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Rebuilding Christchurch following the Canterbury earthquakes – implementation of geotechnical lessons learnt

H.J. Bowen, M.E. Jacka
Tonkin & Taylor Ltd, Christchurch.

ABSTRACT

Liquefaction during the Canterbury Earthquakes caused significant damage to the built environment of Christchurch and provided a significant challenge to the rebuild effort. This paper describes the process that the geotechnical engineering community went through to overcome this challenge, and how the lessons learned and the new knowledge acquired has been used to design and construct new buildings in Christchurch.

The first part of this paper describes key lessons learnt from the earthquakes, summarising information from land damage mapping throughout Christchurch from four major earthquakes. The second part of this paper summarises research projects carried out by MBIE in 2011 to assess foundation performance using blast induced liquefaction techniques.

One key finding from both the damage observation and the research projects was that the thickness and strength of the non-liquefiable crust layer has an enormous impact on the occurrence and severity of land damage in the earthquakes. The final part of this paper describes how this lesson has influenced the foundation design for new ‘anchor projects’ in the Christchurch CDB, including the Justice and Emergency Services Precinct, the Christchurch Hospital Acute Services Building, Canterbury Multi Use Arena, Te Pae Christchurch Convention Centre, the Tūranga Central Library and the repair of the Christchurch Town Hall.

1 LAND AND FOUNDATION DAMAGE MAPPING

The four most significant earthquakes in the 2010-2011 series were the 04 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011 events. Following these earthquakes, land damage mapping was undertaken to assess the extent and severity of surface liquefaction manifestation. The land damage mapping was carried out by a team of geotechnical engineers who cross-checked observations to ensure broad consistency across their assessments. Figure 1 shows an example area of Christchurch affected by liquefaction and lateral spreading.

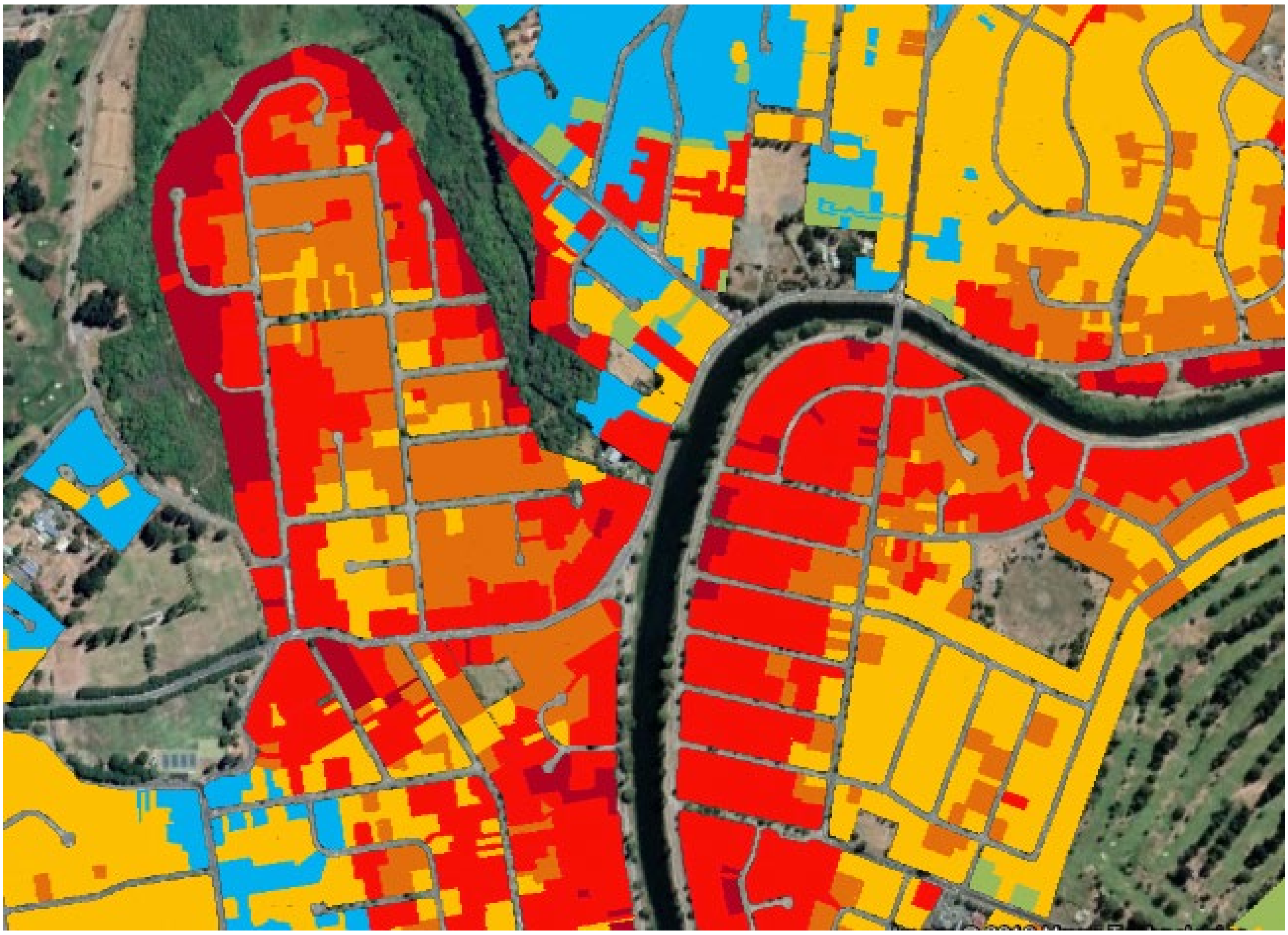

Figure 1: Example of land damage mapping in Christchurch following the 22 February 2011 earthquake. Dark red and red colours indicate lateral spreading damage observed; orange and yellow colours indicate liquefaction damage such as sand boils observed; green colour is minor ground damage and blue colour indicates no damage observed.

The land damage mapping provided a fantastic opportunity to learn about liquefaction and lateral spreading hazards and how they affect buildings and infrastructure. Examples of lessons learned are many, including the links between damage severity and geology, susceptibility of silts and silty soils to liquefaction, how soil deposits with interbedded liquefiable and non-liquefiable layers behave, and the relationship between land damage and foundation damage. One lesson learned was the importance of the non-liquefied crust in assessing liquefaction response; this aspect is the focus of this paper.

2 CRUST THICKNESS OBSERVATIONS

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. Ishihara the developed a simple procedure to predict the occurrence of liquefaction induced ground damage considering the thickness of the non-liquefied crust layer (H_1), the thickness of the underlying liquefied layer (H_2) and the intensity of ground shaking.

A previous study (Bowen and Jacka, 2013) assessed how the Ishihara method performed when predicting liquefaction damage in Christchurch. H_1 and H_2 values were 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.

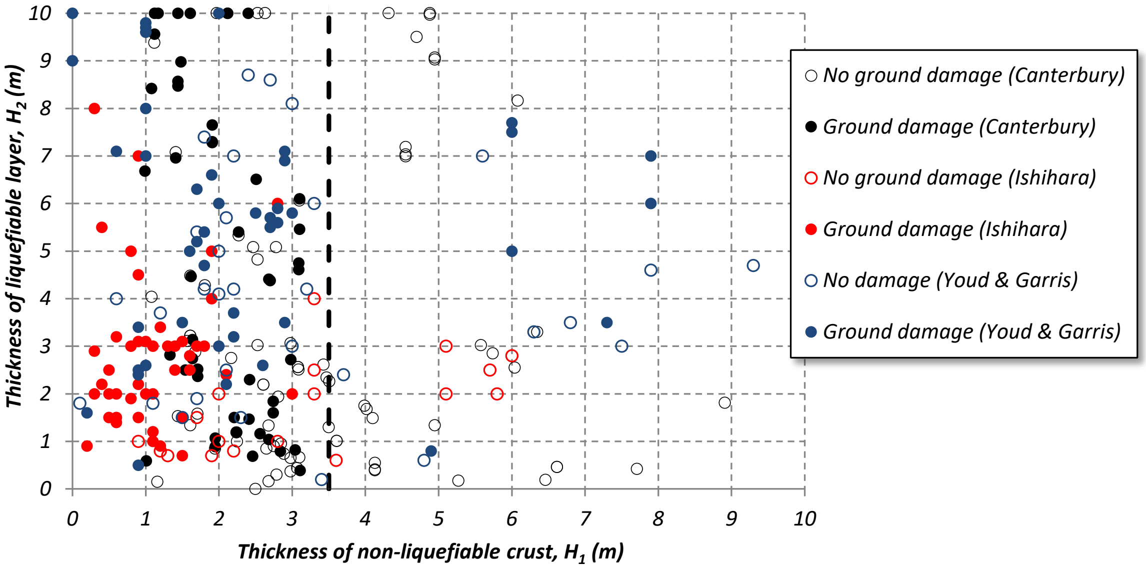

Figure 2: Summary of all observations from Bowen and Jacka (2013), Ishihara (1985) and Youd and Garris (1995)

The data from the Canterbury earthquakes indicates that H_1 is potentially more important with regards to prediction of liquefaction induced ground damage than H_2. This is because there are cases of damage with H_2 less than 1m thick and there appears to be a threshold crust thickness H_1 above which damage is unlikely. Figure 2 collates all observations from the Canterbury earthquakes and the Ishihara (1985) dataset, along with further data from Youd and Garris (1995). It can be seen in Figure 2 that no damage was observed when H_1 > 3.5m. The exception to this observation is seven points from the Youd and Garris dataset. Six of these points correspond to sites with very high peak ground accelerations (PGA = 0.56 to 0.78g).

In addition to the 46 sites described above, a comparison between the estimated crust thicknesses for many locations across the city and the occurrence of liquefaction induced damage was carried out. Figure 3 shows two maps of observed ground damage in the 4 September 2010 and 22 February 2011 earthquakes. The symbols superimposed onto the maps indicate CPT locations. Sites with H_1 > 4m are plotted as blue symbols, sites with H_1 < 4m are plotted as black symbols. Liquefaction induced ground damage generally did not occur in locations where the crust thickness is greater than 4m.

Both Figure 2 and Figure 3 show examples where the crust thickness less than 4m and no damage occurred. This observation suggests that while damage may not be expected if H_1 > 4m, it does not imply that damage is likely to occur if H_1 < 4m. In these cases further analysis of crust quality, post-liquefaction bearing capacity, liquefaction induced settlements and the Liquefaction Severity Number (LSN) (van Ballegooy et al., 2013) is warranted.

3 GROUND IMPROVEMENT TRIALS

3.1 Background

Residential housing was a very important issue for the rebuild, as liquefaction caused significant damage to hundreds of thousands of houses. As the city was rebuilt on land at risk of liquefaction damage, there was a need to develop simple, cost effective engineering measures which increases the resilience of new houses to limit losses and disruption from future earthquakes. To address this need, a number of ground improvement methods were assessed in ground improvement trials, with the purpose of developing recommended foundation solutions for reconstruction and repair of damaged houses in the Canterbury region.

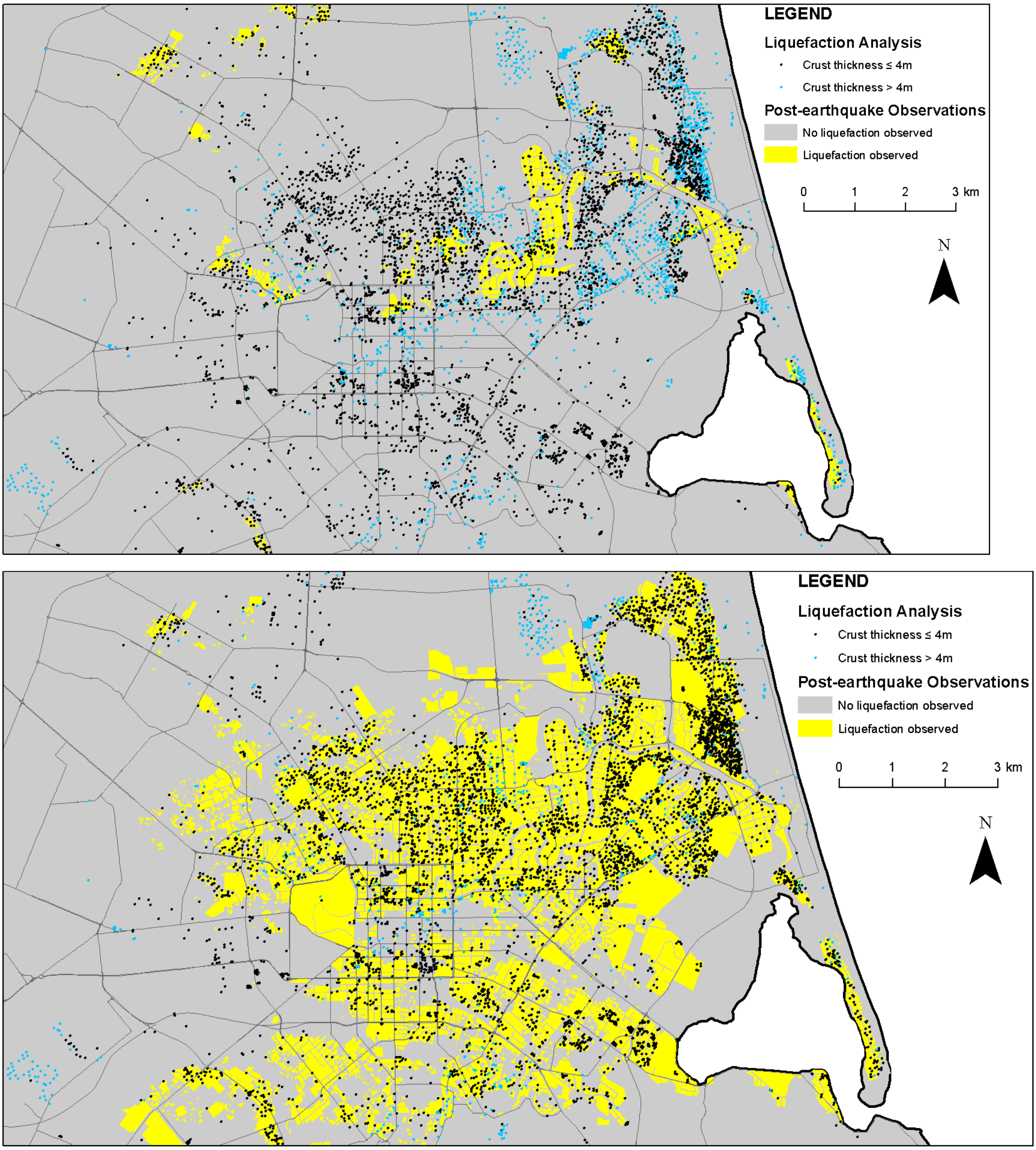

Figure 3: Maps of Christchurch showing correlation of crust thickness, H_1, and observations of liquefaction damage

The trial involved a series of full-scale tests undertaken using four ground improvement methods. The ground improvement options were subjected to simulated earthquakes generated by explosive charges. The tests have provided useful information for the development of foundation solutions for some of the areas of

Christchurch that have been identified as being at a relatively high risk of moderate to severe liquefaction damage in the future.

3.2 Trial details

The foundation systems that were tested include densification of a crust layer, cement stabilisation of a crust layer, construction of a grid of deep soil mix columns, and a perimeter wall of contiguous piles. The test areas were formed around a central core in which a sequence of charges were detonated to generate shaking motion that sufficient to trigger liquefaction.

Figure 4 provides an overview of:

- the general layout of the ground improvement trial, with explosives placed in the central core and around the perimeter;
- the four ground improvement areas (generally 10 x 10m in size) and a control area. Figure 5 shows details of the ground improvement used in the trial.
- instrumentation installed which included piezometers to measure pore pressures in the ground, survey points to measure ground settlement and concrete blocks to simulate building loads;
- observations of sand boils and water inundation following the experiment.

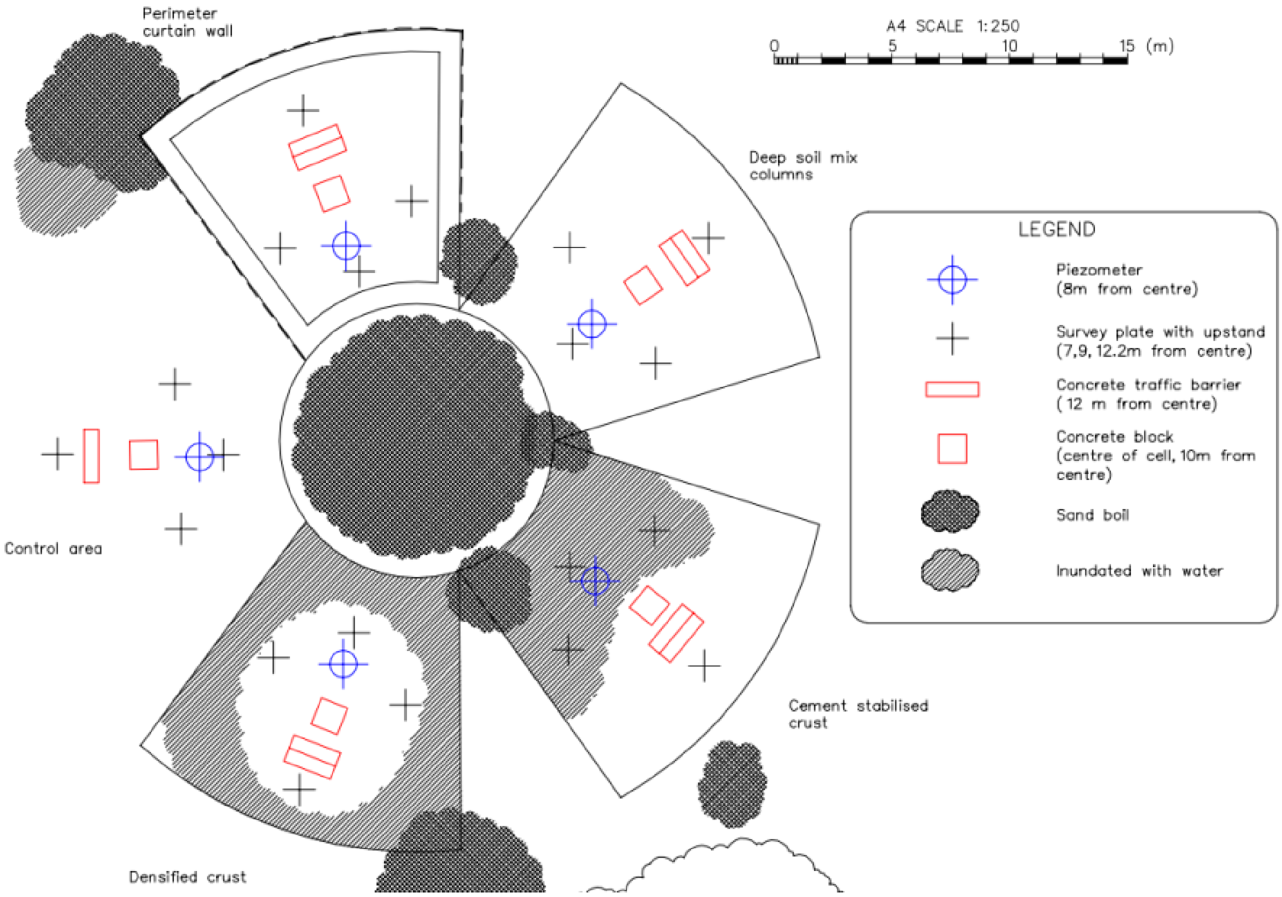

Figure 4: Ground improvement trial layout, showing extent of ground improvement zones, instrumentation layout and observations following the trial.

3.3 Trial Results

Observation of the test showed no significant ejection of material during the blast sequence. Several water spouts were observed some 10-15 seconds after completion of the blasting, with water reaching an estimated height of about 5 m. Sand boils formed in about 10 locations within and around the test area, mostly initiating near shot holes but also along the inside edge of the stabilised crust segment where the contractor had difficulty in maintaining a stable face. Expulsion of material continued for about 10 minutes after the blast. Ground cracking was observed along the inside edge of the perimeter curtain wall and deep soil mix column segments, although no sand boils formed in these areas.

The trial demonstrated that the use of explosive charges is an effective method for triggering liquefaction. Key conclusions regarding ground improvement performance include:

- The most effective and likely lowest cost method of ground improvement is to construct a high strength capping layer. A recompacted 2m crust provided a reduction of shaking induced settlements by over 50% relative to the control area under an equivalent ULS event but a larger improvement of over 80% was achieved by cement stabilisation of a 2m layer.
- The results indicate a relationship between increased strength of the surface crust and settlement of the underlying liquefied soil. This indicates this method might be effective regardless of the thickness of liquefiable soil.
- The use of deep soil mix columns was effective in reducing settlements by 50% but may have achieved higher results if the piles had extended deeper – the columns were 8m deep, liquefaction is estimated to have occurred over the upper 12m of the soil profile. The columns also ensured a uniform settlement of the site.
- The perimeter curtain wall was trialled as a method that could be applied around existing buildings. It was the least effective with a 30% average reduction. Again, the wall did not extend to the base of the liquefied layer.

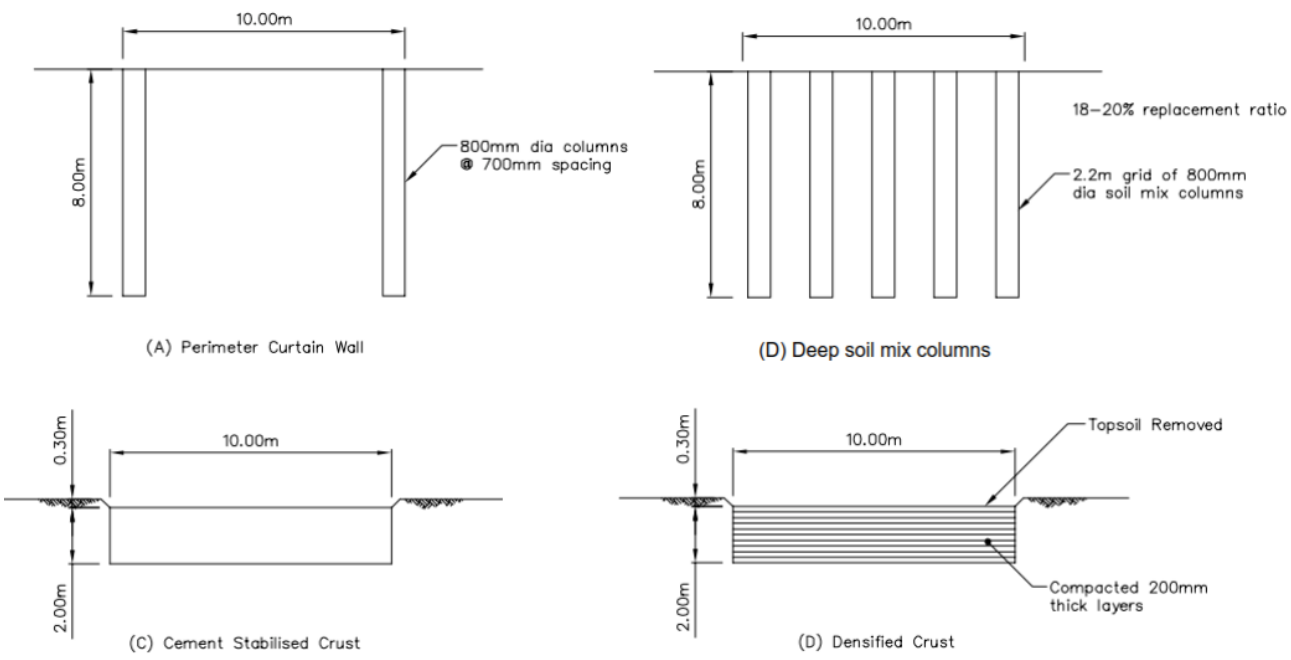

Figure 5: Ground improvement details used in the trial

4 FOUNDATION DESIGN FOR NEW STRUCTURES

A key lesson learned through the land damage observations and reinforced during the ground improvement testing was that the thickness and strength of the non-liquefiable crust layer is very important in assessing the response of a site to liquefaction. These lessons have been implemented in the foundation analysis and design carried out by the authors for six of the anchor projects that have been (or are soon to be) constructed in the Christchurch CBD.

Figure 6 provides an overview of the soil conditions and foundation solutions for six anchor projects. The following sections provide a brief description of each project.

4.1 Christchurch Justice and Emergency Services Precinct

The Justice and Emergency Services Precinct was designed as an Importance Level 4 structure. A cement stabilised soil platform was constructed where the existing soil was excavated, mixed with cement using a pug mill and then compacted back in place. The result was a 9m thick non-liquefiable crust layer where the upper 4m was very stiff and strong. A thick concrete raft foundation was constructed on top the cement stabilised platform. The cement stabilisation had the added benefit of encapsulating contaminated soil on site, avoiding costs associated with disposal of contaminated soil to a controlled landfill.

4.2 Tūranga – Christchurch Central Library

For the six storey Tūranga project the liquefaction hazard was confined to a loose to medium dense sand layer between 9 – 11m depth. Foundation modelling was carried out to determine whether the non-liquefiable crust comprising hardfill and a natural gravel layer was sufficient to resist the foundation loads. A 3D Plaxis analysis using post-liquefaction soil properties was undertaken to demonstrate an acceptable factor of safety against bearing failure, and that differential settlements were within the required limits.

4.3 Canterbury Multi Use Arena (proposed)

Foundation design is yet to be completed for the proposed Canterbury Multi Use Arena. The liquefaction hazard at the site is moderate to high, with liquefaction susceptible soil layers from 3 – 12m depth. For the business case phase of the project, the authors developed a ground improvement concept where liquefaction is mitigated down to a depth of 12m. Variation in soil conditions across the site means that a ground improvement method needs to be able to work across a variety of soil conditions, including gravel, sand, silt and silty sand.

4.4 Te Pae – The Christchurch Convention Centre

The Te Pae Christchurch Convention Centre is founded on a mixture of raft foundations and foundation beams. There was a layer of existing hardfill on site which was a mixture of historic fill, demolition fill and engineered hardfill. The concern was that this uncontrolled fill would result in unacceptable differential settlements, so the site was stripped to the required levels and inspected. Any unsuitable fill was removed and replaced with compacted hardfill. A high energy impact roller was then used across the site, with level surveys undertaken after every ten passes of the roller. After 50 passes the settlements recorded were less than 2mm across most of the site. Where settlements did not stabilise after 50 passes these areas were excavated and replaced with compacted hardfill.

After these works a 10m thick non-liquefiable crust was formed. Foundation analysis was carried out using Plaxis 3D with post-liquefaction soil properties in susceptible layers. The analysis was able to demonstrate an acceptable factor of safety against bearing failure, and that differential settlements were within the required limits.

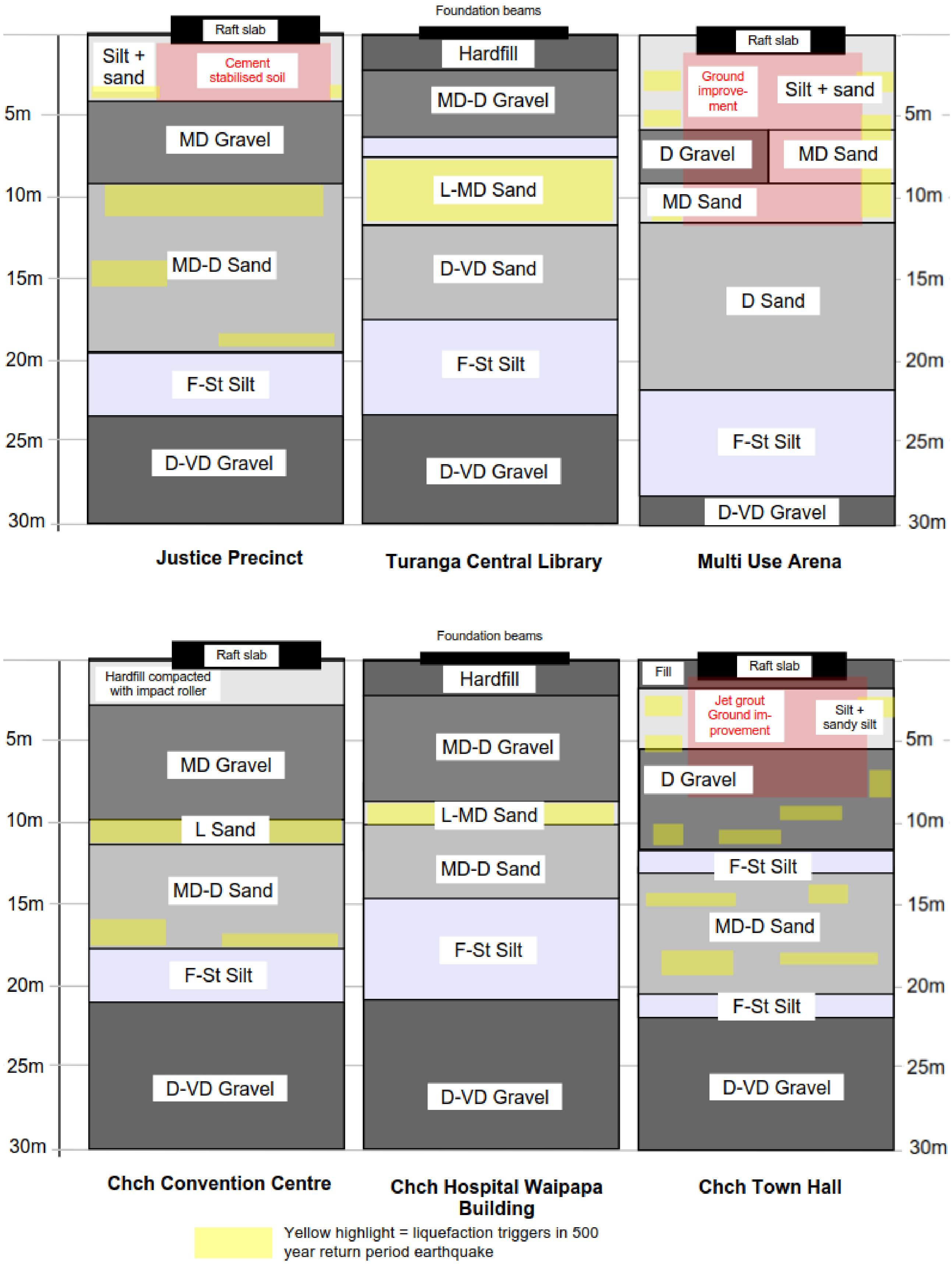

Figure 6: Foundation details, soil profiles and liquefaction hazard for six 'anchor' projects constructed after the Canterbury earthquakes.

4.5 Waipapa – Christchurch Hospital’s Acute Services Building

The ten storey Waipapa Building was designed as an Importance Level 4 structure. A thick concrete raft foundation was constructed on top of a 9m thick non-liquefiable crust layer. Foundation analysis was carried out to ensure the natural crust layer was sufficient to resist the foundation loads. The nearby Christchurch Women’s Hospital Building has a similar soil profile and raft foundation and performed well during the 2010-2011 Canterbury Earthquakes.

4.6 Christchurch Town Hall

The Christchurch Town Hall refurbishment included construction of a new concrete raft slab and jet grout ground improvement. The ground improvement was designed to mitigate against the liquefaction and lateral spreading hazard as the site is located next to the Avon River. Jet grout columns were constructed in interlocking secant walls, forming a lattice grid. Jet grout was chosen as the preferred method due to the need to inside the existing building. The liquefiable soil within the lattice grids is now constrained by the stiff walls, and thus unable to develop enough strain to trigger liquefaction.

5 CONCLUSIONS

The non-liquefied crust thickness was found to be a very important factor in the occurrence of liquefaction induced ground and foundation damage. This has been demonstrated through:

1. Land damage mapping and observation of foundation damage to houses following the 2010-2011 Canterbury earthquakes;
2. Observations of the foundation response of larger commercial buildings following the 2010-2011 Canterbury earthquakes;
3. Experiments where different foundation types were tested using blast induced liquefaction;
4. Foundation analysis and design of new public buildings in Christchurch designed and constructed post-earthquake.

For foundation design of new structures, these observations and case studies can demonstrate acceptable performance of a natural non-liquefiable crust (therefore reducing construction costs) or enable efficient design of ground improvement works to create an artificial non-liquefiable crust.

6 REFERENCES

Bowen, H. J. & Jacka, M. E. (2013) Liquefaction induced ground damage in the Canterbury earthquakes: predictions vs. reality. Proc. 19th NZGS Geotechnical Symposium. Ed. CY Chin, Queenstown

Ishihara, K., (1985). Stability of natural deposits during earthquakes, *Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, 12-16 August 1985

Youd, T. L., and Garris, C. T. (1995) Liquefaction-induced ground-surface disruption, *Journal of Geotechnical Engineering*, v. 121, n. 11, p. 805-809.

van Ballegooy, S., Lacrosse, V., Jacka, M. & Malan, P. (2013) LSN – a new methodology for characterising the effects of liquefaction in terms of relative land damage severity. Proc. 19th NZGS Geotechnical Symposium. Ed. CY Chin, Queenstown