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The Influence of the Non-Liquefied Crust on the Severity of Surficial Liquefaction Manifestations: Case History from the 2016 Valentine's Day Earthquake in New Zealand

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ABSTRACT

The influence of the non-liquefied crust that overlies a liquefied deposit on the severity of surficial liquefaction manifestations has been noted for several decades. In 1985, Ishihara proposed a generalized relationship relating the thicknesses of the non-liquefied crust and of the liquefied stratum to the severity of surficial liquefaction manifestations. Although subsequent studies using data from multiple earthquakes give credence to Ishihara's relationship, the implementation of the procedure is tenuous for all but the simplest of profiles. In an effort to overcome issues with implementing the Ishihara relationship, new procedures have been proposed for predicting the severity of surficial liquefaction manifestations. The efficacies of two of these procedures are currently being assessed in a study using unique case history data from the 2016, M_w 5.7 Valentine's Day earthquake that impacted Christchurch, New Zealand. Preliminary results from this study show that both procedures yield predictions that are in accord with field observations. However, the final results from the ongoing study are expected to more fully assess the efficacies of these procedures.

INTRODUCTION

The study presented herein examines the influence of the non-liquefied crust overlying a liquefied layer on the severity of surficial liquefaction manifestations. Towards this end, preliminary results of a case history from the 2016, M_w 5.7 Valentine's Day (New Zealand) earthquake are used to assess the efficacy of two recently proposed procedures for predicting the severity of surficial liquefaction manifestations, where both procedures account for the thickness of the non-liquefied crust. The significance of the non-liquefied crust on the severity of surficial liquefaction manifestations was initially identified by Ishihara and Ogawa (1978) using data compiled by Kishida (1969) from the 1891 Mino-Owari, 1944 Tohankai, and 1948 Fukui earthquakes in Japan. Ishihara and Ogawa (1978) noticed that no sites having a non-liquefied crust of at least 3 m thick had surficial manifestations of liquefaction resulting from these earthquakes, regardless of the thickness of the underlying liquefied layer. Ishihara (1985) generalized the relationship between the thickness of the non-liquefied crust (H_1) and the thickness of the underlying liquefied layer (H_2) using data from the 1983, M_w 7.7 Nihonkai-chubu and the 1976, M_w 7.8 Tangshan earthquakes (Figure 1). The sites from the Nihonkai-chubu earthquake were estimated to have been subjected to motions having peak ground accelerations (PGAs) of ~ 0.2 g, while those from the Tangshan earthquake were estimated to have been subjected to motions having PGAs of ~ 0.4 - 0.5 g. The sizeable difference between these two curves led to the addition of an interpolated 0.3 g intermediary boundary curve between the two

initial curves. As shown in Figure 1, Ishihara (1985) defined H_1 and H_2 for three scenarios based on the depth of the ground water table and the presence and nature of the overlying non-liquefying soil.

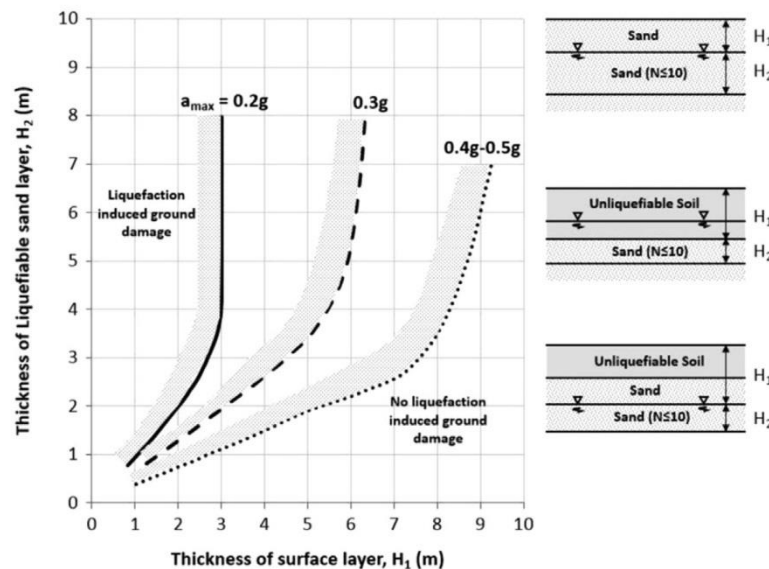


Figure 1. Relationship between thickness of a liquefied layer (H_2) and thickness of the overlying non-liquefied crust (H_1) level-ground sites for predicting when surficial liquefaction manifestations will and will not occur (from van Ballegooy et al., 2015; based on Ishihara, 1985).

Youd and Garris (1995) used a larger database of site observations from 13 other earthquakes and compared these with the Ishihara H_1 - H_2 curves shown in Figure 1. They found that the curves were generally valid for surficial liquefaction manifestations other than either ground oscillation or lateral spread. Additionally, van Ballegooy et al. (2014, 2015) used data from the 2011, M_w 6.2 Christchurch earthquake to examine the Ishihara boundary curves. However, the soil profiles in Christchurch are highly variable with many sites having multiple interbedded non-liquefying layers within liquefied deposits. As a result, a direct application of the Ishihara procedure was difficult. For these deposits, H_1 was taken as the thickness of the non-liquefying crust (consistent with Ishihara, 1985), but for practical purposes, H_2 was taken as the cumulative thickness of the layers predicted to liquefy (CTL) within the top 10 m of the soil profile. For these cases, the Ishihara curves did not provide a clear separation of the sites with observed surficial liquefaction manifestations from those without manifestations. Specifically, ~90% of sites with surface manifestation of liquefaction ejecta plotted to the left of the respective Ishihara boundary curves (i.e., true positives), with the remaining 10% having plotted to the right (i.e., false negatives). However, only ~30–40% of sites without surface manifestation of liquefaction ejecta plotted to the right of the respective Ishihara boundary curves (i.e., true negatives), with the remaining 60–70% having plotted to the left (i.e., false positives).

Despite issues with defining H_1 and H_2 for all but the simplest of profiles, the authors, along with many others, believe that the trends of the Ishihara boundary curves are conceptually correct. For example, Tonkin and Taylor (2013) state: “Visual observations of the land damage and dwelling foundation damage mapping over Canterbury [New Zealand] show that the majority of areas most severely affected by liquefaction coincide with low lying areas where the

ground water table is shallow. Conversely, sites less affected by liquefaction are in areas of higher elevation where the depth to ground water is [high], indicating there is some correlation between liquefaction damage and the non-liquefying crust thickness.” In line with this, NZGS (2017) details approaches for minimizing the risk from liquefaction for residential structures that entail constructing a non-liquefiable crust, in combination with a robust, stiffened foundation system. Figure 2 shows an example where this strategy was implemented for a house located in an eastern suburb of Christchurch, New Zealand, although in this case that added fill only over a limited area may lead to slumping and global stability issues with the perimeter retaining wall if liquefaction occurs at the site. In efforts to quantitatively assess liquefaction damage potential that avoids the difficulties in implementing the Ishihara H_1 - H_2 chart, Maurer et al. (2015a) and Towhata et al. (2016) proposed procedures that combine the thickness of the non-liquefied crust with the Liquefaction Potential Index (LPI: Iwasaki et al., 1978).

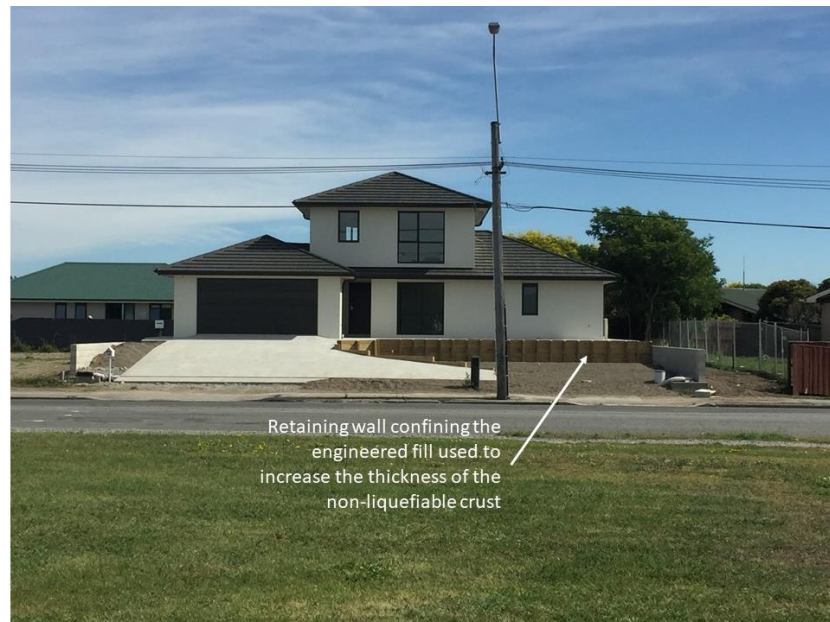


Figure 2. House in an eastern Christchurch, New Zealand, suburb constructed on an engineered fill placed to increase the thickness of the non-liquefiable crust, to mitigation risk from liquefaction.

In the following sections of this paper, overviews of the procedures proposed by Maurer et al. (2015a) and Towhata et al. (2016) are presented. The efficacies of the procedures are assessed using preliminary results from a unique case history from the 2016, M_w 5.7 Valentine’s Day earthquake that impacted Christchurch, New Zealand (Kaiser et al., 2016). The case history consists of two adjacent sites that have non-liquefied crusts with different thicknesses, where surficial liquefaction manifestations were observed at the site with the thinner crust but none were observed at the site having the thicker crust.

MAURER ET AL. (2015A) AND TOWHATA ET AL. (2016) PROCEDURES

Because both the Maurer et al. (2015a) and Towhata et al. (2016) procedures entail the use of the LPI framework, this framework is described first, followed by overviews of the LPI_{ish} (Maurer et al., 2015a) and Towhata et al. (2016) procedures.

LPI Procedure

The LPI framework was proposed by Iwasaki et al. (1978) and results in an index value that correlates to the severity of surficial liquefaction manifestations. The LPI parameter is defined as:

$$LPI = \int_0^{20\text{ m}} F_{LPI}(FS) \cdot w(z) dz \quad (1)$$

where $F_{LPI} = 1 - FS$ for $FS < 1.0$, $F_{LPI} = 0$ for $FS \geq 1.0$; FS = factor of safety against liquefaction, computed via a simplified liquefaction triggering evaluation procedure; and $w(z)$ is a depth weighting function given by $w(z) = 10 - 0.5z$, where z = depth in meters below the ground surface. Inherently, the LPI parameter assumes that each liquefying soil layer contributes to the damage potential at the ground surface. The shallower and/or thicker these layers are, the greater their potential contribution to damage, relative to deeper soil layers. Liquefied layers at depths greater than 20 m are assumed not to contribute to surficial liquefaction manifestations. In reviewing recent liquefaction case history databases (i.e., Cetin et al., 2000; Moss et al., 2003; Kayen et al., 2013; and Boulanger and Idriss, 2014), the maximum documented depth to liquefaction ranges from 15 to 20 m, with median depth for the liquefaction cases being ~5 m. Accordingly, the assumption that liquefied layers at depths greater than 20 m do not contribute to surficial liquefaction manifestations is considered reasonable. LPI can range from 0 for a site with no liquefaction potential to a maximum of 100 for a site where FS is zero over the entire 20 m depth. However, using Standard Penetration Test (SPT) data from 45 liquefaction sites in Japan, Iwasaki et al. (1978) found that 80% of the sites had $LPI > 5$, while 50% had $LPI > 15$. Based on this data, it was proposed that severe liquefaction damage should be expected for sites where $LPI > 15$ but should not be expected for sites where $LPI < 5$. This criterion for liquefaction manifestation, defined by two threshold values of LPI, is commonly used in practice.

LPI_{ish} Procedure

The “Ishihara inspired LPI” (LPI_{ish}) framework was proposed by Maurer et al. (2015a) and is a conceptual and mathematical merger of the Ishihara (1985) H_1 - H_2 chart and LPI framework. LPI_{ish} is defined as:

$$LPI_{ish} = \int_{H_1}^{20\text{ m}} F_{LPI_{ish}}(FS) \frac{25.56}{z} dz \quad (2a)$$

$$F_{LPI_{ish}}(FS) = 1 - FS \quad \text{if} \quad FS \leq 1 \quad \text{and} \quad H_1 \cdot m(FS) \leq 3 \quad (2b)$$

$$F_{LPI_{ish}}(FS) = 0 \quad \text{if} \quad FS > 1 \quad \text{or} \quad H_1 \cdot m(FS) > 3 \quad (2c)$$

$$m(FS) = \exp \left\{ \frac{5}{25.56 \cdot (1 - FS)} \right\} - 1 \quad \text{if} \quad FS \leq 0.95 \quad (2d)$$

$$m(FS) = 100 \quad \text{if} \quad FS > 0.95 \quad (2e)$$

H_1 is the thickness of the non-liquefied crust, taken as the depth from the ground surface to the first instance where $FS < 1$. The most notable differences in the LPI and LPI_{ish} frameworks are that the latter accounts for the relative thickness of H_1 and H_2 via the additional criterion on $F_{LPI}/F_{LPI_{ish}}$ when $FS \leq 1$ and the depth weighting factor is proportional to $1/z$, as opposed to being linear. Specific to the depth weighting factor, in the LPI_{ish} framework shallower liquefied layers contribute more to surficial manifestations than predicted by the LPI framework.

Coincidentally, this depth weighting factor is the same that is used in the Liquefaction Severity Number (LSN) framework proposed by van Ballegooy et al. (2012, 2014).

The optimal LPI_{ish} thresholds corresponding to different severities surficial liquefaction manifestations are dependent on the liquefaction triggering procedure used to compute FS and the characteristics of the profile; the same is the case for LPI thresholds (Maurer et al., 2015b) and for the Towhata et al. (2016) procedure discussed next. Nevertheless, the same thresholds proposed by Iwasaki et al. (1978) are used herein with the LPI_{ish} framework (i.e., $LPI_{ish} < 5$: none to minor surficial liquefaction manifestations are predicted; $LPI_{ish} > 15$: severe surficial liquefaction manifestations are predicted).

Towhata et al. (2016) Procedure

Using data from residential areas impacted by the 2011 M_w 9.0 Tohoku, Japan, earthquake, Towhata et al. (2016) developed a procedure that combines the influence of the non-liquefied crust with LPI in a chart format, shown in Figure 3. The chart consists of five zones that range in probability of severe surficial liquefaction manifestations from unlikely to highly probable, as listed in Table 1.

CASE HISTORY

2016 M_w 5.7 Valentine's Day Earthquake

The 2016 M_w 5.7 Valentine's Day earthquake struck off the coast of Christchurch, New Zealand at 1:13pm local time on 14 February 2016 (Kaiser et al., 2016). It was the largest earthquake to impact the area since an M_w 5.0 aftershock in May 2012. The maximum recorded peak ground accelerations (PGAs) for the event were 0.36 g (vertical: station NBLC) in New Brighton and 0.29 g (horizontal: station PRPC) in Linwood, both are suburbs in eastern Christchurch. The GeoNet ShakeMap for horizontal PGAs for the event is shown in Figure 4.

Table 1. Probability of severe liquefaction manifestations for zones in the Towhata et al. (2016) chart

Qualification	H_1	LPI	Probability of severe liquefaction manifestations
A	> 5 m	0 to 100	unlikely
B1	3-5 m	< 5	low probability
B2	3-5 m	≥ 5	low probability
B3	≤ 3 m	< 5	low probability
C	≤ 3 m	≥ 5	high probability

The event resulted in rockfalls and liquefaction in eastern Christchurch, primarily in areas that had previously been identified as being highly susceptible to these phenomena. Of particular interest to the study presented herein is the occurrence of liquefaction in the eastern Christchurch suburb of Bexley. Bexley experienced severe liquefaction and lateral spreading during the 2010 M_w 7.0 Darfield and 2011 M_w 6.2 Christchurch earthquakes, causing severe damage to houses and buried infrastructure (Cubrinovski and Green, 2010; Cubrinovski et al., 2011). As a result, Bexley is designated as a "flat land residential red zone." Accordingly, rebuilding was prohibited in this area and most residential structures had been cleared from this suburb by the time the Valentine's Day earthquake occurred. This greatly facilitated the observation of surficial

liquefaction manifestations, even of minor severity, because much of the land had been recently graded.

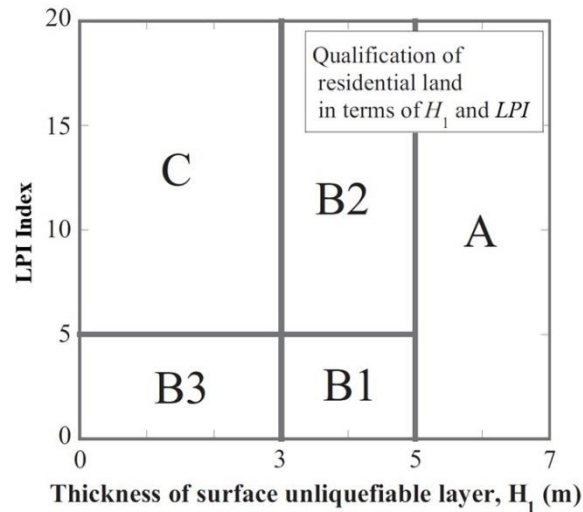


Figure 3. Chart proposed by Towhata et al. (2016) for predicting the probability of severe surficial liquefaction manifestations. (Towhata et al. 2016)

Bexley Development

Bexley is located on the west bank of the Avon River, ~1 km north of the Avon Heathcote Estuary (Figure 5). As a result of the severe liquefaction and lateral spreading that occurred in Bexley during the Darfield and Christchurch earthquakes, the Ministry of Environment commissioned a fact-finding study to determine whether liquefaction and related phenomena were considered in the development of this suburb. The following is a brief summary of relevant information from the resulting report (St. Clair and McMahon, 2011). Bexley is comprised of three land use zones: Bexley North, Bexley Central, and Bexley South. Bexley North and Bexley Central were residentially developed during the post-WWII period, prior to the establishment of land-use zoning of the area outlined by the First District Scheme in 1962. As a result, the designated land use zones for these areas actually reflected the development that already existed, rather than the First District Scheme guiding development. Also, as a result of Bexley North and Bexley Central having been relatively developed in 1962, no considerations were given to environmental constraints/natural hazards in the further development of these areas. However, Bexley South was undeveloped in 1962 and was designated as “Rural” in the First District Scheme. Starting in 1972 changes in the land use designation for Bexley South allowed some development. In 1990 the Christchurch City Council (CCC) proposed Plan Change 57 which divided Bexley South into two parcels, with the northern half designated for residential development and the southern half designated for recreation (i.e., Bexley Wetland). However, with this change in land-use designation, consideration was given to flooding and additional fill was placed in areas targeted for residential development. This is illustrated in Figure 5b which shows that the ground elevation of Bexley South is 2.0-3.0 m above mean sea level, while Bexley Central and Bexley North are only 0.5-1.5 m above mean sea level.

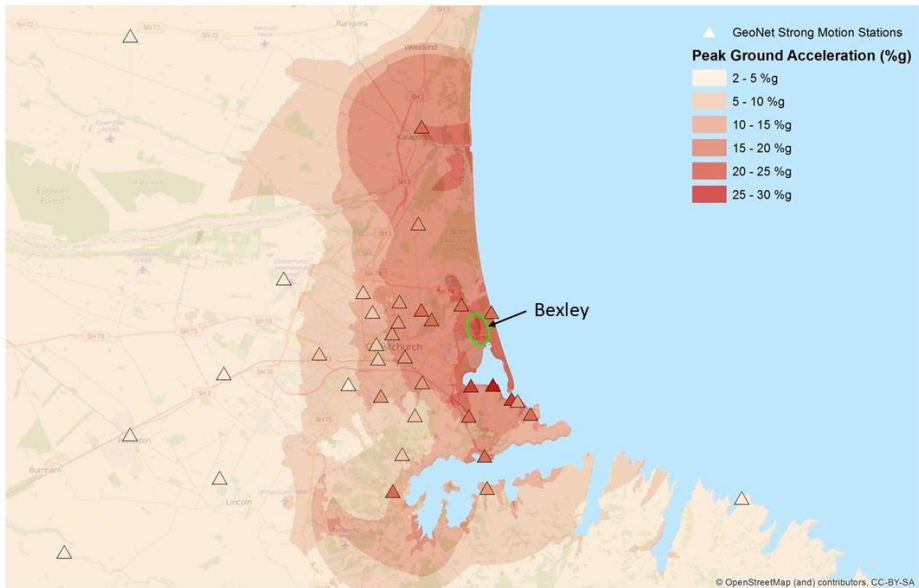


Figure 4. GeoNet ShakeMap of estimated and recorded horizontal PGAs for the 2016, Mw5.7 Valentine's Day earthquake. (Kaiser et al., 2016)

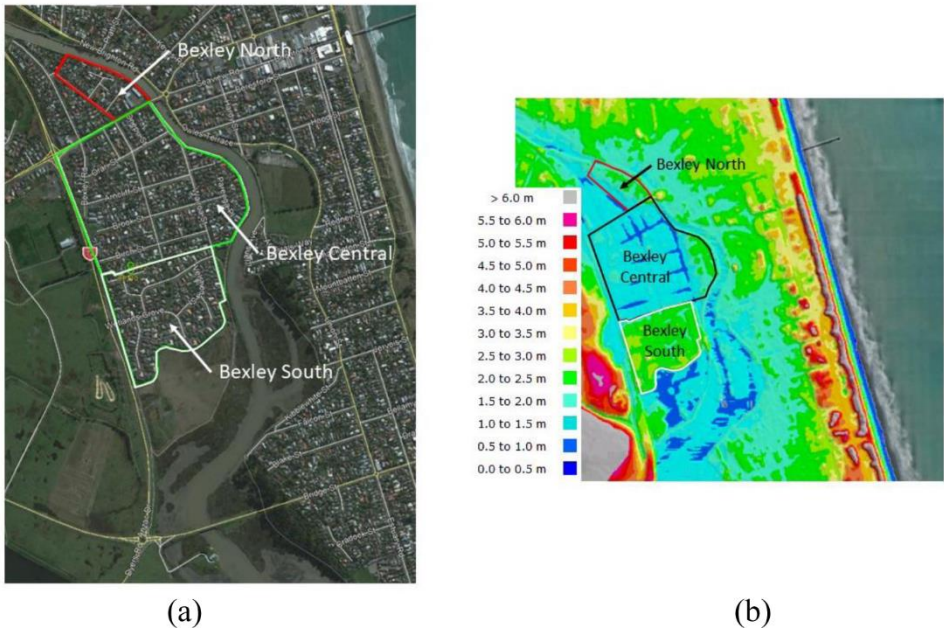


Figure 5. Satellite image and elevation map of Bexley: (a) Satellite image of Bexley; and (b) Map of showing ground surface elevations of Bexley relative to mean sea level (pre-2010-2011 Canterbury earthquake sequence)

The difference in ground elevation between Bexley Central and Bexley South was abrupt and demarcated by a cinderblock wall that separated properties on the south side of Birch St. (Bexley Central) and the north side of Brynn Ln (Bexley South). A photo of the wall is shown in Figure 6, with the wall varying in height along its length from ~0.2 m at the terminal ends of the wall to ~1.0 m in the central stretch of the wall. As shown in Figure 6, there were multiple locations along the wall where liquefaction manifested on the Bexley Central side, but not on the Bexley

South side. As a result, this site provides a unique case history for studying the thickness of the non-liquefied crust on the severity of surficial liquefaction manifestations.



Figure 6. Wall separating Bexley South and Bexley Central. A liquefaction feature is observed on the Bexley Central side of the wall that has a thinner non-liquefiable crust.

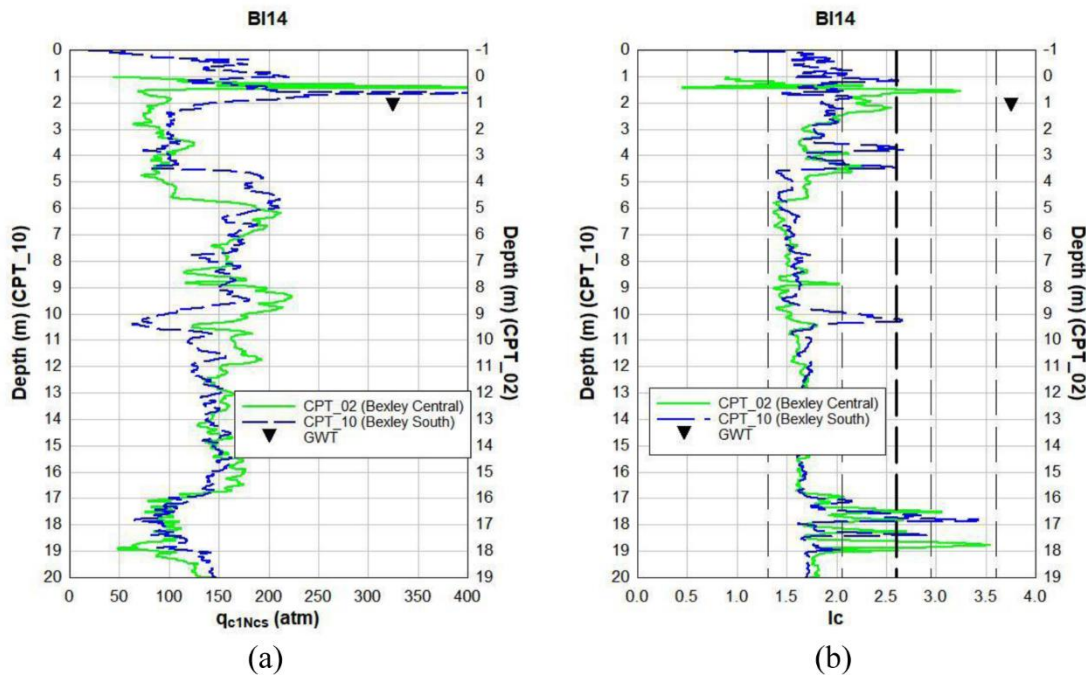


Figure 7. CPT sounding data for Bexley South (CPT_10) and Bexley Central (CPT_02): (a) Normalized CPT tip resistance (q_{c1Ncs}); and (b) Soil Behavior Type Index (I_c).

Predictions vs. Field Observations

Minor to moderate surficial liquefaction manifestations were observed on the Bexley Central side of the wall that separates Bexley South and Bexley Central (e.g., Figure 6). However, no features were observed on the Bexley South side of the wall where the fill was at least ~0.5 m

thick. To better understand these observations, a series of Cone Penetration Tests (CPTs) were performed along both sides of the wall. Figure 7 shows the normalized CPT tip resistances (q_{c1Ncs}) and Soil Behavior Type Index (I_c) for the two soundings, one performed in Bexley Central (CPT_02) and the other performed in Bexley South (CPT_10). The measured CPT tip resistances were normalized per Boulanger and Idriss (2014). To ease the visual comparison of the data from the two soundings, the depth scale for CPT_02 was adjusted so that the ground water table (GWT) for the two soundings plots at the same depth. As may be observed from Figure 7, and considering typical spatial variability in soil profiles, the primary difference between the profiles is the additional ~1 m of fill for Bexley South (CPT_10).

The Boulanger and Idriss (2014) (BI14) simplified liquefaction evaluation procedure was used to compute the FS for the two profiles. Based on Figure 4, the PGAs at the two sounding sites were estimated to be ~0.25 g for the $M_w5.7$ event. The resulting H_1 , LPI, and LPI_{ish} values for the two profiles are listed in Table 2, where H_1 was the depth to the first instance where $FS < 1$. Additionally, predictions of the severity of surficial liquefaction manifestations per the LPI_{ish} and Towhata et al. procedures are shown in Figure 8.

Table 2. Results from liquefaction evaluation using BI14

	CPT_02 (Bexley Central)			CPT_10 (Bexley South)		
	H_1 (m)	LPI	LPI_{ish}	H_1 (m)	LPI	LPI_{ish}
BI14	1.26	7.2	7.1	2.82	2.5	0.6

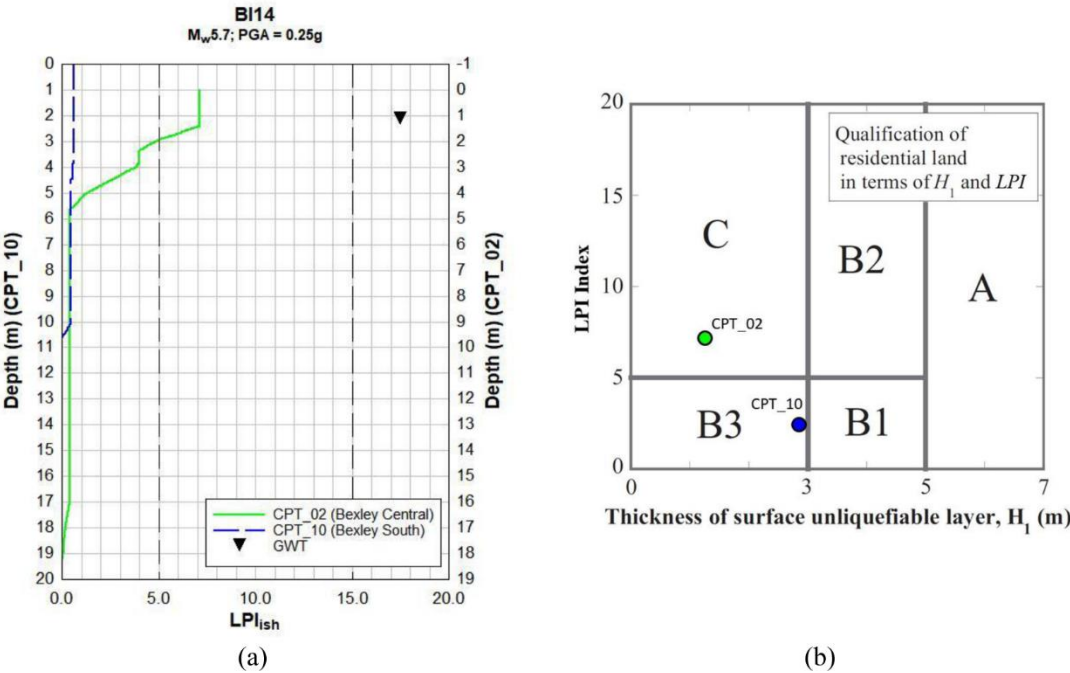


Figure 8. Predictions of severity of surficial liquefaction manifestations: (a) LPI_{ish} procedure; and (b) Towhata et al. (2016) procedure.

DISCUSSION

As shown in Figure 8a, the Maurer et al. (2015a) procedure predicts no-to-minor surficial liquefaction manifestations ($LPI_{ish} < 5$) on the Bexley South side of the wall and moderate manifestations ($5 < LPI_{ish} < 15$) on the Bexley Central side. Also, Figure 8b shows that the

Towhata et al. (2016) procedure predicts a low probability of severe surficial liquefaction manifestations (B3) on the Bexley South side of the wall (CPT_10) but predicts a high probability (C) of manifestations on the Bexley Central (CPT_02) side. Both sets of predictions are in accord with field observations. To more fully assess the efficacies of both procedures, the authors are currently analyzing other sets of CPT soundings performed along the wall where the difference in the thicknesses of the non-liquefied crusts of adjacent sites varies, as well as analyzing other locales throughout Christchurch that were subjected to motions from the Valentine's Day earthquake.

Finally, it is noted that thresholds used to predict the severity for the surficial liquefaction manifestations for the LPI_{ish} procedure and the boundaries for the regions delineating the probabilities of severe liquefaction in the Towhata et al. chart were developed using Japanese variants of the simplified liquefaction evaluation procedure. As a result, implementing these procedures in conjunction with the BI14 simplified procedure can introduce some bias in the results and the conclusions drawn from the results. Although the authors do not believe this bias is significant, they are looking into this issue in the ongoing study.

SUMMARY AND CONCLUSIONS

The influence of the non-liquefied crust that overlies a liquefied deposit on the severity of surficial liquefaction manifestations has been noted for several decades and is in general accord with trends predicted by Ishihara's (1985) H_1 - H_2 chart. However, the utility of this chart is limited due issues of defining H_1 and H_2 for all but the simplest of profiles. In an effort to overcome issues with implementing the Ishihara relationship, Maurer et al. (2015a) and Towhata et al. (2016) proposed procedures that combine the thickness of the non-liquefied crust with the LPI framework. The efficacies of these two procedures are being assessed in an ongoing study using unique case-history data from the M_w 5.7 Valentine's Day earthquake that impacted Christchurch, New Zealand. Preliminary results from this study show that both procedures yield predictions that are in accord with field observations. However, the final results from the ongoing study are expected to more fully assess the efficacies of these procedures.

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