# Swamp Depositional Environment Effects on Liquefaction Performance in Christchurch, New Zealand

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## ABSTRACT

Liquefaction-induced ground failure from the 2010-2011 Canterbury earthquake sequence damaged much of the built environment in Christchurch, New Zealand. State-of-practice liquefaction triggering procedures generally worked well across much of Christchurch. However, there are important cases where liquefaction assessment methods indicate that severe liquefaction-induced ground failure should have occurred, yet none was observed. Surface manifestations of liquefaction damage were not observed frequently in southwestern Christchurch, an area known for its silty soil conditions. While it is likely that several factors may contribute to the discrepancies identified in some areas of Christchurch following the Canterbury earthquakes, a potentially important factor that has not been explored fully is the role of shallow geology and the differing depositional environments that exist across the Canterbury Plains in which Christchurch was built.

In this paper, discrepancies between surface manifestations of liquefaction and estimates using simplified liquefaction assessment procedures are explored at silty soil sites in the context of depositional environment. Soil stratigraphy, soil type, and groundwater table fluctuation are evaluated as potential influences on liquefaction potential at a site and detailed evaluations of stratigraphy are compared for the cone penetration test (CPT), sonic boring, and high quality continuous sampling. Site-specific assessments are supplemented by regional analysis. Differing surficial geology and depositional environments were found to explain, in part, the limitations of simplified liquefaction triggering procedures at stratified, silty soil sites. Silty back-swamp-type deposits are shown to have mitigating effects on liquefaction potential in southwestern Christchurch relative to what can be currently characterized and quantified by simplified CPT-based liquefaction assessment methods. Continuous high-quality sampling and detailed logging provide important insights beyond what can be captured with the CPT at these sites that contain highly stratified, variable deposits of silty sand and sandy silt.

## 1 INTRODUCTION

Liquefaction from the 2010-2011 Canterbury earthquake sequence damaged much of the built environment in Christchurch, New Zealand. State-of-practice liquefaction triggering procedures generally worked well across much of Christchurch. However, there are important cases where liquefaction assessment methods indicate that there should have been severe liquefaction-induced ground failure, yet none was observed (van Ballegooy et al. 2014; Russell & van Ballegooy, 2015). Surface manifestations of liquefaction were not frequently observed in the northwestern and southwestern suburbs of the city. The Liquefaction Severity Number (LSN) captures much of the observed liquefaction-induced ground failure across affected areas of Christchurch, but it consistently over-estimated liquefaction damage in the southwest part of the city (Figure 1), an area known among local engineers for its silty soil conditions.

To investigate the liquefaction resistance of these silty soils and to identify reasons for the discrepancy between state-of-practice liquefaction estimations and post-earthquake observations, researchers from the Univ. of Canterbury, Univ. of California - Berkeley, Univ. of Texas at Austin, and Tonkin + Taylor, Ltd. conducted a comprehensive study called the "silty soils project" (see Beyzaei et al. 2015 and Stringer et al. 2015).

Several factors were identified as potentially contributing to the discrepancy: 1) stratification of interlayered sandy and silty soils, 2) soil fabric, 3) groundwater table fluctuations producing a non-liquefiable crust of unsaturated soil, 4) angularity of the fine sand and coarse silt particles, and 5) uniform particle size distributions of the fine sand and coarse silt where slight shifts can significantly affect the estimated fines content and resulting liquefaction triggering assessment. Additionally, it is possible that some soil layers at these sites did liquefy, but surface manifestations did not occur.

A potentially important factor that has not yet been explored fully is the role of near-surface geology (i.e., 0-7 m) and the differing depositional environments that exist

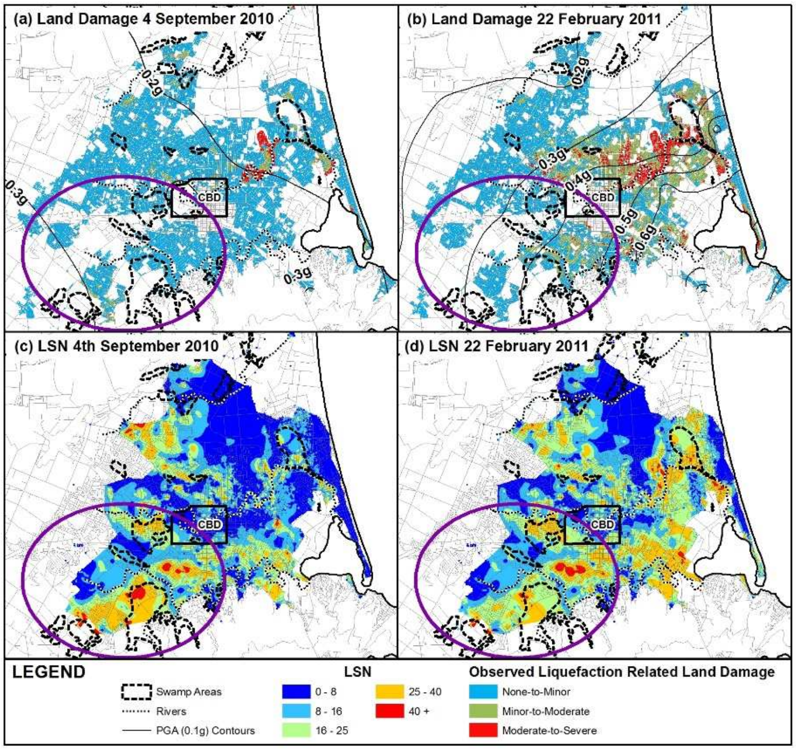

Figure 1. (a,b) Liquefaction-related land damage observations and (c,d) distribution of LSN in Christchurch for the 2010 Darfield and 2011 Christchurch events. Note over-estimation of LSN in circled southwest Christchurch areas of (c,d) compared to observations in (a,b). Swamp zone outlines from NZGD; PGA contours from Bradley & Hughes (2012).

across the Canterbury Plains in which Christchurch was built. The incorporation of surficial geology and depositional environment effects on liquefaction assessments are not often considered quantitatively on a project-specific basis. In this paper, case histories that illustrate subsurface conditions where liquefaction manifestations were over-estimated in southwestern Christchurch are discussed with a focus on depositional environment and its role in liquefaction. Key factors are evaluated in the context of depositional environment.

# 2 SURFICIAL GEOLOGY AND DEPOSITIONAL ENVIRONMENT

## 2.1 Importance of Depositional Environment

The important role of depositional environment in liquefaction assessment has been recognized previously. Youd & Perkins (1978) enumerated several key factors affecting ground failure susceptibility, including age of deposition, sedimentation process, and geologic history. Seed (1979) cites the influences of “method of placement or soil structure” and “age since deposition or placement.” Laboratory testing by Ladd (1974, 1977) and Mulilis et al. (1977) showed clearly the effects of depositional method and fabric can vary the cyclic resistance ratio by almost a factor of two. Seed (1979) recommends obtaining the “best possible undisturbed samples” and using considerable judgement to interpret how these factors may affect in-situ liquefaction response.

Liquefaction research has focused primarily on cohesionless free-draining soil deposits, but Seed (1979) notes that even “a single layer of relatively impervious fine sand or silt in such a deposit would completely invalidate the results of pore pressure dissipation computations for vertical flow.” This detail is relevant for the layered Christchurch swamp deposits composed of silty fine sand, silt, and organics, which are discussed in this paper.

## 2.2 Christchurch Overview and Formation Processes

Christchurch is located in a complex geologic and geomorphic environment with dominant influences from alluvial and coastal depositional processes. The city is primarily situated upon the low-relief and low-elevation alluvial outwash plain of the braided Waimakariri River, which flows eastward from the Southern Alps to the Pacific Ocean. Christchurch is bound to the south by the Port Hills of Banks Peninsula, which comprises the eroded remnants of a Miocene volcanic complex (Brown & Weeber, 1992).

Alluvial sands, silts, and gravels were initially deposited by the Waimakariri River, which regularly avulsed across the region prior to 1850. These sediments have subsequently been reworked and redeposited by meandering rivers and streams that also flooded and avulsed across the area. Two main meandering rivers are present within the city: the Avon River which flows eastward through the Central Business District (CBD) and coastal neighborhoods, and the Heathcote River which flows eastward through the southern suburbs before reaching the coast. The central and eastern areas of

Christchurch are predominantly underlain by alluvial sands, silts, and drained peat swamps, which are interbedded with estuarine dune and foreshore sands associated with coastal progradation and marine regression following the 6,500 BP highstand. Co-evolution of the floodplain and coastal landscapes resulted in significant spatial heterogeneity within the subsurface sediments (Brown & Weeber, 1992).

The western suburbs are predominantly underlain by alluvial sands, silts, and gravels, which also vary spatially as a result of the avulsion of the Waimakariri River and subsequent reworking by the Avon and Heathcote rivers (Brown & Weeber 1992; Cowie 1957). The alluvial plain proximal to braided and meandering rivers is generally comprised of overbank deposits of fine sand to silt deposited as the river overtops its banks. In the case of the braided Waimakariri River, it may also form channels containing gravels to sands. Back-swamps comprised of sand, silt, and peat generally form distal to the river where standing water remains following flood events and may be vegetated (Fryirs & Brierley 2013). These swamps may contain thinly interlayered sand and silt lenses, with silt layers likely to thicken and sands layers thin with increasing distance from the river. Although interspersed pockets of swamp-like deposits underlie much of Christchurch, swamp zones outlined in Figure 1 and highlighted in Figure 2 are characteristic silt-dominant back-swamp deposits, comprised of silt, fine sand, and organics, that have formed in low-lying areas leading to large swamp zones distal to the river.

## 2.3 Regional Assessment

Similar areas of the city should be considered when assessing liquefaction performance to avoid comparing coastal beach deposits with inland river sand and silt deposits. Accordingly, Christchurch is subdivided into four quadrants centered on the CBD: the southwest (SW), northwest (NW), northeast (NE), and southeast (SE). The SW, located at the base of the Port Hills, is characterized by silty back-swamp soil deposits. The NW, located closer to the Waimakariri River, is also characterized by silty and swamp-related soil deposits but without the depositional effects from the Port Hills. However, NW sediments are likely to be younger than sediments in the SW due to proximity to the present Waimakariri River channel. The NE and SE both contain interlayered coastal and fluvial sediments and thus differ greatly from the more inland SW and NW environments. The eastern suburbs do not show the same liquefaction triggering over-prediction seen in the western suburbs, likely owing to the cleaner sands deposited in this setting, which are largely the basis of current simplified liquefaction assessment methods. This paper focuses on SW Christchurch, an area with significant liquefaction over-estimation. The NW quadrant is included in the regional assessment as it contains similar soils to the SW and had similar discrepancies between liquefaction estimations and observations (albeit less dramatic).

Geologic and historical maps are available to discern the shallow geology of Christchurch. The geologic maps currently available for greater Christchurch provide a broad overview of the surficial sediments. However, they are at a scale too coarse for a detailed evaluation. Conversely, the historical maps provide locations of roads, rivers, streams, and swamps and include relatively detailed descriptions of the surficial sediments and vegetation (Wilson 1989; NZGD). They can be used in conjunction with regional geology to interpret shallow subsurface conditions. By using maps dating back to the 1850s, it is possible to obtain an appreciation for Christchurch near-surface ground conditions prior to the city's development.

Historical maps may also be used to interpret spatial variability in the surface manifestation of liquefaction observed during the Canterbury earthquake sequence. Alternative map sources may highlight slightly varied or now-buried features that help explain post-earthquake liquefaction field observations. The use of historical maps is not only appropriate, but also further supports that spatial variability in surficial geology is critically important to understand when undertaking liquefaction assessments.

Figure 2 shows a historical map overlay (Wilson, 1989) with six silty soil case history sites in the SW quadrant identified. Five "no-liquefaction" sites are located in or very near swamps, while one "liquefaction" site is located far from a swamp in all directions. In this discussion, "swamps" refer to large continuous, coherent silty back-swamp zones distal to the river, rather than areas classified as a mix of surface conditions and localized swamp pockets. The low-lying areas of Christchurch contained many pockets of swampy and marshy soils, but it is in these large swamp zones where the depositional environment was consistent enough to have created significantly different subsurface conditions.

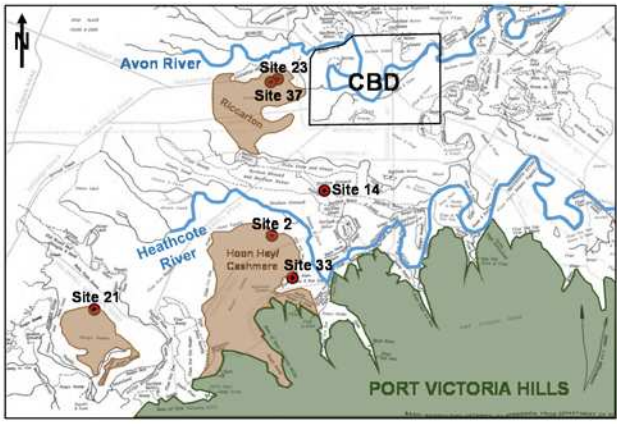

Figure 2. SW quadrant of greater Christchurch; modified from 1989 Sibley Map (Wilson, 1989), which is compiled from 1856 Black Maps. Brown shaded regions show swamp areas, green shaded region shows Port Hills.

Swamp zones delineated among historic, geologic, and geomorphic maps may differ depending on the depth range and corresponding depositional period considered. Deposited sediments are likely to spatially and temporally vary as a result of river avulsion and subsequent shifts in depositional settings across the area. Subsurface sediments may transition between swamp-like deposits, interfluve deposits, or channel deposits with depth, reflecting the varied depositional history at a site. The variability in these deposits and relative thicknesses of strata from different depositional settings may provide additional insight on marginal liquefaction case histories. For the current analysis, the controlling influence of shallow soils on liquefaction response and the distribution of post-earthquake observations support interpretation of silt-swamp locations as shown in the map in Figure 2.

## 3 LIQUEFACTION CASE HISTORIES

Liquefaction field case histories are typically classified as "Liquefaction" or "No Liquefaction" cases based on whether or not surface manifestations of liquefaction damage were observed. This convention is continued herein. It is possible that some of the soil layers within the "No Liquefaction" classified sites did in fact liquefy, but surface manifestations (such as ejecta or cracking) and significant ground settlement did not occur.

### 3.1 Canterbury Earthquake Sequence

The 2010-2011 Canterbury earthquake sequence included the 4 September 2010 Darfield earthquake ($M_w$ 7.1) and the 22 February 2011 Christchurch earthquake ($M_w$ 6.2) (GNS Science). Ground shaking from the Darfield event was relatively uniform throughout Christchurch, because the event was more distant from Christchurch so there was little attenuation of motion across the city. Liquefaction manifestations were observed primarily along the Avon River in the eastern suburbs of Christchurch. Ground shaking from the Christchurch event was variable throughout greater Christchurch, because the event occurred close to the city. Severe liquefaction manifestations were observed throughout over 30% of the city and suburbs, concentrated predominantly in central and eastern Christchurch (GEER Report No. 24 & 27).

The Canterbury earthquake sequence dataset provides an unprecedented amount of well-documented pre- and post-earthquake data that have been made publically available. Figure 1 illustrates the value of these data on the regional scale to gain an appreciation for the distributed effects and general trends throughout Christchurch. Representative individual case history sites can then investigate details that are obscured at the regional level. Considering both regional and site-specific analyses results in the most robust use of the dataset.

### 3.2 Site-Specific Subsurface Investigations

During the "silty soils project," sites with target $I_c$ silty soil layers ($I_c$ ~ 2.2-2.8) and clear discrepancies between triggering estimates and post-earthquake observations were identified and characterized with CPTs, sonic borings, direct push crosshole seismic testing, and laboratory testing of bulk samples. High-quality sampling and cyclic triaxial testing were performed at five silty soil sites (Beyzaei et al. 2015, Stringer et al. 2015). Four no-liquefaction silty soil sites were selected, along with one marginal silty soil site where liquefaction was not observed after the lower intensity 2010 Darfield event, but significant liquefaction was observed after the high intensity 2011 Christchurch event. Clean sand liquefaction sites from along the Avon River were also selected to establish a comparison at sites that performed as the clean sand-based liquefaction assessment procedures indicted they would perform. The four no-liquefaction silty soil sites are: Site 2 - Gainsborough, Site 21 - Caulfield, Site 23 - Riccarton, and Site 33 - Cashmere. The one liquefaction silty soil site is Site 14 - Barrington. The clean sand site considered in this study is EQC-3 - Avondale. All sites were level ground free-field sites with the exception of Site 23 - Riccarton (level site occupied by a two-story commercial structure and parking lot).

High-quality continuous sampling and detailed logging were performed in June 2016 at Site 14, Site 33, and at a new site located 200 m west of Site 23, which was no longer accessible, to evaluate soil stratigraphy in greater detail (Beyzaei et al. 2017). The new site, herein called Site 37 - Clarence, is a no-liquefaction silty soil level-ground site occupied by a one-story commercial structure and parking lot in the Riccarton swamp area. Figure 3 presents the subsurface profiles in the upper 7 m at the six silty soil sites (Figure 3,a-f) and one representative clean sand site (Figure 3g), showing CPT tip resistance ($q_c$), soil behavior type index ($I_c$), and estimated high and low groundwater table (GWT) depths. The upper 7 m contains the critical layer and other key soil layers at each case history site. Although all six sites consist of silty soils, the $q_c$ and $I_c$ profiles begin to show differences in the stratification of each site, especially when compared with the sand site.

### 3.3 Seismic Assessment & Post-Earthquake Liquefaction Observations

Liquefaction triggering was assessed at each site using state-of-practice simplified CPT-based methods (e.g., Boulanger & Idriss 2016) for comparison with post-earthquake observations. As noted previously (e.g., Beyzaei et al. 2015, Stringer et al. 2015), a significant portion of each profile is estimated to have liquefied with the applied seismic loading based on the simplified methods, but post-earthquake investigations and publically available post-earthquake liquefaction observation maps (NZGD) show that surface evidence of liquefaction was not observed at these sites. There are several components to the simplified assessment that can affect estimations of liquefaction triggering and consequences, such as: PGA, GWT, elimination of transitional $I_c$ values, $I_c$ cut-off, fines content (FC) correlation, and model uncertainty ($P_L$). PGA was estimated using the Bradley & Hughes (2012) maps and GWT was estimated using NZGD maps. Within the bounds of reasonable assumptions for each parameter, simplified methods still predict liquefaction triggering at the sites where liquefaction was not observed (i.e., at the "No Liquefaction" sites).

Both the Darfield and Christchurch events induced cyclic stress ratios (CSR) sufficient for simplified methods to estimate liquefaction triggering at the silty soil sites. This paper focuses on the more significant Christchurch event, because it produced the highest seismic demand within greater Christchurch. Additionally, there are recorded field observations with which to compare the simplified liquefaction triggering estimates rather than the inferences that must be made for the Darfield event. Site 14 provides an interesting case history across the multiple earthquake events. It is inferred to have no liquefaction during the Darfield event, but was observed to have liquefied during the Christchurch event.

## 4 EFFECTS OF SWAMP DEPOSITIONAL ENVIRONMENT ON LIQUEFACTION

Focusing on the SW swamp zones in Figure 2, aerial photographs show that in moving from the edge toward the center of the swamp zones, surface manifestations of liquefaction decrease until reaching large areas where no surface manifestations of liquefaction are observed. Thus, liquefaction can be evaluated in three zones: outside of swamps, transitional zones at the edges of swamps, and within swamps. The transition distance for a swamp varies based on many factors, including its spatial extent, thickness, depositional setting (e.g., proximity to river), and paleo-topography, so a single transition distance cannot be applied for all swamps in such a dynamic environment. There is no evidence or only infrequent evidence of liquefaction within swamps in SW Christchurch (Figure 1). At the edges of swamps, there is some evidence of liquefaction, varying on a site-by-site basis. At Site 2 (located at the edge of a swamp), there is no evidence of liquefaction, but sand boils and ejecta occur intermittently at nearby sites. A similar situation occurs at Site 33, where there is more evidence of ejecta in the nearby, developed residential areas. These observations support the post-earthquake reconnaissance investigations that noted general trends of no liquefaction in the silty and swampy areas of SW Christchurch, but by looking in detail at the near surface sediments, it is possible to move past general trends and use historical locations of now-buried features to understand the post-earthquake observations in more detail.

On a regional scale, Figure 4 presents LSN distributions for CPTs across greater Christchurch, showing: (a) CPTs outside swamp areas, (b) CPTs within eastern swamp areas, and (c) CPTs within swamp areas in the NW and SW. To eliminate CPT density bias in the eastern suburbs and CBD, an area-based method was used. LSN values were interpolated between each CPT location and this surface was divided into 25 m x 25 m wide tiles that were matched with the corresponding land damage observation category shown in Figure 1. For the analyses presented in Figure 4, a buffer width of 200 m was applied from the marked perimeter of each well-defined swamp, to account for uncertainties in swamp boundary location and likely transitional area into the swamp deposits, recognizing that actual swamp extents may vary somewhat from the historical map depiction.

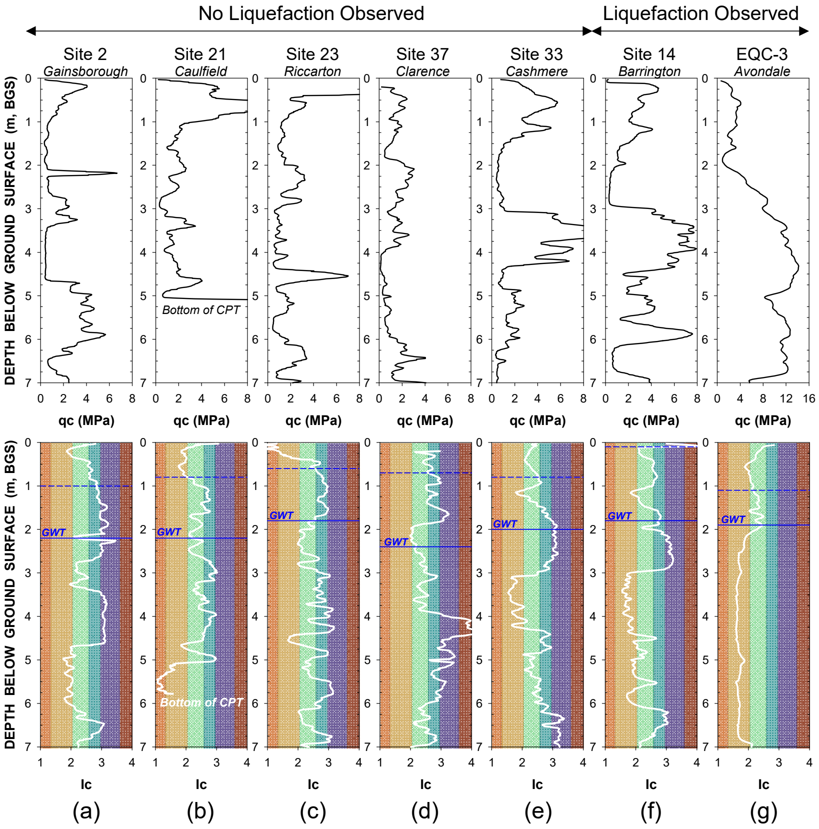

Figure 3. CPT $q_c$ and $I_c$ profiles for six silty soil sites (a-f) and one representative clean sand site (g). Estimated high (dashed line) and low (solid line) GWT also shown.

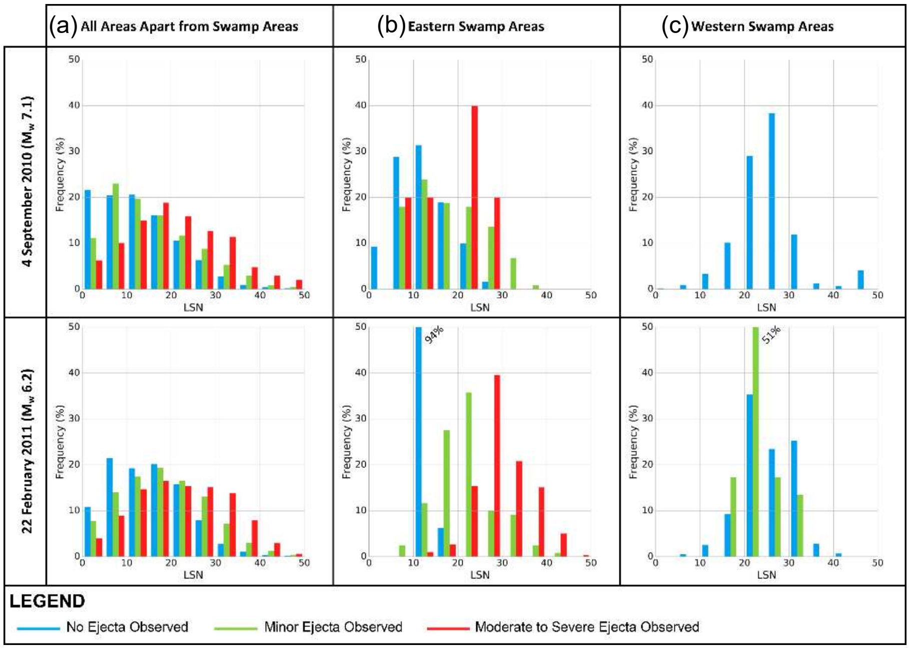

Figure 4. LSN distributions for CPTs across Christchurch. Histograms are normalized to compare distributions (vertical axis shows frequency rather than CPT count), but in the western swamp areas there are much larger areas of blue relative to the areas of green (refer to Figure 1).

LSN values exceeding 16 indicate moderate to severe liquefaction is likely (Russell & van Ballegooy, 2015).The distributions in Figure 4 show that outside of swamps, LSN is able to capture overall differences in damage patterns across the city. The LSN distribution for areas with no liquefaction damage is lower than the LSN distribution for areas with minor to moderate and moderate to severe liquefaction damage. In the eastern (less silty, more sandy) swamps, LSN is able to differentiate between areas that performed well and areas that performed poorly. In the western (more silty and less sandy) swamps, the LSN distribution for areas with no liquefaction damage is high (i.e., over-estimating) and almost the same as the LSN distribution for areas with minor to moderate liquefaction damage. LSN is not able to differentiate between areas that are likely to perform well and areas that are likely to perform poorly, as well as providing an overall over-estimation of liquefaction manifestation. The observations from these histograms are consistent with the visual comparisons of the calculated LSN maps with the respective land damage maps shown in Figure 1.

## 5 STRATIGRAPHY AND GROUNDWATER TABLE EFFECTS

Potential over-estimation factors can be considered in the context of a swamp depositional environment to evaluate if the simplified methods are applicable and in what ways the relevant factors can be modified to capture the swamp depositional environment effect for Christchurch soils. Two likely reasons for the apparent over-estimation are groundwater table and soil stratigraphy effects.

### 5.1 Groundwater Table Effects

Estimated high and low GWT levels shown in Figure 3 were based on piezometer readings, sonic boring core box samples, and direct push crosshole testing estimates of depth to full saturation. Groundwater conditions in Christchurch are seasonably variable, typically fluctuating on the order of a meter or so. Direct push crosshole testing performed by Stokoe, Cox, and others (UT-Austin) at the case history sites shows that the depth to 100% saturation (corresponding to compression wave ($V_p$) velocities around 1500 m/s) can be well below the estimated high GWT. At some sites, $V_p$ values were less than 1500 m/s below the estimated low GWT. However, values of $V_p$ remain generally well above 800 m/s, indicating that soils are saturated or nearly saturated for the purpose of liquefaction assessment (Tsukamoto et al. 2002). Within the zone of GWT fluctuation, soils may be subject to partial saturation, but below the estimated low GWT soils can be considered fully saturated. This observation is confirmed with sonic boring cores that show iron-stained and mottled layers with root voids and desiccation in the zones of GWT fluctuation (Tonkin + Taylor). Seasonal GWT fluctuation in the upper siltier soils at these sites contributes to the development of a pseudo-“non-liquefiable crust” (Ishihara 1985). The nature of the pseudo-crust will vary by site, and in some cases may be sufficient as a cap over liquefaction ejecta, depending on the degree of saturation, integrity of the pseudo-crust, and the quantity of ejecta moving toward the ground surface.

### 5.2 Stratigraphy Effects

Examining the $q_c$ and $I_c$ traces shown in Figure 3, differences in stratigraphy are readily apparent, especially when compared with the EQC-3 clean sand profile. Site 23 is the most highly stratified site, with interlayered thin layers and seams of fine sand and silt on the order of centimeters. Site 14 is the closest to a typical liquefaction site such as EQC-3, having the thickest continuous layer of sandy material. These soil profiles are not easily separated into subsurface profiles that would perform differently. Although Site 14 has the thickest layer of sandy material, it is not significantly thicker than the sandy layer at Site 33. Although Site 23 has the most stratified CPT trace, other sites may have thin-layer stratification not identified by the CPT.

Subsurface interpretations from the standard CPT and sonic borings can be compared with detailed logging of high-quality samples to evaluate subsurface characterization in greater detail, discern the nature of the actual soil fabric and stratigraphy, and assess how well traditional investigation methods capture key aspects of soil layering in these varying depositional environments.

Detailed logging shows clear differences in depositional environment between Riccarton (Site 23), Barrington (Site 14), and Cashmere (Site 33). The Riccarton and Cashmere samples both show thick, continuous deposits of interlayered silt, silty sand, and sand, with the sandy layer at Cashmere interrupted by thinner silt layers. In contrast, the Barrington samples show a thick, relatively continuous deposit composed primarily of silty sand, with some cleaner sand layers. Additionally, the logging program also revealed the scale at which sand, silt, and organic layers and pockets may be discontinuous. The variable Christchurch environment is difficult to simplify to two-dimensional geometry or a soil column for the purposes of simplified liquefaction assessment. Implicit in the discussion of stratigraphy are the effects of vertical and lateral heterogeneity and interlayer hydraulic connectivity.

### 5.2.1 Case History Site Comparisons

Direct comparisons between no-liquefaction and liquefaction case history sites provide further insight on the Christchurch event liquefaction observations. Site 14 (SW non-swamp, liquefaction) is compared with Site 23 (SW swamp, no liquefaction) and Site 33 (SW swamp, no liquefaction).

The CPT traces at Site 14 and Site 23 differ considerably. The Site 23 CPT identifies significant stratification (albeit at a coarser resolution than shown in detailed logging), but it is not well-interpreted with the simplified methods because of the scale of the thin-layer stratification. The simplified liquefaction triggering evaluation procedures estimate a highly stratified subsurface of liquefiable and non-liquefiable layers. It is possible that these thin fine sand and coarse silt seams may have generated high excess pore water pressures, but were unable to coalesce into a hydraulically connected layer capable of generating ejecta flow to the ground surface because of the interbedded layers of non-liquefiable soils. The current liquefaction evaluation framework was not developed for sites with this type of stratigraphy (e.g., Seed 1979).

The CPT traces at Site 14 and Site 33 are similar. Both have a pseudo-crust underlain by a sandy layer that is then underlain by siltier soils. A reasonable hypothesis is that the shallow sandy layer governs the development of liquefaction manifestations at a site and creates an upward path for ejecta to reach the ground surface. Examining the detailed characteristics of the sandy layer at each site is where the variability in depositional environment between the two sites becomes clearer. Figure 5 shows high-quality samples and detailed logs from the sandy soil layer at Site 14 and Site 33, enlarged to show details of the stratification within portions of the CPT profile identified as sands. Silt seams and laminations are evident in the sample from Site 33, including a clear silt seam about 1 cm thick and thin organic seams. In contrast, the sample from Site 14 only has some minor layering of silt and sand within a more homogeneous silty sand to sand matrix. This difference in stratification is a function of the differing depositional environments between the two sites. The silt layers at Site 33 could significantly impact the liquefaction potential of the sandy layer identified with the CPT. This detail is not seen in the sonic boring, and is only hinted at in the CPT trace in two points where the sandy soil reaches slightly higher $I_c$ values. High-quality continuous sampling is required to see the level of resolution necessary to differentiate the layering at these two sites.

## 5.3 Findings

Two important issues are evident. Firstly, there is highly interlayered stratification that is captured only partially by the CPT for which the simplified liquefaction assessment procedures may not provide estimations consistent with observations. Secondly, there is intermittent stratification that is not captured by the CPT, because it occurs in soil layers where thin contrasting seams and layers are smeared over by the CPT. Both issues can be linked back to depositional environment differences between Site 14 and Sites 23 and 33. Additionally, CPT soundings may exhibit reduced tip resistance measurements in the thin sand layers and at transitions between stiffer and softer material (Ahmadi & Robertson, 2005). However, the interbedded nature of these sites and scale of the silt and sand layering differs from the cases for which current thin-layer correction factors have been developed. Without continuous sampling and detailed logging, it is difficult to characterize a sandy layer such as that at Site 33. Samples taken at one-meter depth intervals may miss silt seams, or provide too sparse a subsurface picture. Continuous sampling also provides information on GWT fluctuation and the pseudo-crust, improving on characterization via sonic borings or CPT.

# 6 CONCLUSIONS

Discrepancies between surface manifestations of liquefaction and estimates using established liquefaction assessment procedures were explored at several silty soil and highly stratified silt/sand sites in Christchurch. Silt swamp deposits are shown through regional CPT analysis to have mitigating effects on liquefaction manifestation during the Canterbury earthquake sequence, beyond what can be currently characterized and quantified by simplified

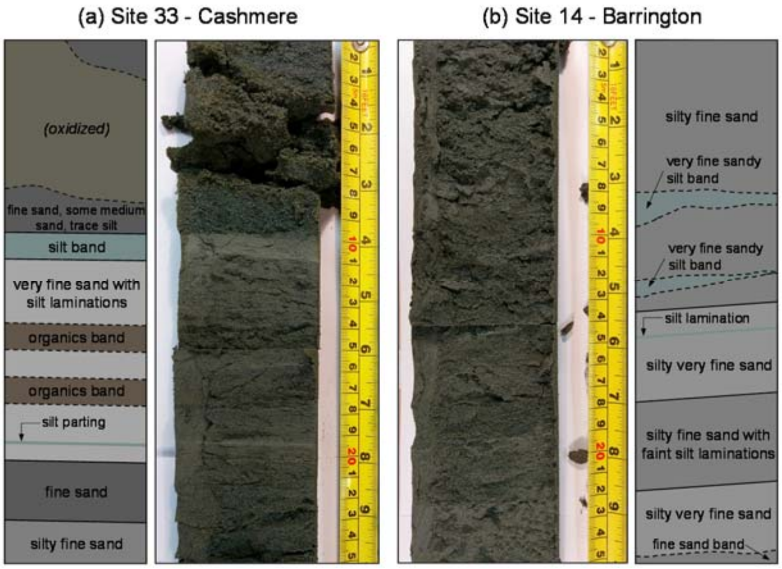

Figure 5. High-quality samples from the sandy layers at: (a) Site 33 and (b) Site 14. Both samples from depth 3.65 m to 4.10 m, cropped to show upper 25 cm of sample.

liquefaction triggering procedures. Differing surficial geology and depositional environments were found to explain in part the limitations of simplified procedures at highly stratified silty soil sites, with swamp environments leading to sites with defined silt layers and more stratified silt/sand deposits. Depositional environment distinguishes between cases that could not be discerned through CPT-based liquefaction assessment alone. CPT resolution is not sufficient for subsurface characterization at these highly stratified sites, and the simplified liquefaction assessment methods do not take into account the effects of such stratification regarding hydraulic connectivity and pore water pressure movement through a stratum.

High-quality continuous sampling and careful, detailed logging of samples can provide sufficiently detailed evaluations of soil fabric and stratigraphy. At sites where simplified methods may not be fully applicable, liquefaction assessments should consider: a) regional scale (depositional environment), b) site scale (shallow subsurface, GWT fluctuation, pseudo-crust, stratification), and c) specimen scale (e.g., gradations, plasticity index). Additional work is warranted to investigate alternative hypotheses that may also contribute to the limitations of current liquefaction assessment procedures.

### 6.1 Implications for Practice & Further Research

High-quality continuous sampling can provide an enhanced characterization and hence understanding of the subsurface conditions at a site. Where historical or geologic maps and preliminary subsurface investigations indicate a complex depositional environment, or a depositional environment different from those of a majority of the liquefaction case history dataset, it would be beneficial to conduct high-quality continuous sampling to evaluate the overall subsurface system and assess the most appropriate methods for evaluating those strata. Simplified liquefaction evaluation procedures were developed largely for clean sand deposits, and silt and stratified silt/sand deposits are not well reflected in the database used to develop the simplified procedures.

The evidence presented in this paper makes a compelling case for further research on depositional and geologic considerations in liquefaction analysis. Depositional environment can matter much in assessing liquefaction potential at a site. Consideration of these issues through a geologic and historical study of the region and through a site-specific investigation that includes continuous high-quality sampling can provide the engineer the information required to employ judgement in the overall assessment.

The detailed evaluation of six individual case history sites provides greater insights and a starting point for further work. Importantly, the findings presented herein are only applicable for free-field or light construction sites; liquefaction may have manifested at the ground surface had there been 4-6 story buildings at each site, as was observed in Adapazari, Turkey (Bray et al. 2004). Additionally, considering the marginality seen at Site 14, liquefaction may have manifested at the ground surface had PGAs been higher at each site. Overall interpretations of depositional environment effects will depend on the depth range being considered and should be used to inform site characterization through sampling. Additional research on the important role depositional environment can play in seismic performance of the ground is warranted.

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