Liquefaction induced ground damage in the Canterbury earthquakes: predictions vs. reality

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ABSTRACT

Predicting the severity of liquefaction induced ground damage is the key outcome from a liquefaction assessment. Ishihara (1985) developed a simple and logical method to predict the occurrence of sand boils, ground fissures and other features of liquefaction damage. This paper examines the effectiveness of Ishihara’s method in predicting the liquefaction damage that occurred in the recent Canterbury earthquakes.

The applicability of the method to complex multi-layered soil profiles encountered in Canterbury is addressed, and a procedure for calculating an equivalent liquefied layer thickness in such profiles is proposed. This procedure is applied to a large number of sites with CPT data in Christchurch, combining simplified liquefaction analyses with detailed observations of ground damage following three large earthquakes.

Ishihara’s method was generally successful in predicting the occurrence of liquefaction damage, and is considered appropriate for simplified assessments of liquefaction hazard in layered Canterbury soils. However, the Ishihara method may unconservatively predict no damage for sites where thin liquefiable layers are present within the upper 3m of the soil profile; observations from the Canterbury earthquakes indicate that significant damage may occur in these cases. The data from Canterbury suggests that once liquefaction is triggered the occurrence of liquefaction damage is primarily dependent on the proximity of the liquefied layer to the ground surface, not the ground shaking intensity. Finally, it was observed that a crust thickness greater than 3.5-4m was sufficient to prevent liquefaction induced damage, even with significant thickness of liquefied soil below.

1 INTRODUCTION

Ishihara (1985) observed that while liquefaction can cause severe damage to buildings, roads and buried infrastructure, little damage occurs unless liquefaction results in some form of ground surface manifestation such as sand boils, fissures or cracking. A simple method was then developed to predict the occurrence of liquefaction induced ground damage. The method considers:

1. The thickness of the non-liquefied crust layer (H_1) – if a non-liquefied crust is too thin, excess pore water pressures from the fluidised soil can easily ‘break through’.
2. The thickness of the underlying liquefied layer (H_2) – the liquefied layer must have sufficient thickness to enable significant excess pore water pressures to develop, in order to allow significant ground deformation and soil deformation to occur.
3. The intensity of ground shaking – the more severe the earthquake the greater crust thickness needed to prevent liquefaction damage.

Using these principles, a chart was developed using observations from the M7.7 Nihonkai Chubu earthquake in 1983, where occurrences of damage and no damage were plotted. The H_1 and H_2 thicknesses were determined from liquefaction triggering analysis; Ishihara concluded sandy soils with SPT N < 10 would have liquefied in this earthquake. Three boundary curves were superimposed onto this data representing earthquakes with different peak ground accelerations. This figure is reproduced in Figure 2(a). If a site plots above the boundary curve, liquefaction induced ground damage is likely.

Youd and Garris (1995) undertook an evaluation of the Ishihara method using data from 15 different earthquakes ranging in magnitude from 5.3 to 8.0. Layer thicknesses were calculated using the Seed and Idriss (1985) triggering method. They concluded that the Ishihara method was reasonably successful in predicting the occurrence of liquefaction damage. However, the method was not accurate for sites affected by lateral spreading. Following these observations, it is now accepted in practice that lateral spreading ground damage arises from a different mechanism, and that lateral spreading cracks can exacerbate the occurrence of sand boils as they provide a path for liquefaction ejecta.

This study is essentially an application of the Ishihara method to sites affected by the Canterbury earthquakes with two minor modifications:

1. A method is proposed to calculate an equivalent liquefied layer thickness, H_2, for interbedded layers of liquefiable and non-liquefiable soil.
2. The magnitude scaled peak ground acceleration ($PGA_{M=7.5)}$ is used as a ground shaking intensity measure rather than the peak ground acceleration (PGA).

Both of these modifications are considered necessary to allow for correct interpretation of the method in the Canterbury earthquakes. Interbedded soil profiles are common due to the alluvial overbank deposits and all three major earthquakes had magnitudes less than M=7.5.

2 CRUST THICKNESS CALCULATION

The proposed calculation procedure can be summarised as follows:

- The crust thickness, H_1, is identified as the depth to the shallowest soil layer where the factor of safety against liquefaction (FOS_{liq}) is less than one. FOS_{liq} is evaluated using a simplified liquefaction triggering calculation (Idriss and Boulanger, 2008).
- The thicknesses of non-liquefied layers between liquefied layers are calculated.
- If a non-liquefied layer is thicker than 1m, then it is considered thick enough to effectively separate the liquefied layers above and below.
- If the thickness of the non-liquefied layer is less than 1m, it is not considered effective in separating the liquefied layers above and below.
- Therefore the bottom of the H_2 layer is the top of the shallowest non-liquefiable layer that is thicker than 1m.

The automatic calculation procedure was applied to 46 locations in the Canterbury region. Table 1 summarises the input data used in the calculations.

Table 1: Inputs to crust thickness calculation

Parameter	Description	Reference
Geotechnical investigation data	Cone Penetration Test (CPT) data from Canterbury Geotechnical Database (CGD), primarily from post-earthquake CPTs undertaken by Earthquake Commission. CPTs in areas affected by lateral spreading were excluded from the data.	CERA (2013)
Ground shaking intensity	Peak ground acceleration (PGA) contours from CGD interpolated from strong motion stations across region; magnitude scaled using factors from Idriss and Boulanger (2008)	Bradley et al. (2012) Idriss and Boulanger (2008)
Groundwater depth	Event specific groundwater contours from CGD created using data from monitoring bores across the region and LiDAR scans of ground elevation	GNS (2013)
Liquefaction triggering	Simplified liquefaction triggering analysis using CPT data (fines correction using Roberston and Wride (1998))	Idriss and Boulanger (2008)

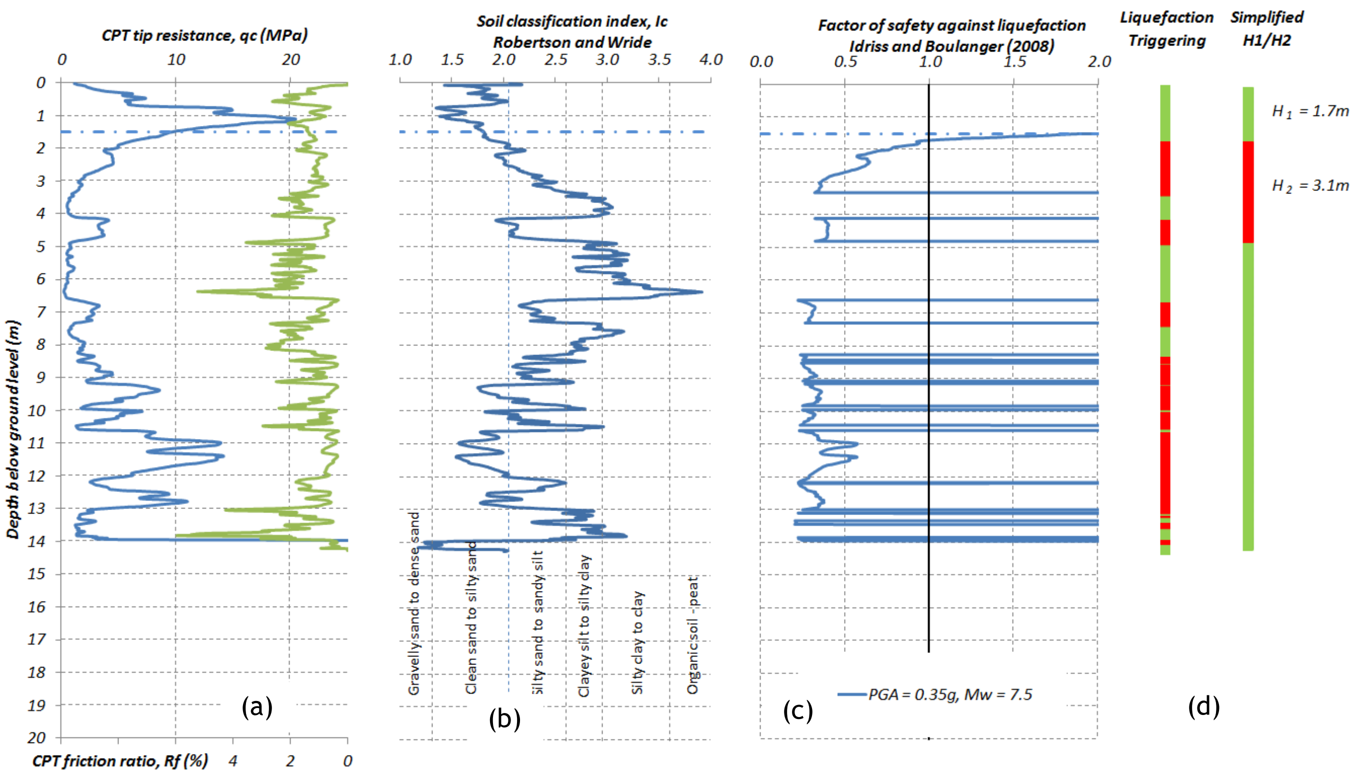

Figure 1: Example calculation of H_1 and H_2 in layered soil profile: (a) CPT results, (b) Soil classification index, (c) Factor of safety against liquefaction, (d) Liquefaction triggering and equivalent crust layer thickness schematic

The choice of 1m as a nominal thickness of non-liquefied soil to separate the effects of two liquefied layers is somewhat arbitrary. Nonetheless inspection of the data indicates that this limit seems to be effective when explaining the occurrence (or otherwise) of observed post-earthquake liquefaction damage following the Canterbury Earthquakes.

To illustrate the application of the method, Figure 1 shows an example CPT from south-western Christchurch. The soil stratigraphy consists of interbedded layers of loose sand and soft to firm low plasticity silt. A liquefaction triggering analysis (using Idriss and Boulanger, 2008) predicts that the sand layers will liquefy in a large earthquake (M=7.5 with PGA=0.35g) and that the silt layers are non-liquefiable.

Figure 1(d) indicates the H_1 and H_2 values calculated using the automated procedure. The liquefied layer thickness H_2 is determined to be H_2 = 3.1m.

3 RESULTS FROM CANTERBURY EARTHQUAKES

Figure 2 summarises the H_1 and H_2 values calculated at 46 sites around Christchurch for three earthquake events; the M_w = 7.1 4 September 2010, M_w = 6.2 22 February 2011 and M_w = 5.9 and M_w = 6.0 13 June 2011 earthquakes. The locations were selected to ensure a wide range of locations, geological conditions and experienced ground shaking intensity.

The data are divided into three bins based on the magnitude scaled peak ground acceleration ($PGA_{M=7.5}$) experienced at the site. Each bin corresponds to a boundary curve proposed by Ishihara (1985) to enable a comparison.

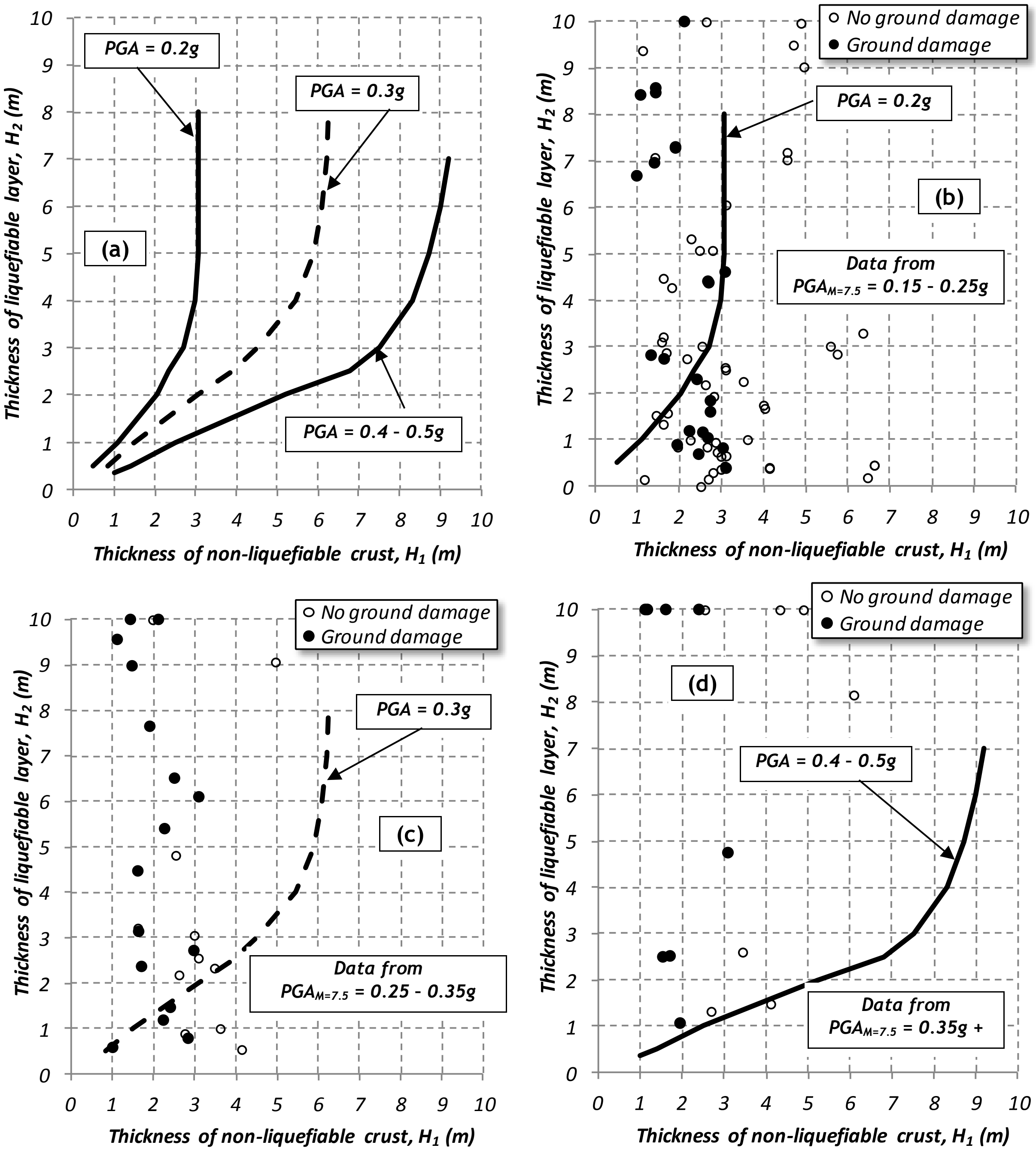

Figure 2: Ishihara crust thickness chart: (a) Boundary curves proposed by Ishihara in 1985, (b) to (d) Data from Canterbury earthquakes using the proposed simplified method divided into three bins based on magnitude scaled peak ground acceleration with the corresponding Ishihara boundary curve

4 DISCUSSION

4.1 Performance of method for Canterbury soils

From inspection of Figure 2 it can be concluded that the proposed equivalent layer thickness is able to provide a good characterisation of the layers critical to predicting the occurrence of liquefaction. Figure 2(b) shows a number of ‘false positive’ results; this may be due to the triggering calculation being slightly conservative, as is necessary for a simplified screening tool.

When assessing the performance of the method it is useful to re-examine the three aspects identified by Ishihara that contribute to the occurrence of liquefaction damage:

1. *The thickness of the non-liquefied crust layer (H_1) – if a non-liquefied crust is too thin, excess pore water pressures from the fluidised soil can easily 'break through'*

The Canterbury data supports the idea that the non-liquefied crust layer is the most critical parameter in determining the occurrence or otherwise of liquefaction induced ground damage.

2. *The thickness of the underlying liquefied layer (H_2) – the liquefied layer must have sufficient thickness to enable significant excess pore water pressures to develop, in order to allow significant ground deformation and soil deformation to occur.*

The results suggest that H_2 thickness is a less critical parameter in the occurrence of liquefaction damage. It is possible that the build up of excess pore water pressure is not related to the thickness of the liquefied layer. There have been many sites where a thin (0.5 – 1m) liquefiable layer close to the surface has caused a large amount of damage; this suggests the location of the liquefied layer is more important than its thickness.

3. *The intensity of ground shaking – the more severe the earthquake the greater crust thickness needed to prevent liquefaction damage*

The data do not seem to support this conclusion; once the ground shaking intensity is great enough to trigger liquefaction further increases in intensity do not seem to affect the occurrence or otherwise of liquefaction damage on the ground surface. However it must be noted that there are limited data for sites where large accelerations were experienced, and the earthquake magnitudes are all in the moderate range (less than M_w = 7.5).

The three observations above are reinforced by analysis of Canterbury dataset using a separate liquefaction vulnerability indicator, the Liquefaction Severity Number (LSN) (T&T, 2013). In calculating LSN, a heavier weighting is given to shallow liquefiable layers than deep liquefiable layers. Analysis of the LSN results across Canterbury indicates that: (1) greater damage is predicted if the liquefiable layer is closer to the ground surface; (2) the thickness of the liquefiable layer is not critical, especially for deeper soil layers; and (3) once liquefaction has triggered in all susceptible soils, further damage is not predicted with increasing ground shaking intensity.

4.2 Required crust thickness to prevent liquefaction damage

The data from the Canterbury earthquakes indicates that H_1 is more important than both H_2 and the intensity of ground shaking. Therefore, it is useful to examine if a threshold crust thickness H_1 exists above which damage is unlikely. Figure 3 collates all observations from the Canterbury earthquakes and the Ishihara (1985) and Youd and Garris (1995) papers. It can be seen in Figure 3 that no damage was observed when H_1 > 3.5m. The exception to this observation are six points from the Youd and Garris dataset. These points correspond to sites with very high peak ground accelerations (PGA = 0.56 to 0.78g). Nonetheless, the data suggests that if H_1 > 3.5m liquefaction induced ground damage is unlikely to occur.

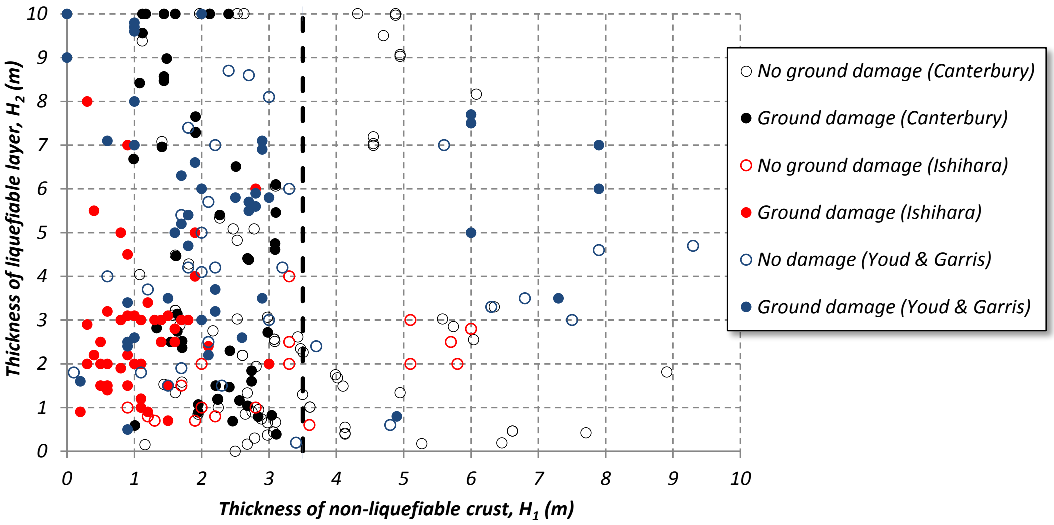

Figure 3: Summary of all observations from this study, Ishihara (1895) and Youd and Garris (1995)

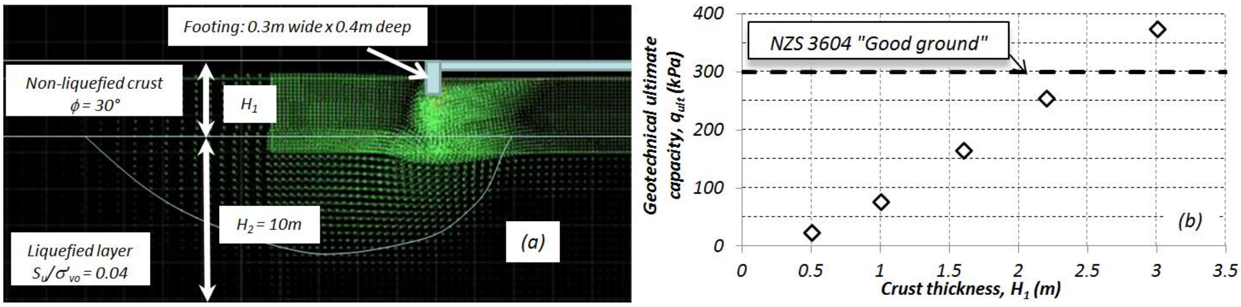

Figure 4: Calculation of crust thickness effect on post- liquefaction bearing capacity (a) FLAC model parameters and failure mechanism; (b) Analysis results

4.3 Numerical modelling

Two observations can be made regarding liquefaction damage in the Canterbury earthquakes:

1. The severity of damage to houses in the Canterbury earthquakes was strongly correlated with the manifestation liquefaction induced damage on the ground surface.
2. There is a strong correlation between non-liquefied crust thickness and the occurrence of liquefaction induced damage at the ground surface.

A simplified numerical model was developed to link these two observations. The aim of the modelling was to determine the effect of the thickness of a non-liquefiable crust layer on the post- liquefaction bearing capacity of a typical shallow foundation detail used for lightweight houses in Canterbury. Canterbury houses typically have a perimeter concrete foundation with either short timber piles or an at grade concrete slab in the interior. The numerical model is shown in Figure 4(a) and consists of a strip footing 300mm wide and 400mm deep. A non-liquefied crust with a friction angle of $\phi = 30°$ was adopted; the thickness of this layer was varied from 0.5 to 3.0m thick. The liquefied layer, H_2 was 10m thick and modelled using a residual strength ratio of S_u/σ_{vo}' = 0.04. This represents a residual strength for very loose sand calculated using the recommendations of Idriss and Boulanger (2008).

The geotechnical ultimate capacity of the foundation was determined by increasing the foundation load until bearing failure occurred using the finite difference software FLAC. Figure 4(a) shows the failure mechanism observed in the model, and Figure 4(b) shows the increase in geotechnical ultimate capacity with increasing crust thickness. It can be seen that once $H_1 > 2.5$m the ultimate geotechnical bearing capacity is above 'good ground' as defined by the New Zealand standard for timber framed houses, NZS3604. While this does not suggest that sand boils or differential settlements cannot be expected in this situation, it does suggest adequate bearing capacity for timber framed houses is likely to be maintained if the non-liquefied crust thickness is greater than 2.5m. From this it can be inferred that, if the crust thickness is greater than 2.5m, then damage to houses is likely to be relatively minor.

4.4 Christchurch wide observations

The second approach taken to verify the threshold crust thickness approach was to compare estimated crust thicknesses for many locations across the city and compare this with the occurrence of liquefaction induced damage. Figure 5 shows three maps of observed ground damage in the 4 September 2010, 22 February 2011 and 13 June 2011 earthquakes. The symbols superimposed onto the maps indicate CPT locations. Sites with $H_1 > 4$m are plotted as blue symbols, sites with $H_1 < 4$m are plotted as black symbols.

It can be seen that liquefaction induced ground damage generally did not occur in locations were the crust thickness is greater than 4m. There were many locations with crust thickness less than 4m where no damage occurred – this observation suggests that while damage may not be expected if $H_1 > 4$m, it does not imply that damage is likely to occur if $H_1 < 4$m. In these cases further analysis of crust quality, post-liquefaction bearing capacity, liquefaction induced settlements and the Liquefaction Severity Number (LSN) (T&T, 2013) is warranted.

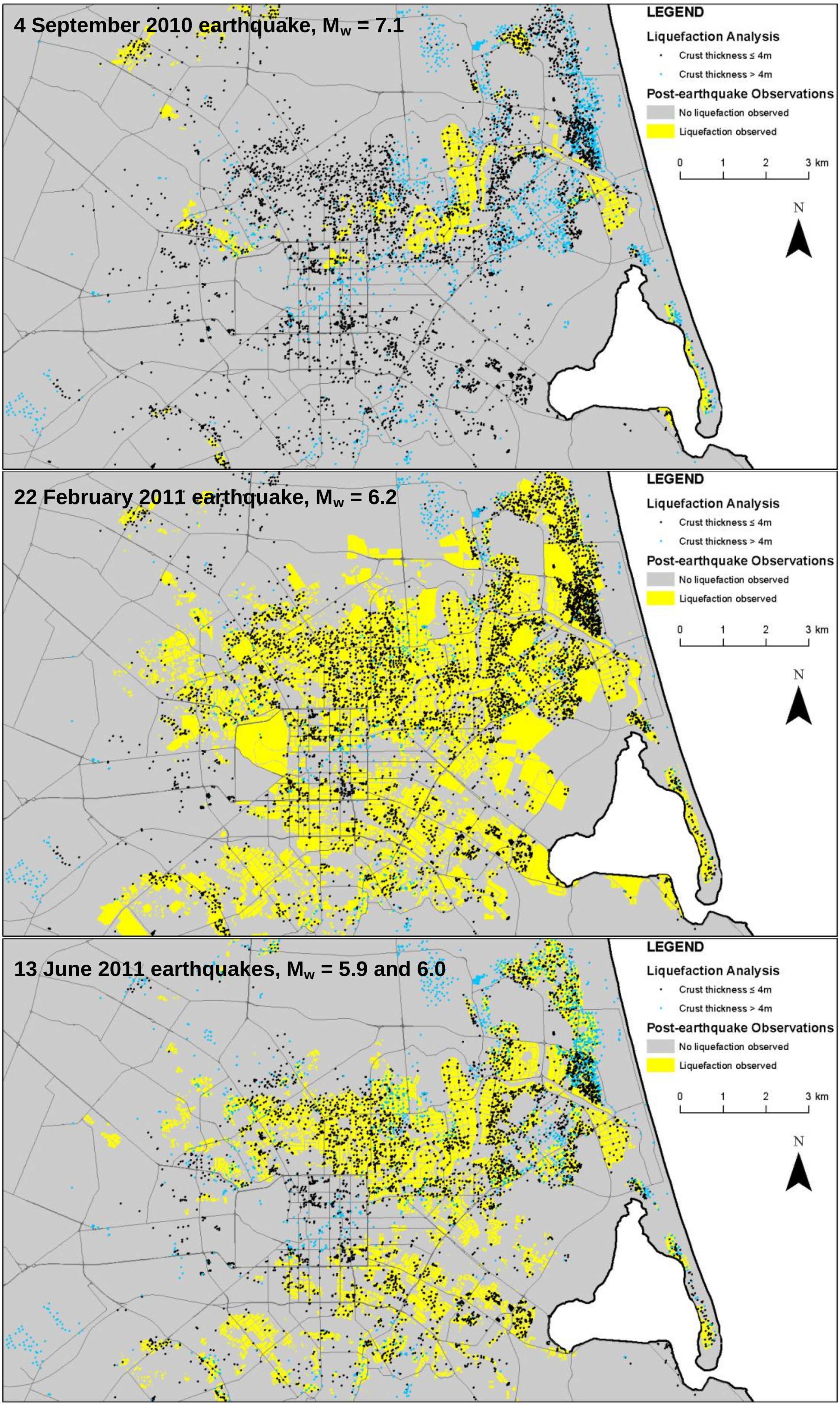

Figure 5: Maps of Christchurch showing correlation of crust thickness, H_1, and observations of liquefaction damage

5 CONCLUSIONS

The performance of a widely used empirical method to evaluate the occurrence of liquefaction induced ground damage was examined using observations from the Canterbury earthquakes. Key conclusions include:

- The Ishihara H_1/H_2 method provides a useful framework for predicting liquefaction induced damage, especially given the uncertainties present in geotechnical earthquake engineering.
- Observations from the Canterbury earthquakes indicate that if $H_1 > 3.5 – 4.0$m then liquefaction damage is unlikely. Numerical analysis suggests that bearing capacity is likely to be adequate for lightly loaded shallow foundations if $H_1 > 2.5$m.
- Liquefaction of relatively thin layers close to the ground surface caused a large amount of damage at certain sites during the Canterbury earthquakes. This suggests the occurrence of liquefaction damage is less sensitive to the thickness of the liquefiable layer, H_2. Consequently, Ishihara's method may be unconservative for the case where 0.5 – 2m thick liquefiable soil layers are present within the upper 3m of soil.
- Once liquefaction is triggered, observations from the Canterbury earthquakes indicate that occurrence or otherwise of liquefaction induced damage is less sensitive to intensity of ground shaking. Rather, the proximity of the liquefied layers to the ground surface is the more important aspect.

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