Christchurch Liquefaction Hazard Mapping

Brent Clough: BE (Hons) Civil, GIPENZ; NZ Geotechnical Society; ISSMGE

A liquefaction study of Christchurch City was undertaken for the Canterbury Regional Council (Environment Canterbury) to create a set of liquefaction hazard and ground damage maps based on actual soil strengths from pre-existing data. The study required research and data collection from records held at Environment Canterbury and various Christchurch City Council offices, as well as contractor/consultancy information to obtain borehole and CPT records. The key information such as soil type, strength and water table levels was entered into a liquefaction database specifically designed for the project. Calculation of the liquefaction hazard for Christchurch utilised the information contained and a program embedded within the database (using the method of Youd & Idriss(1), 2001). The project created liquefaction hazard and ground damage maps at compilation scales of 1:25,000.

INTRODUCTION

In recognition of the earthquake threat to Canterbury and specifically Christchurch, Canterbury Regional Council (Environment Canterbury) initiated a programme in 1996 to assess the risk posed by earthquakes, identify mitigation options, and implement measures to ensure that the level of risk in Christchurch is acceptable.

Earthquake induced liquefaction (where saturated soils lose their strength when shaken) is recognised as a significant potential hazard for many parts of Christchurch City. Liquefaction maps published previously have shown the hazard as a function of soil distribution across the City, but have not taken into account the strength of soils. This may have exaggerated the hazard (as some soils of liquefiable grain size may have been too dense to actually liquefy). This liquefaction study and mapping incorporates the recorded strengths of soils in Christchurch, as well as investigating sensitivity to earthquakes of various magnitudes and water table changes.

LIQUEFACTION OVERVIEW

Liquefaction is the process in which loose saturated soils lose strength when cyclically loaded by earthquake vibrations. This causes soils to temporarily behave in a fluid like manner, similar to a "quick-sand". Susceptibility to liquefaction requires certain criteria to be met before liquefaction can occur. Such conditions lead to liquefaction occurring more frequently in recently (Holocene) deposited saturated sand and silty sand soils. Such deposits are often found near rivers and in coastal areas such as deposits found in the central and eastern side of Christchurch.

CHRISTCHURCH AND ITS GEOLOGY

Christchurch city is located on sandy Holocene deposits along the coastal margin, alluvial outwash gravels to the west, and on the northern slopes of the adjacent loess covered volcanic Port Hills of Banks Peninsula.

Originally the site of Christchurch was a mixture of: swamp lying behind beach dune sand; estuaries and lagoons; and gravel; sand; and silt from the river channel and coastal floodplain of the Waimakariri River. The Avon and Heathcote rivers meander through the city to form the main drainage system. These rivers form an estuary beside the coast where longitudinal movement of the dune sand enclose the estuary. The remnants of the older beach dune sands occur up to 6km inland from the coast.

Christchurch has developed as a service centre for agriculture, horticulture, orchading, and market gardening on the fertile soil of the Canterbury Plains. Groundwater in the gravel aquifers underlying the northern Canterbury Plains provides a plentiful supply of high quality water for domestic, industrial, livestock and irrigation requirements.

Christchurch is adjacent to the tectonically active Alpine Fault region of New Zealand. Consequently, the geology and tectonic setting of the area indicate that future large earthquakes may have a major impact on the city, especially in terms of liquefaction.

STUDY METHODOLOGY

The liquefaction study undertaken has included:

- Research of consent records at Environment Canterbury which may have included soil information (e.g. borelogs), other than that already contained in Environment Canterbury's Well Database(2) (which does not include any soil strength data).
- Research of property files and other general records at Christchurch City Council for soil information (this primarily resulted in shallow borelogs that were required for building consent applications).
- Scanning of paper borelog records to create a digital record of all soil information encountered during the study.
- Research into soil information held by contractors and consultants, and obtaining their borehole and CPT records where this information is obtainable (many instances existed where the information was not made available due to legal reasons).
- Analysis of historical water table information of bores monitored by Environment Canterbury and the Christchurch City Council to determine typical levels.

- Investigations into the level of seismicity of the city and the creation of typical earthquake scenarios.
- Creation of a liquefaction database to store key liquefaction information (such as soil type, soil strength and water table levels).
- Transfer of the key information (such as soil type, soil strength and water table levels) into the liquefaction database.
- Calculation of the liquefaction hazard based on the information contained within the database, via an automated programme embedded in the database.
- The creation of Liquefaction Hazard Maps and Ground Damage Maps (both using two different ground water elevation scenarios), compiled at scales of 1:25,000.

No fieldwork was undertaken to confirm or otherwise the soil and water table information used in the liquefaction hazard assessment.

LIQUEFACTION PREDICTION FORMULAE

The sensitivity of a soil to liquefaction could have been established by either using multiple prediction procedures to estimate liquefaction, or to vary the earthquake parameters used in analysis. In this study the earthquake parameters were varied to establish a soil's sensitivity to liquefaction. The prediction method employed is based on the Simplified Seed procedure (Youd & Idriss[1], 2001), which is a widely used method.

In this method, the onset of liquefaction occurs when the Cyclic Stress Ration (CSR) exceeds the Cyclic Resistance Ratio (CRR). The simplified approach is defined as follows (more information on this procedure can be found in Youd & Idriss[1], 2001):

$$CSR = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma_{vo}'}\right)r_d$$

where:

$a_{\max}$ = maximum horizontal acceleration at the ground surface

g = acceleration due to gravity (9.81 m/s²)

σ_{vo} = total vertical overburden stress

σ_{vo}' = effective vertical overburden stress

r_d = stress reduction coefficient

and

$$\text{CRR} = \left[\frac{1}{34-(N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{[10.(N_1)_{60}+45]^2} - \frac{1}{200}\right]MSF$$

where:

$(N_1)_{60}$ = corrected N-value

MSF = magnitude scaling factor

DESIGN EARTHQUAKES

An Alpine fault, foothills fault and a local earthquake event type scenario were initially considered for the liquefaction analyses. The smaller local earthquake may not have sufficient strong ground motion cycles (e.g. 5 cycles) to cause liquefaction and therefore has not been adopted. The foothills earthquake scenario was considered, but was not chosen due to the return interval being around 2,000 years compared to the Alpine earthquake having a return period of around 300 to 500 years.

Three different ground accelerations, with peak ground accelerations of 0.12g, 0.20g and 0.34g for the Alpine event, have been used to obtain a sensitivity analysis for soil liquefaction. These represent return period events on the Alpine faultline of 50, 150 and 475 years respectively (NZS4203[3]). By choosing different levels of shaking, the trigger points for liquefaction can be determined. For example, where a soil liquefies due to a relatively low level of earthquake shaking, the liquefaction hazard is High, as the soil has a low resistance to liquefaction. Likewise, if a soil liquefies at a threshold of 0.34g shaking and not the lesser value of 0.12g or 0.20g, then the soil has some resistance to liquefaction and is classified as "Low Susceptibility".

A detailed discussion of the earthquake parameters used in this study is included in the Christchurch Liquefaction Study Report[4].

SOIL DENSITIES

Soil densities will vary from site to site across Christchurch, with depth at each site and also as different soil types are encountered, such as peat, clay, silt, sand, or gravel. Furthermore, one sand deposit may have a different density to an adjacent sand deposit, likewise for other soil types. As no laboratory tests are available in the database to define the actual soil densities, only predictions of the densities can be made (usually based on soil strength). To simplify the prediction process, densities of $1.8 t/m^3$ have been used for saturated soils, and $1.65 t/m^3$ for dry soils in the database (non-liquefiable soils are less likely to have densities of this order). The densities used are typical for many of the liquefiable sands within Christchurch.

This generalisation may potentially over or underestimate the confining stress of soil layers and therefore the liquefaction hazard for a site may be misrepresented. However, the difference between actual and estimated overburden pressure is likely to be small and therefore the estimation has a small effect on the prediction process. More complex estimation of the soil density could be undertaken based on the soil type and strength, but this is considered unwarranted for the compilation scale of the maps (1:25,000).

WATER TABLE LEVELS

The water table level affects the confining stresses of soils and, more importantly, any soil that lies above the water table would not liquefy (although may still be able to be densified during an earthquake). Water table levels have been provided with some of the borelogs collected for the database, but not all of them.

Water table levels in Christchurch will vary throughout the year and from year to year depending on ground water balance. Therefore, any reported water table levels might not be typical. To account for this and to provide information for records without water table depth information, all of the borelogs and CPT records were assigned a water level by the same process for the purposes of liquefaction prediction.

To demonstrate the effect of ground water variations, two different ground water level scenarios were analysed as described below.

The first ground water level scenario used as the basis of assigning water levels was based on the map provided in The Geology of the Christchurch Urban Area - Brown and Weeber[5], 1992. The map provided by Brown and Weeber shows the contours lines for the depth below ground surface of the water table. The contour lines generally run north south, with the Port Hills forming a boundary to the south. To the east of Linwood the ground water level is within 1m of the ground surface (due in part to the Avon-Heathcote Estuary and the Avon River). In the analyses it has been assumed that the area between the 1 and 2m contour has a ground water level of 1m, to provide a conservative approach (the same approach has also been used between the other contours, and the area east of Linwood has been assigned a water level equal to the ground level). This water level scenario is assumed to represent a high probable water level.

The second ground water table scenario used the average ground water levels calculated using actual data from Environment Canterbury's Wells Database[2]. The Well Database information was processed by looking at records from the last ten years and from wells with a maximum depth less than 30m (to focus on groundwater levels in the upper unconfined aquifer only). The dataset was also processed to include average data from January only (in order to provide a less conservative approach than the brown and Weeber scenario discussed above). The average (10 year) reduced level water table was then plotted for each well to check for ground water trends that may have be affected by pumping.

The map produced is in general similar to the Brown and Weeber map (with a shallow water table in the east of the city and deeper contours heading west), however the contours were more detailed. Typically the ground water levels are lower than those presented by Brown and Webber.

The water tables used for each of the boreholes and CPT's in the database where determined by interpolation between the contours, rather than the assigning integer water levels (as undertaken with the Brown and Weeber water table scenario).

LIQUEFACTION HAZARD MAP

Following the prediction procedure outlined above, a liquefaction hazard map was produced for Christchurch for both ground water level scenarios. A copy of the resulting map for the lower ground water scenario is shown in Figure 1. The compilation scale of the map was 1:25,000.

The potential for liquefaction is shown on the Liquefaction Hazard Map for Christchurch and this potential has been divided into eight classes:

1. **High Liquefaction Potential** (solid red areas)**:** Areas in which earthquake peak ground accelerations of greater than 0.12g, but less than 0.2g, for a magnitude 8 Alpine fault earthquake, potentially cause some of the soils to liquefy (Scenario 1). Note also that some other soils at the same location may not liquefy or could have a lesser susceptibility to liquefaction.

2. **Moderate Liquefaction Potential** (solid orange areas)**:** Areas in which the earthquake peak ground accelerations of greater than 0.20g, but less than 0.34g, for a magnitude 8 Alpine fault earthquake, potentially cause some of the soils to liquefy (Scenario 2). Note also that some other soils at the same location may not liquefy or could have a lesser susceptibility to liquefaction.

3. **Low Liquefaction Potential** (solid yellow areas)**:** Areas in which only the highest earthquake peak ground acceleration of 0.34g, for a magnitude 8 Alpine fault earthquake, potentially cause some of the soils to liquefy (Scenario 3). Note also that some other soils at the same location may not liquefy or could have a lesser susceptibility to liquefaction.

4. **Liquefaction Not Predicted** (white areas within the city boundary): Areas in which an earthquake ground acceleration of 0.34g failed to predict liquefaction. However, it should be noted that due to the limited spatial extent of soil information in the database, these areas might contain liquefiable soils or could be subject to other forms of instability, for example, ground fissuring.

5. **Insufficient Information Available, but may have High Liquefaction Potential** (red hatched area)**:** No information is available in the database to analyse the liquefaction potential. However, these regions may have areas where High Liquefaction Potential may occur as outlined in point 1. Subjective assessment based on the Brown and Weeber[5] geological map.

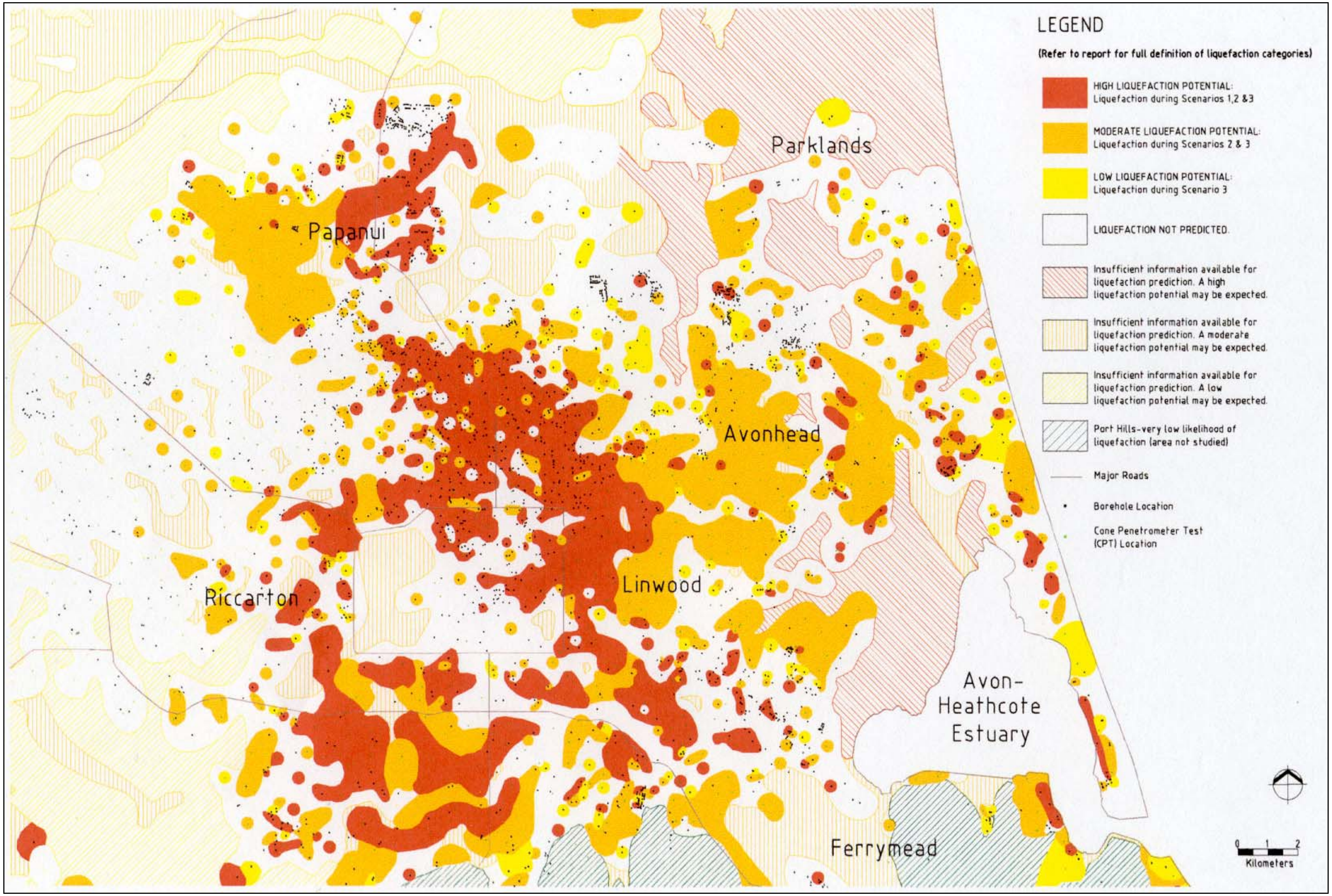

Figure 1: Liquefaction Hazard Map for Christchurch City based on the average January ground water levels over the last 10 years.

6. **Insufficient Information Available, but may have Moderate Liquefaction Potential** (orange hatched area)**:** No information is available in the database to analyse the liquefaction potential. However, these regions may have areas where Moderate Liquefaction Potential may occur as outlined in 2 above. Subjective assessment based on the Brown & Weeber[5] geological map.

7. **Insufficient Information Available, but may have Low Liquefaction Potential** (yellow hatched area)**:** No information is available in the database to analyse the liquefaction potential. However, these regions may have areas where Low Liquefaction Potential may occur as outlined in 3 above. Subjective assessment based on the Brown & Weeber[5] geological map.

8. **Port Hills – Very Low Likelihood of Liquefaction** (green hatched area): Areas not studied. However, it should be noted that these areas might contain small areas of liquefiable soils or could be subject to other forms of instability, for example, slope failure.

Notwithstanding the above determinations, different soil layers at a site may have different susceptibilities to liquefaction. The liquefaction algorithm assigns the liquefaction hazard for a site based on the weakest liquefiable soil. Hence the variability within a soil column is not presented on the Liquefaction Hazard Map.

Reporting of the liquefaction ground settlement, where the cumulative settlement within a soil column is calculated, provides an indication of the severity of liquefaction. (The settlement has been calculated for 200 of the data locations within the database (100 boreholes and 100 CPT's) and separate Liquefaction Ground Damage Maps for Christchurch for the two water table scenarios have been produced. These maps can be found in the Christchurch Liquefaction Study Report[4].)

The Liquefaction Hazard Maps generated (one for each of the ground water scenarios) are similar in distribution of liquefiable deposits to the existing liquefaction hazard maps previously presented by CAE[6] (1997) and Brown and Weeber[5] (1992), in fact it predicts wider spread liquefaction on the eastern side of Christchurch. However, these new maps provide more definition to the extent and severity of the hazard.

In total, liquefaction susceptibility (hazard) was calculated at 2,194 boreholes and 885 CPT's in the study area. This is compiled from a database, which contains approximately 3,700 borehole sites that have been manually entered (with and without strength data), nearly 1,100 CPT locations (all with strength data), and around 4,700 records entered from Christchurch City Council (CCC) Microsoft Excel files (without soil strength data).

One of the main reasons for hazards not being calculated for every database entry was that there was no strength information to match to soil layers, hence calculations could not be undertaken (estimates could be made in the future, but this would be best undertaken on a manual basis). Coordinates for 1,305 sites could not be matched to the addresses supplied with the original data.

DIFFERENCES IN HAZARD MAPS FROM VARYING THE WATER TABLE

There is considerable difference between the liquefaction hazard maps produced using the two water table scenarios described above (Brown and Weeber[4] water table levels, and the water levels obtained from Environment Canterbury's database[2]). The main difference is that there has been a general and widespread lowering of the hazard for the City when using the water well database due to the generally lower ground water levels. Many locations described as high hazard using the Brown and Weeber map have lesser hazards when using the database water levels.

Furthermore, many areas described as moderate or low hazard on the hazard map based on the Brown and Weeber water levels are not predicting a liquefaction hazard for the database water levels. Notwithstanding this, the pattern of liquefaction hazard being greatest on the eastern side of Christchurch has remained unchanged.

The lower water table resulted in a change of liquefaction susceptibility due to the:

- soils that may have been liquefiable in the zone through which the water table has been lowered are no longer liquefiable and therefore this will reduce the hazard (note however that these soils may still densify in a dry state), or

- lowering of the water table increases the overburden confinement pressures and therefore increases a soils resistance to liquefaction.

CONCLUSION

The Christchurch Liquefaction Study has utilised existing data from the Christchurch City Council, Canterbury Regional Council, and several private organisations to produce Liquefaction Hazard and Ground Damage maps for the City of Christchurch. The soil type, strength and water table data collected for each site has been entered into a specially prepared database and then analysed, using an embedded program (using the Youd and Idriss[1] method) within the database to provide a hazard coefficient for each site. These hazard coefficients have been used to form the basis of the Liquefaction Hazard maps.

The study has used the Alpine fault for its design earthquake. The magnitude of this earthquake has been varied to investigate the sensitivity of the various sites within the database to ground shaking.

As no laboratory tests are available for the majority of sites within the database, assumed soil densities of $1.8t/m^3$ for saturated soils and $1.65t/m^3$ for dry soils have been used for the analysis. For simplicity, these densities have been applied to the entire city. They are typical for many of the liquefiable sands within Christchurch.

The water table levels for Christchurch vary across the city and throughout the year. To investigate the city's sensitivity to water table variation, two water table scenarios were analysed. The first ground water level scenario used was based on the map published in The Geology of the Christchurch Urban Area - Brown and Weeber(5), 1992. This approach is considered conservative.

The second water level scenario is based on actual water level records from bores monitored throughout the city by Environment Canterbury and the Christchurch City Council over the last 10 years. This provided a less conservative approach than scenario 1 above.

An example of the Liquefaction Hazard maps produced is shown in Figure 1. Eight different zones are defined, which show various hazard levels for the city.

There is a considerable difference between the liquefaction hazard maps produced using the two water table scenarios. The main difference is a general lowering of the liquefaction hazard due to the lowering of the water table (from scenario 1 to scenario 2).

ACKNOWLEDGEMENTS

The author would like to acknowledge Environment Canterbury for engaging Beca to complete the Christchurch Liquefaction Study, providing assistance throughout the study and for allowing the work to be published.

Special thanks also goes to Christchurch City Council, for their extensive assistance during the research stage of the project, providing unlimited access to their records, and geocoding assistance to determine borehole locations, and the various other organisations that provided data during the project.

Finally, the author wishes to thank Steven Christensen for his guidance and support throughout the project and the preparation of this paper.

REFERENCES

1. Youd, T. L. and I. M. Idriss (2001) "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils", Jr. Geotech. & Geoenviron. Eng., April 2001, pp 297-313.
2. Environment Canterbury Well Database, February 2001.
3. NZS 4203:1992, "Code of Practice for General Structural Design and Design Loadings for Buildings".
4. Beca Carter Hollings & Ferner Ltd (2002), " Christchurch Liquefaction Study – Stage IV", prepared for Environment Canterbury, ECan Report # U02/80, Beca Job # 3812464.
5. Brown LJ and JH Weeber (1992), "Geology of the Christchurch Urban Area", IGNS, Scale 1:25,000.
6. Centre for Advanced Engineering CAE (1997), "Risk & Realities A Multi-disciplinary Approach to the Vulnerability of Lifelines to Natural Hazards based on the Work of the Christchurch Engineering Lifelines Group", November 1997, University of Canterbury, Christchurch.