Evaluation of liquefaction and re-liquefaction observed in Christchurch using CPT data

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ABSTRACT

The Canterbury region experienced widespread damage due to liquefaction induced by seismic shaking during the 4 September 2010 earthquake and the large aftershocks that followed, notably those that occurred on 22 February, 13 June and 23 December 2011. Following the 2010 earthquake, EQC directed a thorough investigation of the ground profile in Christchurch, and to date, more than 7500 cone penetration tests (CPT) have been performed in the region. This paper presents the results of analyses which use a subset of the geotechnical database to evaluate the liquefaction process as well as the re-liquefaction that occurred following some of the major events in Christchurch. First, the applicability of existing CPT-based methods for evaluating liquefaction potential of Christchurch soils was investigated using three methods currently available. Next, the results of liquefaction potential evaluation were compared with the severity of observed damage, categorised in terms of the land damage grade developed from Tonkin & Taylor property inspections as well as from observed severity of liquefaction from aerial photography. For this purpose, the Liquefaction Potential Index (LPI) was used to represent the damage potential at each site. In addition, a comparison of the CPT-based strength profiles obtained before each of the major aftershocks was performed. The results suggest that the analysis of spatial and temporal variations of strength profiles gives a clear indication of the resulting liquefaction and re-liquefaction observed in Christchurch.

1 INTRODUCTION

The Christchurch sequence of earthquakes in 2010 and 2011 caused widespread liquefaction and re-liquefaction in many parts of the Canterbury region. Following the major earthquake on 4 September 2010, the Earthquake Commission (EQC) engaged engineering specialists Tonkin & Taylor Ltd (T&T) to coordinate a subsurface investigation of the ground conditions in the Canterbury region. To date, 7500 cone penetration tests (CPTs) have been carried out in addition to an accompaniment of boreholes, scala penetrometer tests and shear-wave velocity profiles. This information is currently stored in the Canterbury Geotechnical Database (CGD).

In order to analyse the liquefaction and re-liquefaction observed in Christchurch, the CPT component of this database was employed to retrospectively determine the applicability of currently available CPT-based methods in evaluating cyclic liquefaction potential to the ground profile in Canterbury and to see which method best compare with the severity of observed damage. In the process of analysing the data, the CPT strength profiles that were obtained before and after major aftershock events at sites of re-liquefaction were compared.

2 EVALUATION OF LIQUEFACTION POTENTIAL

2.1 CPT-based Liquefaction Potential Evaluation

For the purpose of this research, three CPT-based methods were used to evaluate the liquefaction potential at each site: (1) the method by Robertson & Cabal (2010), which is a refined version of the method by Robertson & Wride (1998); (2) the method by Idriss and Boulanger (2008); and the method by Moss et al. (2006). Broadly speaking, the differences between these methods relate to four factors: the means of normalising the tip resistance; q_c; the correlation between the normalised tip resistance q_{c1N} and the cyclic resistance ratio, *CRR*; the modification factors applied to the calculation of the cyclic shear stress ratio, *CSR*; and the calculation of the magnitude scaling factor, *MSF*. Due to space limitation, the intricacies of these methods are not presented here.

2.2 Liquefaction Potential Index

In order to represent a measure of observed land damage, the Liquefaction Potential Index (LPI) developed by Iwasaki et al. (1984) was used. In addition to taking into account important parameters (liquefaction triggering and earthquake loads), it also considers the severity of liquefaction and the relative location of liquefied layers with respect to the ground surface, i.e., liquefaction at shallower region would be more damaging to the ground surface than liquefaction at deeper one. The weighting function for liquefaction severity decreases linearly with depth, i.e. from 10 at the surface to 0 at 20m (the target limiting depth). LPI values range from 0 (no liquefaction) to 100 (Factor of safety = 0 throughout the 20m depth). Based on case history analyses, LPI < 5 indicates minor damage and LPI > 15 means major damage.

3 METHODOLOGY

3.1 CPT data set used

Using an up-to-date log of all available CPTs (1402 during the time this research was conducted in mid-2012), six raw CPT data sets were assembled through the Google Earth interface. Three event-specific CPT data sets were also constructed for tests performed before the three main aftershock events (22 February, 13 June and 23 December, all in 2011). The remaining two data sets were made for strength profile comparisons between pairs of across event CPTs at sites of re-liquefaction. Two datasets were used to differentiate between the comparisons of CPTs within 20m of each other and those within 50m. Note that significant variations in soil stratigraphy can occur within close proximity in Christchurch; unfortunately, very few data at very close proximity to each other were available (at least when the study was made) and therefore distances of 20m and 50m were considered in analysing re-liquefaction cases.

3.2 Water table models

The water table depth is an integral input into all of the chosen CPT methods for assessing liquefaction potential. Event-specific groundwater models were constructed using a system of wells monitored by Environment Canterbury (2012). From the archives of 21 wells spread over Christchurch which were freely available online, the most recent recorded depth before each major earthquake event was used for constructing earthquake-specific water table interpolations. Extrapolation between the wells was done using the cubic-spline method (Sandwell, 1987). The results of these interpolations were validated through a comparison with the average annual depths which in all cases were found to have a similar spatial form.

3.3 PGA Inputs

The peak ground accelerations (PGAs) required for each of the earthquakes analysed were sourced from 34 strong-ground-motion stations of GeoNet (GNS 2012). Using the three closest stations, the PGA at each CPT location for a specific earthquake was estimated through a triangulated linear interpolation.

3.4 Land Damage Information

Maps of a land damage grade, developed from T & T's property inspections, were used for the February and June events (Figure 1). The benefit of these maps was that lateral spreading sites could be filtered out to avoid potential skewing effects. The only land damage data available for the December 2011 aftershock event was based on observations of liquefaction from aerial photography. There were also incremental, non-tectonic settlements from light detection and ranging surveys (LiDAR) on the CGD for all events. These were used to perform a supplementary analysis addressing the uncertainties associated with the other measures of observed land damage.

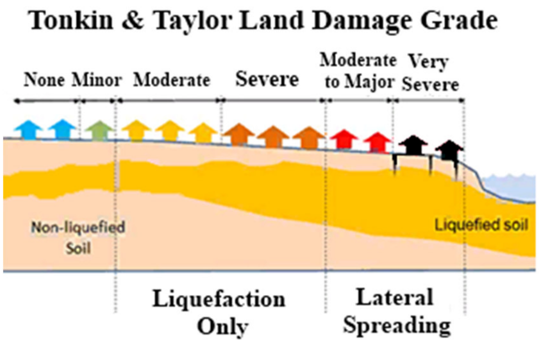

Figure 1. Visual description of land damage grade, developed for the Canterbury earthquake recovery (Reproduced from Canterbury Geotechnical Database, 2012b)

3.5 Data analysis

MATLAB was the main platform used to code the computational components of this research. For the first objective, this involved implementing the three chosen CPT-based liquefaction assessment methods and calculating the corresponding LPI. The code was developed to allow bulk processing of CPT data sets. This functionality facilitated a broader analysis than could be achieved using discrete calculations. MATLAB code was also used for the re-liquefaction objective to output overlaid CPT strength profiles.

Following this initial implementation work, a sensitivity analysis was performed on a representative dataset of 11 shallow CPTs (depth < 10m) and 15 deep CPTs (depth > 10m). This was done to determine the sensitivity of the three CPT-based methods to variations in earthquake magnitude, PGA and water table depth. Additionally it gauged the impact of different analysis depths which was important to validate assumptions made in the full-scale analyses. Each of these aspects was varied individually using arbitrary values for the purposes of comparison. Graphical and spatial comparisons were made between the analysed liquefaction potential and the observed liquefaction land damage. These comparisons were initially performed using pre-event CPTs for the three main aftershock events and were later extended to include the entire CPT data set for all earthquake events.

The statistical graphics package R was used to construct side-by-side boxplots of this comparison. These plots were judged to be the best means of performing graphical comparisons for entire populations of analysed CPTs. LPIs (analysed land damage) were plotted on the vertical axis with observed land damage (derived from damage maps) on the horizontal axis. Once constructed, individual event plots were amalgamated to summarise all major earthquake events. The observed damage axis was broken down into three segments which were allocated to each aftershock event. Using these boxplots, the applicability of the individual CPT-based methods and the LPI to Christchurch soils could be gauged by how well the analysed damage potential corresponded to what was observed. To clarify the physical meaning of these correlations, event-based LPI interpolation maps were constructed for each CPT liquefaction assessment method.

4 RESULTS AND DISCUSSION

4.1 Sensitivity Analysis

It was essential to establish the depth over which each of the CPT analyses would be performed before carrying out full-scale processing. Initially, an analysis depth of 20m was applied to deep CPTs and used as a baseline because this is the threshold depth to which the LPI is calculated. This baseline was compared to the shallow CPT portion of the dataset and an alternative analysis depth for deep CPTs of 15m. Despite these cases having shallower analysis depths than 20m, the traditional LPI weighting function was still applied over the actual CPT depth. Using a 15m analysis depth reduced the computation time for bulk processing by 30% to between 2-4 hours. From the sensitivity analysis it was determined that the difference between a 15m and 20m analysis depth was minimal in terms of the calculated LPIs from all methods (typically <5%). Therefore, a 15m maximum depth was adopted for full-scale analyses which would incorporate both shallow (<10m) and deep (>10m) CPTs.

The sensitivity of the shallow and deep CPTs to PGA was determined using a fixed earthquake magnitude of 7.5 and an arbitrary water table depth of 1m. LPIs were calculated for all CPTs, for PGA values varying between 0.1g and 1.0g at 0.1g increments. For both shallow and deep CPT populations the general trend was as expected from all CPT methods: increasing PGA resulted in higher LPIs which tended towards a reduced gradient at PGA values beyond 1.0g. LPIs calculated from the Robertson and Cabal (2010) method were the most sensitive to PGA. This was for a PGA change from 0.3g to 0.4g which resulted in a median LPI change of approximately 8. The increased sensitivity associated with the Robertson and Cabal (2010) method is likely due to the calculation of the stress reduction coefficient (r_d) which only depends on depth. The two alternative methods use other variables in this calculation (e.g. PGA and magnitude).

The sensitivity to the groundwater level was assessed by increasing the arbitrary depth from 1m. This was first done in 0.5m increments but later in 2m increments. The earthquake magnitude was kept at 7.5 and the median of the most sensitive PGA range was used (0.35g). LPIs calculated from each of the methods were found to be insensitive to 0.5m water table depth changes. Using the larger increments, it was found that, provided the water table depths were accurate to within 1m, the worst case error in the LPI would be approximately 4. This was judged to be tolerable.

The final calculation input tested was the earthquake magnitude which was varied in increments of 0.5. The PGA used was a value of 0.5g (taken during the models validation phase) and the water depth was taken as 1m below the ground surface. Again the Robertson and Cabal (2010) method was found to be the most sensitive to changes due to its definition of the magnitude scaling factor (MSF). The calculated LPIs for shallow and deep CPTs were severely reduced in comparison to those for a magnitude 7.5 earthquake. While LPIs calculated from the methods of

Moss et al. (2006) (see Figure 2) and Idriss and Boulanger (2008) were less sensitive to changes in earthquake magnitude, there was still a significant reduction at magnitudes below 6.5.

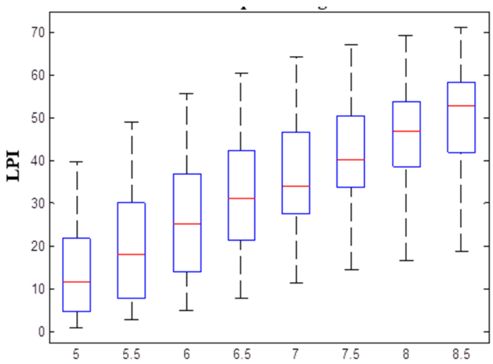

Figure 2. Typical sensitivity analysis output depicting the influence of earthquake magnitude on calculated LPIs (as calculated from the Moss et al., 2006 method)

4.2 Applicability of CPT-based methods

The graphical analysis was focused on the three main aftershock events with the highest quality results being obtained using the event-specific CPT datasets. LPIs calculated from all three CPT methods correlated positively with the damage observed in each aftershock event. This observation was made using the median LPI values for different severities of land damage as well as the corresponding upper and lower quartiles. This shows that the three CPT-based methods assessed were all, to some degree, applicable to Christchurch soils. It also shows that liquefaction induced land damage can be estimated using the LPI. The correlation was best observed in LPIs calculated from the Moss et al. (2006) method (Figure 3). Results indicated that the Robertson and Cabal (2010) method was the least applicable to Christchurch soils. This was attributed to the method's high sensitivity at earthquake magnitudes below 7.5.

It was also evident from these plots that LPI ranges corresponding to different severities of damage lowered in later events. Taking the February 2011 LPI ranges as a baseline, this indicated that June and December 2011 LPIs underestimated the land damage that was observed. The first theory postulated for this trend was the inclusion of cumulative damage effects in the measures of land damage. By performing a similar analysis using non-cumulative LiDAR settlements from each aftershock, it was found that any cumulative damage effects incorporated in the measures of observed land damage did not fully explain this trend. Upon further thought it was concluded that a more likely cause for this trend was the severe reduction in LPIs at lower earthquake magnitudes established during the sensitivity analysis. The close time proximity of the largest June and December 2011 events to separate events of slightly lower magnitude means the magnitudes used in the CPT-based methods would likely result in an underestimate of the cyclic stress actually experienced by soil profiles.

To improve the robustness of the three CPT-based methods tested, a review of magnitude scaling factor calculations is recommended. Particular emphasis should be placed on their validity in cases where high magnitude earthquakes ($M_w \geq 5.0$) are in close time proximity. It will be necessary to determine the time required for complete excess pore water pressure dissipation after liquefaction triggering as well as the amount of seismic energy converted into subsurface stresses in multiple, closely spaced earthquakes.

The 1402 CPT dataset introduced significant variability into the graphical comparisons but were useful for improving the resolution of event-specific LPI interpolations. These interpolations were used to provide a physical representation of the comparison between analysed liquefaction potential and the observed land damage for each earthquake event.

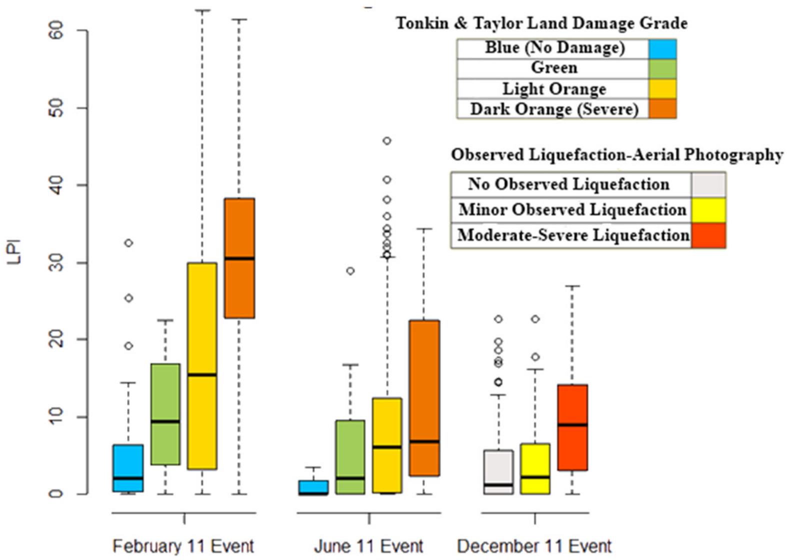

Figure 3. Graphical analysis comparing the analysed LPIs (calculated from Moss et al., 2006) to the observed land damage for each aftershock event.

4.3 Distribution of Liquefied Layers in Major Aftershock Events

In continuity with the previous analysis, the distributions of liquefied layers were determined by applying the Moss et al. (2006) method to event-specific CPTs. In general, the event-based distributions (Figure 4) indicated that deposits within 10m of the ground surface liquefied most frequently in the February 2011 aftershock event (on average ≈45%). The analysis suggests that this zone of surficial soil liquefied less often in the June and December 2011 aftershocks (on average ≈33% and ≈25% respectively). Liquefaction processes are more likely to manifest as land damage when they occur closer to the ground surface. Consequently these plots provide a potential explanation for why the liquefaction damage observed in the February 2011 event was more severe than for other aftershocks.

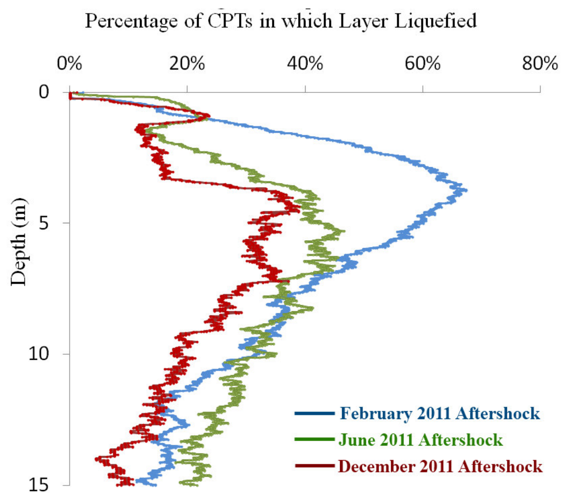

Figure 4. Comparative analysis of liquefied layer distributions for event-specific CPTs relating to the main aftershock events in Christchurch.

4.4 Re-liquefaction Process

In this section, geological sections were assumed not to vary much over short distances such that available CPT data can be compared. Both the 20m and 50m distance CPT strength profile comparisons at sites of re-liquefaction indicate no significant strengthening has occurred across any of the major aftershock events. This inference was made after applying best-fit lines to the scatter plots (Figure 5). Both sets of comparisons produced best-fit lines with gradients less than 1 (0.96 and 0.94 for 20m and 50m distance comparisons, respectively). The best-fit line for comparisons of CPTs within 20m had an R^2 value of 0.72 which, for a geotechnical engineering correlation, is fairly strong. The R^2 value for the 50m comparisons was 0.59 which is likely to be lower due to the increased geological variation incorporated with this longer offset. The 20m comparisons were broken down further into three increments of depth to determine if any particular part of the profile was changing (0-5m, 5-10m and >10m). All increments had best-fit lines with gradients less than 1 which was consistent with the total analysis, indicating that no significant strengthening had occurred in any part of the profile.

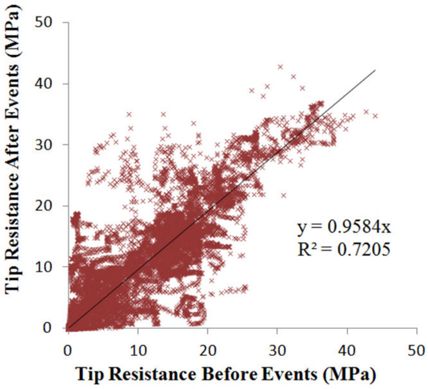

Figure 5. Scatter plot comparing the tip resistance before earthquake events against the tip resistance after for CPT comparisons at sites of re-liquefaction in Canterbury (20m maximum offset)

Individual CPT comparisons (with the 50m maximum offset) were mapped according to whether the tip resistance generally increased, decreased or remained unchanged (Figure 5). Of the 30 comparisons made, 83% were unchanged or had lower tip resistances. This indicated that the liquefaction and re-liquefaction of sites had not significantly densified the loose deposits and therefore the pre-earthquake liquefaction risk across Christchurch had not changed. Note that the 50m spatial distance between adjacent CPTs may be too large to compare; however, as mentioned earlier, these were the data available when the study was made.

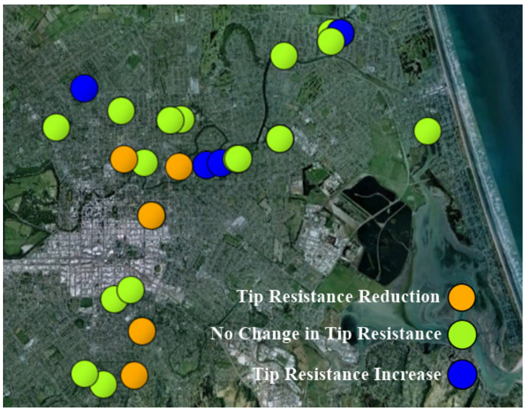

Figure 6: Mapped CPT tip resistance change for sites of re-liquefaction in Christchurch (50m maximum CPT offset)

5 CONCLUSIONS

The liquefaction observed in Christchurch was analysed using three CPT-based assessment procedures. The results showed that all methods correlate well with those observed in Christchurch. Moreover, the LPIs calculated were effective estimates of the damage observed at the ground surface, with the factor of safety obtained from the Moss et al. (2006) method showing the best correlation. Through analysis of the temporal and spatial variability in CPT strength profiles at re-liquefied sites, it has been concluded that no noticeable strengthening has occurred in Christchurch and the city remains vulnerable to liquefaction induced land damage in future earthquakes of similar magnitude to those experienced in 2010 and 2011.

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