using the default soil behavior-type index ($I_c$)-FC correlation from Boulanger and Idriss (2015) was used and the factor of safety (FS) against liquefaction as a function of depth was calculated for all material with $I_c < 2.6$. Soils with $I_c > 2.6$ were assumed too clay-like to liquefy. In order to condense the factors of safety for each CPT sounding into a single number representative of the estimated severity of liquefaction manifestation, several commonly used liquefaction severity parameters were considered:

- Liquefaction Potential Index (LPI), proposed by Iwasaki (1978)
- Ishihara-inspired Liquefaction Potential Index ($LPI_{ISH}$), proposed by Maurer et al. (2015)
- Liquefaction Severity Number (LSN), proposed by Tonkin & Taylor (2013) and Van Ballegoooy et al. (2014)
- 1-D vertical reconsolidation settlement ($S_{VD}$), calculated using the methods of Ishihara and Yoshinine (1992) and the volumetric strain relationships recommended by Zhang et al. (2002)
- Cumulative Thickness of Liquefaction (CTL), meaning, the cumulative thickness of subsurface soil layers with a FS against liquefaction less than one

A number of these liquefaction severity parameters require some sort of integration and/or summing of the factor of safety down to a common depth reference. As discussed in Maurer et al. (2014), much of the CPT database available in Christchurch contains CPTs that terminate at depths shallower than 20 m below ground surface due to the presence of the Springston or Christchurch gravel formations. Hence, at most sites it is not possible to perform these calculations down to the commonly-used reference depth of 20 m. This does not necessarily mean that the liquefaction severity parameters calculated from CPT soundings that terminate at shallower depths are underestimated in comparison to previous studies. As pointed out by Maurer et al. (2014) in regard to their estimates of LPI, it is unlikely that soils deeper than
CPT-based liquefaction severity predictions based on LPI

Table 1. Assessment matrix for quantifying the accuracy of liquefaction severity predictions based on LPI

<table>
<thead>
<tr>
<th>Predictions</th>
<th>Observations (Tonkin &amp; Taylor 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Maurer et al. 2014)</td>
<td>None to Minor</td>
</tr>
<tr>
<td>None to Marginal LPI &lt; 8</td>
<td>Correct</td>
</tr>
<tr>
<td>Moderate 8 ≤ LPI &lt; 15</td>
<td>Slightly Over</td>
</tr>
<tr>
<td>Severe LPI ≥ 15</td>
<td>Severely Over</td>
</tr>
</tbody>
</table>

The LPI-based assessment matrix was used to evaluate the accuracy of the liquefaction severity predictions for each of the 31 case history sites in this study in comparison to the observations of liquefaction following each earthquake. One false-positive case history site, St. Teresa's School, which classified as “severely over-predicted” during both the 2010 Darfield and 2011 Christchurch earthquakes, has been selected for further examination in this paper. While detailed examinations of single case histories are important and necessary, it should be stressed that conclusions derived from a single site should not be extrapolated too far until they have been put into context with all of the other case history sites in Christchurch.

3 ST. TERESA’S SCHOOL: OBSERVED VS. PREDICTED LIQUEFACTION

3.1 CPT-based Deterministic Liquefaction Triggering Analysis

St. Teresa’s School is located at the corner of Riccarton Road and Puriri Street in the Riccarton suburb of Christchurch. No observations of surficial liquefaction manifestation were noted at this site (or even in the vicinity of Riccarton) during the 2010-2011 Canterbury Earthquake Sequence. However, as discussed below, standard CPT-based methods resulted in predictions of severe liquefaction during both the 2010 Darfield and 2011 Christchurch earthquakes. Testing for the August 2015 study took place in the parking lots surrounding the school building. The site plan indicating the locations of the essentially collocated SCPT 57345, DPC1 Vp-Vf, and BH 57241 advanced as a part of the August 2015 study is shown in Figure 1. Three other CPTs advanced in August 2013 were also available at this site.

![Figure 1. St. Teresa’s School site plan showing in-situ test locations and absence of surficial liquefaction manifestations (image taken on 24 February 2011, base layer from NZGD).](image)

A standard deterministic liquefaction triggering analysis using the Boulanger and Idriss (2015) procedure was run on each CPT available at the St. Teresa’s School site. The mean PGAs used at this site were 0.22 g and 0.34 g for the September 2010 and February 2011 earthquakes, respectively, based on the conditional distributions described by Green et al. (2014) and Bradley (2014).
Several liquefaction severity parameters were calculated over the top 10 m of the subsurface. The CPTs in Figure 1 have been color coded to represent relative severity of predicted liquefaction manifestation. For this specific figure, LPI calculated using parameters for the February 2011 earthquake was used as the indicator of severity. LPI values ranged from 21 to 25 across the site. The SCPT advanced in the August 2015 study resulted in the smallest LPI value of the CPTs at this site. However, even an LPI value of 21 is much larger than expected for a site at which no liquefaction manifestation was observed.

The borehole, CPT, and DPCH data collected at St. Teresa’s School are presented in Figure 2. The CPT data [friction ratio (R_f), tip resistance (q_c), and soil behavior-type index (I_c)] are color coded according to LPI severity, identical to the coloring scheme used in Figure 1.

Figure 2. St. Teresa’s School 1D site profile with: continuous core sonic borehole log (BH 57241), data from all of the CPT soundings color-coded according to LPI severity, and direct-push crosshole V_P and V_S profiles. The range of September 2010 and February 2011 water table levels are indicated by the blue dashed lines.

The continuous core sonic borehole log in Figure 2 shows a soil profile primarily composed of low-plasticity silt (ML) with some thin layers of poorly-graded sand (SP) between 6 m and 7.25 m below ground surface. Within the ML layers are smaller breaks, indicated by black dashed lines, where the ML was noted to differ slightly in composition. Trace sand, organics, and gravel were also noted throughout the ML layers. The q_c and I_c plots for all CPTs show general continuity in layering across the site, with distinct layers classifying as either clean sand or silt mixtures/clay based on I_c, with transitional material in between. However, the CPT sounding collected during August 2015 (i.e., SCPT 57345) does have higher than average q_c values between 3 - 4 m. The V_P data briefly exceeds 1500 m/s (the lower-bound threshold indicating 100% saturation) at approximately 1.75 m below the ground surface, but does not stabilize above 1500 m/s until approximately 5.5 m below the ground surface. The depth to the water table at this site fluctuated very little from September 2010 to February 2011, ranging from 0.96 m to 1.04 m. Thus, the V_P profile indicates that the soil is not fully saturated for about 4.5 m below the hydrostatic water table. The V_S profile is fairly uniform, but does contain clear breaks at 1.6 m, 3 m, 4.4 m, 6.8 m, and 8.6 m that reflect the changing shear stiffness between the corresponding layers indicated by the q_c and I_c plots.

Liquefaction severity parameters were calculated for each of the four CPT soundings at the site using results from standard CPT-based liquefaction triggering analyses, as summarized in Table 2.
This site was classified as a “slight over-prediction” in the September 2010 earthquake based exclusively on the LPI prediction from the single, new CPT taken as a part of the August 2015 study (i.e., LPI = 14 for SCPT 57345). However, the mean LPI value of 16, calculated from all the CPTs collected at this site, would place this site in the “severe over-prediction” category. The LPI values for the February 2011 earthquake are even higher than those for the September 2010, with a mean LPI = 23, which places this site into the “severe over-prediction” category. Furthermore, all other liquefaction severity parameters are high and inconsistent with observations. For example, CTL values range from 5.2 – 6.0 m in both earthquakes, indicating that over half of the top 10 m of this profile is predicted to liquefy, which is too large to be consistent with the observation of no liquefaction manifestation at this site. In an attempt to reconcile this severe over-prediction case history, several potential factors not considered in the standard CPT-based analyses were identified and refinements were made, as discussed below.

3.1.1 Refined CPT-based Liquefaction Triggering Analysis

In addition to the standard CPT-based deterministic analyses most commonly used to evaluate liquefaction triggering, subsequent “refined” analyses were performed for the St. Teresa’s School case history site in an attempt to reconcile predictions of severe liquefaction with observations of no-liquefaction. Specifically, several additional factors were considered, including: (1) site-specific soil plasticity and FC data, (2) partial saturation (as indicated by $V_P$), (3) coarse-to-fine-grained soil interlayering, (4) non-liquefying crust thickness and (5) microstructure.

Discrete samples taken from the continuous sonic borehole core were used to obtain site-specific soil plasticity information (i.e., Atterberg Limits) and FC (percent of soil sample finer than 0.075 mm). The plasticity index (PI) values from five samples in the top 10 m at this site ranged from a low of zero (i.e., non-plastic; two out of five samples) to 8 (one sample at 9.8 m). Thus, the top 10 m of soil is expected to exhibit sand-like behavior rather than clay-like behavior according to Boulanger and Idriss (2006). While the in-situ water content ($w_c$) for these samples is unknown, it is expected that the $w_c$ values would be high enough for this low PI soil to be susceptible to liquefaction by the Bray and Sancio (2006) criteria. Thus, high soil plasticity is not believed to be responsible for the over-prediction of liquefaction severity at the site.

The grain size distributions were determined for eight samples in the top 10 m using laser diffraction. None of these samples had a FC less than 44%, with most ranging between 50-90%. Upon inspection, it was found that the FC estimated using the default $I_C$-FC correlation from Boulanger and Idriss (2015) yielded FC values that were quite low in comparison to the measured values. Thus, a site-specific FC fitting parameter ($C_{FC}$) was developed according to the procedure suggested in Boulanger and Idriss (2015). The CPT-based liquefaction triggering analyses were then re-run with the site-specific $C_{FC}$ = 0.402. The FC correction had a significant impact on the FS and liquefaction severity parameters calculated from the CPT data at this site. For example, the original and revised estimates of FS, LPI, LPI$_{ISH}$, LSN and $S_{V1D}$ obtained from SCPT 57145 for the September 2010 Darfield earthquake are shown in Figure 3. All of the liquefaction severity parameters were reduced substantially simply by including the site-specific $C_{FC}$ factor.

An additional refinement can be made to the standard liquefaction triggering analyses in order to account for the presence of partially saturated soils below the groundwater table. Based on our DPCH tests, many of the false-positive sites in Christchurch were found to be partially saturated ($V_P < 1500$ m/s) for several meters below the water table (refer to Figure 2). Without accounting for the effects of partial saturation at these sites, the liquefaction resistance of soil will be underestimated, causing the liquefaction severity parameters to be over-predicted. Ishihara and Tsukamoto (2004) proposed a relationship between $V_P$ and B-value, and subsequently provided a relationship between $V_P$ and the ratio of the cyclic stress of a partially saturated sand ($C_{RR_{partial sat}}$) and a fully saturated sand ($C_{RR_{sat}}$). For example, their relationship indicates that soil with $V_P = 700$ m/s has a

### Table 2: Liquefaction severity parameters (LPI, LPI$_{ISH}$, LSN, $S_{V1D}$, and CTL) for all CPTs at St. Teresa’s School based on the September 2010 and February 2011 earthquakes and the Boulanger and Idriss (2015) CPT-based liquefaction triggering procedure using a $P_L$ = 15%

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Value</th>
<th>LPI</th>
<th>LPI$_{ISH}$</th>
<th>LSN</th>
<th>$S_{V1D}$ (mm)</th>
<th>CTL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 2010</td>
<td>Range</td>
<td>14-17</td>
<td>10-14</td>
<td>29-38</td>
<td>126-153</td>
<td>5.2-6.0</td>
</tr>
<tr>
<td>(MW = 7.1, PGA = 0.22 g)</td>
<td>Mean</td>
<td>16</td>
<td>12</td>
<td>35</td>
<td>143</td>
<td>5.6</td>
</tr>
<tr>
<td>February 2011</td>
<td>Range</td>
<td>21-25</td>
<td>17-21</td>
<td>35-40</td>
<td>136-157</td>
<td>5.3-6.0</td>
</tr>
<tr>
<td>(MW = 6.2, PGA = 0.34 g)</td>
<td>Mean</td>
<td>23</td>
<td>19</td>
<td>38</td>
<td>148</td>
<td>5.7</td>
</tr>
<tr>
<td>CTL (m)</td>
<td>σ</td>
<td>1.7</td>
<td>1.7</td>
<td>2.2</td>
<td>9.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

This site was classified as a “slight over-prediction” in the September 2010 earthquake based exclusively on the LPI prediction from the single, new CPT taken as a part of the August 2015 study (i.e., LPI = 14 for SCPT 57345). However, the mean LPI value of 16, calculated from all the CPTs collected at this site, would place this site in the “severe over-prediction” category. The LPI values for the February 2011 earthquake are even higher than those for the September 2010, with a mean LPI = 23, which places this site into the “severe over-prediction” category. Furthermore, all other liquefaction severity parameters are high and inconsistent with observations. For example, CTL values range from 5.2 – 6.0 m in both earthquakes, indicating that over half of the top 10 m of this profile is predicted to liquefy, which is too large to be consistent with the observation of no liquefaction manifestation at this site. In an attempt to reconcile this severe over-prediction case history, several potential factors not considered in the standard CPT-based analyses were identified and refinements were made, as discussed below.

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CRR_{partial sat}/CRR_{sat} ratio of 1.24. Meaning, soil with \( V_P = 700 \text{ m/s} \) is 24% more resistant to liquefaction than soil that is fully saturated with \( V_P > 1500 \text{ m/s} \). Thus, the CRR_{partial sat}/CRR_{sat} ratio can be visualized as a multiplier to the factor of safety that increases its value for any soils with \( V_P < 1500 \text{ m/s} \).

The Ishihara and Tsukamoto (2004) CRR_{partial sat}/CRR_{sat} and \( V_P \) relationship was digitized for use in our calculations. The impact of partial saturation adjustments on the liquefaction severity parameters obtained from SCPT 57145 for the September 2010 Darfield earthquake are shown in Figure 3. The partial saturation adjustments were not very significant at this site since most of the soils in the top 4.0 m already had FS > 1.0 following the corrections for site-specific FC.

Another adjustment to the standard CPT-based analyses can be made to account for the presence of thin, interlayered soil deposits at many of the false-positive sites in Christchurch. This coarse-to-fine-grained soil interlayering can be observed from the thin, abrupt swings in the FS, which are based on the I_C values alternating back and forth across the I_C = 2.6 threshold. These interlayered deposits tend to disrupt the upward flow of water during liquefaction, limiting surficial manifestations. Furthermore, due to the underdevelopment of \( q_c \) values measured by the CPT in thin, coarse-grained layers sandwiched in between softer, fine-grained layers the liquefaction resistance can be under-estimated, causing liquefaction severity to be over-estimated. Ahmadi and Robertson (2005) concluded that in a loose sand layer embedded in a soft clay the correct \( q_c \) value is likely reached only if the thin layer is more than eight cone diameters thick (about 30 cm). Additionally, a smearing effect, due to the cone tip zone of influence, is present in the transition zones where the cone first passes from the softer, fine-grained soil into the thin, coarse-grained layer. This smearing effect results in \( q_c \) values in the transition zones that are not truly representative of the coarse-grained material. Thus, theoretically, corrections are needed to account for both thin-layer and transition-layer effects in order to obtain the correct \( q_c \) and I_C values.

Unfortunately, the application of layer corrections is quite subjective and several different combinations of methods are currently being used to account for increased liquefaction resistance due to these effects. Youd et al. (2001) suggested using thin-layer corrections to increase the \( q_c \) values in a thin layer of granular soil (< 1-m thick) to be representative of the \( q_c \) values that would be measured in a thicker layer of the same soil. The commonly used CLiq software package (GeoLogismiki 2006) can be used to remove \( q_c \) data points in the transition zones, but CLiq does not separately increase the remaining \( q_c \) values to account for thin-layer corrections. Boulanger et al. (2016) and Munter et al. (2017) applied a combination of thin- and transition-layer corrections to CPT data from a highly interlayered false-positive lateral spread case history following the procedures outlined in Idriss and Boulanger (2008) and Youd et al. (2001). However, their procedure cannot be automated and must be applied subjectively on a sounding-by-sounding basis to avoid over-correction in zones with natural fining sequences.

![Figure 3](image.png)

**Figure 3.** CPT data, factor of safety, and liquefaction severity parameters (LPI, LPI{ISH}, LSN, and SV1D) after progressively applying the site-specific C_{FC} and partial saturation corrections, followed by removal of thin (< 30-cm thick), interbedded sand layers from the standard deterministic liquefaction triggering analysis for SCPT 57145 in the September 2010 Darfield earthquake.
Due to the difficult nature of accurately applying thin- and transition-layer corrections to a large number of CPT logs across all false positive case history sites, we have chosen to first apply a simple screening process to each log in order to see if thin coarse-to-fine-grained soil interlayering is significantly contributing to the overestimation of liquefaction severity at the site. The screening process simply involves removing the contribution of any coarse-grained soils less than a certain thickness from the liquefaction severity parameters. At St. Teresa’s School, the thin layer screening process was applied after all other refinements had been made to the liquefaction triggering analyses by setting the factor of safety in layers less than 30-cm thick to a value of 2.0. This simple process allows one to readily quantify the impact of thin layers on the liquefaction severity parameters without attempting to make difficult corrections to the CPT data itself. If thin layers are found to significantly affect the severity parameters, further refined analyses would be required to correct the data.

An example of the progressive application of these refinements to SCPT 57145 at the St. Teresa’s School for parameters associated with the 2010 Darfield earthquake is illustrated graphically in Figure 3. Table 3 summarizes the effects of the refinements on the mean liquefaction severity parameters calculated from all four CPTs at this site.

Table 3. Mean liquefaction severity parameters (LPI, LPIISH, LSN, SV1D, CTL) obtained from all four CPT soundings at St. Teresa’s School after progressive application of the site-specific Cc and partial saturation corrections, followed by removal of thin (<30-cm thick), interbedded sand layers from the standard deterministic liquefaction triggering analyses for both the September 2010 and February 2011 earthquakes

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Corrections</th>
<th>LPI</th>
<th>LPIISH</th>
<th>LSN</th>
<th>SV1D (mm)</th>
<th>CTL (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darfield</td>
<td>None</td>
<td>16</td>
<td>12</td>
<td>35</td>
<td>143</td>
<td>5.6</td>
</tr>
<tr>
<td>Sep. 2010</td>
<td>FC</td>
<td>10</td>
<td>7</td>
<td>22</td>
<td>93</td>
<td>4.3</td>
</tr>
<tr>
<td>(Mw = 7.1,</td>
<td>Saturated</td>
<td>9</td>
<td>6</td>
<td>19</td>
<td>87</td>
<td>4.1</td>
</tr>
<tr>
<td>PGA = 0.22g)</td>
<td>Layer</td>
<td>7</td>
<td>4</td>
<td>16</td>
<td>67</td>
<td>3.3</td>
</tr>
<tr>
<td>Christchurch</td>
<td>None</td>
<td>23</td>
<td>19</td>
<td>38</td>
<td>148</td>
<td>5.7</td>
</tr>
<tr>
<td>Feb. 2011</td>
<td>FC</td>
<td>16</td>
<td>13</td>
<td>27</td>
<td>106</td>
<td>4.8</td>
</tr>
<tr>
<td>(Mw = 6.2,</td>
<td>Saturated</td>
<td>14</td>
<td>11</td>
<td>25</td>
<td>103</td>
<td>4.7</td>
</tr>
<tr>
<td>PGA = 0.34g)</td>
<td>Layer</td>
<td>12</td>
<td>9</td>
<td>21</td>
<td>83</td>
<td>3.9</td>
</tr>
</tbody>
</table>

The mean LPI value for the September 2010 earthquake after all refinements were made is 7, which would be categorized as a "none to marginal" liquefaction prediction according to Table 1, resulting in an accuracy assessment of "slightly over-predicted". However, despite significant reductions in all liquefaction severity parameters with the progressive application of all adjustments, the parameters are still too large for the February 2011 earthquake to be consistent with the lack of observed surficial liquefaction manifestation at this site. Furthermore, the CTL values indicate that more than 3 m of soil are still predicted to liquefy during both earthquakes. One might expect to see some surface manifestations of liquefaction if more than 3 m of soil out of the top 10 m liquefied. Nonetheless, the presence of a thick, stiff surface crust can reduce the potential for liquefaction manifestation.

Ishihara (1985) proposed boundary curves for liquefaction-induced surface damage using the relationship between the thickness of a non-liquefiable surface layer (H1) and an underlying liquefiable sand layer (H2). The value for H1 is defined as the crust thickness from the surface down to the first depth where liquefaction is predicted to occur (i.e., where FS < 1.0). In a stratified soil profile, like the one at St. Teresa’s School, it is difficult to determine an appropriate H2 value. However, for a given PGA, Ishihara’s boundary curves have a limiting H1 such that regardless of H2, liquefaction-induced surface damage would not occur. For PGA of 0.22 g and 0.34 g in the September 2010 and February 2011 earthquakes, respectively, these limiting H1 values are approximately 3 m and 7.5 m, respectively. While these limiting H1 values from Ishihara (1985) are for M7.5 earthquakes, they still provide some interesting numbers to consider relative to what we observe at the St. Teresa’s site. Using the CPT-based liquefaction triggering procedure after all refinements were made, the September 2010 and February 2011 mean crust thicknesses were found to only be H1 = 1.5 m and H1 = 1.15 m, respectively. These values are significantly smaller than the limiting H1 values estimated above, so it is unlikely that the CPT-based surface crust thickness at St. Teresa’s School was large enough to prevent liquefaction manifestation. Furthermore, the effects of crust thickness are already incorporated into the LPIISH and LSN liquefaction severity parameters, and their values still remain high after adjustments.

3.2 Shear-Wave Velocity Based Deterministic Liquefaction Triggering Analysis with Refinements

The high-resolution DPCH data collected at this site allowed for the use of liquefaction triggering procedures based on shear-wave velocity. The Kayen et al. (2013) procedure with a P1 = 15% was applied to the shear-wave velocity data to calculate the factors of safety for the September 2010 and February 2011 earthquakes. ic from the CPT collected during the August 2015 study was used to identify non-liquefiable layers with ic > 2.6 as well as to estimate FC using the default ic-FC relationship from Boulanger and Idriss (2015). The standard Vg-based analysis was then refined with the progressive consideration of the site-specific Cc = 0.402 and corrections for partial saturation. The results are shown in Figure 4.
Figure 4. Profiles of soil behavior-type index, $V_p$, $V_s$, and factor of safety obtained from the Kayen et al. (2013) Vs-based liquefaction triggering procedure with refinements for site-specific CFC and partial saturation for both the September 2010 and February 2011 earthquakes. Water table levels in September and February are indicated by the blue dashed lines and are shown for the respective events on the factor of safety plots.

The LPI values calculated using the FS from the standard Kayen et al. (2013) deterministic procedure are 9 for both the September 2010 and February 2011 earthquakes. The September 2010 Vs-based LPI is reduced from 9 to 8 after using the site-specific CFC values (note that FC is not a significant factor in Vs-based liquefaction triggering procedures) and is further reduced to 7 after correcting for partial saturation, which yields a “none to marginal” liquefaction prediction, resulting in a “correct” accuracy assessment according to Table 1. This corrected LPI value based on Vs is very similar to the mean LPI value of 6 obtained after all refinements were made to the CPT-based triggering procedure. Furthermore, the $H_1$ estimated from the Vs procedure is approximately 3 m, which is the value required to suppress surficial liquefaction manifestations during the 2010 Darfield earthquake according to Ishihara (1985). While this is a positive finding in light of the St. Teresa’s case history, it should be noted that the Kayen et al. (2013) Vs-based procedure has been found to result in a number of false negative liquefaction predictions across Christchurch. So, one must be careful about extrapolating this success without first considering a large number of case histories.

The February 2011 Vs-based LPI is reduced to 7 after adjusting for the site-specific CFC and applying partial saturation corrections, which is smaller than the mean value of 11 from CPT-based procedures after all refinements were made. This also yields a “none to marginal” liquefaction prediction, resulting in a “correct” accuracy assessment. Furthermore, the $H_1$ value during the February 2011 earthquake is also about 3 m, which is significantly smaller than the 7.5 m needed to completely suppress surficial liquefaction manifestations according to Ishihara (1985). However, the Vs-based liquefaction triggering predictions, including adjustments for site-specific FC and partial saturation, seem to reconcile the false-positive prediction of moderate-to-severe liquefaction at this site during the February 2011 earthquake even without depending exclusively on a very thick non-liquefying crust.

3.3 Combined CPT-Vs Approach for Investigating Microstructure

The DPCH Vs data can be used in conjunction with the CPT data to consider the modified normalized rigidity index, $K_g^* = (G_o/q_o)(Q_{en})^{0.75}$ after Schneider and Moss (2011), Robertson (2015) and Robertson (2016). A $K_g^*$ value over 330 could indicate soils with significant microstructure due to the combined effects of cementation/bonding and aging that would result in a higher liquefaction resistance than indicated by $q_c$ alone. Figure 5 shows the $K_g^*$ data corresponding to the colocated DPCH Vs profile and the CPT data collected during the August 2015 study (i.e., SCPT 57345) at St. Teresa’s School relative to the $K_g^*$ boundaries proposed by Robertson (2016).
DISCUSSION AND CONCLUSIONS

The false positive liquefaction case history site at St. Teresa’s School was scrutinized in this paper by considering additional refined analyses to both the “standard” [refer to Section 2.0 four our definition of standard] Boulanger and Idriss (2015) deterministic CPT-based liquefaction triggering procedure and the Kayen et al. (2013) deterministic Vs-based liquefaction triggering procedure as a means to reconcile over-prediction of liquefaction severity. The factors considered in these refined analyses included: (1) site-specific soil plasticity and FC data, (2) partial saturation (as indicated by Vs), (3) coarse-to-fine-grained soil interlayering, (4) nonliquefying crust thickness and (5) microstructure. Adjustments made to the standard CPT-based liquefaction triggering procedures based on (1), (2) and (3) significantly lowered the liquefaction severity parameters at this site, reconciling the over-prediction of liquefaction severity for the September 2010 Darfield earthquake and reducing the over-prediction from “severe” to “slight” in the February 2011 Christchurch earthquake. Adjustments made to Vs-based liquefaction triggering procedures based on (1) and (2) reconciled the “slight” over-prediction of liquefaction severity for both the September 2010 and February 2011 earthquakes to a “correct” prediction.

Non-liquefying crust thickness based on Vs were found to be thicker than those based on CPT. While crust thickness based on Vs may have played a strong role in mitigating surficial liquefaction manifestations in the September 2010 earthquake, its role in the February 2011 earthquake was likely less pronounced and could not be used to exclusively justify the absence of liquefaction manifestation in that event. Soil microstructure was found not to be a significant factor contributing to the over-prediction of liquefaction severity at St. Teresa’s School, as the Kc values did not indicate significant cementation/bonding or aging that would result in increased liquefaction resistance.

After considering all reasonable adjustments to the standard CPT-based liquefaction triggering procedures, it appears that the most significant factor in the over-prediction of liquefaction severity at St. Teresa’s School based on CPT data is the high FC measured in the silty soils throughout the profile, which appears to have been underestimated using the default Ic-FC correlation from Boulanger and Idriss (2015). This underscores the importance of considering site-specific FC data for liquefaction triggering analyses, as stressed by Boulanger and Idriss (2015). However, it is likely that a number of other factors like partial saturation, thin coarse-to-fine grained interlaying, and non-liquefying crust thickness combined in a complex manner to increase the overall liquefaction resistance at this site. Cyclic laboratory testing performed on silty soils at nearby sites in Christchurch may provide additional insight. However, Beyzaei et al. (2015) presented a case study at Riccarton Road, and concluded that while the CRR found through cyclic triaxial testing compared well to the CRR estimated through simplified CPT methods, the CRR values from both approaches were significantly lower than the CSR in the February 2011 earthquake. Thus, the absence of liquefaction manifestations could not be explained.

While detailed examinations of single case histories (or even groups of similar case histories) are important and necessary, it should be stressed that conclusions derived from a single site should not be extrapolated too far until they have been put into context with many different types of case history sites. Thus, we must ensure that corrections made to increase liquefaction resistance and reconcile false positive liquefaction case histories do not result in false negative predictions of liquefaction at sites that did in fact liquefy. For example, Lees et al. (2015) and Leeves et al. (2015) describe efforts to refine Ic-FC correlations for Christchurch soils. However, higher FC values resulting from these new correlations tended to alter many sites that were correctly predicted to liquefy based on default Ic-FC correlations to false negative predictions.

As discussed above, this paper does not attempt to reconcile the false-positive predictions at St. Teresa’s School based on adjustments to the PGA and/or P1 CRR curves. While PGA is a very important factor, the ground motion estimates throughout the city were fairly well constrained by recordings at nearby strong motion stations. Furthermore, the PGA values recorded during the February event, when over-prediction was most severe, were high.
enough that the liquefaction triggering predictions were not overly sensitive to reasonable perturbations of PGA. The fragility of liquefaction severity parameters due to PGA and $P_S$, CRR curves at our case history sites remains a topic of interest.

We cannot yet fully explain the observed no-liquefaction behavior at the St. Teresa’s site (particularly for the higher ground motions imparted by the February 2011 Christchurch earthquake) and continue to study this case history, as well as the other 30-plus case history sites we collected data at, in order to better understand the complex factors affecting liquefaction triggering and surface manifestation.

5 ACKNOWLEDGEMENTS

This work was supported by U.S. National Science Foundation (NSF) grant CMMI-1547777, the N.Z. Earthquake Commission (EQC), and QuakeCoRE, University of Canterbury. However, any opinions, findings, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors. We also wish to thank: Dr. Mark Stringer for his laboratory testing contributions and his investigations related to $I_c$-FC correlations for Christchurch soils; Dr. Kenneth H. Stokoe for his help collecting DPCH data for this project and insights regarding liquefaction potential of unsaturated soils; Dr. Jonathan Bray for his insights gained from lab and field investigations at false positive silty soil sites in Christchurch; and Dr. Peter Robertson for his thoughts and publications regarding combined CPT-Vs approaches for evaluating soil liquefaction potential.

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