Post Earthquake Recovery – Development of a Geotechnical Database for Christchurch Central City

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SUMMARY:
The moment magnitude (M_W) 6.2 Christchurch earthquake on 22 February 2011 caused extensive damage to the Canterbury region of New Zealand. Buildings and infrastructure were affected as a consequence of land deformation, including ground oscillation, liquefaction induced settlement and lateral spreading.

Subsurface geotechnical investigations were undertaken to assist with the preparation of the draft Central City Plan for the rebuild of the Christchurch Central Business District (CBD). A database of geotechnical information has been made publicly available to facilitate the development of preliminary ground improvement and foundation concept designs. The information acquired from these investigations has been used to assess the extent of the liquefaction hazard within the CBD in conjunction with the detailed land damage mapping undertaken after the earthquakes.

This paper describes the scope of investigation and findings drawn from the assessment of information.

Keywords: Geotechnical earthquake engineering, subsurface investigations, redevelopment planning

1. INTRODUCTION

The 22 February 2011 Christchurch Earthquake caused significant damage to buildings within the Christchurch Central City Business District (CBD). To assist with planning of the CBD and development of preliminary ground improvement and foundation concept designs, subsurface investigations were undertaken by engineers for the Christchurch City Council (CCC).

This paper describes the philosophy, results and lessons learnt during the geological subsurface investigations and a summary of the preliminary assessment of the ground conditions.

2. CANTERBURY EARTHQUAKE SEQUENCE

At the time of writing, the Canterbury earthquake sequence included significant events occurring on 04 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011.

On 04 September 2010, a M_W7.1 earthquake occurred near Darfield, approximately 40 km west of Christchurch CBD. This earthquake triggered liquefaction in some areas of Christchurch and parts of the CBD.

A M_W6.2 earthquake occurred near Lyttelton, approximately 7 km south east of the CBD on 22 February 2011. This earthquake caused widespread damage in central Christchurch, and liquefaction occurred throughout much of the CBD.

Two significant earthquakes, of $M_W5.6$ and $M_W6.0$ respectively, occurred in the Christchurch area on 13 June 2011. These earthquakes were centred near Sumner, approximately 10 km south-east of the CBD. These earthquakes caused further damage in Christchurch and localised areas outside the city.

Further seismic events of $M_W5.8$ and $M_W6.0$ occurred on 23 December 2011. These events also caused damage in Christchurch and surface manifestation of liquefaction in the eastern CBD.

3. PROJECT SCOPE

3.1. Purpose of Investigations

Geotechnical investigations were undertaken to provide a broad overview of the nature and variability of the ground conditions in the CBD. These were to aid the post-earthquake recovery and rebuilding process of the predominantly commercial and industrial areas of the central city.

The focus was to identify if any areas within the CBD had ground conditions that could limit the feasibility of rebuilding on the land and/or to highlight those locations where significant mitigation measures were likely to be required for different types of development.

A secondary purpose was to publish a high quality, publicly available post earthquake geotechnical database of the soil deposits and ground water levels. To ensure consistency of the data, the investigation rigs, drilling and strength testing methods were carefully assessed and completed over a relatively short period of time. This data compilation allowed the authors and their colleagues to better understand the extent and severity of the observed land damage resulting from the Canterbury Earthquake Sequence, and areas that may be subject to damage from future seismic events.

3.2. Project Area

The project area covers a distance of approximately 3km from west to east (Deans Avenue to Fitzgerald Avenue) and 2km north to south (Bealey Avenue to Moorhouse Avenue). The dominant features include Hagley Park and the meandering course of the Avon River. The CBD and adjacent commercial areas are relatively level, typically ranging in elevation of around 8 to 9m above Lyttelton Harbour datum (mean sea level) along the western side of Hagley Park, reducing to elevation 3m adjacent to the Avon River in the north-east corner of the CBD. The area covered by the ground investigations and assessment is shown in Figure 4.1.

The ground surface topography is typically flat or slopes very gently in a north easterly direction towards the Avon River. A former river terrace, which is generally approximately 100 and 200m from the existing channel, can be defined in some parts of the CDB. This terrace is typically around 0.5 to 1.0m high, although urbanisation has meant that its presence cannot be defined in many areas.

4. SUBSURFACE INVESTIGATIONS

The fieldwork component of the Christchurch City Council CBD investigation was largely completed between June and November 2011. Groundwater level monitoring is planned to continue for at least 12 months to assess seasonal variability.

The investigations comprised the following:

- 48 machine boreholes (referenced BH-CBD-01 to BH-CBD-48);
- 151 Cone Penetration Tests (CPTs) with measurement of pore water pressures (referenced CPT-CBD-01 to CPT-CBD-151);
- Multichannel Analysis of Surface Waves (MASW) geophysical testing; and,
- Laboratory tests including particle size distribution, fines content and water content have been

completed on selected samples to aid understanding of the nature of the deposits encountered across the CBD. More extensive laboratory testing was not possible due to demand for testing services at the time and the tight project deadlines.

The test locations are shown in Figure 4.1.

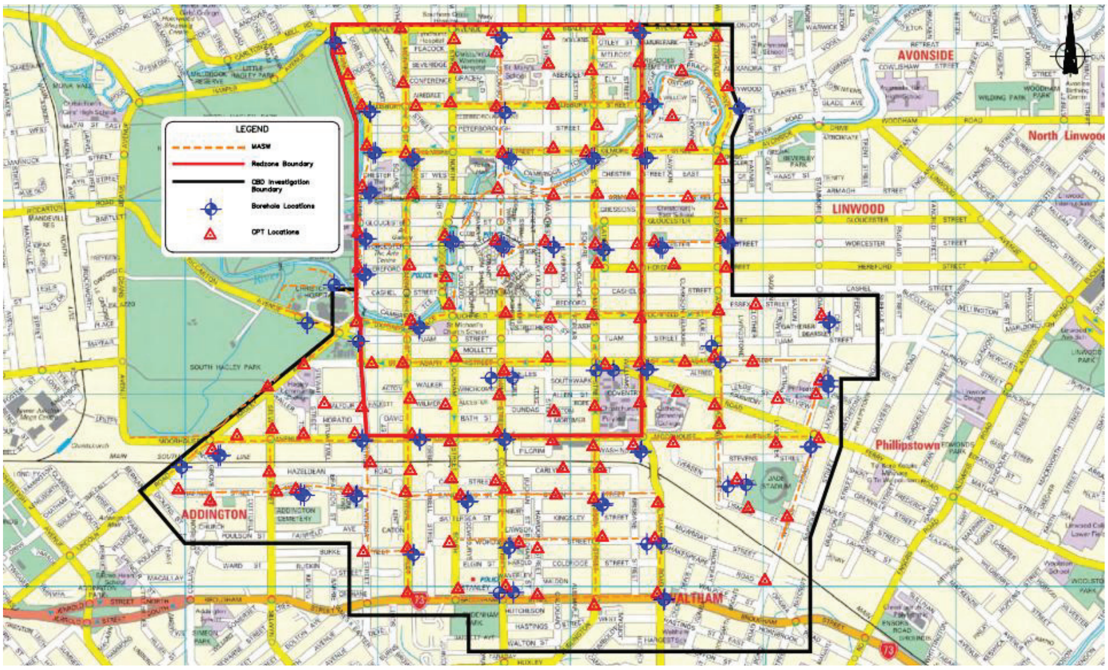

Figure 4.1. Investigation locations

Top-drive rotary or sonic vibration drilling methods were used extensively in the CBD. The boreholes were advanced to depths of up to 30m to prove the depth and nature of the upper zones of the Riccarton Gravels. Standard Penetration Tests (SPTs) were typically undertaken at 1.5m vertical intervals as the holes were advanced. Standpipes or data loggers were installed in each borehole to measure shallow groundwater levels. The recovered core was photographed and logged in accordance with the NZGS (2005) and selected samples taken for laboratory testing.

Predrilling was also undertaken at the location of CPT tests where shallow refusal resulted from the presence of gravel layers and the developing geological model suggested that significant deposits of potentially liquefiable loose sands and silts may exist at depth.

To provide a correlation of the interpreted soil types predicted by the empirical formula used in the processing of the CPT data, one CPT was positioned close to each of the 48 machine boreholes.

Geophysical surveying was undertaken to provide some ‘connectivity’ between the borehole and CPT investigation locations. This method was able to penetrate through shallow gravels that are present over extensive areas of the central city and allow rapid investigation of the nature of the underlying weaker, potentially-liquefiable deposits. The derived shear wave velocities provided a measure of the small-strain shear modulus of the soil. However, the limited spatial resolution afforded by this method meant that the information could not be reliably used to characterise the presence of specific stratigraphical units or the local variability (heterogeneity) of the sediments.

Cost advantages were realised due to the scale of the investigation project and minimisation of mobilisation and demobilisation costs. This work was also implemented under a single contract to enable better management of the additional health and safety issues during the ongoing period of enhanced seismic activity including control of site access and working in close proximity to unstable buildings.

4.1. Investigation Challenges

A number of challenges were encountered and had to be overcome during the field investigation phase. These included obtaining permissions for a large number of personnel from a wide range of companies to access the controlled cordon around the CBD (known as the "Red Zone"), develop appropriate evacuation protocols, and work around damaged buildings and active demolition works.

One of the most significant challenges faced during the investigation was the deconstruction of buildings and the presence of cordons around buildings considered dangerous. Investigation equipment access was limited in these locations resulting in reduced SPT frequency or relocation of the investigation point. Frequent communication with the authority that was in control of the "Red Zone" access, the Canterbury Earthquake Recovery Authority (CERA), allowed the location of hazardous buildings and demolition works to be confirmed immediately prior to relocating an investigation rig.

A protocol introduced by CERA was to work in pairs within the Red Zone; one staff member to control the site and one staff member to act as a "spotter" for the work site. This was to assist with rescue efforts in the event of a building collapse. This demanded additional resources at a time when the demand for geotechnical specialists was very high.

Following the 13 June 2011 event, evacuation protocols were put in place by CERA. An arbitrary $M_W5.0$ earthquake was used to trigger the Red Zone evacuation and enable reassessment of the areas safety to be completed. Issues involved with the evacuation included lost time, equipment down time and interruption to the investigation program.

Additional communication protocols were implemented by the project team following a loss of cell phone service during the 13 June 2011 event. Following this event, cell phone networks were overloaded and communications were unable to be immediately established between team members to determine their safety. Short wave radios were then used in the Red Zone to ensure a constant line of communication, with entry and exit notifications between project team members.

A number of subsurface drilling issues arose during the investigation, these ranged from equipment failure to unusually high artesian pressures from the Riccarton Aquifer. Sand heave on the retraction of the drill string prior undertaking to SPT investigations caused challenges for the drillers and also resulted in abnormally low SPT results.

5. ASSESSMENT OF SUBSURFACE CONDITIONS

5.1. Introduction

The published geology of the Christchurch area (Brown and Weeber, 1992, Brown et al. 1995), indicates that the CBD area is underlain by Holocene-age (<10,000 years old) well sorted gravels, fine sands and silts. These represent the deposition of post-glacial fluvial channel and overbank sediments from distributaries of the Waimakariri River, during the coastal progradation that took place after the present sea level became established around 6,500-6,000 years ago. Associated with these are the peat deposits that formed in swamps as a result of the elevated groundwater levels present. These sediments are collectively known as the Yaldhurst Member of the Springston Formation (spy).

The Yaldurst Member sediments are underlain by a succession of beach, estuarine, lagoonal, dune and coastal swamp deposits, which include sands, silts and clays, with shell and peat layers. These are collectively referred to as the Christchurch Formation (ch) and were deposited during the post-glacial marine transgression that advanced east to west from the present coastline between 9,000 and 6,500 years ago. Fluvial gravels, sands and silts were deposited during periodic incursions of the Waimakariri River during this marine transgression and occur interbedded with the marine-dominated sediments.

The Christchurch Formation sediments are underlain at depths in excess of 20m below ground level by well-graded gravels deposited during the last glacial period (14,000 to 70,000 years ago). These glacial outwash deposits are known as the Riccarton Gravels (rg) and represent the uppermost confined aquifer in the Christchurch area; often with artesian groundwater pressures. The Riccarton Gravels are typically a few metres to 20m thick and are underlain by swamp and associated deposits of the Bromley Formation (br). These are, in turn, underlain by a series of further glacial outwash gravel layers separated by lower energy deposits (sands, silts and clays interbedded with peats and shell beds), to bedrock at depths of up to 500m or greater.

5.2. Conceptual Ground Model

5.2.1. General

An interpretation of the geological conditions revealed by the investigations and existing geotechnical data has aided understanding of the geological and geomorphological evolution of the CBD. The findings of this assessment are summarised in a number of geological cross sections and plans indicating distribution of materials at different depths down to the Riccarton Gravels (see Figure 5.1).

A number of pertinent observations regarding the observed ground conditions are summarised in this section.

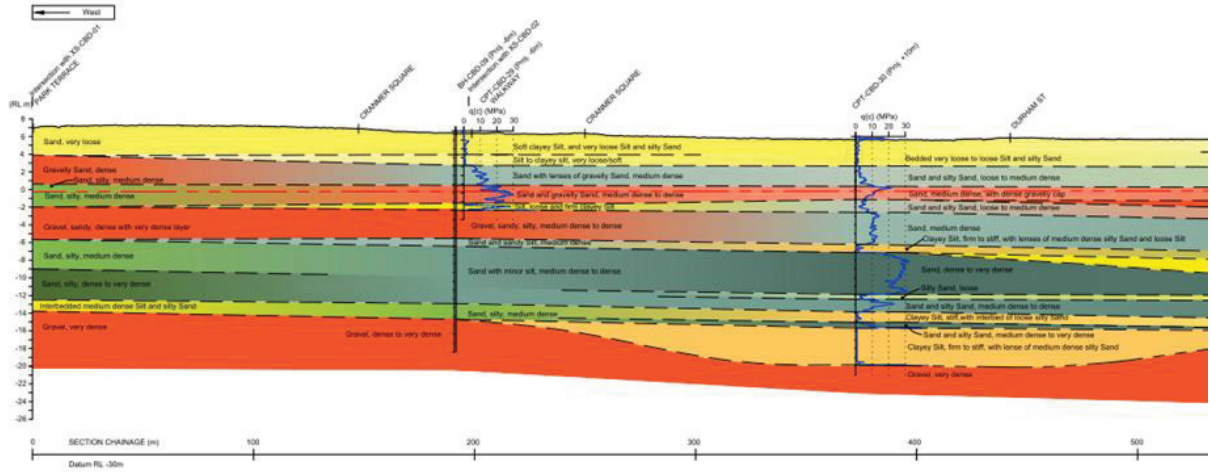

Figure 5.1. Example geological cross section *(drawing extract courtesy of Land Development and Exploration Ltd)*

In order to assess the consistency of the piezocone data obtained from the different subcontractors employed, a small-scale calibration exercise was completed. This involved the two rigs completing three test holes located within approximately 1m from each other.

The calibration exercise indicated that:

- The data obtained from the different contractors equipment is reasonably consistent; and,
- The ground conditions are highly variable even on a local scale as can be seen in Figure 5.2.

5.2.2. Buried and Infilled Channels

The MASW data provided a good indication of the location of buried and infilled channels in the CBD. An example of an infilled channel is shown in Figure 5.3. These may be natural channels infilled with flood gravels or possibly backfilled open channels, as identified on historic maps. Care is required during geotechnical investigations not to mistake such features with shallow gravels suitable for founding structures.

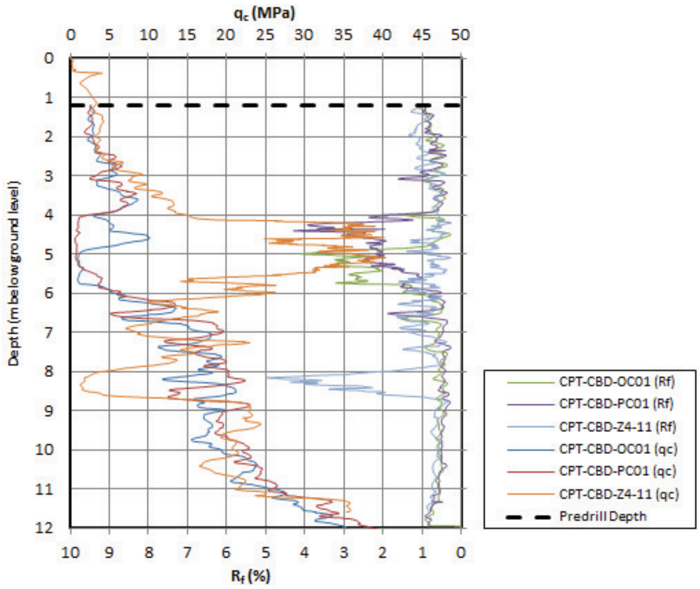

Figure 5.2. Piezocone calibration plots

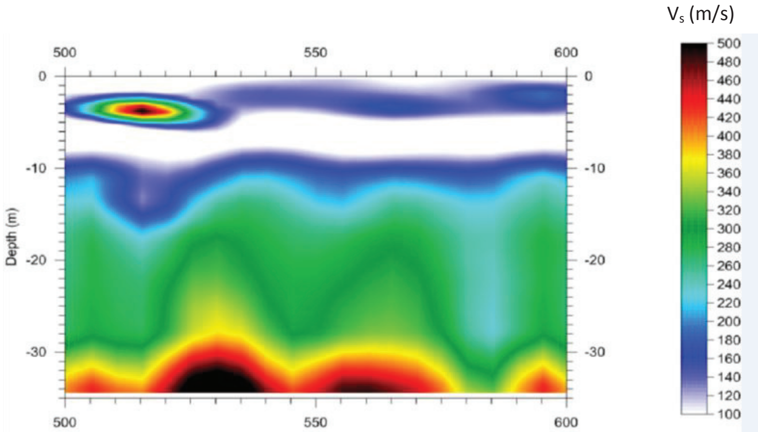

Figure 5.3: MASW data taken along Park Terrace indicating presence of an infilled channel

5.2.3. Riccarton Gravels

The investigations confirmed the approximate depth to the Riccarton Gravels across the central city increases from west to east (at 18 to 30m below ground level), but also the variability of this surface. It is important to note that the MASW data does not provide a clear indication of the surface profile of the Riccarton Gravels, as is shown in Figure 5.4. Reflection data filtered out of the MASW processing provides a better indication of the upper surface of the Riccarton Gravels.

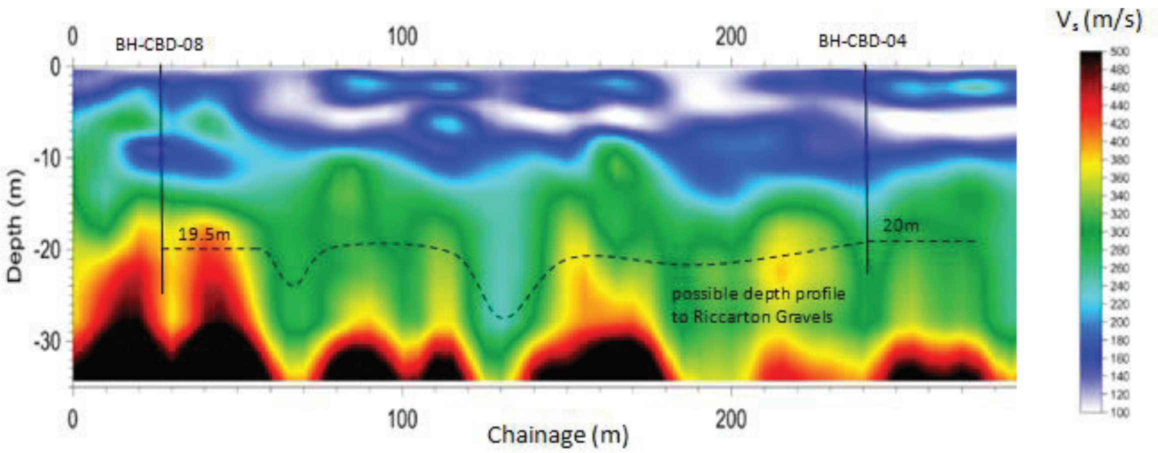

Figure 5.4: Depth to Riccarton Gravels indicated by machine boreholes and inferred from MASW

5.2.4. Groundwater Levels

There is reasonable variability in the depth to measured groundwater level across the central city, ranging from 0.2m below ground level to a maximum recorded depth of 3.7m. The average depth across the central city is around 1.9m below ground level; however, groundwater levels are being monitored to assess the seasonal variability throughout the CBD.

5.3. Lessons Learnt

The investigations undertaken to date have provided a useful overview of the geologic conditions underlying the CBD. However, these investigations have also identified that:

- Detailed site specific investigations are required that include a high density of investigation points both for design and subsequent construction control and monitoring;
- Great care is required when assessing the ground conditions encountered. Sound engineering judgement should be applied to any geotechnical analyses as variations to the assumed ground conditions can have a significant impact on unrealistically precise calculations.

6. LIQUEFACTION HAZARD

Detailed ground investigations aimed at identifying the local variability of the soil deposits, their geotechnical properties (i.e. plasticity, grading and density) and the local groundwater regime, help to refine the extent and severity of the liquefaction hazard. With appropriate data regarding the geotechnical properties of the soil and local groundwater conditions, liquefaction analyses can then be completed, taking account of the predicted ground motions, to further define the likelihood and severity of liquefaction that could occur under certain scenarios.

6.1. Land Damage Mapping

Shortly after each of the main earthquake events, detailed mapping of the extent and severity of land damage of the CBD was completed. This mapping was based largely on observed surface manifestation of liquefaction and included lateral spreading, the presence of ejected material (groundwater, sand and silt), ground cracking and general deformation of the ground surface. A simplified plan indicating the extent and level of the observed land damage reported following the 22 February 2011 event is presented as Figure 6.1.

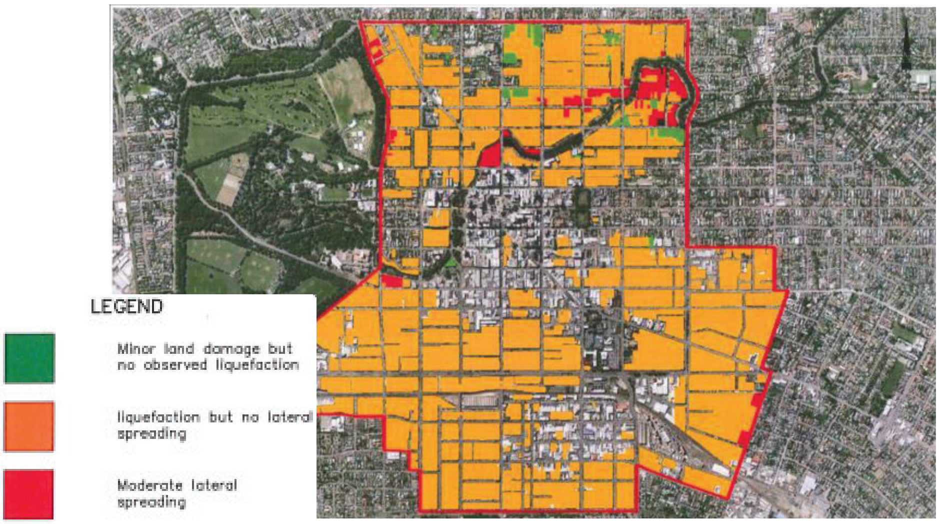

Figure 6.1. Simplified plan indicating observed land damage following the 22 February 2011 event

It is important to appreciate that the absence of sand boils or other ground disturbance does not mean that liquefaction has not occurred beneath the surface. The extensive coverage of land within the central city by large footprint buildings and thick pavements may have prevented significant formation of sand boils. Additionally, there are many locations within the central city where a relatively thick crust of non-liquefiable materials may have prevented surface expression of liquefaction.

6.2. Liquefaction Assessment

The data obtained from the piezocones spread across the CBD has been used to undertake preliminary liquefaction analyses. This has been completed for the following principal purposes:

- To permit a better understanding of the distribution and severity of the observed liquefaction-induced land damage across the CBD and commercial areas;
- To assess which areas may have been subject to liquefaction where little or no land damage has been observed;
- To provide an indication of the level of ground accelerations required to trigger liquefaction in the susceptible layers to highlight the potential extent of the liquefaction hazard across the central city from future seismic events;
- To provide some insights into the applicability of the liquefaction analyses methodology currently adopted as state-of-the-practice for such assessments for the soils encountered; and,
- To enable predictions of future land performance and extent of liquefaction to be 'calibrated' against field observations.

The liquefaction analyses have been carried out by the authors using the simplified method of Seed et al. (2003), with estimates of the potential ground deformations (settlement) based on the procedure presented by Ishihara & Yoshimine (1992).

6.2.1. Earthquake Scenarios

The triggering of liquefaction in susceptible materials is dependent upon the ground motions to which the soil is subjected. For the procedure used in this report, the ground motion is specified in terms of the amplitude (peak ground acceleration – PGA) and duration of the shaking, for which the moment magnitude (Mw) is adopted as a proxy.

For the purposes of comparing the results of the analyses with the observed liquefaction-induced land damage resulting from each of the major earthquakes, the analyses have been completed adopting the geometric mean of the of the highest recorded ground accelerations of the four strong motion stations located within the CBD. The analyses have been undertaken using the serviceability limit state (SLS) and ultimate limit state (ULS) peak ground level horizontal accelerations (PGA_H) recommended in NZS 1170.5 (2004) adopting the updated Zone factor (Z) issued by the Department of Building & Housing New Zealand (DBH, 19 May 2011). A summary of the six 'scenarios' considered are presented in Table 6.1.

A groundwater level of 1.2m below existing ground level was assumed for the analyses. This was a conservative assumption for some parts of the CBD as indicated by the ongoing groundwater monitoring.

Table 6.1. Summary of liquefaction analyses ground motion parameters

Scenario	Zone Factor (Z)	Return Period Factor (R_S / R_U)	Moment Magnitude (Mw)	Peak Ground Acceleration (g)[1,2]
(1) 1170.5 (2004) – ULS	0.22	1.02	7.5	0.25
(2) DBH Update – SLS	0.30	0.252	7.5	0.11
(3) DBH Update – ULS	0.30	1.02	7.5	0.34
(4) 22 February 2011	-	-	6.2	0.52
(5) 04 September 2010	-	-	7.1	0.25
(6) 13 June 2011	-	-	6.0	0.26

1. Assumes a Site subsoil class – D (deep or soft soil) for calculation of the spectral shape factor (Ch(0)).
2. Corresponding to an annual probability of exceedance of 1/25 for SLS and 1/500 for ULS.

6.2.2. Summary of Results

The analysis results indicate and confirm that a liquefaction hazard is present throughout the CDB. Such hazard is not limited to those locations where liquefaction-induced land damage has been observed. This observation is considered generally consistent with satellite based ground surface survey data (LiDAR data) which suggests settlement may have occurred in some areas where no land damage has been mapped at the ground surface.

In general, the severity of liquefaction assessed for the different scenarios are relatively comparable and the new Z factor of 0.30 paired with a Mw = 7.5, predicts marginally higher levels of liquefaction than the M_W6.2, 22 February 2011 event. Figure 6.2 illustrates the variation in liquefied thickness for the various scenarios for each piezocone that penetrated a minimum depth of 15m below ground level.

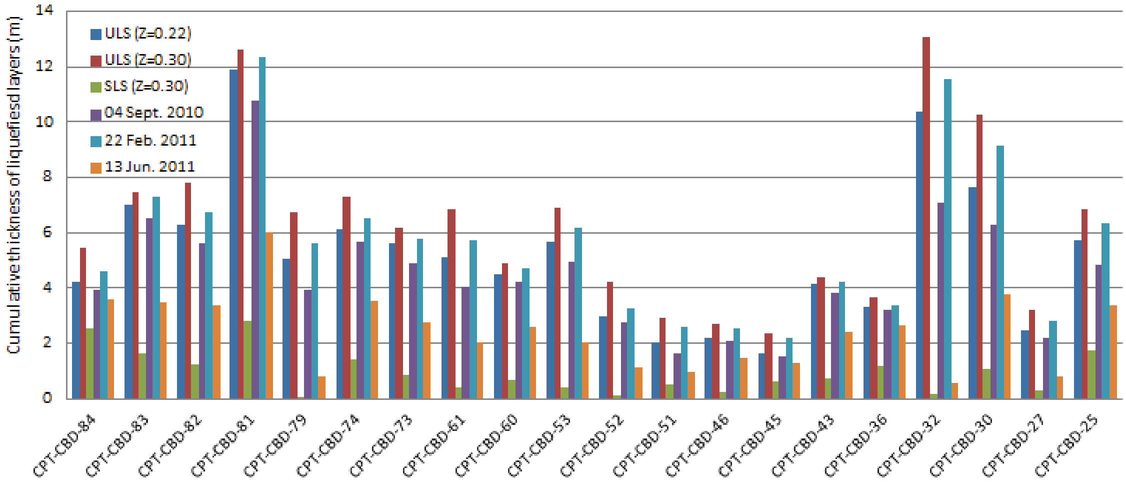

Figure 6.2. Estimate of liquefied layer thicknesses for different seismic events

The amount of liquefaction predicted from the 04 September 2010 earthquake is typically higher than that for the 13 June 2011 aftershock; yet the level of observed liquefaction within the CBD and adjoining areas was generally more widespread and severe for the 13 June 2011 event. It should be noted that the liquefaction analyses for the 13 June 2011 event takes no account of the M_w5.3 event that occurred just prior to the M_w6.0 event. The effects of the M_w6.0 event may have been heightened if the M_w5.3 event had caused elevated pore water pressures.

In general, the predicted liquefaction-induced ground settlements are greater than the ground deformations approximated by the LiDAR data within the CBD. This may be accounted for, in part, by the fact that the analyses have adopted the upper limit of PGAs recorded across the entire CBD, whereas the actual ground accelerations at specific locations may be at lower levels. However, a reduction in the ground acceleration does not account for the total difference in assessed and approximated settlements. More rigorous analyses of the data, taking better account of the grain size and shear wave velocity of the liquefiable layers, may reduce the differences observed.

Furthermore, detailed analyses are required to better understand these observations. The information collated for this study is likely to provide valuable data for future research efforts in this area. Locations where more precise actual settlement records are available may be useful for comparison with the predicted settlements and allow fine-tuning of the method to suit the Christchurch soils.

7. PRINCIPAL GEOTECHNICAL CONSIDERATIONS FOR FUTURE DEVELOPMENT

The investigations and assessment identified that the main geotechnical issues that will need to be addressed include:

- soft, highly compressible soils that may also be susceptible to cyclic softening;
- shallow and deep liquefiable materials;

- deep, very soft / weak soils, often overlying dense gravels with varying ground response characteristics to seismic loads;
- shallow gravels which may or may not be underlain by deeper liquefiable materials; and,
- Sites where liquefiable materials extend to considerable depth (up to 20m).

At some sites more than one of these ground conditions may exist.

8. CONCLUSIONS

The investigations undertaken in the Christchurch CBD have:

- Confirmed the lateral and vertical variability of the subsurface conditions, even on a very local scale, highlighting the need for detailed and comprehensive deep site-specific geotechnical investigations;
- Identified that considerable care is required when completing and interpreting the results of SPTs completed in saturated loose sands due to boiling at the base; and,
- Aided the design of site-specific investigations, particularly with respect to required minimum depth of investigations and presence of shallow gravels for limiting use of cone penetration testing without pre-drilling.

The preliminary liquefaction analyses have confirmed that:

- Areas where no evidence of significant land damage was observed may have been affected by liquefaction of deep layers beneath a competent crust and may be susceptible to liquefaction from future seismic events;
- Further work should be undertaken to refine analysis methods used in the assessment of the liquefaction potential and estimation of liquefaction induced settlement.

The work undertaken for the Christchurch City Council has also highlighted the benefits of establishing and developing a database of high quality geotechnical information accessible to geotechnical practitioners.

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