Regional Liquefaction Study for Waimakariri District

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ABSTRACT: A study has been undertaken to provide a better understanding of the liquefaction potential of the eastern side of the Waimakariri District in Canterbury, an area of historical liquefaction. Field investigations, including 26 boreholes, were used to supplement existing regional data. Two different earthquake scenarios (a nearby Foothills Earthquake and a more distant Alpine Fault Earthquake) were used to model the susceptibility to liquefaction. Using these two earthquake scenarios, liquefaction susceptibility was predicted using three different liquefaction models. It was found that the eastern side of the Study Region, which contains deep dune sand deposits, has a high susceptibility to liquefaction. This high susceptibility extends out to the western boundary of the Study Region in three locations and into the heart of the largest town in the Study Region, Kaiapoi. Level ground liquefaction settlements were also predicted for both earthquake scenarios. The extent of areas classified as having a high susceptibility to liquefaction is not significantly different to those in the eastern side of Christchurch and some other geologically young coastal areas around New Zealand.

1 INTRODUCTION

Summarised herein are the results of an investigation undertaken to evaluate the liquefaction susceptibility for the eastern side of the Waimakariri District (refer to Figure 1 for the extent of the Study Region). The investigation included a desk top study of existing soils information, reviewing evidence of historical liquefaction, physical field investigations, analysis of data, and presentation of the analysis in the form of a liquefaction susceptibility map. It is noted that the study is based on a relatively limited level of investigation aimed at providing a general view of liquefaction potential; the large distance between boreholes are such that site specific conclusions can not be drawn. This Project does not provide a definitive geotechnical study for individual parcels of land; however it does identify where the highest risk areas are likely to be.

2 STUDY OBJECTIVES

Part of the purpose of this investigation is to assist the Waimakariri District Council and Environment Canterbury (formerly Canterbury Regional Council, CRC) to fulfil statutory functions and duties. The two Councils have respective functions under the Resource Management Act 1991 (RMA) s31(b) and s30(1)(c) to collect information on natural hazards and to develop objectives and policies for hazard avoidance and mitigation. The District Council also has duties under RMA s106 when considering applications for subdivision consent, not to grant consent if it considers that the land is likely to be subject to damage by land movement. The District Council has additional requirements in terms of the Building Act 1991 s31(2) to provide any information it knows about potential land movement or inundation that may affect any building work. The Local Government Official Information and Meetings Act 1987, s44(a) also requires the District Council to provide information it knows that identifies land subject to movement or inundation.

Therefore, the objective of the study was to: provide better definition of areas susceptible to liquefaction; define two or three probable and realistic earthquake scenarios likely to cause liquefaction; provide information on soils; and to collate evidence to enable the district and regional councils to discharge their statutory obligations. A major benefit of the study is that the need for detailed site investigations has been defined. Furthermore, quality information is now available for ratepayers through Resource and Building Consents (PIMs and LIMs), and the council's have information for planning, emergency management, environmental and monitoring and education/advice.

3 HISTORICAL EVIDENCE OF LIQUEFACTION

The University of Canterbury has investigated liquefaction during the 1901 Cheviot Earthquake and especially its effects in Kaiapoi. The results of this work have been published as a university research report (Berrill et. al., March 1994) and in a NZSEE Bulletin (Berrill et. al., September 1994). In summary, the 1901 Cheviot Earthquake, which had a Richter Magnitude 6.9 ± 0.2, caused sand boils and other liquefaction effects at Kaiapoi at a distance of at least 90km from the epicentre of the earthquake. "From newspaper reports, it is clear that liquefaction occurred over an area of about two or three town blocks at the eastern end of Sewell and Charles Streets on the north bank of the Kaiapoi River ..." (Berrill et. al., September 1994). In addition to these occurrences, minor occurrences of liquefaction at Waikuku and Leithfield beaches in the 1922 Motunau Earthquake are reported by Sterling et. al. (1999). Figure 2 shows the locations of reported historical liquefaction within the Study Region.

4 DEFINITION OF THE STUDY REGION

The northern and southern edges of the Study Region are bounded by the limits of Waimakariri District and the eastern extent by the coastline of Pegasus Bay. The western boundary is defined by the maximum inland extent of post-glacial marine transgression, some 6,500 to 6,000 years before present (refer to Figure 2 for the Study Region boundaries).

Soils are susceptible to liquefaction when they are recently deposited (within the Holocene Epoch, i.e. up to 10,000 years old). Radiocarbon tests within the Study Region indicate that deposits of around 7,000 years before present are located at depths of 9 to 15 m below ground level (Brown, 1973). Therefore, an investigation depth of 15 m has been used. Note that the western boundary does not delineate any transgressions of either the Waimakariri or Ashley Rivers. Therefore, it is probable that the Study Region will not cover all liquefaction possibilities within the Waimakariri District.

5 EXISTING SOILS INFORMATION

5.1 *Geological Maps*

The eastern extent of the Canterbury Plains in the vicinity of the Waimakariri District consists of outwash alluvial deposits comprising gravel, sand, silt, clay and peat. The coastal margin of the district is bounded with sand dune and inter-dune deposits. Brown and Weeber (1992) state: "Coastal outbuilding or progradation began after the present sea level became established about 6,500 – 6,000 years ago". From Brown (1973) the following is ascertained for the Study Region:

- Christchurch Formation inter-dune, semi-fixed dunes, and coastal swamp/lagoon deposits comprise the surficial deposits of the eastern side.
- Springston Formation silt, sand, and gravels dominate the surficial deposits of the western side.
- Radiocarbon tests that indicate that soils around 7,000 years old exist to depths of around 9 to 15m below the present ground surface.

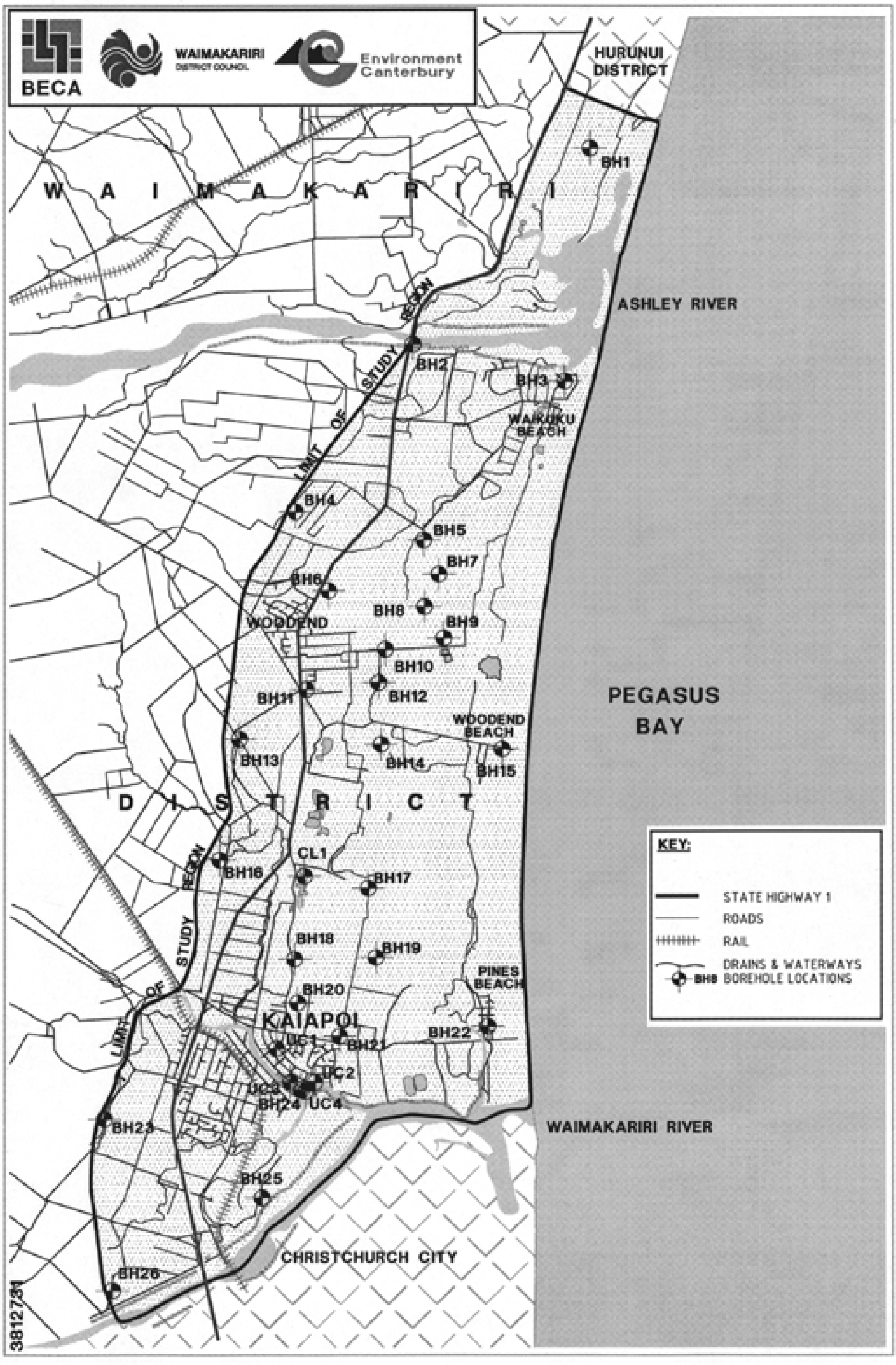

Figure 1. Study Region and location of study boreholes.

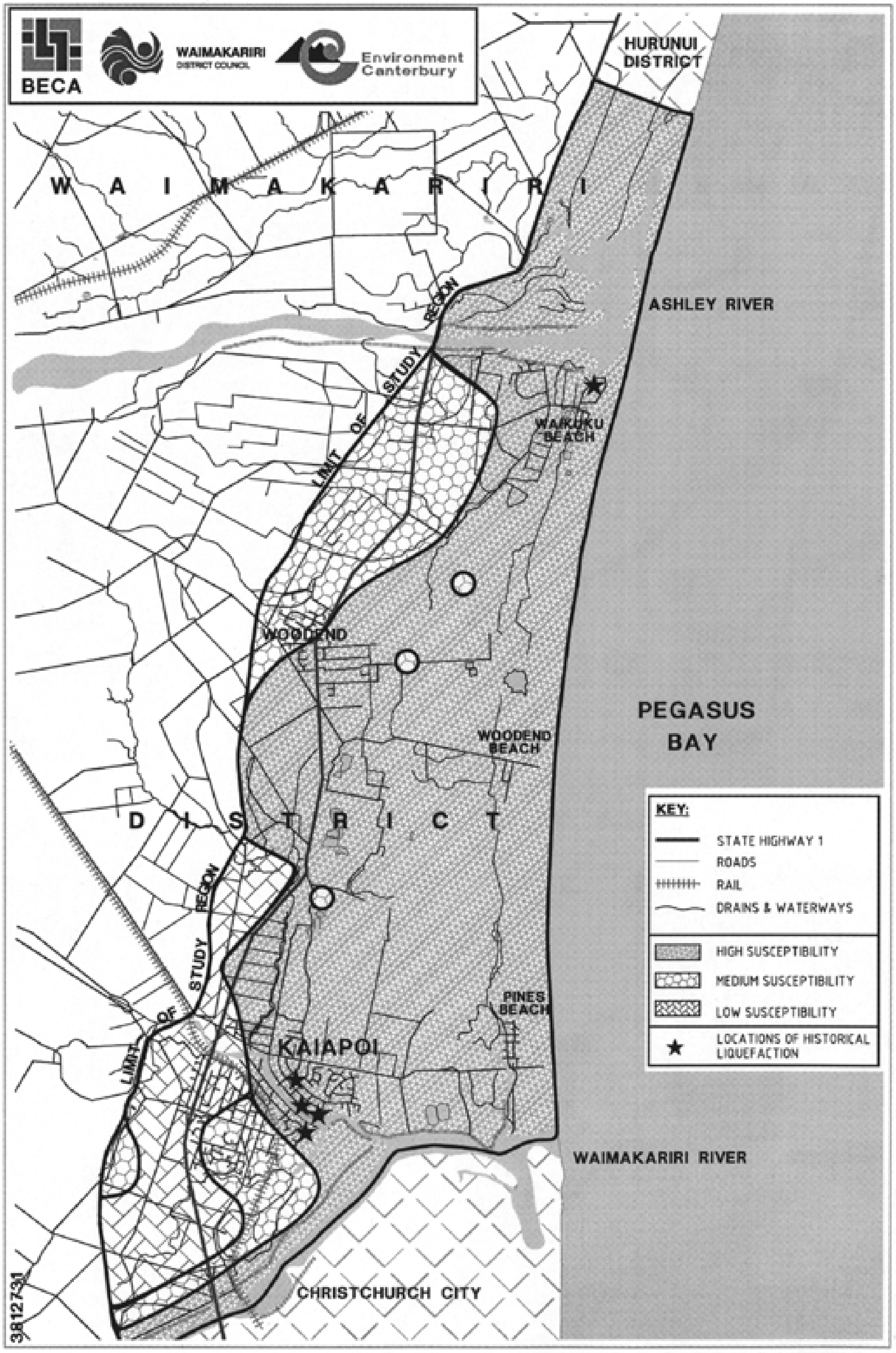

Figure 2. Liquefaction Hazard Map for the Study Region, showing locations of historical liquefaction.

5.2 *Environment Canterbury Database*

Environment Canterbury operates a well database for the Canterbury Region. From this database a total of 355 well logs, with data up to 200m in depth, were examined within the Study Region. Generally the borelogs contained very simple descriptions of the strata encountered (e.g. clay, silt, sand or gravel), but the database does not store soil strength/density information such as Standard Penetration Tests. The following general trends in the upper 15m of deposits were observed in the bore logs:

- Gravel was not usually encountered within 1-2km from the coastline in the first 15m-ground depth between Pines Beach in the south to Waikuku Beach in the north.
- A large number of "inland" bores first encountered gravels at depths of 8 to 10m below the ground surface. Most of the "inland" bores encountered gravel within 15m of the ground surface.
- The location of gravels within the soil stratum was highly varied with many instances of gravel at the ground surface while adjacent bores did not encounter gravels until depths of 10m or greater.

5.3 *Other Sources of Data*

A total of 17 Cone Penetration Tests (CPT's) and two rotary boreholes, up to 9m depth, were undertaken by the University of Canterbury (Berrill et. al., March 1994) at four sites on the eastern side of Kaiapoi. The purpose of these investigations was to assess the liquefaction susceptibility and to trial alternative CPT equipment. A geotechnical investigation consisting of five shallow CPT's, a 10m depth borehole and four test pits were also reviewed (data from Canterbury Lakes development located between Kaiapoi and Woodend). A mixture of predominantly gravel and coarse sands was encountered.

5.4 *Limitations of Existing Data*

The 355 Environment Canterbury bore logs used in this study give a general indication of soils across the Study Region. However, the description of soils is very basic and there are no soil densities recorded with the bore logs. Consequently, the bore logs are of limited use by themselves in this liquefaction study. The in situ testing undertaken by the University of Canterbury and Canterbury Lakes is restricted to depths of up to 10 m. These depths appear to correlate with the maximum penetration depth of the CPT rig in use.

6 FIELD AND LABORATORY INVESTIGATION METHODS

Based on existing information, the investigation envelope was expected to encounter thick seams of gravel, gravelly soils, and very dense sands. Therefore, CPT probes would not have been sufficient to fully investigate the "envelope". While the gravels are predominately located at the bottom of the investigation envelope, they are also widespread at higher elevations and overlay fine-grained soils that could be susceptible to liquefaction. Therefore, rotary boring with Standard Penetration Tests (SPT's) was recommended for this investigation.

Notwithstanding this, parts of the Study Region that are free of gravels would benefit from more detailed investigations at a later date using CPT techniques. The field investigations provided a general idea of the distribution of deposits within the investigation envelope. As soil types are likely to vary greatly within short distances, especially within the Springston Formation deposits, a closely spaced mesh of boreholes would be required to delineate changes in strata; this was not considered economic for a regional study. Furthermore, complex laboratory testing of soil samples was not considered warranted given the large distances between boreholes and hence discrete nature of the study. A total of 26 boreholes (locations shown on Figure 1) to a depth of 15m were undertaken with SPT's at one metre centers from the ground surface. Twenty-nine particle size distribution tests (hydrometer/wet sieve) were undertaken on representative soil samples that may be susceptible to liquefaction

7 GROUND CONDITIONS ENCOUNTERED

Gravels were encountered in the majority of the boreholes (21 of 26) undertaken, with the exceptions being those located along the coastline. The level and/or elevation where gravel was first encountered within the boreholes was variable and trends were not apparent, except that the likelihood of encountering gravels increases with distance from the coastline. In half of the boreholes gravel was encountered within 5m of the ground surface.

Sands dominated in the soil samples recovered in this investigation. Sands were encountered in all but one borehole, and accounted for 61 per cent of the samples recovered. The sands were more prevalent along the coastline of Pegasus Bay and were less apparent along the western boundary of the Study Region. The sands encountered were typically described as uniformly graded fine sands.

Silt sized soils were relatively uncommon across the Study Region and accounted for only 6 per cent of the soil samples recovered. Most commonly when the silts were encountered they were within 5m of the ground surface (Springston Formation soils). Silts and other finer-grained soils were more prevalent on the western side of the Study Region.

Clays and peats were encountered in 11 of the 26 boreholes drilled. Often the clay seams were relatively thick at around 4m to 5m. These fine-grained soils did not appear to be restricted to any particular depth or elevation. However, they were not widely encountered in the Christchurch Formation soils along the coastline of Pegasus Bay.

Soil densities were indirectly assessed based on SPT's. The weaker soils with N-values less than 10 blows/300mm were typically comprised of sand sized particles or smaller and were located within 10m of the ground surface. These low strength soils comprised approximately one quarter of the soils encountered and of this approximately half were sandy soils. Dense to very dense (N>30 blows/300mm) soils were regularly encountered throughout the Study Region and more especially below a depth of around 8m to 9m. SPT N-values were consistently highest along the northern side of Kaiapoi.

8 LIQUEFACTION ASSESSMENT

8.1 *Earthquake Scenarios*

The project brief stated "It is considered that the latest publication from CRC is the most definitive summary of the frequency and characteristics of earthquakes in the Canterbury Region." The report being referenced is the Probabilistic Seismic Assessment and Earthquake Scenarios for the Canterbury Region, and Historic Earthquakes in Christchurch (Stirling et. al., 1999). Information within this document, relevant to the liquefaction study, is summarised in Table 1 and below.

Table 1. Earthquake Parameters Used in Analysis (Stirling et. al., 1999)

Parameter	Foothills Earthquake	Alpine Earthquake
Return Period	150 years	475 years
Peak Ground Acceleration	0.28g	0.44g
Modified Mercalli Intensity (MMI)	8.2	8.7
Richter Magnitude (M)	7.2	8.0
Epicentral Distance	50km	150km

This Foothills Earthquake scenario will originate on the faults located in foothills of the Southern Alps, and will produce shaking of up to MMI 8 for around 30 seconds. This earthquake will be likely to originate at depths of less than 15 km on the Ashley, Springbank and Porters Pass – Amberley Faults. Disruption to services and utilities closest to the fault rupture is likely. Many aftershocks of M5 to 6 are expected in the vicinity of the main shock, but these are unlikely to cause damage at the towns. The closest historical analogues to this scenario earthquake are the 1888 North Canterbury earthquake and the 1901 Cheviot earthquake (Stirling et. al., 1999).

MMI 7-8 shaking and accelerations for the Alpine Earthquake may be less than for the

Foothills Earthquake scenario, but the duration of shaking will be much longer (60 seconds or more). Damage to materials (e.g. furniture) inside tall buildings may occur as a result of the longer period or wavelength of the seismic waves that originate from a great earthquake. Liquefaction will be extensive with lateral spreading along many river and estuary margins. It is possible that there will be major disruption to utilities and services, and this could continue for days or weeks. The many M 6-7 aftershocks that will accompany the earthquake will not produce significant shaking in any of the towns (Stirling et. al., 1999).

8.2 *Liquefaction Prediction*

Laboratory soil gradings were available for around 8 per cent of the soils recovered during this investigation, the remaining soil's parameters were estimated based on these results and their field descriptions. The liquefaction prediction methods of Law et. al. (1990), Taiping et. al. (1984) and the Simplified Seed Method (Youd and Idriss, 1997) were used to evaluate liquefaction susceptibility using these soil parameters and field testing results. A full explanation of these liquefaction prediction methods can be found in their respective references. Following evaluation of all of the soils potential to liquefy, the results were then filtered to eliminate soils not noted as being liquefiable. For example: soils above the water table; peats, clays and clayey soils with moderate to high plasticity; gravels and cobbles without at least 10 per cent sand or silt component; and those that lay outside the criteria set by the prediction models, were considered unlikely to liquefy. This analysis was repeated for both the Foothills and Alpine Earthquake scenarios.

The results for each scenario were then compiled together and plotted on a single graph, the Alpine Earthquake scenario is shown in Figure 3. Susceptibility trends from one borehole to adjacent ones were not clear in this format, nor were trends in a cross section format (either north-south or east-west cross sections). Therefore, regional liquefaction susceptibility trends are not easily defined.

To interpreting Figure 3, where a pyramid is absent then the soil at this depth and for that borehole is not considered liquefiable (by any of the three prediction methods). Furthermore, where pyramids exist, their heights depict the level of susceptibility. A full height pyramid indicates a soil that is predicted to be liquefiable by all three models ("High Susceptibility"). Whereas, a pyramid that is truncated to a low level depicts a soil that was classified by only one prediction model ("Low Susceptibility").

Both the Alpine and Foothills Earthquake scenarios predicted almost the same soils to liquefy. Although, the severity and number of soils predicted to liquefy is higher in the Alpine Earthquake scenario, albeit marginally (20 per cent). Notwithstanding this, their maps of liquefaction hazard are exactly the same.

Some regional observations are made as follows:

- A large number, 60 per cent, of the soils predicted to liquefy are located near to the ground surface (i.e. within 5m). The reason for this is that they are the youngest soils and therefore more prone to liquefaction. Furthermore, their confining stresses are low.
- Conversely the soils between 10m to 15m depth are the least prone to liquefaction with only 10 to 15 per cent of the soils predicted to liquefy. On average the tendency to liquefy decreases with depth. Notwithstanding this, the exception to this rule is evident in some of the boreholes.
- Another spatial observation that could be developed is that the severity of liquefaction appears to decrease with distance back from Pegasus Bay. This trend could be expected as the thickness of sand deposits (primarily Christchurch Formation sands) decreases with distance inland from the coastline and also the average age of the soils increases. In general 17 per cent of the soils examined for the Foothills Earthquake were found to be liquefiable and 21 per cent for the Alpine Earthquake. Furthermore, around one third of the silts and sands encountered during this investigation were found to be liquefiable to some degree.

9 LIQUEFACTION HAZARD MAP

For ease of reference the three-dimensional results generated for the liquefaction prediction have been plotted on a Liquefaction Hazard Map (Figure 2). Three sets of data were used to

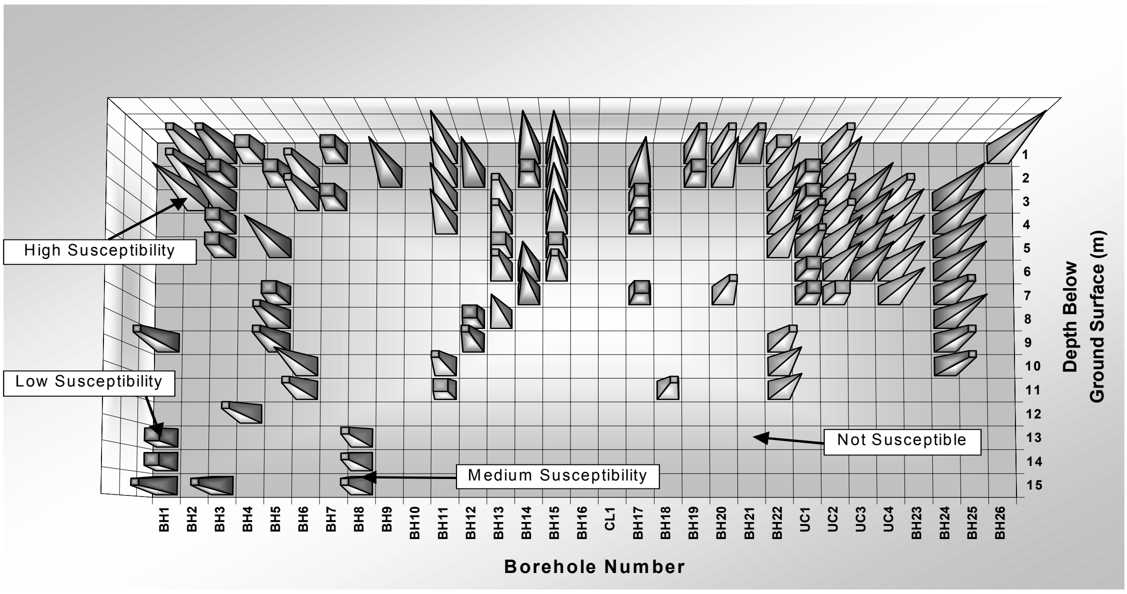

Figure 3. Liquefaction susceptibility for all boreholes based on a M=8.0 Alpine Earthquake

generate the map as follows:

- The results of this current borehole investigation were used to define regions of high, medium and low hazard of liquefaction. These results were given a high rating in terms of accuracy.
- The University of Canterbury and Canterbury Lakes data was treated in a similar manner as the BCHF results and also given a high accuracy rating.
- Lastly the Environment Canterbury well logs (January 2000) were used, albeit cautiously, to in-fill areas between the above two sets of data. This set of data was given a low rating in terms of accuracy and therefore when a conflict arose, the more highly rated data above was given priority.

The Liquefaction Hazards were generated by the method outlined in Table 2.

Table 2. Logic for Defining Levels of Liquefaction Hazard

Soil Susceptibility	Liquefaction Hazard
Many metres of soil with high susceptibility	HIGH
Less than one metre of soil with high susceptibility	HIGH
Greater than one metre of soil with medium susceptibility	HIGH
Less than one metre of soil with medium susceptibility	MEDIUM
Greater than one metre of soil with low susceptibility	MEDIUM
Less than one metre of soil with low susceptibility	LOW

This procedure helps to quantify the fact that many metres depth of soil predicted to have medium susceptibility may cause greater ground damage than only a single metre thickness of soil predicted to have high susceptibility. Environment Canterbury well data was mapped as follows:

- 0 – 1m of sand recorded within 15m of ground surface – low susceptibility
- 2 – 5m of sand recorded within 15m of ground surface – medium susceptibility
- 5 – 15m of sand recorded within 15m of the ground surface – high susceptibility

Liquefaction settlements were calculated for both the Foothills and Alpine Earthquake scenarios based on the method of Bartlett & Youd (1992). Historically, there has been a lack of detailed investigations into observed liquefaction settlement and hence empirical prediction formulae should be considered indicative only. Level ground settlements ranged up to 300mm for both the Foothills and Alpine Earthquake scenarios. By far the largest predicted settlements occur adjacent to the coastline and beside Kaiapoi River (i.e. at the location of the youngest soils). Large settlements are also predicted for the south/south-western end of Woodend.

The prediction of lateral spreading and also the horizontal displacements that it causes was not possible in any meaningful sense given the broad nature of the investigation undertaken.

10 CONCLUSIONS

A study has been undertaken to provide a better understanding of the liquefaction potential that may affect the eastern side of the Waimakariri District in Canterbury, an area of historical liquefaction. Twenty-six boreholes were used to supplement existing geotechnical data within the Study Region. Using two earthquake scenarios (a nearby Foothills Earthquake and a more distant Alpine Fault Earthquake), liquefaction susceptibility was defined using three different models. The results generated indicated that the eastern side of the Study Region, which contains deep dune sand deposits (Christchurch Formation), has a high susceptibility to liquefaction. Furthermore, 21 per cent of the soils encountered were found to be liquefiable in an Alpine Earthquake scenario. The high susceptibility region extends out to the western boundary of the Study Region in three locations and into the heart of the largest town, Kaiapoi. Level ground liquefaction settlements of up to 300mm were predicted for both earthquake scenarios.

A major benefit of this regional liquefaction study is that the need for detailed site investigations has been defined. Furthermore, information is now available for ratepayers through Resource and Building Consents (PIMs and LIMs), and information is available for planning, emergency management, environmental and monitoring and education/advice.

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REFERENCES

Alabaster, D and B Fairburn, 1999. Canterbury Lakes Development Sub-division Consent Application Liquefaction Study Report. *Connell Wagner Ltd*, for Canterbury Lakes Development Ltd.

Bartlett, S. F. and T. L. Youd 1992. Empirical Prediction of Lateral Spread Displacement. *Proc. 4th Japan-US Workshop on Earthquake Resistant Design of Lifeline Facilities, Honolulu.* pp 351-366.

Beca Carter Hollings & Ferner Ltd, 2000. Liquefaction Study. *Beca Carter Hollings & Ferner Ltd Job No. 3812731*, Prepared for Waimakariri District Council (Contract #99/17) and Environment Canterbury (EC Pub No. U00/12).

Berrill JB, PC Mulqueen, ETC Ooi and J-L Pautre, March 1994. Liquefaction at Kaiapoi in the 1901 Cheviot, New Zealand Earthquake. *Research Report, Dept. of Civil Eng., University of Canterbury*, Report 94/3.

Berrill, JB, PC Mulqueen and ETC Ooi, September 1994. Liquefaction at Kaiapoi in the 1901 Cheviot, New Zealand, Earthquake. *Bull. NZ Nat. Soc. of Earthquake Eng.*, Vol. 27, N° 3.

Brown LJ, 1973. Geological Map of New Zealand, Sheet 76, Kaiapoi, 1:63,360. *NZGS*.

Brown LJ and JH Weeber, 1992. Geology of the Christchurch Urban Area, 1:25,000. *IGNS*,.

Environment Canterbury, 2000. Wells With Strata Data. Unpublished data.

Law, K., Y. Cao and G. He, 1990. An Energy Approach for Assessing Seismic Liquefaction Potential. *Can. Geotech. J.* Vol. 27, No. 3, pp 320-329.

Stirling, M, M Yetton, J Pettinga, K Berryman and G Downes, 1999. Probabilistic Seismic Hazard Assessment and Earthquake Scenarios for the Canterbury Region, and Historic Earthquakes in Christchurch: Stage 1 (Part B) of Canterbury Regional Council's Earthquake Hazard and Risk Assessment Study. *IGNS.* Canterbury Regional Council Report N° U99/18.

Taiping, Q., W. Chenchun, W. Lunian and L. Huishan, 1984. Liquefaction Risk Evaluation During Earthquakes. *Int. Conf. on Case Histories in Eng.- Proc.*, St Louis, Vol. 1, pp 445-454.

Waimakariri District Council and Canterbury Regional Council, 1999. Professional Services Contract 99/17 Liquefaction Study. Tender Documents.

Youd, T. L. and I. M. Idriss, 1997. Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils. *Technical Report NCEER-97-0022.* Salt Lake City, Utah.

12 **RETURN TO INDEX**