Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts

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H. L. Brackley (compiler)

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1.0 INTRODUCTION

1.1 PROJECT PURPOSE

The Mw 7.1 Darfield earthquake on 4 September 2010, the Mw 6.2 Christchurch earthquake on 22 February 2011, and subsequent earthquakes on 13 June and 23 December 2011 caused widespread damage in the greater Christchurch area and parts of north and mid Canterbury. Much of the damage to residential buildings and infrastructure in Kaiapoi, Christchurch and parts of rural Selwyn district was caused by permanent ground damage, including liquefaction and lateral spreading in areas close to rivers, wetlands and estuaries. As a result there is now widespread awareness of and concern about liquefaction hazards in the Canterbury region and elsewhere in New Zealand.

Over the last 20 years several liquefaction studies, at both district and site-specific scales and using different methodologies, have been completed in Christchurch City, and Selwyn and Waimakariri districts. The Canterbury earthquakes of 2010-2012 provide a wealth of new data and a better understanding of the nature of liquefaction in the greater Christchurch area and potentially elsewhere in New Zealand.

This report reviews existing knowledge regarding liquefaction hazard, drawing upon the observed effects from the Canterbury earthquakes, the resulting engineering and legislative responses, and in particular, the state of knowledge of near-surface geological materials that underlie the eastern Canterbury area. These information sources provide the basis for the up-to-date assessment of the extent of liquefaction susceptible ground in eastern Canterbury, which is presented in this report. The most important outcome of the report is the mapping that distinguishes land that may be susceptible to damaging effects of earthquake-induced liquefaction and related phenomena (e.g. lateral spreading) from land where liquefaction damage is unlikely in future earthquakes.

The project area is shown in Figure 1.1. It covers an area of eastern Canterbury bordering the coastline between the Rakaia and Waipara Rivers and includes Christchurch city (including Banks Peninsula) and parts of Selwyn, Waimakariri and Hurunui districts. It excludes those parts of the Christchurch urban area that have been assigned a Foundation Technical Category (TC) by the Department of Building and Housing (DBH) because those areas already have specific conditions and guidance regarding planning and building requirements1, 2.

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2 Foundation Technical Category Maps http://cera.govt.nz/maps
The liquefaction hazard information in this report is intended to be used by territorial authorities and communities in decision making for land use planning and consenting. The report incorporates new data and knowledge that have been gathered and developed and also provides a consistent approach to regional-scale assessment of liquefaction hazard across four territorial authority areas. The information and interpretations in this report are primarily intended to provide guidance for where geotechnical investigation and engineering assessment with respect to liquefaction are required for plan changes, subdivision consents, and building consents in the greater Christchurch area. The information within this report may also be useful for lifeline utility planning and emergency management planning.
In this report we summarise the methodology used to delineate areas of potentially liquefiable ground and the subsequent liquefaction susceptibility zonation maps. The uses and limitations of the information presented are then explained. The current review of the Resource Management Act and its potential national implications for liquefaction hazard are briefly discussed. Finally, we present the conclusions and recommendations for refining the boundaries of areas susceptible to liquefaction hazard in Canterbury to improve the management of liquefaction risk.

The information contributing to this zonation and assessment is set out in appendices accompanying this report:

- Land classification and guidelines (Appendix 1);
- Overview of the 2010-2012 Canterbury earthquake sequence (Appendix 2);
- Identification and mapping of liquefaction resulting from the Canterbury earthquakes sequence (Appendix 3; GIS shapefiles on the enclosed CD);
- A folio and review of Canterbury liquefaction susceptibility and hazard maps compiled prior to the 2010-2012 earthquake sequence (Appendix 4);
- Geological information relevant to the liquefaction hazard assessment and liquefaction susceptibility zoning (Appendix 5);
- Probabilistic liquefaction hazard mapping based on a range of design-level earthquakes (Appendix 6).

Notes

- The referenced DBH documents are subject to on-going review. Always check that the latest relevant guidance is referred to. At the time of writing this report, the DBH November 2011 and DBH April 2012 guidance documents for residential recovery were the current documents.
- The Foundation TC boundaries are subject to on-going review and may change over time.
2.0 LIQUEFACTION HAZARD ASSESSMENT

2.1 HISTORIC LIQUEFACTION IN CANTERBURY

There is long-standing awareness of the existence of soft, poorly consolidated ground along parts of the coastal fringe of eastern Canterbury. Prior to the 2010-2012 Canterbury earthquake sequence, localised liquefaction had been reported from the estuary of the Avon and Heathcote rivers in 1869 (Christchurch earthquake) and coastal areas from Kaiapoi northwards during large earthquakes centred in North Canterbury in 1901 (Cheviot earthquake) and in 1922 (Motunau earthquake) (Appendix 3). Combined with knowledge derived from earthquake-generated liquefaction elsewhere in the world, it was known that the central to eastern Christchurch area was underlain by potentially liquefiable geological materials. This potential became reality in the Darfield Earthquake of 2010 and its large aftershocks.

2.2 METHODOLOGY OVERVIEW

A review and compilation of available datasets relevant to liquefaction hazard within the study area was made. This included the Environment Canterbury well and bore-logs (12,100 wells in the study area), geological maps of various scales (Forsyth et al., 2008; Brown and Weeber, 1992), LiDAR topographic data, and soil maps. Using these datasets (Appendix 5) a methodology was developed to identify variations in the expected extent of liquefaction caused by strong earthquake shaking. The methodology was in two parts:

1. Liquefaction susceptibility - identifying areas susceptible to liquefaction (Figure 2.1);
2. Probabilistic liquefaction hazard - mapping variations in the extent of liquefaction for different earthquake shaking scenarios (Appendix 6).

The occurrence of liquefaction depends fundamentally on whether the underlying geological material includes liquefiable sediments, and if these sediments are water saturated. Generally, three criteria need to be met for sediment to be considered liquefiable:

- Loose and young (often Holocene in age)
- Fine-grained and cohesionless coarse silt and fine sand
- Water-saturated.

Using available datasets, the following methodology was used to identify areas that fit the above criteria. First, the LiDAR topographic data was used as a base to map landform types (geomorphology). This was checked against mapped soil information, which provides an estimate of the age of landforms. The Environment Canterbury well dataset was then used to correlate surface geomorphology with sub-surface materials to a depth of 10 metres.

The second step was to create a model of the unconfined groundwater surface (UGS) in the study area. Again the Environment Canterbury well dataset was used, but filtered to remove data derived from artesian pressures in confined aquifers, because to the best of existing knowledge, it is generally depth to the water table that influences the degree of saturation of near-surface, potentially liquefiable sediments. Accordingly, we also used surface water (i.e. lakes, streams, rivers) data to aid in building the groundwater model (Appendix 5). Confined water pressures and their effect on liquefaction susceptibility are not addressed in this report.
These data provide the ability to spatially differentiate liquefaction susceptibility. This information was calibrated against observations of liquefaction that occurred during the 2010 Darfield and 2011 Christchurch earthquakes (Appendix 3) to produce the liquefaction susceptibility zones (Figure 2.1).

International historic experience suggests that most surface deformation results from liquefaction of materials within the top 10 m; however, there is some evidence of surface deformation as a result of liquefaction at depths of up to 20 m. For this study, we limited the investigation of lithologies recorded in drillhole logs to 10 m depth, as the contribution to surface deformation from deeper materials is likely to be smaller than the inherent uncertainties of the groundwater model. In addition to this, planning requirements of site specific investigations for development are likely to involve liquefaction susceptibility characterisation to depths in excess of 10 m.

A further consideration for this study was the liquefaction susceptibility of ground alongside waterways. Where a waterway has shallow incision and the groundwater table is high, there is potential for liquefaction to occur and result in damage to the surrounding ground, particularly due to lateral spreading. While buffer zones along waterways have not been included on the liquefaction susceptibility zonation map, such areas could be considered as being susceptible to liquefaction. However, ground that may be subject to liquefaction in this way is likely to fall within zones where the flood hazard dominates and therefore controls development.
Figure 2.1 Liquefaction assessment area map for the eastern Canterbury project area. Liquefaction susceptibility is categorised in two areas, “damaging liquefaction unlikely” and “liquefaction assessment needed”. The area covered by DBH Technical Categories at the time of this report is excluded.
2.3 LIQUEFACTION ASSESSMENT AREAS

The areas identified on the liquefaction assessment map and included in the report are:

- **Damaging liquefaction unlikely** - in this area there is little or no likelihood of damaging liquefaction occurring during strong ground shaking. This assessment area consists of the western part of the project area, and most of Banks Peninsula. Within this area, investigations in most cases can be designed primarily for other geotechnical hazards. Liquefaction however must at least be considered by the geotechnical professional in all cases.

- **Liquefaction assessment needed** - in this area there is a small to considerable likelihood of damaging liquefaction occurring during strong ground shaking. The eastern part of the project area and some low-lying areas of Banks Peninsula, close to the sea or the Canterbury Plains lie within this area. Specific investigation of liquefaction susceptibility is required as well as assessment of other geotechnical hazards.

- **DBH Foundation Technical Category (TC) areas** - these are excluded from the study area (Appendix 1).

GIS shapefiles of the liquefaction assessment areas are provided in the enclosed CD, and should be used when more detail is required than that presented in Figure 2.1.

**What the areas mean**

**Damaging Liquefaction Unlikely:**

- The geological nature of the ground is such that future design-level earthquakes are unlikely to cause land damage from liquefaction\(^3\)
- Other geohazards are likely to be more dominant, if present at all
- The ground in this area would likely qualify as TC1 were it assessed using the TC methodology. For consenting purposes, a similar process to that applied in TC1 areas is appropriate.
- Normal geotechnical assessment practises apply. For residential development the ground investigation provisions of NZS 3604 with DBH amendments apply.
- Standard foundation investigations (i.e. as specified in NZS 3604) will normally be adequate for residential construction.

**Liquefaction Assessment Needed:**

- The geological nature of the ground is such that future design-level earthquakes may cause ground damage from liquefaction and the effects may be complex and damaging to ground, buildings and infrastructure
- The severity of damage is likely to range from negligible to severe, depending on local geological conditions
- Any development necessitating geotechnical assessment must include specific identification and evaluation of liquefaction hazard
- If a particular site has already been assigned a Technical Category, follow the DBH Guidelines

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\(^3\) This wording is in keeping with the DBH/CERA wording for Technical Category 1 land.
If the site of interest is not assigned a Technical Category the geotechnical assessment must be undertaken by a geotechnical professional. Such an assessment must include subsurface investigations to determine the liquefaction hazard (if any) at a site so that appropriate foundations can be designed and built or land use planning decisions can be made to not urbanise this land.

2.4 Uses and Limitations of Information

Information and interpretations within this report are regional in scale and are not site specific. The report provides general guidance on where investigations are required to assess the liquefaction hazard at a site. Should the degree of liquefaction hazard of a particular residential section or subdivision need to be determined, a specific geotechnical investigation would be necessary. One liquefaction-related hazard that is not addressed in the report is settlement caused by sand compaction of the zone above the saturated interval. If liquefiable but dry sediments are present, there could still be a hazard posed by compaction and settlement.

The liquefaction susceptibility zonation map (Figure 2.1) is intended primarily for use by territorial authority staff to help them:

- Understand where the likelihood of liquefaction is significant enough that a specific evaluation is warranted as part of a development's geotechnical assessment;
- Show the public where an evaluation of the liquefaction hazard should be specifically included in any relevant application under the Resource Management Act or Building Act;
- Avoid requiring liquefaction hazard studies for areas where damage from liquefaction is unlikely;
- Identify areas where development may result in unacceptable economic risk or the cost-benefit of development is questionable.

The focus of this report is on liquefaction hazards in relation to land use planning for general residential and light commercial development. Major infrastructural developments and critical facilities have information needs that are beyond the scope of this report.

This report is a guide to where the DBH guidelines (Appendix 1) on the level of geotechnical investigation and specific engineering assessment required to adequately evaluate the risk of liquefaction should be applied. Liquefaction is just one of a range of possible geohazards, and for any site there may be other geotechnical considerations, which means that a broader geotechnical engineering assessment may be necessary.

2.5 The Resource Management Act and National Implications

National concerns about liquefaction

Since the 2010-2012 Canterbury earthquakes, there has been heightened concern about liquefaction hazard throughout New Zealand. Having seen the degree to which liquefaction may cause damage, it is prudent that consenting authorities in other parts of the country assess their own region's liquefaction potential. It is, however, very important to recognise that not all regions are as susceptible to liquefaction as Christchurch. Much of New Zealand is underlain by rocks and soils not susceptible to liquefaction and these will never liquefy, no
matter how much the ground shakes. In such areas, other natural hazards may be more significant.

**Regional approach**

Areas that are potentially more susceptible to liquefaction than others can be identified using geomorphological modelling and pertinent information about ground conditions: depth to water table; indications of the presence of low plasticity, unconsolidated sediments. A regional approach can highlight a zone that COULD be susceptible to damaging liquefaction and eliminate areas that are NOT susceptible to liquefaction (i.e. areas where large-scale damaging liquefaction is unlikely). The zone that could be susceptible is then flagged as needing a site specific geotechnical evaluation by a qualified professional.

Using this regional approach, local authorities will be able to exclude areas identified as “not susceptible to liquefaction”, and thus be able to significantly reduce the area requiring detailed and expensive liquefaction hazard investigations.

**Risk-based approach**

The Christchurch Earthquake of February 2011 was a 1 in 10,000 year event, i.e. an extreme event. It would be unfortunate if this extreme event were used to set a new precedent in limiting future land use more than is appropriate, especially in regions that are less prone to earthquake hazard.

During the consenting process, a risk-based approach is appropriate. Risk has two components: a) how likely is an area to experience an earthquake with ground motions sufficient to cause liquefaction and b) what level of damage would be caused if those ground motions were to occur.

Whilst buildings may be constructed with foundations suitable to withstand liquefaction, when approving subdivisions and building on liquefiable ground, local authorities should also consider the likely effects of liquefaction on the infrastructure that is required to support such buildings. The consequences of damage to roads and bridges, power, telecommunications, gas lines, sewage and potable water systems are far reaching in terms of cost, loss of amenity to residents and harm to the environment.

Saunders and Berryman (2012) present a framework that allows land use planners to assess if liquefaction is a hazard that should be included in the planning process. To achieve this, an explanation of liquefaction and peak ground acceleration is provided, followed by a decision tree for planners to use when deciding if liquefaction should be included in land use plans. Each of the questions in the decision tree is then outlined in further detail. Key questions include: are the soils susceptible to liquefaction? What is the likelihood of an earthquake above 0.1g peak ground acceleration occurring? Are the consequences of liquefaction significant? Concluding the report is an overview of future research into liquefaction and its management. The Saunders and Berryman (2012) report does not provide guidance on how to include liquefaction into planning documents – additional multi-disciplinary guidance to assist with this will be provided once lessons from liquefaction in Canterbury have been understood and published.

**Learning from the Canterbury Events**

Sharing of geotechnical and hazard-related information between many agencies and organisations and consultants has proven to be extremely important and useful in the
earthquake recovery in the Christchurch, Waimakariri and Selwyn districts. This includes national (CERA, EQC), regional (Environment Canterbury) and local (CCC, WDC, SDC) government, and many private consultancies. What has been learned is that not only is such sharing and cooperation very valuable, but also that it is possible, not just hypothetically, but in reality. This experience is a role model for a nationwide change in culture, where openness, cooperation and free exchange of technical information are seen as priority, and happen as a matter of course.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

The eastern part of the Canterbury region, between the Rakaia and Waipara Rivers, has been assessed for its susceptibility to damage caused by liquefaction.

Using knowledge derived from the 2010-2012 earthquakes and their effects on land, and knowledge of near-surface geological materials and groundwater levels, a liquefaction susceptibility zonation has been developed. This zonation comprises two categories:

1. Damaging liquefaction unlikely. This zone includes the western part of the project area, and most of Banks Peninsula.

2. Liquefaction assessment needed. This zone comprises the eastern, coastal part of the project area and low-lying areas of Banks Peninsula close to the sea or adjacent to the Canterbury Plains.

3.2 RECOMMENDATIONS

It is recommended that current efforts to set up a national geotechnical database be supported so that geotechnical information collected electronically via the consenting process or other routes is captured and publically available. The cost of setting up such a database will be offset by savings in future projects due to the time saved by having the information readily at hand, and the avoidance of inadvertent repetition of work. A readily accessible geotechnical database would also improve the quality and reliability of future hazard maps, and enable councils to manage their liability by keeping a very clear picture of the information they have in their possession.

Groundwater information in Canterbury is also collected by many different organisations: Environment Canterbury, Territorial Authorities, CERA, NIWA, GNS Science and geotechnical consultants. It would be very advantageous to have a single repository for such information, a similar method of capturing incoming data and to develop an integrated ground water model for the region. We recommend supporting current efforts to establish such a database and model in Canterbury. This would also inform the refinement of this study and feed into many other future projects. Other local authorities that do not have such a database should also consider developing a single storage point for groundwater information in their region.
4.0 ACKNOWLEDGEMENTS

This review of the liquefaction susceptibility and hazard information for Christchurch City and parts of Selwyn, Waimakariri and Hurunui districts was jointly funded by Environment Canterbury and the Natural Hazards Research Platform\(^4\).

The project was overseen by a steering group comprising:
- Kelvin Berryman (Natural Hazards Research Platform)
- Ian Butler (Selwyn District Council)
- Gerard Cleary (Waimakariri District Council)
- Helen Grant (Environment Canterbury, chair)
- Marion Irwin (Environment Canterbury)
- Jarg Pettinga (University of Canterbury)
- Chris van den Bosch (Christchurch City Council)

The project team comprised:
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- Sarah Bastin (Lincoln University)
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- Helen Grant (Environment Canterbury)
- Nick Harwood (Coffey Geotechnics Ltd)
- Marion Irwin (Environment Canterbury)
- Mike Jacka (Tonkin & Taylor Ltd)
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- Katie Jones (GNS Science)
- Julie Lee (GNS Science)
- Ian Lynn (Landcare Research)
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- Eileen McSaveney (GNS Science) - Editor
- David Scott (Environment Canterbury)
- Dougal Townsend (GNS Science)
- Pilar Villamor (GNS Science)
- Heath Wells (Christchurch City Council)
- Paul White (GNS Science)

The report was peer reviewed by Charles Price, Chief Geotechnical Engineer, MWH Ltd, Christchurch and Thomas L Holzer, USGS, California.

\(^4\) The Natural Hazards Research Platform was created by the Government to provide secure long-term funding for natural hazard research in New Zealand, and to help research providers and end users work more closely together. The Platform is anchored by GNS Science and NIWA, and also includes the University of Canterbury, Massey University, Opus International Consultants and the University of Auckland as partners, and a wide range of other research providers as subcontractors. See [www.naturalhazards.org.nz](http://www.naturalhazards.org.nz) for more information.
### 5.0 DEFINITIONS

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>CPEng Geotechnical Engineer</td>
<td>An engineer who holds a current Annual Practising Certificate as issued by The Institution of Professional Engineers New Zealand (IPENZ) and who has been assessed for current competency in the Geotechnical Practice Field as defined. The CPEng register can be searched here: <a href="http://www.ipenz.org.nz/ipenz/finding/cpeng/search/search.cfm">http://www.ipenz.org.nz/ipenz/finding/cpeng/search/search.cfm</a> The Council staff member can ask for verification of the CPEng engineer’s Practice Field. This is as stated in their IPENZ competence-based membership application form that they submitted when applying for their current CPEng registration: <a href="http://www.ipenz.org.nz/publications-forms/default.cfm?g=1&amp;catID=20">http://www.ipenz.org.nz/publications-forms/default.cfm?g=1&amp;catID=20</a> Chartered Professional Engineer (CPEng) is the most important quality mark attesting to the current competence of a professional engineer in New Zealand. It is a statutory title under the Chartered Professional Engineers Act of New Zealand 2002, (<a href="http://www.ipenz.org.nz/IPENZ/finding/CPEng/">CPEng Act</a>), which established a register of professional engineers whose competence is up-to-date. [Source: <a href="http://www.ipenz.org.nz/IPENZ/finding/CPEng/">http://www.ipenz.org.nz/IPENZ/finding/CPEng/</a>]</td>
</tr>
<tr>
<td>Damage (from liquefaction)</td>
<td>Earthquake-induced liquefaction-related ground deformation can take a number of forms and can lead to excessive total and differential settlement or rupture of structures, pavements and buried services. Under certain conditions in liquefiable soils, differential settlement, sand boils and lateral spreading can occur, and in the non-liquefiable “dry” zone above the groundwater level, densification, ground rupture (tension cracking) and differential settlement can occur in some soil types. See also Appendix B1 of DBH (April 2012): <a href="http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/guide-canterbury-earthquake-revised.pdf">http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/guide-canterbury-earthquake-revised.pdf</a></td>
</tr>
<tr>
<td>DBH</td>
<td>Department of Building and Housing. <a href="http://www.dbh.govt.nz/index">http://www.dbh.govt.nz/index</a> The DBH is now formally referred to as the Building &amp; Housing Group within the Ministry of Business, Innovation and Employment (MBIE). The MBIE came into existence on 1 July 2012. It integrates the functions of the former Department of Building and Housing, Ministry of Economic Development, Department of Labour and the Ministry of Science and Innovation.</td>
</tr>
<tr>
<td>Geohazards</td>
<td>Natural ground-related hazards, the more common examples being: • liquefaction • lateral spread • fault rupture • soft or compressible ground (e.g. peat) • landslip • rockfall • tunnel-gully erosion • riverbank erosion</td>
</tr>
</tbody>
</table>
**Geotechnical assessment**

The process of characterising the ground conditions at a site, and the evaluation of potential risks to the project associated with those conditions. The geotechnical professional will look at the soil or rock properties and the groundwater environment.

Following confirmation of the work brief, the process normally has a number of steps, including but not limited to:
- site inspection,
- desk study,
- fieldwork (e.g. drilling, pitting),
- laboratory testing,
- analysis, and
- reporting.

The scope of work required very much depends on the nature of the project and the complexity of the ground conditions. Depending on the objectives of the assessment, sometimes an inspection and desk study can suffice, especially where existing reports or geotechnical records exist. Conversely, the scope may require detailed and extensive fieldwork. Almost invariably, the minimum undertaken would be site inspection and desk study, with comments collated into a brief report.

For house development projects there is a minimum scope of geotechnical assessment work required, as set out in NZS 3604:2011 *Timber-framed buildings* [http://www.standards.co.nz/default.htm](http://www.standards.co.nz/default.htm)


**Geotechnical professional**

(Council staff are recommended to check the suitability of the reporting personnel)

The geotechnical professional must be either:
- a CPEng Geotechnical Engineer or
- for the purposes of this report, in relation to geotechnical assessment for residential properties, a PEngGeol. *Engineering Geologist* with suitable relevant training and experience in foundation investigations and liquefaction assessment.

These professionals are reminded that they are bound by the IPENZ Code of Ethical Conduct, which states (Rule 46) that the professional must undertake engineering activities only within his or her competence. Practitioners who do not have suitable geotechnical training, qualifications and experience must seek the supervision of a CPEng Geotechnical Engineer.

This wording is as presented in Section C3.1 of the DBH Guidelines (April 2012).

**Liquefaction**

The process in which strong ground shaking transforms saturated granular soils from a solid state into a heavy liquid mass, and thus loses strength and stiffness. The most susceptible soils are loose coarse silts and sands.

<table>
<thead>
<tr>
<th><strong>Liquefaction potential</strong></th>
<th>The likelihood that deposits of defined liquefaction susceptibility will liquefy under specific shaking scenarios; the term incorporates the concepts of sediment liquefaction susceptibility with specified intensities of ground shaking with resultant liquefaction.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Liquefaction susceptibility</strong></td>
<td>The physical properties, characteristics or “state” of a sediment (including looseness, grain shape and size characteristics, grain packing and water saturation) that determines whether the deposit may liquefy under cyclical loading, usually earthquake-generated ground shaking.</td>
</tr>
<tr>
<td><strong>MBIE</strong></td>
<td>Ministry of Business, Innovation and Employment.</td>
</tr>
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</table>
| **PEngGeol Engineering Geologist** | A professional Engineering Geologist who has been assessed as competent to practice in New Zealand, having undergone a competency assessment via IPENZ and whose competence is up-to-date.  

The PEngGeol accreditation is not equivalent to the CPEng accreditation but follows a similar competency assessment process. (Also, see comments above re CPEng Geotechnical Engineer).  

The PEngGeol accreditation is new and is expected to be formally established by early 2013. Details of the PEngGeol accreditation and its register of accredited professionals is likely to be available via IPENZ: [http://www.ipenz.org.nz/ipenz/](http://www.ipenz.org.nz/ipenz/) |
| **Technical Category** | All greater Christchurch land is being progressively mapped into land zones. Green zone areas are generally considered to be suitable for residential construction.  

Land in the green zone has been divided into three technical categories – TC1 (grey), TC2 (yellow) and TC3 (blue). These categories describe how the land is expected to perform in future earthquakes, and also describe the foundation systems most likely to be required in the corresponding areas.  

6.0 REFERENCES


APPENDICES
APPENDIX 1: LAND CLASSIFICATION AND GUIDELINES

A1.1 DEPARTMENT OF BUILDING AND HOUSING FOUNDATION TECHNICAL CATEGORY ZONES

Following the February 2011 Christchurch earthquake, the Canterbury Earthquake Recovery Authority (CERA) classified residential “red zones” within existing residential areas affected by the Canterbury earthquake sequence. Residential red zones were declared in the areas of the most severe land damage as a consequence of liquefaction.

All flat-land in existing residential areas affected by the Canterbury earthquake sequence (i.e. land not on the Port Hills) that did not fall into a red zone was classified as “green zone”. In this area land is generally considered suitable for residential construction, with varying foundation requirements depending on the land damage experienced from liquefaction and likelihood of further land damage in future significant earthquakes.

The green zone was further divided into three Foundation Technical Categories (TC) (Figure A1.1). These categories describe how land is expected to perform in future significant earthquakes and guide the level of specific engineering assessment necessary to guide the selection of appropriate foundation solutions under the Department of Building and Housing (DBH) guidance for the repair and reconstruction of houses following the Canterbury earthquake sequence. There is no requirement to upgrade undamaged house foundations.

Technical Category 1

Land in TC 1 is unlikely to experience future land damage from liquefaction. The approach to foundation investigation and design as set out in NZS 3604 is considered acceptable.

Technical Category 2

Land in TC 2 could experience minor to moderate land damage from liquefaction in future significant earthquakes, and the foundations required as part of repairing or rebuilding range from standard timber pile foundations to enhanced concrete foundations, depending on the house design.

Technical Category 3

Land in TC 3 may experience moderate to significant liquefaction in future significant earthquakes. Where foundation repair or rebuilding is required, each site must be assessed individually through a site-specific, deep geotechnical investigation to determine an appropriate engineering foundation design specific to the site. This could include standard TC 2 foundations, deep pile foundations or ground strengthening.
Figure A1.1 DBH Foundation Technical Category zones.
A1.2 DBH changes to the Building Code

DBH amended the Acceptable Solution (B1/AS1) to the Building Code in May 2011 to exclude ground where liquefaction and/or lateral spreading could occur from the definition of “good ground” within the Canterbury Earthquake Region5.

This project helps define these areas where liquefaction and/or lateral spreading could occur, in areas outside the DBH Foundation Technical Category zones. The zones developed as part of this project can be considered as a similar concept to the DBH Foundation Technical Category zones, but have been developed using a different methodology, based on a lower density of source data, and do not necessarily have the same requirements.

A1.3 DBH Guidelines for the Geotechnical Investigation and Assessment of Subdivisions in the Canterbury Region

DBH issued Guidelines for the geotechnical investigation and assessment of subdivisions in the Canterbury region in November 2011. This outlines the level of geotechnical investigation required for plan changes and subdivisions in the Canterbury region (in this case meaning the Christchurch City, Waimakariri District and Selwyn District areas). The Guidelines state that “appropriate geotechnical investigations shall be carried out to enable the characterisation of ground forming materials to at least 15 m depth below ground level, unless the ground is known to be of acceptable quality from lesser depths (for example, in areas known to be underlain by competent gravels and deep groundwater profiles, or in hillside areas)”. CERA’s Recovery Strategy for Greater Christchurch (2012) requires that “when making a resource consent application or a request for a plan change for the subdivision of land, the person proposing the subdivision must address the risk of liquefaction. As a minimum, that person must provide the local authority with a geotechnical assessment in accordance with the Guidelines for the geotechnical investigation and assessment of subdivisions in the Canterbury region”. This requirement applies unless the Resource Management Act is changed to address how natural hazards are considered when subdividing land.

This project helps define areas where there is generally a higher or lower risk of damaging liquefaction occurring in future design-level earthquakes. In conjunction with the DBH guidelines, this information is intended to provide a guide to the level of geotechnical investigation and specific engineering assessment required to adequately address the risk of liquefaction. However, it is important to remember that liquefaction is just one of a range of possible natural hazards, and for any site there may be other geotechnical considerations, which mean that a more detailed engineering assessment is necessary.

A1.4 Exclusion of the DBH Foundation Technical Category Zones from this Study

Within the study area there are two quite distinct regions with regard to the quality and quantity of data available. The central and eastern parts of Christchurch city have thousands of cone penetrometer test (CPT) results and detailed ground-based mapping of liquefaction damage caused by the recent earthquakes, while outside this area the only significant

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5 The Canterbury Earthquake Region is Waimakariri District, Christchurch City and Selwyn District.
dataset is the Environment Canterbury well and bore-log dataset and mapping of liquefaction inferred from aerial and satellite imagery.

When the project was first put forward, the intended methodology was to use the high quality CPT data available in the central and eastern parts of Christchurch to characterise different geological environments and then extrapolate the results throughout the study area. However, as the project progressed it became apparent that the central and eastern areas of Christchurch that were well investigated only represented ground conditions with a susceptibility to liquefaction. And although analytical techniques such as the CPT-based Liquefaction Potential Index (Iwasaki et al., 1978, 1982; Holzer et al., 2006, 2009) can be used to delineate variations in liquefaction hazard in areas where there is an adequate density of data, it is very difficult to then extrapolate these results into data-poor areas without making gross simplifications and assumptions.

This study excludes those parts of the Christchurch urban area that have already been assigned a Foundation Technical Category (TC) by DBH. Those areas already have specific conditions and guidance regarding planning and building requirements.

REFERENCES


APPENDIX 2: THE 2010-12 CANTERBURY EARTHQUAKE SEQUENCE

A2.1 THE DARFIELD EARTHQUAKE OF 4 SEPTEMBER 2010

The moment magnitude (M_w) 7.1 Darfield Earthquake occurred at 4:35 am local time on 4 September 2010, approximately 10 km southeast of the town of Darfield and at a depth of about 10 km (Gledhill et al. 2011).

A 29-km long east-west trending fault rupture on the Canterbury Plains extended to within 18 km of the Christchurch urban area. The fault surface rupture had primarily strike-slip (sideways) motion, clearly shown by offset ground-surface features along the fault trace (Figure A2.1). However, records from strong-motion seismographs and geodetic data indicate that the subsurface fault movement was complex, including an important reverse (compressional) component. The duration of strong ground motions on sites with firm soils was about 15 seconds.

Numerous strong ground motion recorders were triggered by the mainshock and many of the aftershocks, with maximum ground accelerations exceeding 100% of gravity (1 g) in the epicentral area and 20-30% of gravity (0.2-0.3 g) in the city. Further analysis of the ground motion data, (particularly in relation to energy release at wave periods that affect built structures, potential instability of the recording sites, and effects of weak near-surface ground conditions in parts of Christchurch and the wider region) indicates that in the city the
earthquake was below the ultimate limit state (ULS) design spectra at spectral frequencies pertinent to low-rise buildings, but significantly above the design spectra for high-rise buildings (above approximately 20 stories). There have been many aftershocks from this major earthquake.

A2.2 The Christchurch Earthquake of 22 February 2011

The Mw 6.2 Christchurch Earthquake occurred at 12:51 pm local time on 22 February 2011, about 10 km southeast of the Christchurch city centre at a depth of about 5 km (Figure A2.2). It produced extreme ground shaking, with recorded ground motions up to 2.2 g near the epicentre (Kaiser et al. 2012).

The Christchurch Earthquake is considered to be an aftershock of the 4 September 2010 Darfield Earthquake, based on the size of the earthquake, its location within the overall aftershock zone, and because it occurred less than six months after the mainshock. Seismic activity in the Canterbury Plains was historically very low prior to the September 2010 Darfield Earthquake, and the likelihood of the 22 February 2011 earthquake occurring without the mainshock would also have been very low. Typically around the world, the largest aftershock observed is about one magnitude unit less than the mainshock, which is about the size of the 22 February 2011 earthquake relative to the 2010 Darfield Earthquake. Despite being an aftershock, the 22 February 2011 earthquake was large enough to have its own set of aftershocks. It produced an unusually active sequence of aftershocks in the first 24 hours, with 39 aftershocks greater than Mw 4.0, and three aftershocks greater than Mw 5.0.

The Christchurch Earthquake was a complex event, involving rupture of three closely aligned fault segments. Collectively, these buried fault segments are informally called the Port Hills fault, which extends in a general way from near Brighton Beach in a south-south west direction across the northern side of the Heathcote estuary and toward Cashmere (Figure A2.2). The fault did not rupture the ground surface, unlike the much larger magnitude Darfield Earthquake. At depth, fault slip was as much as 2.5 m, but only a small portion reached the ground surface, by way of the Port Hills being raised up by as much as 0.4 m. Conversely, the New Brighton area subsided by as much as 0.1 m on the north side of the surface projection of the fault plane (Beavan et al., 2012).

The Christchurch Earthquake produced very strong shaking for the size of the earthquake, and the duration of strong shaking varied according to site geology and distance from the epicentre. Strong shaking lasted 8-10 seconds close to the epicentre (e.g. Heathcote Valley), 15-20 seconds on the soft sediments underlying the Christchurch urban area, and over 20 seconds out on the plains (e.g. Darfield area). Liquefaction was widespread across the eastern suburbs of the city, and rockfalls and landslips were widespread in the Port Hills, particularly where natural hillslopes had been cliffed by past wave action or modified by quarry excavation in Sumner and Redcliffs.

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6 Refers to the pre-earthquake design spectra as defined in NZS 1170.5:2004. Design seismic levels for Canterbury have subsequently been raised.
A2.3 THE CHRISTCHURCH 2 EARTHQUAKE OF 13 JUNE 2011

By mid-2011 the aftershocks of the Christchurch Earthquake were diminishing in frequency, and preparations to begin the reconstruction programme were well-advanced. A major setback occurred on 13 June 2011 when a $M_w$ 6.0 earthquake, the Christchurch 2 Earthquake, struck at 2:20 pm, producing high horizontal accelerations (~2 g) at the southeastern edge of the city (Kaiser et al. 2012). There was renewed liquefaction and further damage, including partial collapse of already weakened buildings in the CBD Red Hazard Zone. The earthquake epicentre lay 10 km east-southeast of the CBD, well within the aftershock zone of the Christchurch Earthquake. The interesting feature of this earthquake is that it was on an approximately north-north-west to south-south-east oriented fault approximately orthogonal to the Port Hills fault. The aftershock pattern associated with this earthquake extended south across Banks Peninsula toward Akaroa (Figure A2.2).

The ground motions in both the 22 February 2011 $M_w$ 6.2 and the 13 June 2011 $M_w$ 6.0 earthquakes were significantly stronger in the Christchurch urban area than in the 4 September 2010 Darfield Earthquake, because of the proximity of their epicentres to the city, even though the Darfield Earthquake had a larger magnitude. In eastern suburbs, Port Hills suburbs, and in much of the CBD, the ground motions exceeded the 500-year return period code level of 0.3 g PGA.

A2.4 THE CHRISTCHURCH 3 EARTHQUAKE OF 23 DECEMBER 2011

A $M_w$ 5.8 earthquake struck east of Christchurch at 1:58 pm on 23 December 2011, approximately 8 km off the coast of New Brighton, followed shortly afterwards by a $M_w$ 5.9 earthquake at 3:18 pm. As with other earthquakes of this shaking intensity, liquefaction occurred in the eastern suburbs of Christchurch. This sequence of earthquakes occurred further eastward than the 13 June 2011 sequence of aftershocks. Being further offshore from the coast and being of comparatively smaller magnitude and somewhat greater depth, the effects were less damaging to structures and land than in the previous large earthquakes. Following the 23 December 2011 earthquakes, aftershocks continued on throughout the afternoon and overnight, with several over $M_w$ 5.0.

The $M_w$ 5.8 and $M_w$ 5.9 earthquakes did not produce ground motions as large as those of the Christchurch and Christchurch 2 earthquakes, except for an isolated high recording at Brighton Beach in the $M_w$ 5.8 earthquake that may reflect the seismograph’s proximity to the epicentre and related near-fault directivity effects.

On 2 January 2012, an intense burst of aftershock activity with more than 30 events above $M_w$ 3.0, and two events $>M_w$ 5.0 occurred largely offshore, about 20 km northeast of the city.
Figure A2.2 Map of the aftershocks produced after the 4 September 2010 Darfield Earthquake (green circles), 22 February 2011 Christchurch Earthquake (red circles), 13 June 2011 Christchurch 2 Earthquake (blue circles) and 23 December 2011 Christchurch 3 Earthquake (pink circles). The epicentres are shown by the coloured stars, and the surface rupture of the Darfield Earthquake is shown by the red line. Yellow dotted lines indicate the subsurface rupture of the Christchurch Earthquake in the city area (SW to NE), and the Christchurch 2 (N-S) and Christchurch 3 (SW to NE) earthquake ruptures and other inferred subsurface rupture planes of the Darfield Earthquake (Beavan et al., 2012).

A2.5 SEISMIC HAZARD FOR CANTERBURY

In considering the Canterbury earthquakes with respect to the existing national seismic hazard model (Stirling et al. 2012) and the regionally-based Canterbury seismic hazard model (Stirling et al., 2008) GNS Science and University of Canterbury scientists had previously identified three classes of earthquakes as potential major hazards to the city:

- moderate-sized (about $M_w$ 5.0-6.5) earthquakes at a close proximity to the city;
- large regional earthquakes (about $M_w$ 7.0-7.5) on faults beneath the Canterbury Plains and foothills of the Southern Alps, and;
- great earthquakes (about $M_w$ 8.0) on the distant Alpine Fault.

The Christchurch earthquakes have clearly been close-by, moderate-sized earthquakes, and the Darfield Earthquake was in the category of a large regional earthquake. The unusual aspect of the Christchurch earthquakes has been their very strong shaking relative to the size of the earthquake.
REFERENCES


APPENDIX 3: IDENTIFICATION AND MAPPING OF LIQUEFACTION RESULTING FROM THE 2010-2011 CANTERBURY EARTHQUAKES

A3.1 HISTORIC OCCURRENCE OF LIQUEFACTION IN CANTERBURY

On five occasions prior to 2010, earthquakes have caused ground damage in parts of Canterbury, at distances of as much as 100 km from the earthquake epicentre (Figure A3.1).

Figure A3.1  Reported historical occurrences of liquefaction in eastern Canterbury.
5 June 1869 (*Christchurch Earthquake, M ~5.8*)

This earthquake may have caused some ground settlement in the Heathcote Estuary, as locals describe the tide as running higher up the Heathcote River afterward (Pettinga et al., 2001).

5 December 1881 (*Castle Hill Earthquake, M ~6.0*)

Sand fountaining occurred at Lake Sarah near Cass (Enys, 1882).

1 September 1888 (*Amuri Earthquake, M 7.0–7.3*)

Liquefaction was evident near Glynn Wye, causing the formation or enlargement of large pits and sandblows. On the West Coast the strongest shaking was reported from the Otira Gorge, where new springs were observed and a large fissure was reported to have formed in Kelly’s Creek (Pettinga et al., 2001).

16 November 1901 (*Cheviot Earthquake, M 6.9 +/- 0.2*)

Shaking of MM VII was recorded in Christchurch, and similar or somewhat greater shaking would have occurred in Kaiapoi. Contemporary newspapers and scientific papers contain several reports of ejected sand and water in the epicentral region near Parnassus, and other incidents of lateral spreading due to liquefaction. Minor liquefaction occurred at Waikuku and Leithfield beaches. The most widely reported cases of liquefaction occurred in Kaiapoi, about 90 km south of the estimated epicentre. These reports and subsequent studies are discussed in detail by Berrill et al. (1994), who estimate that liquefaction occurred over an area of 2-3 town blocks at the eastern end of Sewell and Charles Streets on the north bank of the Kaiapoi River and probably extended east to the Waimakariri River (Pettinga et al., 2001).

25 December 1922 (*Motunau Earthquake, M 6.4*)

Intensities of at least MM7 were experienced in Rangiora, with liquefaction effects reported along the Pegasus Bay coast (Pettinga et al., 2001). It appears from press reports that water ejection occurred behind the sandhills at Waikuku, and liquefaction leading to the loss of soil strength caused a tree to topple and motor cars to become bogged at Leithfield Beach (McCahon, 2011).

It should be noted that liquefaction resulting from the above historic earthquakes may also have occurred in some places outside these areas, but without ejecta rising to the surface. Where no ejecta is seen it is very difficult to detect liquefaction, but that does not mean it has not occurred and remained confined.
A3.2 MAPPING THE LIQUEFACTION OF THE SEPTEMBER 2010 AND FEBRUARY 2011 CANTERBURY EARTHQUAKES

A3.2.1 Introduction

Ground shaking during the September 4, 2010 (Mw 7.1) Darfield Earthquake reached peak ground acceleration values of up to 1.25 g, causing widespread land damage due to liquefaction. Liquefaction can occur in saturated, poorly consolidated sediments. During earthquake shaking, soil particles are rearranged and attempt to compact. Water is forced out of pore spaces and the grains are no longer able to support an overburden weight. If the pressurised water is able to escape to the ground surface, e.g. through cracks, it can take silt and sand with it, forming sand boils and causing surface flooding. The expulsion of water and silt causes a volume decrease, and the result is surface subsidence. Lateral spreading can also occur, particularly close to waterways, where there is typically a high water table and unconfined ground is able to move sideways on liquefied ground at depth. This is manifest as cracking and differential settlement of the affected ground.

Immediately following the Darfield Earthquake, digital satellite images and aerial photograph mosaics were obtained for the wider Canterbury region, covering the area affected by liquefaction based on incoming reports from the region (Figure A3.2). Examination of the images confirmed the presence of widespread liquefaction in rural areas and localised damage in the Christchurch urban area (near the Avon River) and at Kaiapoi. GNS Science was tasked by Environment Canterbury to produce a map (including a GIS layer) of rural areas affected by liquefaction during the Darfield Earthquake. Observations of liquefaction and lateral spreading in the main urban residential areas affected by liquefaction were mapped on the ground by Tonkin & Taylor Ltd. on behalf of the Earthquake Commission.

The February 22, 2011, Christchurch Earthquake caused more substantial damage to land in eastern Christchurch than occurred in the 2010 Darfield Earthquake, and moderate amounts of liquefaction in rural areas. After the acquisition of new aerial photographs and satellite images, liquefaction mapping was undertaken by Environment Canterbury/GNS Science in the same manner as for the Darfield Earthquake (Figure A3.3). Ground-based mapping of liquefaction and lateral spread observations was undertaken by Tonkin & Taylor Ltd. across the Christchurch urban area. Data were also received and incorporated from Geotech Consulting Ltd, Lincoln University and University of Canterbury.

One of the difficulties encountered was that different types and resolutions of images affect the certainty of interpretations and consequently the precision of mapping. The mapping for the Darfield Earthquake heavily relied on various high-resolution aerial photograph mosaics from New Zealand Aerial Mapping (NZAM) and on slightly lower resolution satellite images (See Figure A3.2 for details). The NZAM aerial photograph mosaics have ground resolutions of 0.25 m, and there was generally no problem discerning the effects of liquefaction (see below). Elsewhere, using relatively low resolution satellite images, with ground resolutions of 0.5 m or lower, it was more difficult to distinguish liquefaction, but there were still unmistakeable patterns of land damage. Farther afield from the main centres, where mapping was done using 0.5 m resolution Worldview satellite images, it was harder to detect surface damage. In the north of the area assessed, only 0.5 m resolution black and white (b/w) images were available, in which it was very difficult to detect damage features. Mapping based on the b/w Worldview images is of a lower quality than in areas covered by colour images.
Figure A3.2  Aerial photo and satellite coverage for the 4 September 2010 Darfield Earthquake.
Figure A3.3  Aerial photo and satellite coverage for the 22 February 2011 Christchurch Earthquake.
Another difficulty was that in September 2010 there was a lot of surface water ponding, which tended to obscure the underlying paddocks. This may have been as a result of liquefaction/ground shaking or from a wet winter (or both).

For the February 2011 Christchurch Earthquake we generally had better imagery than previously. The 0.1 m resolution NZAM photo mosaic has outstanding clarity and definition, and it covers most of the affected area.

### A3.2.2 GIS mapping methodology

Mappers experienced in the interpretation of ground surface features from images carried out the work. Images were visually assessed on screen using ArcMap GIS. Specific areas (polygons) were drawn within the GIS by eye. For each polygon, descriptive information (attributes) was assigned, including a general “code” and a notation, along with several other attribute fields pertaining to the image source and the name of the person who mapped the polygon. The scale of mapping depended on the resolution of the images, but was generally in the order of 1:1000 for 2010 photo mosaics and satellite images, and 1:500 for very high resolution (0.1 m pixel resolution) aerial photos (see Figures A3.4 to A3.8). Colour images were much better than black and white for identifying features on the ground; however for some areas, only black and white images were available. In general, images with pixel resolutions coarser than 1 m did not have enough detail for mapping liquefaction damage.

The maps that have been produced (Figures A3.9a to 3.10d) provide an overview of areas that were affected by liquefaction but are not able to show the amount of detailed mapping that was done; the GIS dataset (CD enclosed) is better at displaying the high resolution mapping and also contains site visit and quality assurance information.

### A3.2.3 GIS categories for the shapefiles

The mapped polygons have been grouped into the categories of liquefaction, flooding-sediment, flooding-water, old-flooding or unknown, and they are attributed in the GROUP field.

#### Liquefaction

The liquefaction category comprises areas of lateral spread and ground surface sedimentation resulting from liquefaction, usually where a vent area can be related to that sediment. Large areas with several sand boils and/or fissures were commonly incorporated into “ejecta fields” (individual sand boils were not mapped separately). Also mapped in this category are areas of obvious lateral-spread damage. APPEARANCE: pale to dark grey sand and silt covering roads and in paddocks. Often manifest as overlapping or en-echelon fissures or individual sand boils (vents) with ejected sediment. Lateral spreading is indicated by fissures or cracks without visible sediment ejecta.

#### Flooding – sediment

This category includes areas of surface sedimentation, but for which no vent area could be directly related – probably the result of liquefaction close by, but may also include secondary “run off”. APPEARANCE: dark grey (where wet) or pale grey to pale brown sediment in paddocks or on roads; typically not thick enough to entirely mask the ground surface features.
Flooding – water

Large areas of standing surface water and saturated ground, and flooded drains were possibly the result of (temporary?) alteration of the water table due to ground shaking; they may also be due to a very wet winter prior to the Darfield Earthquake (not as apparent for February 22). APPEARANCE: darker colour than the surrounding land but, depending on the depth of the water, crop/grass textures may still be visible.

Unknown

In some areas features resembling liquefaction or surface sediment can be seen on the images, but their origin(s) are uncertain. They are possibly the result of liquefaction, but could also be anthropogenic/agricultural. APPEARANCE: mottled ground or subtle darker patches in paddocks.

Other (sand dunes, landslides)

In coastal areas, bare sand forming dunes was initially mapped as liquefaction, but later comparison with pre-earthquake images suggested that these were pre-existing features. In some steeper areas of the Port Hills, debris flow paths (landslides) could be mapped from the GeoEye image. These are likely a result of the very wet/saturated ground, and some were noted to have occurred before the Darfield Earthquake. APPEARANCE: sand dunes appear as patches of bare sand/soil, commonly with shadows caused by relief. Landslides appear as brown streaks of bare soil in valleys and can usually be traced back to a source area or head scarp.

Old flooding

A new category was added to the assessment for the February 22 earthquake. This includes areas that were under water in the September 2010 images, but were dry in February 2011 and subsequently remained as bare ground or were overgrown by weeds. APPEARANCE: patches of bare soil (grey to brown) or areas of new vegetation, sometimes with discrete white spots (flowering plants - yarrow?).

Agricultural, Anthropogenic

Some polygons that had been mapped as “liquefaction” were subsequently re-categorised as agricultural or anthropogenic (or unknown) as a result of review of the mapping (quality assurance (QA) process - see below). Where polygons were reclassified, it was because features in the images, although resembling liquefaction, were judged more likely to be crop patterns/textures resembling liquefaction, hay feed-out lines, or bare ground along fences and in gateways, etc. These reclassified polygons were retained in an archived version of the dataset, as they may have value for future research into the interpretation of imagery.

Polygons identified as “agricultural” or “anthropogenic” are not included in the final dataset, as it is unlikely they are related to liquefaction. APPEARANCE: mottled darker or lighter ground within paddocks. Typically these features may be in a regular pattern, or are restricted to one or two paddocks and do not cross fence lines, suggesting that they are man-made.
Examples

Figure A3.4.1  Liquefaction (sand boils, cracking/lateral spread and fissures) east of Kaiapoi, September 2010. Image is NZAM CANT_ortho_Kaiapoi; centre of view approximately 1573200, 5195800 (NZTM). Rectangle indicates location of detail shown in Figure A3.4.2.

Figure A3.4.2  1:1 pixel resolution detail of Figure A3.4.1.
Figure A3.5  Liquefaction at Rawhiti, south of Halswell, September 2010. Damage includes cracking/lateral spread of the road, and sand boils and flooding (including sedimentation) in the paddocks (image Christchurch_GeoEye_4-9-10-All_data_Ortho.ecw; centre of view approximately 1564800, 5173000).

Figure A3.6  Sand boils and surface flooding across Carters Road, southwest of Tai Tapu, September 2010 (image Selwyn_DG_12_Sept_2010.img; centre of view approximately 1560000, 5164000).
Figure A3.7  Liquefaction adjacent to the Styx River, west of Brooklands, February 2011. This area was also affected in September 2010 (image NZAM_mosaic_03_03_2011.ecw; centre of view approximately 1574970, 5194550).

Figure A3.8  New (darker grey/wet) and old (paler grey/dry) sand boils west of Lansdowne, February 2011 (image NZAM_mosaic_03_03_2011.ecw; centre of view approximately 1565000, 5171530).
**Levels of certainty**

Each polygon has been attributed with a level of certainty and the ADOPT_CERT field should be used with the GROUP field when displaying the polygons. The ADOPT_CERT field relates to the level of certainty placed on the GROUP classification, with four categories: certain, probable, possible and uncertain. This is an overall assessment that takes into account all external quality assessment comments by Landcare Research (see below) and assessments from site visits. The legend on the attached printed maps displays the liquefaction mapping by GROUP and ADOPT_CERT. Because of the small scale at which the maps have been printed, it is difficult to see all levels of certainty. The different colours for the “probable”, “uncertain” and “unknown” fields are more clearly seen in the larger scale maps provided. In areas greatly affected by liquefaction, most polygons are attributed as “certain”.

**A3.2.4 Internal data review (quality assurance) process**

GNS Science undertook some desk-based verification of the digitised polygons. This quality assurance (QA) process involved a check and re-evaluation of every polygon by another mapper. This “second look” meant that sometimes the initial classification of the polygon was changed, and occasionally more liquefaction was noted (which was subsequently QA’d by another mapper). Fields within the shapefile show the QA process:

- **ORIGINATOR** - initials of the person who mapped (interpreted and digitised) the feature.
- **ORIG_NOTE** - brief description or comment about the feature made by the “originator” at the time of mapping.
- **GNS_QA** – identifies via their initials the person who has reviewed the digitised polygon, prior to external QA.
- **GNSQA_NOTE** - additional comments about the digitised polygon made by the GNS QA person.

**A3.2.5 External quality assurance process**

External quality assurance review of the earthquake liquefaction mapping was provided by staff from Landcare Research. Spot check locations were selected by generating a series of random points both within and outside of the polygons, and the imagery at those locations was re-examined (Belliss & Lynn, 2012). Polygon extents and attributes were reassessed where there was disagreement with the original classification and the polygon re-categorised, or the level of certainty downgraded, as necessary. In some cases, additional areas of liquefaction were identified and polygons added accordingly. The EXTRNAL_QA field identifies which polygons have been assessed and incorporates any relevant comments.

Belliss and Lynn (2012) commented that GNS Science had not mapped the main urban areas of greater Christchurch for the February 2011 earthquake, even though these areas were clearly affected by liquefaction. The reason for this is that these areas were outside the scope of the project brief of “rural areas affected by liquefaction”. Liquefaction in these urban areas was mapped by Tonkin & Taylor.
A3.2.6 Site visits

Site inspections were carried out at selected locations to confirm or otherwise the interpretations made from the aerial and satellite imagery. Greg Curline (Lincoln University) carried out site inspection of some areas of liquefaction mapped from imagery during the summer of 2011-2012. In some cases, it was unclear as to whether the mapping of liquefaction was correct, as evidence of liquefaction was no longer obvious.

Also, some of these polygons are attributed as showing no evidence of liquefaction from field checks, but liquefaction can be clearly seen in the aerial photographs. The ADOPT_CERT field takes into account these discrepancies and provides an overall assessment of the polygon. More details about Greg Curline’s field checks are available in his report (Curline 2012).

Site visits were also undertaken by the University of Canterbury, Tonkin & Taylor, Beca and GNS Science (attributed as SITE_VISIT).

Tonkin & Taylor’s parcel-based liquefaction data is not displayed on the September 2010 printed maps where aerial photo mapping by GNS Science is available. However, Tonkin & Taylor mapping is shown on the February 2011 maps for the main urban areas of greater Christchurch where there was no aerial photo mapping done by GNS Science. Tonkin & Taylor’s shapefile data for both the September 2010 and February 2011 earthquakes were incorporated into the liquefaction datasets (attributed as T&T in the ORIGINATOR field).
A3.2.7 Maps of liquefaction during the 4 September 2010 and 22 February 2011 earthquakes

Figure A3.9a Total coverage of liquefaction mapping for the September 2010 Darfield earthquake. See following figures for detail from Kaiapoi, Christchurch city and the Halswell River area. The Tonkin & Taylor field data is not displayed on this map.
Figure A3.9b  Larger view of the liquefaction map of the northern city and Kaiapoi for the September 2010 Darfield earthquake.
Figure A3.9c  Larger view of the liquefaction map of the Christchurch CBD for the September 2010 Darfield earthquake.
Figure A3.9d Larger view of the liquefaction map of the Halswell River area for the September 2010 Darfield earthquake.
Figure A3.10a Total coverage of liquefaction mapping for the February 2011 Christchurch earthquake. See following figures for detail at Kaiapoi, Christchurch city and the Halswell River area.
Figure A3.10b Larger view of the liquefaction map of the Kaiapoi area for the February 2011 Christchurch earthquake.
Figure A3.10c: Larger view of the liquefaction map of Christchurch city for the February 2011 Christchurch earthquake. Mapping for this area is mostly from Tonkin & Taylor site visit information.
Figure A3.10d Larger view of the liquefaction map of the Halswell River area for the February 2011 Christchurch earthquake.
REFERENCES


APPENDIX 4: REVIEW OF EXISTING CANTERBURY LIQUEFACTION SUSCEPTIBILITY AND HAZARD MAPS

The GIS layers of the areal extent of liquefaction during the 4 September 2010 Darfield Earthquake and the 22 February 2011 Christchurch Earthquake (as described in Appendix 3) were used for a qualitative comparison with previous predictions of liquefaction occurrence.

The previous studies created liquefaction susceptibility maps based on: (a) a review of the near-surface geology and hydrogeology; or (b) calculations of liquefaction potential based on geotechnical data and assumed earthquake characteristics (peak ground acceleration, earthquake magnitude and epicentral distance) that correspond to an assumed average recurrence interval or specific earthquake scenario. The earthquake scenarios typically comprise an Alpine Fault earthquake, a nearby large earthquake corresponding to a known fault, or a smaller random (“distributed”) earthquake occurring on an unknown fault.

The specific liquefaction susceptibility/hazard maps that were reviewed are:

- The Earthquake Hazard in Christchurch: A Detailed Evaluation (Elder et al., 1991)
- Geology of the Christchurch urban area (Brown & Weeber, 1992)
- Risks and Realities (Christchurch Engineering Lifelines Group, 1997)
- Liquefaction assessment of Waimakariri District (Beca, 2000)
- Liquefaction assessment of Christchurch City (Beca, 2002–2005)
- Earthquake hazard assessment for Selwyn District (Yetton & McCahon, 2006)
- Earthquake hazard assessment for Waimakariri District (Yetton & McCahon, 2009) and
- Christchurch liquefaction study update (Beca, 2012).

A4.1 CHRISTCHURCH URBAN AREA (ELDER ET AL. 1991)

In an assessment of the Christchurch urban area, Elder et al. (1991) included a map of soil types’ susceptible to liquefaction, a map of depth to groundwater, and a seismic hazard map showing general areas of severest shaking amplification. The susceptible soil types map was the closest to a liquefaction hazard map. It was based on soil type maps prepared from all subsurface data available at that time. No attempt was made to refine the map further, as there was very little data on soil density outside the CBD at that time. The authors concluded that a substantial area of Christchurch was underlain with sand that would be susceptible to liquefaction if sufficiently loose, including the eastern city and parts of Merivale, Spreydon and Hoon Hay.

7 In this Appendix, ‘soil’ refers to ‘engineering soil’, meaning an unconsolidated or very weak geological material.
Much of the liquefaction that was recorded during the September 2010 and February 2011 earthquakes occurred in areas predicted by Elder et al. (1991) to be highly susceptible. However, the areas northwest of the CBD experienced significant liquefaction during the February 2011 earthquake that Elder et al. did not predict to be significantly susceptible to liquefaction.

**A4.2 CHRISTCHURCH URBAN AREA (BROWN AND WEEBER 1992)**

As part of a summary publication on the geology of the Christchurch area, Brown and Weeber (1992) presented a map (their Figure 72, page 84) showing areas that are predicted to be susceptible to liquefaction, based on the dominant grain-size of the near-surface strata and likely depth to groundwater. The map (Figure A4.2) only indicates areas where there is potential for earthquake-induced foundation failures to occur, and recognises that subsurface soils in Christchurch are extremely variable over short distances, both horizontally and vertically. This study does not assume a particular intensity of shaking, but indicates that the central and eastern areas of the city are susceptible to liquefaction and the western part of the city is generally not susceptible to liquefaction. The accompanying text recommended site-specific investigations for foundations for all but the lightest of structures and cautioned against extrapolating conditions from adjacent sites.
In comparison to the liquefaction caused by the Darfield and Christchurch earthquakes, the Brown and Weeber (1992) assessment correctly predicted that the eastern and central parts of the city would experience liquefaction in strong shaking.

**A4.3 RISKS AND REALITIES (1997)**

A map of liquefaction susceptibility zones was produced as part of the *Risks and Realities* report of the Christchurch Engineering Lifelines Group in 1997. This map, which had been compiled 4 years previously in 1993, was based on the Elder et al. (1991) map, with the addition of a depth-to-groundwater table cut-off to the east and an extension north to the Waimakariri River. An estimation of how much of the susceptible areas might be affected was added to assist the lifeline users. The map (Figure A4.3) delineated two zones determined by soil type and depth to groundwater. However, the zones do not take into account:

- areas of gravel or peat within the zones, which would not liquefy;
- localised areas within the zones that have high topography and therefore greater depth to groundwater, and thus would not liquefy;
- soil density variations.
Figure A4.3 Seismic and Liquefaction hazard map for Christchurch, from “Risks and Realities” (1997).

Zone A (high susceptibility) delineates areas underlain predominantly by sands 2-10 m deep, and where depth to groundwater is generally 1-1.5 m. Twenty to thirty percent of Zone A could liquefy (most likely estuarine sediments), and lateral spreading of some river banks is likely.

Zone B (moderate susceptibility) delineates areas underlain predominantly by silts and sandy silts 2-5 metres or more deep, and where depth to groundwater is generally 1-2 m. Ten to fifteen percent of Zone B could liquefy and lateral spread of river banks is likely to be of limited extent.

Widespread liquefaction in eastern Christchurch during the September 2010 earthquake is consistent with the prediction that “20 to 30%” of this area “could liquefy”. The February 2011 earthquake appears to have caused more liquefaction than predicted in the CBD and areas northwest of the CBD.

A4.4 WAIMAKARIRI DISTRICT (Beca 2000)

Beca undertook a study for Environment Canterbury on the liquefaction susceptibility of Waimakariri District, focussed on the area within 5-10 km from the coast. The study collated available subsurface and geological data for the study area, supplemented by 29 boreholes with standard penetration (SPT) testing to provide in situ test data with which to quantify the liquefaction potential. The borehole data were analysed for two earthquake scenarios – an Alpine Fault earthquake and a foothills earthquake (Beca, 2000).

The results were summarised in a map (Figure A4.4) showing areas of high, medium or low susceptibility to liquefaction and maps of estimated settlement for each of the two scenarios.
Beca (2000) correctly predicted that strong earthquake shaking would cause liquefaction in east and central Kaiapoi and to the east of Kaiapoi. Minor liquefaction was also observed within the medium susceptibility zone north of Kaiapoi during the September 2010 earthquake; however peak ground accelerations were comparatively low in this area.

A4.5 CHRISTCHURCH CITY (Beca 2002-2005)

The Beca liquefaction study of Christchurch City was initiated by Environment Canterbury in 2001 and aimed to improve on earlier liquefaction susceptibility maps, which were based mainly on soil type and depth to groundwater, by incorporating soil strength data into the liquefaction analysis.
Stages 1 and 2 of the study (Christensen, 2002) reviewed and collated available geological and geotechnical data held by Environment Canterbury and Christchurch City Council and produced liquefaction potential and ground damage maps. The maps were generated using a liquefaction prediction formula based on the Simplified Seed procedure. An Alpine Fault earthquake scenario with three different peak ground accelerations was used to obtain a sensitivity analysis for soil liquefaction, and the model incorporated depth to groundwater data from Brown and Weeber (1992).

Stage 3 of the study reviewed the availability and usefulness of geotechnical data held by other organisations. Stage 4 of the study (Christensen, 2004) updated the Stage 2 liquefaction hazard and ground damage maps with further data collected from these other organisations, and included two additional maps indicating sensitivity of liquefaction to groundwater levels.

Stage 4a of the study (Clough, 2005) used revised groundwater levels and adjustments to the liquefaction prediction algorithm to produce liquefaction potential and ground damage maps for both average summer (low) and average winter (high) groundwater levels. The figures from Stage 4a are presented in this report as Figures A4.5 and A4.6.

While the Beca maps gave a useful overview of liquefaction susceptibility in Christchurch city, they still could not replace a site-specific investigation because soil properties are so variable over short distances.

Figure A4.5  Liquefaction hazard map for Christchurch city – summer groundwater level, from Clough (2005).
Conditions at the time of the September 2010 earthquake, in conjunction with the measured ground accelerations in Christchurch, correspond most closely with the winter groundwater level, Scenario 2 peak ground acceleration. The Beca liquefaction hazard map ground damage map correctly predicted widespread liquefaction north and east of the central city. However, the map also predicted widespread liquefaction south of the CBD, where little occurred during the 10 September 2010 earthquake, despite the recorded peak ground accelerations. The map also appears to under-predict liquefaction in the Halswell area. The map also slightly under-predicts liquefaction in the Dallington, Wainoni, Avondale and Burwood areas.

The February 2011 earthquake does not correspond well with the predicted distribution of liquefaction, though this probably reflects, at least in part, the added complexity of large variability in peak ground accelerations from place to place across Christchurch.

A4.6 SELWYN DISTRICT (YETTON AND MCCAHON 2006)

A district-scale liquefaction potential map was developed for the whole of Selwyn District by Geotech Consulting as part of the Earthquake Hazard Assessment for Selwyn District (Yetton and McCahon, 2006), commissioned by Environment Canterbury. This map (Figure 4.7) is based primarily on surface geology (derived from published geological maps), with some interpretation of subsurface information from available borelogs and groundwater information from the Environment Canterbury Wells database, and local knowledge from limited site specific investigations. Geotechnical data, such as Cone Penetration Tests (CPTs), were not analysed.
Liquefaction potential for most of the district was classed as nil, very low or low. Only the low-lying areas around the Port Hills/Banks Peninsula and Lake Ellesmere were considered to have moderate liquefaction susceptibility. The boundaries between the zones are approximate and do not indicate that liquefaction will or will not occur in the zone in any given earthquake. The zones are indicative of the relative susceptibility.

Given the large areal extent of the Selwyn District project, the boundary between the areas of moderate and low risk could not be located precisely. The available borelogs in the area indicate a complex sedimentary environment and the boundary between the zones is likely to be much more variable than indicated on the map, with tongues of gravel (lower susceptibility) extending into silt-dominated sediments (higher susceptibility). Published maps of surface soil types guided the placement of the low risk/moderate risk zone boundary, with the boundary drawn to coincide approximately with the distinction between lowland and swamp soils, as distinct from the gravelly soils of the Waimakariri fan (Raeside and Rennie, 1974). The boundary also coincides with the western extent of flood ponding in the Tai Tapu/Greenpark area.

This map was the only liquefaction susceptibility map that was available for Selwyn District prior to the September 2010 Darfield Earthquake.

Figure A4.7  Liquefaction susceptibility map for Selwyn District, from Yetton and McCahon (2006).

Liquefaction as a result of the September 2010 and February 2011 earthquakes occurred mostly in the area mapped as moderate susceptibility with a small amount in the area mapped as low susceptibility. This map provides a good prediction of areas with a significant susceptibility to liquefaction, as demonstrated in the 2010-2011 earthquakes.
A district-scale liquefaction potential map was developed for the whole of Waimakariri District by Geotech Consulting as part of the Earthquake Hazard Assessment for Waimakariri District (Yetton and McCahon, 2009) commissioned by Environment Canterbury. For most of the district, this map (Figure A4.8) is based primarily on surface geology (from published geological maps), with some interpretation of subsurface information from available borelogs and groundwater information from the Environment Canterbury Wells database; geotechnical data (such as CPTs) were not analysed. Liquefaction potential for most of the district was classed as nil, very low or low.

Only the low lying coastal part of Waimakariri District was delineated as having highly variable (low to high) liquefaction potential. Subsequent to the Beca (2000) report for Waimakariri District, extensive investigation and construction work was undertaken for the development of Pegasus township between Woodend and Waikuku. Waimakariri District Council commissioned three geotechnical assessment studies as part of a long-term strategy for future urban growth, and investigations were undertaken for the construction of the Eastern Districts Sewerage and Ocean outfall project. This 2009 study analysed the new data, along with available surface geology (from published geological maps), the 1995 Ashley floodplain geomorphological map (from the Ashley River Floodplain Management Plan) and Environment Canterbury borelogs and groundwater information. While not using the same analytical methods as the Beca (2000) study, the 2009 study showed that the liquefaction susceptibility in eastern Waimakariri district was in fact much more variable than previously suggested, and that liquefaction susceptibility was extremely difficult to predict without a site-specific investigation.

This 2009 study shows that the actual boundary between different areas of liquefaction susceptibility would be very difficult to determine and instead takes a simple approach of aligning the boundary of the potentially liquefiable coastal zone with a projected 5 metre contour on the original river fan surface prior to sea level rise post-6,500 years ago. This marks approximately the furthest extent of marine inundation and the limit of all estuarine and marine deposits. The contour can be reasonably well inferred between the Cam River and Sefton, and close to the Waimakariri River. To the north of the Ashley River there is a well-defined boundary, based on surface soil types, between older alluvium and recent Ashley floodplain deposits, and an abandoned sea cliff 0.5 km west of State Highway 1 at the northern extremity of the district. The boundary was not intended to signify that liquefaction will occur to the east and not to the west – it simply delineated the coastal area where significant and widespread liquefaction is likely to be an issue.
Observations following the September 2010 and February 2011 earthquakes suggested that nearly all of the liquefaction occurred in the coastal strip and relatively little occurred inland. This map generally provided a good prediction of areas with significant susceptibility to liquefaction, though for the February 2011 event it over predicted for some of the south, west and northwest parts of the city – liquefaction did occur in these areas, but in a much more sporadic pattern than the map suggests.

A4.8 CHRISTCHURCH UPDATE (BECA 2012)

Beca’s 2004/2005 model for Christchurch city has recently been re-run to include the actual peak ground accelerations and anticipated groundwater levels experienced during the September 2010 Darfield and February 2011 Christchurch earthquakes. The updated mapping adopted the same liquefaction modelling technique as that used in 2004/2005.

Each earthquake event was modelled with two different groundwater scenarios, being: the best fit scenario from the 2004 study; and the current 2012 model of groundwater levels (Beca 2012). The models analysed were:

- September 2010 peak ground accelerations combined with 2012 groundwater model (Figure A4.9);
- September 2010 peak ground accelerations combined with the 2004 winter groundwater model (Figure A4.10).
- February 2011 peak ground accelerations combined with 2012 groundwater model (Figure A4.11);
- February 2011 peak ground accelerations combined with the 2004 summer groundwater model (Figure A4.12);
It is noted that the goal of the groundwater mapping to date has been to create conservative models to ensure that a conservative value is used for liquefaction potential.

Figure A4.9 Updated liquefaction hazard map for Christchurch using September 2010 peak ground accelerations combined with the 2012 groundwater model (Beca, 2012).

Figure A4.10 Updated liquefaction hazard map for Christchurch using September 2010 peak ground accelerations combined with the 2004 winter groundwater model (Beca, 2012).
Figure A4.11 Updated liquefaction hazard map for Christchurch using February 2011 peak ground accelerations combined with the 2012 groundwater model (Beca, 2012).

Figure A4.12 Updated liquefaction hazard map for Christchurch using February 2011 peak ground accelerations combined with the 2004 summer groundwater model (Beca, 2012).
The Beca 2012 assessment over-predicts the liquefaction that occurred during the September 2010 earthquake, predicting that significant liquefaction would have occurred in central, southern and western Christchurch during that earthquake. However, the assessment predicts reasonably well the liquefaction that occurred during the February 2011 earthquake, with the exception of under-prediction of liquefaction in the Wainoni and Halswell areas. Two different groundwater surfaces modelled by Beca predict a slightly different extent of liquefaction. However, inadequate groundwater level data from the shallow strata around Christchurch has meant that accurate modelling of groundwater levels at the time of each earthquake is not possible.

A4.9 **KEY CONCLUSIONS**

In all of the reviewed studies, observed liquefaction in the September 2010 and February 2011 earthquakes generally occurred in areas where liquefaction susceptibility was predicted to be relatively high. A number of small areas recorded as having experienced liquefaction during these earthquakes were located in areas mapped as having a relatively low susceptibility to liquefaction. The most notable difference between the observed and predicted liquefaction relates to the significant areas predicted to be vulnerable to liquefaction where in fact no significant liquefaction damage occurred.
REFERENCES


APPENDIX 5: GEOLOGICAL INFORMATION RELEVANT TO THE LIQUEFACTION HAZARD ASSESSMENT AND LIQUEFACTION SUSCEPTIBILITY ZONING

A5.1 INTRODUCTION

A definition of the terms liquefaction susceptibility and liquefaction potential is useful in the discussion below. Liquefaction susceptibility is a term that refers to the physical state of materials that determines whether they have the “ability” (suitable physical characteristics) to liquefy. Liquefaction potential is a concept that incorporates liquefaction susceptibility plus the nature of ground shaking for specific earthquake scenario events that may induce a state of liquefaction (Obermeier et al., 2005). Holzer (2008) discusses the use of probabilistic liquefaction hazard maps which can display liquefaction potential for a scenario event or for a uniform hazard level.

This appendix describes and evaluates the information sets that provide knowledge of the geological materials relevant to liquefaction susceptibility beneath the liquefaction hazard project area. The geological information broadly comprises ground-surface data sets, and sub-surface data sets. The ground-surface data sets include topographic maps, detailed imaging of ground-surface topography (terrain) using LiDAR, and maps of the distributions of soil types and landforms (geomorphology). The sub-surface data sets include maps of the distributions of rocks and sediments (geological maps), records of geological materials intersected in drillholes (drillhole data), logs from geotechnical bores or probes (geotechnical data) and depth to the unconfined water table (groundwater data). First, we provide a summary of the geological setting of the project area (Section A5.2), followed by a description of the various data sets contributing to the regional liquefaction susceptibility assessment (Sections A5.4 to A5.8). An overview of the methodological approach used to integrate these various data sets is provided in Section A5.9.

A5.2 GEOLOGICAL SETTING

The area covered by this report comprises the eastern part of the Canterbury Plains and Banks Peninsula. The underlying basement rock consists of hard or firmly indurated sandstone and mudstone (known respectively as greywacke and argillite), with some volcanic rocks, formed between the start of the Permian Period (~300 million years ago (Ma)) and the middle of the Cretaceous Period (~100 Ma). A cover of sedimentary and volcanic rocks was laid down over the basement rocks from the latter part of the Cretaceous Period (~80 Ma) through to the middle part of the Quaternary Period (~1 Ma). Within this drape of cover rocks, a large composite volcano was constructed during the latter part of the Miocene Epoch between ~11 and ~6 Ma. This volcanic massif, although now much eroded, forms Banks Peninsula (Figure A5.1).

Over the past 25 million years or so, tectonic deformation caused by the collision of the Australian and Pacific plates has resulted in uplift of the Southern Alps and the ranges of northern Canterbury and Marlborough, including the Canterbury foothills overlooking the project area from the northwest. Much of the cover rocks have been eroded away in the foothills, exposing the basement rock (Figure A5.1).
Figure A5.1 Geological setting of the project area. Geology is from the GNS Science QMAP digital database (Cox & Barrell, 2007; Forsyth et al., 2008). Faults related to the 2010-2011 earthquake sequence include the ground-surface rupture marked by the Greendale Fault (Barrell et al., 2011; Quigley et al., 2012), and subsurface faults defined by geodetic modelling (Beavan et al., 2012) and by clusters of epicentres within the aftershock pattern (J.R. Pettinga, personal communication, May 2012).

The Pleistocene Epoch, which began at ~2.6 Ma, was characterised by ice ages, in which episodes of cooler climate were interspersed with phases of warmer interglacial climate, such as the past ~12,000 years of the present Holocene Epoch. Large volumes of sediment generated during cycles of glaciation in the Southern Alps were carried eastwards via the river systems and deposited on the Canterbury Plains. Beneath the plains and offshore, the basement rocks are still overlain by cover rocks, but the cover rocks (including the flanks of the Banks Peninsula volcanoes) are blanketed by mid- to Late Pleistocene and Holocene sediments that in places are up to several hundred metres thick (Jongens et al., 2012).

Near the Canterbury coast, through several glacial/interglacial cycles, low sea levels during glacial periods and high sea levels during interglacials have produced an interfingering of river gravels with coastal sand, silt, clay and peat (Figure A5.2). During the most recent phase of this cyclic pattern, the sea, which was at its glacial minimum level (about 125 m below present sea level) ~18,000 years ago, progressively rose to its present level by ~6,500 years ago, in the middle of the Holocene Epoch. During this period, a wedge of fine-grained
shallow marine and coastal sediment (Pegasus Bay Formation/Christchurch Formation) was deposited over glacial outwash (Burnham-Windwhistle Formations/Riccarton Gravel/Canterbury Bight Formation (upper)) (Figure A5.2). The age of the base of these marine deposits becomes progressively younger to the west. By 6,500 years ago the shoreline had transgressed to a position beyond the inland extent of Lake Ellesmere, west of Hagley Park in Christchurch, west of Kaiapoi, Woodend and just east of Leithfield. Since the 6,500 year sea level was attained it has remained near its present level, and river sediment has built up (Springston Formation) in unison with the accretion of beach and dune sediments (Christchurch Formation) along the coastal fringe. Since 6,500 years ago the shoreline has progressively migrated eastward to its present position (Figure A5.1). Lake Ellesmere is a former embayment of Canterbury Bight that has been enclosed by a beach-gravel barrier, Kaitorete Spit, while the Avon-Heathcote Estuary, enclosed by the Brighton Spit sand barrier, is a former part of Pegasus Bay, now largely infilled by river and coastal sediments. The post-glacial sea level rise drowned the lower reaches of the valleys of Banks Peninsula, creating the harbours and bays that we see today, while wave attack has created tall, actively eroding cliffs on many of the headlands. Over the past ~6500 years, sediments have built up in the main harbours and many of the larger bays.

Speight (1928) postulated a long-term trend of subsidence in the eastern Christchurch-Kaiapoi and Lake Ellesmere areas (see also Suggate, 1958; Brown & Weeber, 1992; Figure A5.2). In contrast, there are indications of ongoing long-term tectonic uplift north of about the Ashley River (Forsyth et al., 2008). No rates for these tectonic trends have yet been established.

![Figure A5.2 Interfingered glacial and interglacial Pleistocene to Holocene sediments beneath the coastal fringe of the Christchurch and Lake Ellesmere area are illustrated schematically in this geological section (after Brown and Weeber, 1992). River gravel formations (e.g. Burwood and Wainoni) extend well below glacial minimum sea level, indicating there has been a slow, long-term subsidence of the coastal fringe in the Christchurch and Lake Ellesmere areas.](image-url)
A5.3 GEOLOGICAL MAPS

Geological maps depict an interpretation of the geological materials of the near sub-surface (e.g. within the top 10 m or so), based on observation of the nature of these materials. For the most part, soil and vegetation obscure the underlying geological materials, and a geological map is typically based on observations made at scattered locations, from natural outcrops of rock or sediment, surface excavations such as for roads and buildings or at quarries, and drillhole records. Boundaries between different types of rock or soil are commonly positioned according to geomorphological considerations, such as the nature of landforms and soil types. A geological overview of the entire project area was provided by the first edition of the 1:250,000-scale Geological Map of New Zealand (Oborn & Suggate, 1959 – Christchurch sheet, and Gregg, 1964 – Hurunui sheet), and subsequent more detailed mapping covering the Kaiapoi area (Brown, 1973), the Canterbury Plains (Wilson, 1989) and Banks Peninsula (Sewell et al., 1992 and references therein). The most detailed map is that of Brown and Weeber (1992), covering the Christchurch urban area at a scale of 1:25,000. All of these information sources were included in the recent QMAP 1:250,000-scale geological map compilation of Forsyth et al. (2008).

A5.4 TERRAIN MODELS

High quality Light Detection and Ranging (LiDAR) digital elevation models (DEMs) and derivative hillshade images provide a very high resolution depiction of the form of the ground surface. Thus they provide detailed insights into the nature and origin of landforms, and in turn the likely character of the underlying geological materials. LiDAR DEMs can also be processed to distinguish areas with significant topographic slopes, a factor in identifying susceptibility to lateral spreading. LiDAR coverage is available for the Canterbury Plains/Port Hills sector of Christchurch City, all of Waimakariri District and most of the eastern part of Selwyn District within the area of interest. Areas not covered include a small area of the coastal plain north of Amberley, from the Waimakariri River south to Rolleston and Burnham, the area inland from Ellesmere around Leeston and Southbridge, and much of Banks Peninsula.

Pre-earthquake LiDAR data suites within the area of interest, primarily for the purpose of flood hazard research and management, were collected in 2003, 2005 and 2008 (see Table A5.2 for detail).

Following the September 2010 Darfield Earthquake, further suites of LiDAR acquisitions by AAMHatch and New Zealand Aerial Mapping (NZAM) followed each significant earthquake.
Table A5.1 LiDAR data sets with collection dates, providers, commissioning agencies and a description of general areas of coverage.

<table>
<thead>
<tr>
<th>Collection date</th>
<th>Provider</th>
<th>Commissioning agency</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-9 Jul 2003</td>
<td>AAMHatch</td>
<td>CCC</td>
<td>Christchurch City</td>
</tr>
<tr>
<td>6-11 Feb 2008</td>
<td>AAMHatch</td>
<td>Environment Canterbury &amp; SDC</td>
<td>Banks Pen., Ellesmere, Selwyn, Prebbleton</td>
</tr>
<tr>
<td>5 Sep 2010</td>
<td>NZAM</td>
<td>Environment Canterbury</td>
<td>Christchurch City, Greendale Fault.</td>
</tr>
<tr>
<td>8-10 Mar 2011</td>
<td>NZAM</td>
<td>MCDEM</td>
<td>Kaiapoi, eastern Christchurch City, Tai Tapu</td>
</tr>
<tr>
<td>20-30 May 2011</td>
<td>AAMHatch</td>
<td>CCC</td>
<td>Christchurch City, Lyttelton</td>
</tr>
<tr>
<td>18 &amp; 20 Jul, 11 &amp; 27 Aug, 2-3 Sep 2011</td>
<td>NZAM</td>
<td>EQC</td>
<td>Christchurch City</td>
</tr>
<tr>
<td>17-18 Feb 2012</td>
<td>NZAM</td>
<td>EQC</td>
<td>Kaiapoi, eastern Christchurch</td>
</tr>
</tbody>
</table>

Providers classified the acquired points into early and last returns, allowing the creation of a bare earth or terrain model by removing points for structures and vegetation judged to be higher than 0.5 m above the surrounding ground. Buildings and vegetation were removed by extrapolating elevations and slopes from surrounding last return points. Points, usually with a ground density of c. 2 points per square metre (usually better than averaging 1.2 m point separation, and each laser point footprint of c. 0.2 m), were modelled using the triangulation (TIN) method.

Metadata supplied with the source LiDAR indicates a vertical accuracy of ±0.07 to ±0.15 m (excluding GPS error and Geoid modelling error) and 0.40 to 0.55 m horizontal accuracy. The pre-earthquake LiDAR has lower accuracy and sparser LiDAR point sets than the post-earthquake sets. A post-February 2011 DEM was created from two partially overlapping LiDAR sets, with points taken from the more accurate 20-30 May set in preference to the 8-10 March set wherever the two sets overlapped.

Elevations from LiDAR were calibrated against land-based survey data supplied by Christchurch City Council, Land Information New Zealand and Environment Canterbury from surveys of their benchmark networks. All of the LiDAR elevation measurement points within a 1 m radius of each benchmark were extracted from each of the point clouds. The elevation difference between each measurement point and its adjacent benchmark were incorporated in a separate layer. The accuracy of the supplied survey data was not quantified.

GNS Science generated 1 m resolution DEMs for each LiDAR data suite from supplied *.las LiDAR last return point data, using LP360 software (2.0.0 Build 11). DEMs with colour-ramped elevations were viewed in combination with derived hillshades to provide geomorphologic information for mapping. These DEMs were also used to provide surface elevations for Cone Penetration Tests (CPT), drillhole collars and elevations of standing surface water for modelling depth to groundwater.

Slope maps were generated from LiDAR DEMs for the areas covered, providing information useful in determining susceptibility to lateral spreading.
A5.5 SOILS AND GEOMORPHOLOGY

A5.5.1 Introduction

The form and origin of the ground surface (geomorphology) generally reflects the nature of underlying geological materials, whether solid rock or a variety of poorly consolidated or loose sediments. Although records from the drilling of water bores, geotechnical probes or excavations provide direct information on subsurface materials, each of these points of information may lie a considerable distance apart. Thus, geomorphologic information provides an area-wide, general indication of what lies beneath the near-surface, i.e. within 10 m or so of the ground surface (Barrell et al., 2011), as well as providing insights into the processes such as erosion and deposition that have shaped the ground surface.

Until the development of LiDAR technology and acquisition of LiDAR datasets, topographic maps with elevation contours at 10-m or 20-m intervals were a major source of information on the form of the land surface. Aerial photographs, which for the Canterbury Plains include many sets of photos dating back to the 1940s, are an important resource of detailed information on the character of the ground surface. But LiDAR datasets provide information on the form of the ground surface to an unprecedented precision. This in turn allows construction of detailed elevation contours at intervals of 1 m, or less.

The nature of soils developed on any landforms is an expression of the underlying near-surface geological materials (i.e. the soil source material; Hewitt, 2010). Furthermore, the soil maturity is necessarily a function of the age of the landform upon which they are developed, climatic factors, drainage and the activity of processes that may modify these surfaces and their developing soils (Webb, 2008).

Soil maps are based on field surveys, involving observation of soil profiles by auger borings, soil pits or natural exposures. These observations, together with aerial photographs and inspection of the landscape, are used to delineate areas dominated by particular types of soil (soil map units). Soil maps are useful because they reflect the underlying geologic source materials and moisture conditions.

Based on LiDAR data (where available), soil maps, and as well as some insights into the nature and age (via radiocarbon dating) of subsurface materials from scattered drillholes or excavations, a geomorphological map has been constructed for the project area. In areas outside LiDAR coverage, geomorphologic mapping is based on topographic maps, aerial photos and soil maps (Fig. A5.3).
A generalised soil map for the project area is presented in Figure A5.4. The plains are dominated by fluvial soils, divided into five general age groups (Table A5.2). Towards the coast, these fluvial soils are adjoined by a variety of coastal soils associated with sand dunes, beach ridges, estuaries and salt marshes. The digital soil map (Webb, 2010) has its origins in a regional reconnaissance soil survey which, in the 1960s, was compiled onto a 2-miles-to-the-inch base map (Kear et al., 1967). The soil information from that map was re-examined and recompiled, with substantial revision of soil unit boundary positions, onto 1:50,000 scale topographic maps by T.H. Webb in the 1990s and 2000s (Webb, 2010), also incorporating information from more detailed soil surveys (e.g. Raeside & Rennie, 1974; Cox, 1978).

The fluvial soils of the Canterbury Plains vary in character and type according to variations in three major factors: soil parent material, soil drainage and soil age. The soil parent materials are almost ubiquitously derived from the basement rocks of the Canterbury foothills and
Southern Alps (see Section A5.2). As a consequence, the fluvial soils have a generally uniform mineral make-up, irrespective of age or drainage. An exception is peaty (Organic) soils, for which the parent material is organic matter.

Drainage is determined largely by particle-size distribution (texture), which most commonly reflects the flow regime of the river that deposited the sediment. Western parts of the project area are dominated by gravelly materials, while towards the coast, sands through to clays are more prevalent. Towards the west, the water table lies several metres or more below the ground surface, and away from modern river floodplains rarely if at all rises into the soil profile, further enhancing the well-drained nature of the gravel-dominated soils there. Closer to the coast, water tables at or close to the ground surface, compounded with slower permeability within the predominantly fine-textured deposits, results in imperfectly or poorly drained soils.

Finer-scale variability of soil patterns reflects the inherent complexity of the lower reaches of the river systems where, as revealed in the LiDAR imagery, there is a subtle topography of distributary channels, with sand bars or levees standing slightly higher than adjacent low-lying swamp basins. Well-drained sandy soils on the channel bars or levees pass progressively to finer textured and more poorly drained soils in the swamp basins. Prior to European drainage works, the lowest lying swampy areas would have had near-permanent standing water, within which organic material accumulated, giving rise to Organic Soils.

The degree of soil development, along with scattered information from radiocarbon dating of wood or charcoal within soil profiles, reflects the geologically-recent history of the plains. Late Pleistocene river plain surfaces have very well developed soil profiles (Lismore and Darnley age-groups), with Brown Soils (Hewitt, 2010) on well-drained materials, and Pallic to Gley Soils on finer-textured materials or where drainage is inhibited by high water tables. The next set of soils (Templeton age-group) is notably less well developed, and formed on mid-Holocene fluvial sediments deposited between about 6000 and 3000 years ago. Fluvial sediments deposited between 2400 and 700 years ago are characterised by soils of the Waimakariri age-group, while Selwyn age-group soils are only minimally developed (Table A5.3). Each age-group includes soils with a range of textures and drainage characteristics.

The physical characteristics of soils, in addition to providing information on the relative age of the ground surface (or at least the materials immediate below) also highlight parameters relevant to liquefaction susceptibility. Soil age is a relevant factor, because older soils are generally denser and more consolidated, and particle bonding which tends to accompany aging means that older soils are likely to be more resistant to the effects of earthquake shaking. Soil texture (particle-size distribution) reflects porosity and density (void space), and thus potential water saturation), while soil drainage reflects the frequency of saturation, commonly pointing towards the existence or otherwise of high groundwater tables. Having recognised that these characteristics impact on liquefaction susceptibility, it is important to note that any Holocene deposit with suitable physical characteristics is potentially susceptible to liquefaction, and some poorly drained older deposits may also have some liquefaction susceptibility.
Table A5.2  Key fluvial soil types on the Canterbury Plains (after Cox & Mead, 1963; Basher et al., 1988; Webb, 2008).

<table>
<thead>
<tr>
<th>Geological unit</th>
<th>Springton Formation</th>
<th>Burnham Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil age (years)</td>
<td>&lt;300 700-2400 3000-6000 14,000-20,000 &gt;20,000</td>
<td></td>
</tr>
<tr>
<td>Soil age-group name</td>
<td>Selwyn Waimakariri Templeton Lismore Darnley</td>
<td></td>
</tr>
</tbody>
</table>

**Shallow and stony soils**

| Soil types | Rangitata Rakaia Eyre Lismore Darnley |
| Classification | Fluvial Recent Fluvial Recent Orthic Recent Firm Brown Argillic Pallic |

**Deep, well-drained soils**

| Soil types | Selwyn Waimakariri Templeton Hatfield Mayfield |
| Classification | Fluvial Recent Fluvial Recent Immature Pallic Argillic Pallic Argillic pallic |

**Deep, imperfectly drained soils**

| Soil types | Kaiapoi Wakanui Lowcliffe Pahau |
| Classification | Fluvial Recent Immature Pallic Argillic Pallic Argillic Pallic |

**Deep, poorly drained soils**

| Soil types | Te Kakahi Taitapu Temuka Waterton Waterton |
| Classification | Gley Raw Recent Gley Orthic Gley Orthic Gley Orthic Gley |
Figure A5.4  Generalised soil map for the project area. The digital soil map (Webb, 2010) is based predominantly on the mapping of Kear et al. (1967), supplemented with more detailed soil maps by Raeside and Rennie (1974) and Cox (1978), and further refinements in the 1990s and 2000s (Webb, 2010). There is no detailed soil map information for Banks Peninsula, except for the northern flank of the Port Hills.
A5.5.3 Geomorphology map description

Landforms of the project area are categorised according to their origins and ages, as illustrated in a generalised geomorphologic map presented in Figure A5.5 and described, along with individual types of landform in each category, in Table A5.3. The categories comprise:

- Dynamic features of the land surface (natural water bodies and river courses);
- Landforms of the Holocene Epoch (the last ~12,000 years), which dominate the lowland sectors of the Canterbury Plains and coastal margin of the project area. The Holocene landforms are subdivided into those formed by river/stream processes versus those produced by coastal processes;
- Landforms of the Late Pleistocene Epoch, which in the project area comprise river and stream plains formed during the last glaciation;
- Landforms of the Middle Pleistocene Epoch, which in the project area are confined to downland areas west and north of Rangiora;
- Landforms of Banks Peninsula which, although not subdivided further, include various hill-country features such as slopes, ridges, benches and gullies, as may be seen in the terrain model in Figure A5.5. Landforms in the lower reaches of valleys and at harbour/bay margins, are included in the Holocene landform category.

Different parts of the project area have been mapped in differing detail, as indicated in Figure A5.3. For example, Holocene gully landforms have been mapped only in areas of high-resolution LiDAR coverage in the Christchurch City area (northwest of the Port Hills) and in the Halswell River catchment area south towards Lake Ellesmere. Holocene fluvial distributary lobes, lobe margins and intervening fluvial troughs are only readily discernible in the very detailed terrain images derived from LiDAR, as is illustrated in Figure A5.6. Availability of LiDAR information, and its use for detailed landform mapping as part of this report, provides a far more detailed picture of landform character than could be achieved previously in regional studies relying on topographic maps and aerial photographs (Barrell et al., 2011). Geological mapping of the Canterbury Plains lying in the project area (e.g. Brown & Weeber, 1992; Forsyth et al., 2008) is based on landform information. When this is integrated with soil mapping information it provides a fuller and more detailed picture of landforms, with implications for subsurface geology, than has been achieved in any previous studies.
Table A5.3  Landform types in the project area (see Figure A5.5).

<table>
<thead>
<tr>
<th>Dynamic features</th>
<th>Human landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>natural water body</td>
<td>Includes the sea, estuaries, lagoons and lakes</td>
</tr>
<tr>
<td>river bed or channel</td>
<td>Approximate ‘bank-full’ river or stream channel, whether natural or controlled by artificial levees (stopbanks)</td>
</tr>
<tr>
<td>Human landforms</td>
<td>result from human modification of the natural ground surface</td>
</tr>
<tr>
<td>undifferentiated</td>
<td>No differentiation shown in Fig. A5.5, but within the digital dataset divided into categories that include fill, excavated ground, ponds, engineered embankments, stopbanks and ditches (see Appendix Map).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Holocene coastal landforms</th>
<th>Holocene river/stream landforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand dune</td>
<td>Dune or sheet of wind-blown coastal sand</td>
</tr>
<tr>
<td>beach ridge</td>
<td>Constructional linear or curvilinear ridge of sandy or gravelly beach sediment. Includes the complex of multiple ridges forming Kaitorete Spit</td>
</tr>
<tr>
<td>sand or mud flat</td>
<td>Flats or plains associated with estuaries, bay-heads and Lake Ellesmere</td>
</tr>
<tr>
<td>Holocene river/stream landforms</td>
<td></td>
</tr>
<tr>
<td>youngest river/ stream courses</td>
<td>River plains or channels pre-dating human river control engineering; characterised by Selwyn age-group soils (Table A5.3)</td>
</tr>
<tr>
<td>river/stream plain or channel</td>
<td>River plains or channels, including raised ‘distributary’ lobes of river sediments near the coastal fringe. Within the digital dataset, further subdivided into plains/channels with Waimakariri age-group soils (‘Yaldhurst Surface’) and those with Templeton age-group soils (‘Halkett Surface’) (Table A5.3)</td>
</tr>
<tr>
<td>river/stream system margin</td>
<td>Margins of, and troughs between, raised ‘distributary’ lobes of river sediment near the coastal fringe. Within the digital dataset, further subdivided into margins/troughs with Waimakariri age-group soils (‘Yaldhurst Surface’) and those with Templeton age-group soils (‘Halkett Surface’) (Table A5.3)</td>
</tr>
<tr>
<td>swamp basin</td>
<td>Low-lying poorly drained basins associated with river/stream distributary lobe/trough landforms. Within the digital dataset, further subdivided into basins with Waimakariri age-group soils (‘Yaldhurst Surface’) and those with Templeton age-group soils (‘Halkett Surface’) (Table A5.3)</td>
</tr>
<tr>
<td>gully</td>
<td>Narrow, commonly sinuous, ephemeral stream channel cut within older landforms. Within the digital dataset, further subdivided according to whether the landform incised by the gully has Waimakariri (‘Yaldhurst Surface’) or Templeton (‘Halkett Surface’) age-group soils (Table A5.3)</td>
</tr>
<tr>
<td>sand dune</td>
<td>Dune or sheet of wind-blown river sand</td>
</tr>
<tr>
<td>alluvial/colluvial fan</td>
<td>Valley-floor plains and constructional fan-shaped sediment accumulations (fans) at the margins, or alongside harbours and bays, of Banks Peninsula, and at the flanks of downs or hill-country north and west of Rangiora.</td>
</tr>
</tbody>
</table>

Late Pleistocene landforms  
[formed between 12,000 and 125,000 years ago]

| river sand dune                   | Dune or sheet of wind-blown river sand                                         |
| river plain                       | Constructional river plains, including glacial outwash plains of the Waimakariri and Rakaia rivers, and fluvial plains of the Ashley and Kowai rivers. |
| alluvial fan                       | Fans at the foot of downs west and north of Rangiora.                          |

Middle Pleistocene landforms  
[formed more than 125,000 years ago]

| alluvial fan                       | Dissected, loess-covered fans forming downs west and north of Rangiora.        |

Banks Peninsula landforms  
[undifferentiated hill country landforms]
Figure A5.5  A generalised landform map for the project area. Refer to Table A5.4 and Section A5.6.3 for further explanation.
Figure A5.6    An illustration of the detailed imaging of topographic elevations derived from a) LiDAR (top) and b) the landform map (bottom; refer to Fig. A5.5 for key to units). The landform map is based on detailed interpretation of the LiDAR imagery, in conjunction with information from soil mapping and aerial photographs. Elevation contours on the surface of the Late Pleistocene river plain are an interpretation based on extrapolation of trends and gradients of modern topographic contours on Late Pleistocene river plain surfaces (pink in the lower image). See Fig. A5.7 for more information.
A5.5.4 Geomorphology map interpretation and limitations

The geomorphologic map provides a record of the processes and times at which the land surfaces of the project area took their present form. This is a reflection of the recent geological evolution of the project area, of which we now provide a summary.

At the height of the Last Glaciation, in the latter part of the Late Pleistocene, global sea level had declined to about 125 m below present (Martinson et al., 1987; Clark et al., 2009), and the shoreline lay at the seaward margin of the Canterbury continental shelf, far offshore of the modern coast (see Section 4.1). The Canterbury Plains were by and large an active floodplain, with each of the braided gravel-bed rivers migrating back and forth across their sector of the plains, moving and depositing fluvial sediment (Browne & Wilson, 1988). As the Last Glaciation came to a close about 18,000 years ago, improving climate and the stabilising influence of revegetation in upper catchments induced more stability in the courses of rivers on the plains. As a result, the main rivers proceeded to entrench within the mid- to upper reaches of their plains. Figure A5.7 presents an interpreted reconstruction of topographic contours on the surface of the plains at the onset of their stabilisation in the Late Pleistocene, prior to any incision into the middle reaches of the plains.

The rising sea lapped up over the seaward parts of the Late Pleistocene plain, attaining its modern level ~6500 years ago. Near the completion of sea level rise, and more so after sea level stabilised, sediment brought down by the main rivers began to build up at and near the coast (Suggate, 1958, 1963, 1965; Basher at al., 1988; Brown & Weeber, 1992). This was most notably the case with the Waimakariri River, due to the sheltering effects from waves and currents afforded by Banks Peninsula. Progressive sedimentation led to shallowing of the near-shore parts of Pegasus Bay and the Lake Ellesmere embayment. Progressive outbuilding of river plains and distributary channels into the coastal zone, commonly overtopping shallow marine and estuarine sand, silt and mud deposits, was accompanied by the formation of swampy zones at the margins of the distributary channel lobes, some of which enclosed low-lying swamp basins.

Movement of sandy and/or gravelly sediment along the coast led to formation of barriers that partially, or largely, enclosed estuarine areas such as Lake Ellesmere, the Avon-Heathcote Estuary, and Brooklands Lagoon. Paleontological and radiocarbon ages from the Bexley drillhole indicate that the New Brighton barrier had already begun to form by the time the present sea level was reached (6,500 years ago; Beu, in Brown 1998). Migratory dune-fields encroached inland in places. North of the Ashley River, and southwest of Lake Ellesmere, the Holocene coastline has predominantly been erosional, with coastal cliffs cut into the Late Pleistocene river gravel plain deposits. Along-shore sweeping of the gravel by waves and currents has produced the spectacular gravel barrier of Kaitorete Spit.
Figure A5.7 An interpretation, by way of elevation contours on the ground surface, of the form and gradient of the Canterbury Plains, at the time, perhaps about 14,000 years ago, that the plains surface had stabilised following the end of the Last Glaciation. The background is the modern geomorphologic map (see Figure A5.5 for key to landforms). On preserved Late Pleistocene river plain surfaces, the elevation contours coincide, with minor generalisation, with modern topographic contours on published topographic maps (NZTopo50 1:50,000 scale, Land Information New Zealand, Crown copyright reserved). In areas later subject to erosion or sedimentation during the Holocene, the contour spacing is inferred by extrapolation from preserved Late Pleistocene landform surfaces. Contour trends are based on the contour form on preserved Late Pleistocene surfaces, aided by a generalised interpretation of the broadly fan-like geometry of the river plains. Subsurface information from selected Environment Canterbury drillhole logs has aided the placement of the -20 and -40 m contours in proximity to Lake Ellesmere and eastern Christchurch.
A5.6 DRILLHOLE DATA

A5.6.1 Environment Canterbury drillhole data

Environment Canterbury’s drillhole database provides information that allows linkage of the geomorphologic map with underlying materials across the project area. This information tests whether the geomorphologic map can also be used as a geologic map. Understanding the spatial distribution of subsurface materials is important in defining liquefaction susceptibility.

While international historic experience suggests that liquefaction with limited surface expression may happen to depths as great as 15 or even 20 m, by far the most significant contribution results from liquefaction of materials in the top 10 m. The reason we have chosen this 10 m depth cut-off value for this study needs some explanation. Consequential liquefaction at the surface is the product of the summation of deformation contributions associated with liquefiable materials at depth. There is an exponential decay relationship between the contributions with depth below the surface for each liquefiable unit. For materials at depths of greater than 10 m, the contribution to surface deformation is small, even where thick susceptible deposits are present. In contrast, the contribution to surface deformation resulting from the depth to the unconfined groundwater table is extremely important when this is less than a few metres, yet our modelled unconfined groundwater surface (UGS) (see Section A5.8) carries significant uncertainty. Given the large contribution to surface deformation associated with small variation in depth to the UGS, the contribution to surface deformation from materials deeper than 10 m is deemed insignificant. In addition to this, site specific investigations required for development involve liquefaction susceptibility characterisation to depths in excess of 10 m.

Most domestic and industrial water used in Christchurch is from groundwater within buried alluvial gravels and tapped by drillholes. The value of drillhole logs was realised from early colonial days and logs have been recorded and archived for the last 130 years (Brown & Weeber, 1992). These have been digitised during the last 30 years and incorporated within a database managed by Environment Canterbury. Although the Environment Canterbury drillhole database is inherently heterogeneous, having been recorded at various levels of detail throughout more than a century by a large number of different people using a number of different techniques, it is still a rich source of descriptive data on materials beneath the surface.

A total of 15,732 collars are listed in the project area in the Environment Canterbury database (Figure A5.8), although only 12,108 of these have a description of the geological materials intersected. The spatial distribution of collars across the area is good, although there is a high density cluster in the Christchurch urban area. In contrast, collars are relatively sparse in parts of the adjacent rural area, notably west of Christchurch Airport on the south bank of the Waimakariri River and near the coast between Leithfield and the Ashley River mouth and between Pegasus and the Waimakariri River mouth. In contrast to most of the rest of the project area, there are relatively few drillhole logs for the Banks Peninsula area, so information on sub-surface materials around Banks Peninsula’s bays and harbours is limited.

The Environment Canterbury collar data table includes fields for the well number, geographic (x, y) coordinates, drillhole depth, collar elevation, and water level intervals. The interval data table includes the well number, from- and to- interval depths, a “strata code” (an abbreviated symbol for stratigraphic unit), a “lithology code” (abbreviated symbol for summarising interval
lithology), and a “strata description” field with a more extended description of materials within the interval.

Figure A5.8  Locations of drillhole collars within the project area held in the Environment Canterbury drillhole database. The base map is the NZTopo50 map, with a 1-km grid spacing.

Given the regional scale of this project, the method adopted to investigate the distribution of subsurface lithologies involved initially restricting records to a manageable number of logs. Logs were thinned by eliminating all drillholes located in areas where last glacial and older deposits are present at the surface. The rationale for this selection is that older materials are considered less likely to be susceptible to liquefaction, due to mineral weathering and soil development resulting in higher relative densities. Also, these areas are commonly better drained than other parts of the project area. These characteristics are supported by the extremely limited extent on these areas of liquefaction accompanying the Darfield and Christchurch earthquakes (as mapped in Appendix 3).

Selection of remaining logs, ensuring a relatively even distribution with a density of about one drillhole per square kilometre, completed the thinning process (Figure A5.9). A copy of the collar table representing the selected drillholes was modified to include columns summarising dominant lithology (using a standardised descriptive glossary) for each metre downhole to a depth of 5 m. A column summarising the aggregated dominant lithology in the uppermost 5 m was added and a further column representing materials in the interval between 5 to 10 m was appended.
Because the spatial separation of drillhole data points is approximately 1 km, the data is of regional scale only and data cannot be extrapolated to site specific or local scales. At best, the data provide a first approximation of likely subsurface materials across the project area.

This suite of data allows a spatial assessment of materials in the top 10 m of selected drillholes across the project area to help establish a relationship between the geomorphologic map units and subsurface materials. The nominal depth of 10 m was chosen for this project, on the assumption that the most significant contribution of subsurface materials to surface liquefaction susceptibility is from these uppermost materials. We are aware that this differs from the 15 m depth specified in Department of Building and Housing (DBH) guidelines for geotechnical investigations in the Canterbury region (see Appendix 1), but consider the 10 m depth to be adequate for the regional-scale project reported here.

![Image](image_url)

**Figure A5.9** Drillhole logs summarised for predominant materials in every metre interval below the surface, and with an aggregated predominant material description for the interval 0 to 5 m, and for 5 to 10 m. Yellow areas mark the extent of Last Glaciation sediments, as estimated from regional geological mapping (Forsyth et al. 2008), but note that revisions have been made to the extents of Last Glaciation landforms as a result of this project (see Fig. A5.4).

From these data it is possible to represent materials in the uppermost 10 m across the region of interest reasonably reliably either as sequential maps, or in 3D software (e.g. ArcScene or Leapfrog).
A5.6.2 Conclusions from drillhole data

This evaluation indicates that, in general terms, the Yaldhurst and Halkett geomorphologic surfaces in the west form a domain consistently underlain by gravel and sandy gravel to the full depth of the analysis (Figures A5.10, A5.11). This general statement does not preclude the local presence of peat, silt or clay on or within these gravels. In the east, another domain beneath the dunefields consists dominantly of loose and very loose sand with minor interdune surficial peat deposits. The area between these two domains comprises largely loose and very loose distal alluvial and swamp sediments of varying thickness, and in detail containing a broad variety of sediments, including peat, clay, silt, sand and (usually fine and/or sandy) gravel. Materials within both eastern domains are considered to have significant liquefaction susceptibility when saturated. The basement greywacke, Cretaceous cover, volcanic rocks, loess and other Quaternary materials of the elevated parts of Banks Peninsula comprise a further domain not prone to liquefaction. But Holocene materials underlie the low-lying bay-heads of the peninsula, and the few drillhole logs available suggest the presence of Holocene fine grained materials likely to be susceptible to liquefaction.
Figure A5.10a  Map summarising materials recorded in drillhole logs within the upper 5 m. The aggregated description for the top 5 m represents a summary of metre-by-metre dominant lithologies present. The boundary between liquefaction susceptibility zones ultimately adopted in this project is shown in black.
Figure A5.10b Map summarising materials recorded in drillhole logs in the interval between 5 and 10 m depth. Small white points indicate drillholes that do not penetrate to 10 m depth. The boundary between liquefaction susceptibility zones ultimately adopted in this project is shown in black.

An independent test of the validity of our conclusions regarding the liquefaction susceptibility of these domains (i.e. the influence of their subsurface materials) is provided by comparing their spatial distribution against the areas of mapped liquefaction associated with the September 2010 Darfield and February 2011 Christchurch earthquakes. The mapped occurrences of liquefaction are consistent with our conclusion that the western domain is not prone to widespread liquefaction, but that the eastern domains incurred substantial surface liquefaction damage. Liquefaction was also mapped locally in a few bay-heads of Banks Peninsula.
The distinction between gravel-dominated subsurface materials of the western domain and finer and more variable domains to the east will contribute to the definition of a line separating areas of low liquefaction susceptibility from those with moderate to high susceptibility.

It is important to note that in some conditions, even saturated loose gravel may liquefy, but those conditions tend to be extreme (e.g. gravelly liquefaction ejecta reported near the Hororata and Selwyn Rivers near the Darfield Earthquake epicentre; see also Seed et al., 2003; Obermeier et al., 2005). The only places where such liquefaction happened during the Darfield and Christchurch earthquakes were where ground water levels were very high (in active river beds) and at extremely high levels of ground shaking. In most places, rivers and streams are incised below gravel surfaces, leaving those gravel surfaces well drained and therefore reducing liquefaction susceptibility.

A5.6.3 Post-Darfield Earthquake investigations

Following the September 2010 Darfield Earthquake, and its associated liquefaction in the eastern suburbs of Christchurch City, 109 boreholes and c. 1530 CPT geotechnical probes were put down across the city to investigate the materials beneath the surface, in order to define the origin of the liquefaction and better characterise difficulties with foundation conditions. These investigations were located largely in areas that experienced liquefaction in the September 2010 or February 2011 earthquakes, or within the Christchurch Central Business District (CBD). These data provide a rich source of information for understanding subsurface materials, but because most of them lie in the DBH Technical Category zonation area (see main report) of Christchurch, they have little direct relevance to this study.

However, because drillholes and CPTs were completed in a short period of time by a small number of contractors, drillhole logging and digital geotechnical data are more homogeneous and reliable than for most of the Environment Canterbury well logs. The value of these investigations to this project is in applying knowledge gained of materials and their characteristics within the city to other areas across the region.

While the huge volume of close-spaced digital geotechnical data provides a powerful tool for analysing subsurface materials, CPT logs are somewhat ambiguous in defining some materials, such as differentiating between gravel and gravelly sand. For this reason, analysing information from drillholes and CPT data in parallel is essential.

A5.6.4 Investigation boreholes

The principal qualitative conclusions from examination of the investigation borehole logs relate to the materials and three-dimensional distribution of three stratigraphic units, the uppermost non-marine Springston Formation, the underlying marine Christchurch Formation, and a further part of the non-marine Springston Formation that underlies the Christchurch Formation.

The upper part of the Springston Formation distal alluvial and swamp deposits forms an eastward-thinning wedge across the top of the underlying Christchurch Formation, and its materials include peat, clay, silt, sand and gravel. These materials vary more laterally and stratigraphically and are thinner bedded than those of the underlying Christchurch Formation. The eastern edge of the upper Springston Formation lies through the suburbs of Linwood, Avonside, Aranui, Burwood and Marshlands. East of this line, marine Christchurch Formation lies at or very close to the surface.
The Christchurch Formation comprises a west-thinning, more homogeneous wedge of sand-, silty sand- and silt-dominated marine and estuarine materials, the leading edge of which lies buried beneath Springston Formation materials through the suburbs of Spreydon, Riccarton, Fendalton, Bryndwr, Casebrook and Belfast.

Beneath the Christchurch Formation, non-marine back-beach swamp and distal alluvial deposits of the lower part of the Springston Formation, as with the upper part of this formation, are also characterised by fine bedding and lateral and stratigraphic variability.

Finally, the underlying last glacial alluvial Riccarton Gravel is lithologically relatively homogeneous, and dominated by gravel, sandy gravel and gravelly sand. The ECan drillhole database shows that Riccarton Gravel lies beneath Springston and Christchurch Formation materials across much of the study area, except for Banks Peninsula and parts of the area north of the Ashley River.

**Grain-size distribution of drillhole samples**

In addition to providing downhole logs for each of the post-earthquake boreholes, core was photographed, and 910 laboratory samples (for grain size analysis and moisture content) taken from many of the drillholes contribute to the understanding of materials throughout the city (and Kaiapoi). Grain-size analysis of loose sand and silt traditionally provides an indicator of their susceptibility to liquefaction (Tsuchida, 1970; Obermeier, 2005; Figure A5.11). Well sorted (poorly graded) loose materials in the sand to coarse silt grades are vulnerable to liquefaction if they are saturated and if > c. 70% of their grains fall within the range of 1 to 0.05 mm (JSCE, 1977; New York State Department of Transportation, 2007; Chang et al., 2011).

This understanding of liquefaction susceptibility according to grain size has, however, been subject to more recent research that suggests that some materials with an extended fine-grained “tail” may still be vulnerable to liquefaction, depending on the plasticity of the fine-grained interstitial component (Seed et al., 2003).

Analysis of graphs depicting 195 of these samples, varying in depth from 1.1 m to 20.4 m depth, indicates that on the basis of grain-size analysis, almost 55% (106) have moderate to high liquefaction potential and only ~24% (46) have low potential (Figure A5.10). Samples with moderate to high liquefaction susceptibility appear to more numerous to the east, and within the Christchurch Formation. Conversely, poorly sorted (well graded) samples appear to preferentially lie in the west and above the top of the Christchurch Formation.

In conclusion, these data may be extrapolated outside the city area, particularly to the north, providing some degree of probability that materials with moderate to high liquefaction susceptibility are more likely beneath the coastal areas and less likely in the distal alluvial materials of the lower Waimakariri and Ashley river fans. It is likely that this relationship does not hold true for the Halswell-Tai Tapu-Lake Ellesmere area as subsurface materials there are commonly finer grained than in the north.
Figure A5.11 Grain-size analyses from a selection of post-Darfield earthquake borehole samples. A) The upper suite of analyses illustrate grain size distributions of 37 samples (pink lines) that have a high susceptibility for liquefaction on the basis of conventional boundary lines (solid dark red lines represent high potential for liquefaction, dashed red lines represent some potential for liquefaction; after JSCE, 1977). B) Grain-size analyses for 30 samples (gold lines) for samples showing uncertain susceptibility for liquefaction. C) Grain-size analyses for 9 samples that have distributions unlikely to respond to strong ground shaking by liquefying. The blue hashed areas on the graphs represent areas where grain-size distribution is such that liquefaction is extremely unlikely.
A5.7 GEOTECHNICAL DATA

Geotechnical data provide information on the physical properties of materials below the ground surface. A variety of geotechnical tests are available to study liquefaction susceptibility, including standard penetration tests (SPTs), downhole (drillhole) sampling and cone penetration tests (CPTs). CPTs and dilatometer tests (DMTs) are increasingly being used in liquefaction susceptibility assessment because they are relatively cheap, provide more detailed measurements of sediment properties and because measurements are more accurate because they provide data from near in situ materials. Results from about 1530 post-Darfield Earthquake CPTs collected mostly in the Christchurch City area were available for this project. SPT data run during post-earthquake drilling, mostly within the city boundary, are recorded in drillhole logs. A small number of analogue SPT records were retrieved from the Waimakariri District Council files, and a selection of these (29 of the deepest, well distributed records) has been digitised. These data provide a useful complement to the Environment Canterbury drillhole logs in the Kaiapoi/Rangiora area.

A5.7.1 Waimakariri District Standard Penetration Test data

SPT values for a small number of drillholes in the Kaiapoi-Woodend-Waikuku area were collected from Waimakariri District Council files. Only preliminary assessments of these data were undertaken as their spatial extent is not significant for the regional scale of this study. The significant variability of N values at all depths was used to corroborate the location of the boundary line between the “liquefaction assessment needed” and “damaging liquefaction unlikely” zones; i.e., the boundary is located west of these drillhole locations. More could be done to develop and understand the implications of these SPT data.

SPT data in the Kaiapoi/Rangiora area show great variability in soil densities in the upper 10 m, although there is a general trend of increasing N values with depth. In general, the restricted number of SPT records show materials east of Kaiapoi are mostly dense from shallow depths (<5 m), although intervals of loose materials may be present to depths of 12 m. Similarly, within Kaiapoi township, densities are variable and may be loose or even very loose to depths of >15 m, although layers of medium dense materials may be found above this.

A5.7.2 Cone Penetration Test data

Of the c.1530 available CPT probes, all but 117 are located within the Christchurch urban area, i.e. in the eastern zone of “liquefaction assessment needed” (this study). Most of the others are in the Kaiapoi/Pines Beach area, but 7 are located at Tai Tapu. The urban Christchurch area is covered by the more detailed DBH TC zonation and not addressed in this study. The main value of the CPT data to this regional project is to estimate the liquefaction susceptibility of similar sediments in the rest of the area.

A5.7.3 Calibrating Cone Penetration Test data against drillhole logs

The post-earthquake drillhole logs are particularly valuable in better understanding subsurface materials because many were located very close to CPT probes (many within 10 m), and comparative studies helps develop confidence in interpreting CPT results.

A non-quantitative comparison of logs and CPT data was made from a selection of logs from within 10 m of a CPT probe. The drillhole logs were independently assessed for material and geotechnical properties and subsequently compared with similar assessments of the nearby
CPT logs. Results of material comparisons were good, with the principal exception that gravelly sand was not easily identified in the CPT logs. Downhole Standard Penetration Tests (SPT) recorded in drillhole logs were in general agreement with the derivative CPT N60 values, and major changes in material density were recorded in both.

A5.8 GROUNDWATER DATA

Depth to the unconfined groundwater surface (UGS) is a critical factor in determining liquefaction susceptibility, because liquefaction can occur only when materials of suitable grain-size distributions are saturated. The UGS is defined as the depth at which water level in a hole stabilises following an undisturbed period of several hours. Surface standing water and stream levels are presumed to represent this unconfined water surface unless clearly isolated from groundwater by artificial means.

This section outlines methods used to model a surface that represents the UGS. The initial goal was to model surfaces for high groundwater (wet season) and low groundwater (dry season) conditions and to ensure that a conservative value is used for liquefaction potential evaluation in all cases. A secondary goal was to provide estimates of the depth to UGS that existed prior to the September 2010 and the February 2011 earthquakes.

Three sources of data were used to generate points upon which to build the model:

1. The Environment Canterbury drillhole database;
2. Surface water elevations derived from LiDAR elevations on river and stream margins and pit ponds and small lakes; and
3. Points placed on major waterways (Ashley, Cust, Waimakariri and Selwyn rivers) where topographic contours cross them, and on the shore of Lake Ellesmere on aerial photographs. The elevation of the Ellesmere shoreline is assigned a value of 1 m on the basis of the 2011 LiDAR DEM.

Further sets of data exist for the Christchurch City area (CCC groundwater monitoring sites, and c. 5 m deep piezometers installed at post-Darfield Earthquake CPT borehole sites), but these were not available for this project. For this reason the model developed and used in this report will quickly be superseded.

Elevations of the measured UGS during late winter months present in the Environment Canterbury groundwater drillhole database were extracted. A total of 276 records were filtered from the database and these were examined for inclusion as base point data for the model.

Collar locations, which were given in New Zealand Map Grid (NZMG) coordinates, were converted to NZTM2000. Collar heights for all drillholes, derived from the GNS Science 2 m DEM for the Christchurch area (CC_region_2003_dtm), were calculated and appended to each record. Where drillholes fell within the Halswell to Ellesmere area, elevations were calculated from the GNS Science LiDAR 1 m cell size LiDAR DEM (2011a_dsm_s).

Drillholes with screens at a depth greater than 5 m were excluded on the basis of the possibility of leakage from confined aquifers. Some drillholes contained no high groundwater level observations and were deleted. Records with maximum recorded groundwater levels greater than the elevation of the ground surface (determined from LiDAR) were also deleted.
The extent of the model is dictated by available data, and data outside the Christchurch urban area were very sparse. To supplement this sparse drillhole data, points were added where surface water (flowing streams and rivers, ponds, lakes and standing water in gravel pits etc.) was seen in aerial photographs, using LiDAR DEMs to define elevation. Where LiDAR coverage was not available, some points were added where the 20 m topo contours coincided with surface water (e.g. streams and rivers). Little control is available on whether these supplementary data points represent winter or summer levels. For these reasons, the robustness of the model depends on the context of the data points from which it was generated. The UGS model presented here is an interim model only, and should soon be supplanted by a more comprehensive version using all existing data with seasonal validation.

Following definition of data points to feed into the model, three main models were developed in the course of this project. The first model is a simple grid of the RL of UGS (Relative Level; i.e. the elevation in metres above sea level). This grid was contoured to illustrate elevation on the map face.

The second model takes the elevation of the unconfined groundwater data point and subtracts the surface elevation of each point (where possible, derived from the LiDAR DEM), providing the depth to the UGS. This derivative depth to the UGS was then contoured, providing a smoothed and generalised model that is somewhat independent from the elevation of the ground surface between data points. The model produced using this method probably under-estimates the depth to groundwater where surface elevation rises between streams and standing water and over-estimates the depth to the UGS in areas of low elevation.

The third model is a synthetic model, taking the RL of the UGS and subtracting the LiDAR DEM ground elevation surface. This provides a much more detailed surface (due entirely to the detail of the LiDAR DEM), but it means the derivative UGS reflects the surface topography between data points.

The third model was selected for use in this project because it is responsive to surface elevation as well as point data. The modelled surface representing depth to the UGS was contoured, with particular emphasis being placed on the 0 m contour (groundwater very close to the surface), the -2 m contour (groundwater within 2 m of the surface) and the -6 m contour (groundwater sufficiently deep to preclude liquefaction in most situations).

Building a widely accepted, high quality unconfined groundwater model for the project area would greatly enhance the reliability of liquefaction susceptibility assessment and should also prove useful for other purposes.

A5.9 Defining liquefaction susceptibility zones

Having investigated these significant contributing factors to liquefaction susceptibility, the challenge was to define zones that honour the various data and derived important conclusions. The purpose of defining such lines is to provide guidelines upon which authorities can base requirements for ground investigations for new developments to mitigate hazard from liquefaction.

Defining boundaries within areas that may be locally susceptible to liquefaction is problematic, even when high concentrations of suitable data are available, so for this regional project we conclude that the only appropriate boundaries that can be drawn are
between land that clearly has very limited susceptibility to liquefaction from that which has a significant susceptibility.

In years to come, the advent of new data will probably result in changes to the location of these boundaries. It is important to state that our philosophical approach is to locate the lines conservatively, so any future change in their positions will result in amelioration of requirements for investigation for most sites.

The methods used in integrating the geomorphologic map with soil and subsurface drillhole data have been explained in Section A5.7.1. This process shows that, to a high degree of reliability, the geomorphologic map may be used as a geological map. The geological map is underpinned by drillhole data as described above, involving 8342 data points recording dominant lithology within 1 m intervals (using a standard and restricted dictionary of lithologies) from 1713 boreholes relatively evenly distributed across the area. The data discussed above provides an assessment of liquefaction susceptibility.

The notable exception to this method was locating boundaries between liquefaction-susceptible areas and probable low liquefaction susceptible areas on Banks Peninsula lowlands. The elevated areas of Banks Peninsula are underlain by materials unlikely to liquefy significantly, and the boundary adopted around the peninsula was the geological boundary between Holocene and older materials.

Further boundaries are required to define liquefaction susceptibility in low-lying areas of Banks Peninsula. These have had to be drawn in greater detail than other boundaries adopted elsewhere, because the areas are relatively small and isolated. Yet data available to draw the boundaries (only restricted LiDAR coverage, limited drillhole logs and no groundwater information) is lacking or significantly sparser than for other areas of the project. Available drillhole data indicates that flat land close to sea level is commonly underlain by thick silt- and/or peat-dominated materials. For these reasons, a decision was made to use the 20 m topographic contour as the boundary. This boundary is well-defined and conservative.

The intent of this work is to provide boundaries that are defined by likely surface damage and that will be useful for planners to differentiate areas requiring different levels of geotechnical investigation for new development. Within the Christchurch urban area, foundation technical category (TC1 to 3) zones have been defined by the levels of damage resulting from the recent earthquakes, and also to describe how the land is expected to perform in future earthquakes. Boundaries between these zones are similar in concept to the boundaries generated in this work. However, the quantity and density of data available for this regional project is orders of magnitude poorer, precluding the use of these boundaries in the same way as those between the foundation technical category zones.

With a view to providing clarity, we choose to call the boundaries generated in this project as separating areas characterised by “damaging liquefaction unlikely” from those characterised as “Liquefaction assessment needed”. Land west of the westernmost line may therefore be thought of as “TC1-equivalent” land; similarly, land inside the Banks Peninsula line can be thought of as “TC1-equivalent”. However, land east of the line on the plains is designated as not achieving these standards, and thus should require more intensive assessment in the development consent process. Similarly, land seaward of the 20 m contour around flatland areas of Banks Peninsula represents land that does not meet “TC1-equivalent” standard.
REFERENCES


Japanese Society of Civil Engineers 1977: Earthquake resistant design for civil engineering structure, earth structure and foundation in Japan.


A variety of methods have been used over the years to attempt to develop probabilistic liquefaction hazard maps. The key is to determine the probability of liquefaction occurring in a given geological unit for some level of seismic shaking. In New Zealand this has been done using the New Zealand Modified Mercalli Intensity Scale as the seismic parameter and matching historical accounts of the severity of liquefaction to geological units (Dellow et al, 2003). More detailed work on developing probabilistic liquefaction hazard maps has been undertaken in the United States by Thomas Holzer and his co-workers (Holzer, 2008; Holzer et al., 2011). The work by Holzer utilises the Liquefaction Potential Index (LPI) derived from analysing cone penetrometer test results using the Robertson and Wride (1998) simplified procedure. This analysis allows a magnitude weighting factor to be included in the analysis. There are substantial uncertainties involved in the methodology adopted (outlined below) that are far greater than the uncertainty that would be present if magnitude weighting were included in the analysis. These uncertainties include determining the boundaries between areas where the severity and extent of liquefaction varies, the assignation of liquefaction damage ratings to geological units for different peak ground accelerations and variability in the groundwater model.

As part of the work programme to investigate liquefaction hazard in the study area, a series of probabilistic liquefaction hazard maps were prepared using a deterministic methodology as outlined in Dellow et al. (2003). This was done by generating a matrix for each of the geological units within the study area. This involves defining expected liquefaction effects for each geological point, for a given groundwater depth below ground surface (<2 m, 2-6 m, >6 m) at a particular peak ground acceleration (in this instance equivalent to 25, 100, 500 or 2500 year return periods). The liquefaction damage scale has four ratings (Table A6.1).

Table A6.1 Liquefaction damage ratings.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Expected severity and extent of liquefaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No liquefaction damage</td>
</tr>
<tr>
<td>B</td>
<td>&lt;100 mm settlement, few sand boils, &lt;10% area affected</td>
</tr>
<tr>
<td>C</td>
<td>100-250 mm settlement, 10-25% area affected</td>
</tr>
<tr>
<td>D</td>
<td>&gt;250 mm settlement, &gt;25% area affected</td>
</tr>
</tbody>
</table>

The liquefaction susceptibility data are now used in conjunction with four peak ground accelerations in the following manner to estimate liquefaction potential.

The basic tool used was a spreadsheet listing all drillhole data, with appended columns of geomorphic map unit code, lithologic data and groundwater depth (from the groundwater model). A matrix for each of the geological units (and associated lithologies) within the study area was developed reflecting given groundwater levels (<2 m, 2-6 m, >6 m) at particular peak ground accelerations (in this instance equivalent to 25, 100, 500 or 2500 year return periods). The expected liquefaction damage scale was a four-fold one (A to D; see Table A6.1), that is supplemented by +ve and –ve suffixes in cases where groundwater level and/or lithological conditions are marginal (Table A6.2).
Table A6.2  Summary of liquefaction potential ranking derived from unit code, lithological, groundwater depth and PGA.

<table>
<thead>
<tr>
<th>Geomorphic map category</th>
<th>Comments</th>
<th>Expected dominant lithology</th>
<th>Age</th>
<th>PGA 0.13g (25-yr return earthquake)</th>
<th>PGA 0.22g (100-yr return earthquake)</th>
<th>PGA 0.39g (500-yr return earthquake)</th>
<th>PGA 0.6g (2500-yr return earthquake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater conditions:</td>
<td></td>
<td></td>
<td></td>
<td>S M D</td>
<td>S M D</td>
<td>S M D</td>
<td>S M D</td>
</tr>
<tr>
<td>S: depth to unconfined groundwater table 0 to 2 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>M: depth to unconfined groundwater table 2 to 6 m</td>
<td></td>
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<tr>
<td>D: depth to unconfined groundwater table &gt;6 m</td>
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</tr>
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</table>

**DYNAMIC FEATURES**

<table>
<thead>
<tr>
<th>natural water body</th>
<th>current</th>
<th>not classified</th>
</tr>
</thead>
<tbody>
<tr>
<td>river bed or channel</td>
<td>current</td>
<td>not classified</td>
</tr>
</tbody>
</table>

**HUMAN LANDFORMS**

| undifferentiated | current and historic | not classified |

**HOLOCENE COASTAL LANDFORMS** (developed on Christchurch Formation)

<table>
<thead>
<tr>
<th>sand dune</th>
<th>includes historic and current dune fields</th>
<th>sand, includes sand/silt/peat in interdune depressions</th>
<th>mid-late Holocene</th>
<th>B</th>
<th>A</th>
<th>A</th>
<th>C</th>
<th>B</th>
<th>A</th>
<th>C</th>
<th>C</th>
<th>A</th>
<th>D</th>
<th>C</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>beach ridge</td>
<td>includes historic and current beaches</td>
<td>gravel/sand, loose sand or gravel in modern beach</td>
<td>mid-late Holocene</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>A</td>
<td>D</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>sand or mud flat</td>
<td>sand/silt/peat</td>
<td>late Holocene</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>A</td>
<td>D</td>
<td>C</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

**HOLOCENE RIVER/STREAM LANDFORMS** (developed on Springston Formation)

<p>| youngest river/stream courses | youngest river/stream courses | Yaldhurst 2 and 3 Surfaces | gravel/sand | latest Holocene | A | A | A | A | A | A | A | A | A | A | A | A |
| river/stream plain or channel | Yaldhurst 1 and Halkett Surfaces | gravel/sand | mid-late Holocene | A | A | A | A | A | A | A | A | A | A | A | A |
| river/stream system margin | undifferentiated Yaldhurst and Halkett surfaces | sand/silt/gravel | mid-late Holocene | B | B | A | C | B | A | C | C | B | C | C | B |
| swamp basin | undifferentiated Yaldhurst and Halkett surfaces | sand/silt/peat | mid-late Holocene | B | B | A | C | B | A | C | C | B | C | C | B |
| gully | undifferentiated Yaldhurst and Halkett surfaces | gravel/sand/silt | mid-late Holocene | not classified |                              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |</p>
<table>
<thead>
<tr>
<th>Geomorphologic map category</th>
<th>Comments</th>
<th>Expected dominant lithology</th>
<th>Age</th>
<th>PGA 0.13g (25-yr return earthquake)</th>
<th>PGA 0.22g (100-yr return earthquake)</th>
<th>PGA 0.38g (500-yr return earthquake)</th>
<th>PGA 0.6g (2500-yr return earthquake)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand dune</td>
<td>undifferentiated Yaldhurst and Halkett surfaces</td>
<td>sand</td>
<td>mid-late Holocene</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>alluvial/colluvial fan</td>
<td>undifferentiated</td>
<td>silt/gravel/sand</td>
<td>mid-late Holocene</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

**LATE PLEISTOCENE LANDFORMS** (developed on Burnham Formation)

| river plain | includes Darfield Surface | gravel | Late Pleistocene | A | A | A | A | A | A | A | A | A | A | A |
| river sand dune | undifferentiated | sand | Late Pleistocene | A | A | A | A | A | A | A | A | A | A | A | A |
| alluvial fan | (only mapped north of Ashley River) | silt/gravel/sand | Late Pleistocene | A | A | A | A | A | A | A | A | A | A | A |

**MIDDLE PLEISTOCENE LANDFORMS** (developed on Woodlands Formation)

| alluvial fan | only mapped north & northeast of Rangiora | silt/gravel/sand | Middle Pleistocene | A | A | A | A | A | A | A | A | A | A | A | A |

**BANKS PENINSULA LANDFORMS** (in hill country)

| undifferentiated | rock, loess, alluvium, colluvium. | not differentiated | A | A | A | A | A | A | A | A | A | A | A |

**Rules applied**

1. A - is added to a rank where groundwater is <2m, and/or where >2m of liquefaction susceptible materials are in the top 5m.
2. A + is added to a rank where groundwater >6m (except for A, which is the max rank), or where gravels lie <3m below the surface.
3. Incised channels are unattributed (although they could be).
4. Human-related deposits are unattributed (excepht where drillholes show unambiguous stratigraphy).
5. Organic, where abundant, is granted a -ve

When combined, these data provide a ranking for liquefaction probability at each drillhole collar location (two examples are shown in Figure A6.1). Mapped liquefaction hazard probability ranking is consistent with the location of the boundaries drawn as the principal output for this project.

The final stage of drawing boundaries that conservatively represent boundaries between areas where liquefaction susceptibility is minimal from areas where liquefaction is possible was undertaken by excluding all areas where indications of liquefaction susceptibility or liquefaction potential were present in any of the investigations described above.
Figure A6.1  Two examples of maps showing rankings derived from drillhole logs (lithologies in the top 5 m), and also taking into account map unit code and depth to groundwater. The left map shows a liquefaction potential ranking for the 100-year recurrence earthquake (PGA 0.22g). The right map shows ranking for the 2500-year recurrence earthquake (PGA 0.6g). Points from A to C+ are regarded as having acceptable liquefaction potential for most development purposes. The line separating green points from yellow ones approximates a line that honours the data feeding into this analysis. Similar maps were generated for the 25-year (0.13g) and 500-year (0.38g) recurrence interval earthquakes, and a similar suite of four maps were generated for materials recorded in the 5 to 10 m deep interval in each drillhole log. Black lines are the boundaries ultimately defined in this report for reference.

REFERENCES


Holzer, T.L. 2008: Probabilistic liquefaction hazard mapping. ASCE Geotechnical Earthquake Engineering and Soil Dynamics IV.

