A 3D Geological Model of the Whakatane Central Business District, Bay of Plenty, New Zealand – with estimate maps illustrating possible earthquake land damage

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CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

APPENDIX TABLES

EXECUTIVE SUMMARY

GNS Science was engaged by Whakatane District Council to provide guidance on cone penetration test (CPT) procedures and data requirements for a drilling and geotechnical campaign. In addition, the contract required building a 3D model of materials beneath the Whakatane Central Business District (CBD) from this drillhole and geotechnical data and a descriptive report suitable for structural and geotechnical engineers and geologists. Digital outputs are required to be suitable for loading onto the WDC website. In particular, CPT derivative data suitable for liquefaction assessment were specified.

Liquefaction is a natural process that normally results from earthquake ground-shaking, the presence of suitable materials and that these materials are saturated. Whakatane is subject to a significant seismic (ground-shaking) hazard as characterised by the national seismic hazard model (Stirling et al. 2012). This project explores the extent of saturated materials susceptible to liquefaction beneath the Whakatane CBD and provides Whakatane District Council and engineers strategies available to mitigate the hazard, based on best practise adopted in Christchurch, and consistent with developing national guidelines.

Following a brief description of the geomorphology and geological setting of Whakatane, this report details the data and methods used in building the 3D Geological Model and 3D Interpolant Geotechnical Models of the Whakatane central business district (CBD) (Appendix 1). The model uses a LiDAR-derived digital elevation model (DEM) as an accurate base topography.

Surface geology and high quality, homogeneous drillhole and CPT data collected specifically for the project are the anchor-stones of the modelling. A summary of the findings of subsurface modelling is presented. Collar density (for CPTs, the average collar separation is 71 m) is inferior to that discussed in preliminary meetings (20 m grid) and thus the resulting models have less reliability than originally envisaged. Four major lithological surfaces separate five lithologic units, in stratigraphic and chronologic order, basement greywacke (bedrock), and four Quaternary units, a lower sandy silt, a dense, sand-dominated unit, a loose sand-dominated unit and an upper silt. Volumes representing these major geological units, along with two gravel/shell lenses are modelled in the 3D Geological Model.

The Geological Model defines the extent and feeds information on the geometry of the young materials into the interpolated Geotechnical Models. The interpolated Geotechnical Models include volumes for normalised cone resistance (Q_{tn}), fines content (FC), soil unit weight (Gamma) and Normalised Soil Behaviour Type Index (I_c). All model volumes are defined by the Geological Model extent and geometry.

The extent of liquefaction susceptibility is restricted by the following factors: the unconfined groundwater surface, Holocene materials of low density and a maximum depth of 20 m below the ground surface. Two main volumes of potentially liquefiable materials are differentiated, an upper volume consisting of the silt and loose sand beneath the unconfined groundwater surface up to a depth of c. 9 m, and a second volume between the base of these loose materials to the limit of liquefaction potential (c. 20 m deep). The upper volume represents by far the most important liquefaction hazard. The lower volume represents materials that CPT characterisation suggests are liquefiable, but SPT data suggest the contrary.

Most of the CPTs available for this work are located in the eastern two thirds of the model area and cover the CBD with acceptable density. We provide the Geological and Geotechnical models, suitable for use at a map scale of 35 to 40 m where data is dense, as a scientific basis for the liquefaction susceptibility assessment that follows.

Our liquefaction susceptibility assessment for the Whakatane is based on applying the methodology developed for Christchurch site ground classification following the devastating 2010-2011 Canterbury Earthquake Sequence. Establishing a good linkage to the Christchurch site ground classification system enables the Council to leverage off the considerable investment that has gone into the development of the Christchurch system. This method characterises land according to settlement values determined from analysis of CPT data as “Good ground”, “Poor ground” or “Poor with lateral spread” under specific earthquake conditions. These settlements can then be related to “Foundation Technical Categories” TC1, TC2 and TC3, in order of increasing land settlement values.

Index settlement values derived from CPTs for the Whakatane CBD for Serviceability Limit State (SLS) and Ultimate Limit State (ULS) are correlated to equivalence with TC2/TC3 (Technical Category 2 and 3) land in Christchurch and information presented here describe how land is expected to perform in design earthquake events such as ULS and SLS.

Although minor lateral spreading was an issue near Landing Bridge during the 1987 M6.3 Edgecumbe Earthquake, the absence of a record of lateral spreading close to the Whakatane CBD in that one in 110 year recurrence event, suggests that lateral spreading is unlikely during SLS earthquakes.

Liquefaction assessment is assisted by information on likely earthquake magnitude, information on peak ground acceleration (PGA) and details of surface topography that may be used to calculate susceptibility to liquefaction and in some places, to lateral spreading. One such scenario using reasonable values for these other variables is presented in a limited form (M7, PGA 0.3 g, equivalent to earthquake ground shaking expected every c. 250 years, representing an earthquake at the extreme end of Taupo Fault Belt events, but under-representing what might be expected from a North Island Fault System earthquake) as a pointer to potential liquefaction susceptibility.

Using data collected and analysed from the 2010-11 Canterbury Earthquake Sequence, the Ministry for Business, Innovation, and Employment (MBIE) and Ministry of Education (MoE) have developed guidelines for building foundations that are appropriate for application in the Whakatane CBD. Their intention is to develop guidelines recommended for application across the country.

We strongly recommend that a Whakatane Geotechnical Database in a digital format equivalent to the Canterbury Geotechnical Database is established as part of the building consent application process within the Town. This would ensure consultants and interested citizens have access to such data and grow the database over time to the benefit of all. Geotechnical and borehole data collected in the process of building and also resource consents should be lodged within the database. WDC would ensure regular updates of both the database and derivative 3D models.

The Geotechnical Models show that Whakatane CBD is built upon materials with high liquefaction susceptibility. While this inference is qualified because pumiceous materials beneath Whakatane may be significantly different from those beneath Christchurch where the LSN and technical category zoning criteria were developed, in our assessment the analysis of CPT data to provide SLS and ULS index settlement values provides a rational basis for the application of Foundation Technical Categories to Whakatane, following those established in Christchurch.

1.0 INTRODUCTION

GNS Science was engaged by Whakatane District Council to provide guidance on CPT procedures and data requirements for a drilling and geotechnical campaign. An additional component of the contract was to build a 3D model of materials present beneath the Whakatane Central Business District (CBD) and provide a descriptive report suitable for structural and geotechnical engineers and geologists. Specific engineering advice relating engineering practise in Christchurch following the 2010-2011 earthquakes to the Whakatane CBD situation is provided in this report from GHD under a separate contract. Outputs are required to be suitable for loading onto the WDC website. In particular, CPT derivative data suitable for liquefaction assessment was specified.

1.1 AREA OF INTEREST AND RATIONALE FOR THIS WORK

The specific area of interest for this project is the Whakatane CBD from about Mataatua Street in the east to McAlister Street in the west with the Whakatane River representing the northern boundary and Louvain Street the southern boundary.

The project is driven by the fact that Whakatane District Council owns most of the CBD land and has leased it long term to various businesses who have invested in capital developments. Following the 2010-11 Canterbury Earthquake Sequence (CES) where liquefaction caused a very high proportion of the cumulated damage claims, councils around the country have been assessing their own risks to liquefaction. Those with very low-lying land and high groundwater levels have reason to clarify liquefaction hazard in these areas. This is particularly so where significant development has taken place or may take place on that land. Better understanding all aspects of safety and risk is the first step in mitigating damage from this kind of hazard.

The models developed in this project are designed to inform the council and businesses with their investments on the CBD land in better understanding liquefaction hazard.

Reference is made throughout this report to scenes (e.g. Scene 7) within the accompanying Leapfrog Viewer project. This draws attention to the part of the model that the text is dealing with and can be viewed as the text is read (see particularly Appendices 1 and 2).

2.0 GEOMORPHOLOGY AND GEOLOGICAL SETTING

2.1 GEOMORPHOLOGY

The Rangitaiki Plains is a distinctive low-lying area with an area of c. 250 km^2 adjacent to the central Bay of Plenty coastline and hosts the lower reaches of the Tarawera, Rangitaiki and Whakatane rivers, from west to east respectively. The eastern part of the Rangitaiki Plains from Awakeri to Whakatane (Figure 1; Scene 1) comprises a very low-lying landscape, almost all between 6 and 0 m elevation, extending c. 10 km from the Bay of Plenty coast south to the steep hills at its southern edge. The boundary between the hills and the Rangitaiki Plains between Awakeri and White Pine Bush represents an ancient sea cliff eroded about the time that sea level attained its present elevation c. 7000 years ago. The eastern side of the Rangitaiki Plains between Pahou and the Whakatane CBD is flanked by a sea cliff essentially equivalent, though perhaps in part, somewhat younger. The area between the ancient coastal cliff in the south and the present day Bay of Plenty shoreline is characterised by low-lying land, commonly with shallow stream channels punctuated by more elevated areas with remnant beach ridges aligned with the present day coastline. One such remnant of beach ridges is preserved within Whakatane itself, extending west to east between Landing Road/Domain Road and Alexander Ave/Kirk Street. Behind the present shoreface beach ridges, there exists a zone of discontinuous dune sands up to more than 20 m elevation and 700 m wide.

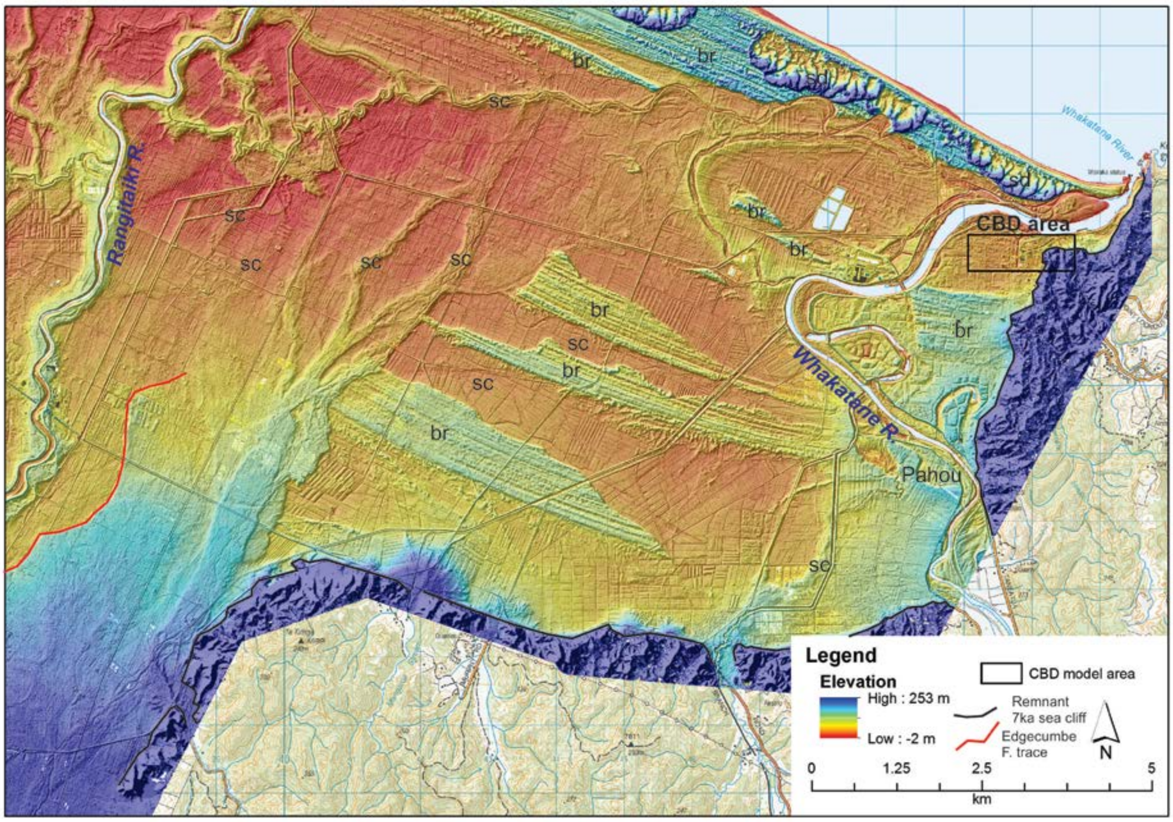


Figure 1 Geomorphology of the eastern Rangitaiki Plains. Note the c. 7000 year sea cliff around the southern and eastern margins of the area shown, the northern surface extent of the Edgecumbe Fault in the southeast (red line), stranded beach ridges (br), old stream channels (sc) and dune sands (sd), and the location of the CBD model extent. The Whakatane Fault is not shown, but emerges onto the eastern Rangitaiki Plains close to where the Whakatane River emerges from the hills in the southeast.

The Whakatane CBD itself is very low-lying, largely below 3 m elevation, with substantial parts less than 2 m. Little topographic variation exists north of the packet of beach ridges that terminate near Domain Road. This probably reflects extensive reclamation and land surface modification undertaken since a map dated 1867 was drawn (WDC archives). Through the southern and western suburbs of today's Whakatane, a number of abandoned oxbows define old river courses of the Whakatane River. The abandoned oxbow immediately south of Riverside Drive and west of Hinemoa Street represents the main channel of the Whakatane River in the 1867 map. The same map depicts the presence of a "mud flat" beneath the eastern part of the CBD and an area between McAlister Street and McGarvey Road is annotated "liable to floods" (see also Pullar 1963). The archival map also indicates patches of vegetation across the low-lying land north of Domain Road. The development of the port area was serviced at the time by a single road, now Commerce Street and The Strand.

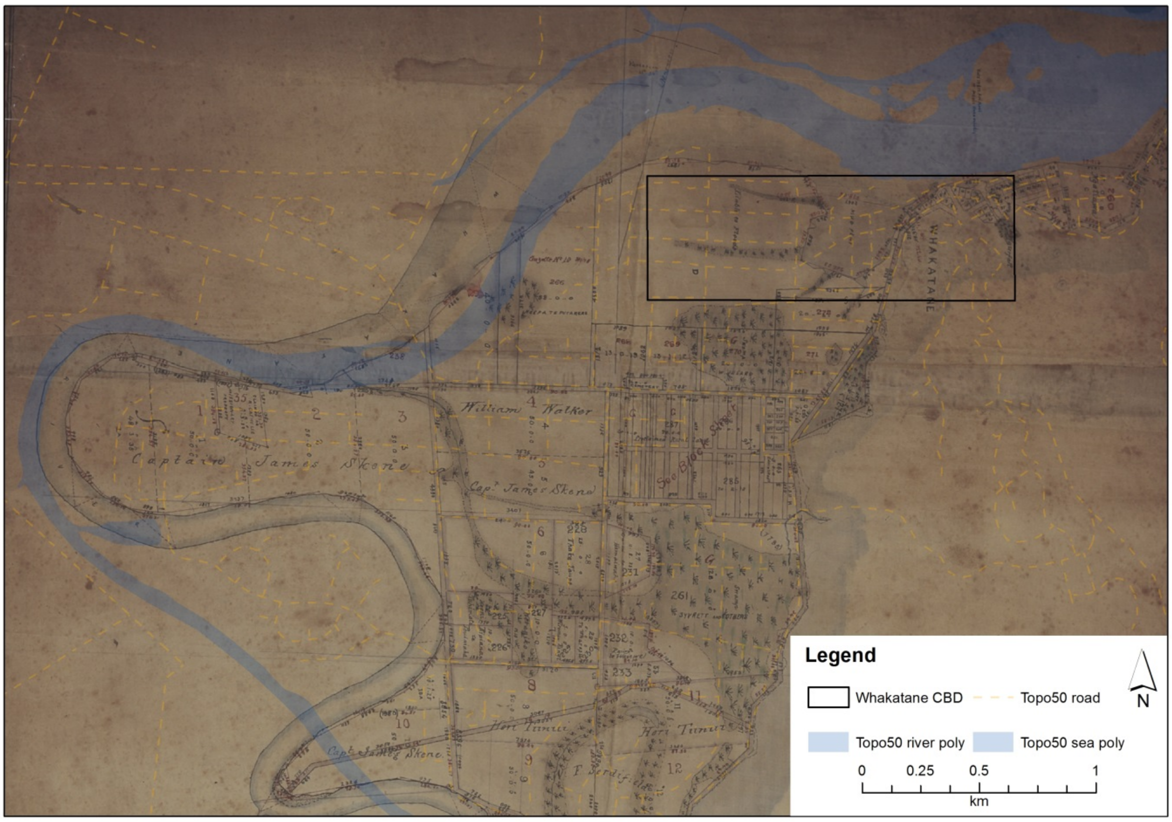


Figure 2 Whakatane District Council archival map dated 1867, showing geographic features present at that time, including the course of the Whakatane River and swampy estuary in the centre of the present CBD (the modelled CBD area is outlined in black). The present course of the Whakatane River (from Topo50) is shown in muted blue tones and roads are shown as muted dashed orange lines.

2.2 GEOLOGICAL SETTING

The Rangitaiki Plains lies upon the Australian Plate, about 200 km northwest of the Australia-Pacific plate boundary at the Hikurangi Trough, east of the Raukumara Peninsula coast of the North Island. From the Hikurangi Trough, the Pacific Plate is being subducted eastward beneath the Australian Plate. The Taupo Volcanic Zone (TVZ) traverses the central North Island, New Zealand, for approximately 250 km with an average NE-SW strike and here the Pacific Plate lies at a depth of about 150-180 km. The TVZ is the locus of rifting related to the plate boundary and accommodates extension at a rate of up to 18 mm/yr (Davey and Lodolo 1995, Villamor and Berryman 2001, Wallace et al. 2004). Northeast of the Bay of Plenty coast, the twin submarine volcanic ridges, Colville and Kermadec, and their intervening backarc rift, the Havre Trough, strike towards the Rangitaiki Plains (Wright 1993, Wysoczanski et al. 2009).

The old basement rocks (Jurassic to Early Cretaceous periods; 160 to 115 million years) of eastern New Zealand are present on the margins of, and beneath the Rangitaiki Plains area (Mortimer 1995, 2004, Mortimer et al. 1997, Edbrooke 2001, Kear and Mortimer 2003).

Regionally, basement rocks are overlain by a succession of little-deformed late Early Cretaceous mainly marine sedimentary rocks of the Matawai Group to the southeast of the Rangitaiki Plains. The area from Whakatane to the east is traversed by a number of active strike-slip faults of the North Island Fault System (NIFS; Mouslopoulou et al. 2009). These almost certainly have an extended Late Miocene to Recent history of activity (11 million years to the present day) although in the Miocene and Pliocene tectonic activity may have been largely compressional in sense rather than their extensional sense today.

The Taupo Volcanic Zone is a zone of volcanic activity that extends northeast from Mt Ruapehu to the Bay of Plenty coastline and beyond. It is studded with active volcanic and geothermal features and is also a belt of active extensional faulting, the Taupo Rift. On average the TVZ is 50 km wide. No volcanic rocks older than about 1.5 million years (Ma) have been found within the TVZ and it is thought to be entirely Quaternary in age (<2.58 million years). Volcanic pyroclastics, ashfall and lavas dominate deposits of the TVZ and the areas adjacent to it. These are mostly rhyolitic in origin, although minor intermediate and basic volcanics are present. On-going normal faulting of the Taupo Rift is at least partly associated with Quaternary volcanic activity in the TVZ. These faults are almost certainly restricted in age to about the same period as the age of the volcanic zone. The Rangitaiki Plains lie across the Taupo Rift, near where the strike-slip NIFS intersects and transfers most of its slip into the rift (Mouslopoulou et al. 2007; Mouslopoulou et al. 2009; Begg and Mouslopoulou 2010). Here, basement rocks present at the surface around the margins of the plains have subsided to depths of up to 2 km as a result of this rifting (Scene 1). This developing hole has been infilled during the Quaternary largely by materials generated by the volcanoes of the TVZ and deposited in terrestrial and marine environments. These deposits are named Tauranga Group and include marine deposits from interglacial periods, when climate was relatively warm and sea levels were high (like today), and terrestrial depositional phases during glacial periods when sea levels retreated to the edge of the continental shelf.

The most active fault of the NIFS in the Bay of Plenty is the Whakatane Fault that is exposed along the eastern side of the Whakatane River along and east of Taneatua Road, but its location is not well defined through Whakatane township, a subject of current investigation (Mueller pers. comm. 2015). Three ruptures of this fault in the last 12 kyr are recorded in a trench at Ruatoki North (Mouslopoulou 2006) and recurrence interval is estimated at c. 4010-4490 years (GNS Science Active Faults Database). The last rupture was 320 to 720 years ago and rupture probably involves an earthquake of c. M7+.

In the TVZ, extension in the upper crust is primarily accommodated by fault-slip during large magnitude earthquakes (e.g., Beanland et al. 1989, Berryman et al. 1998, Villamor and Berryman 2001, Nicol et al. 2007, Begg and Mouslopoulou 2010). The 1987 M6.3 Edgecumbe Earthquake, for example, the largest historic earthquake in the rift, resulted in extensional slip at the ground surface on eleven traces of six faults (including the Edgecumbe Fault) across the Rangitaiki Plains (Beanland et al. 1989). During this ground shaking, sand boils (liquefaction) was reported across a significant area of the Rangitaiki Plains around the fault rupture, involving mostly materials from 0.6 to 0.1 mm (coarse to very fine sand; Franks et al. 1989). Minor liquefaction and sand boils were reported near The Landing Bridge and in suburban Whakatane close to the river margins.

Materials beneath the surface that have potential to liquefy during strong ground shaking include water-saturated coarse to very fine sand and coarse silt that are poorly consolidated. International experience indicates that only materials less than about 12 thousand years old (kyr) are likely to liquefy. At Whakatane, these materials post-date sea level rise that saw the paleoshoreline extend inland to the ancient sea cliff at Awakeri about 7000 years ago.

2.3 PURPOSE OF THIS STUDY

Given the damage caused in Christchurch by liquefaction, Whakatane’s exposure to seismic ground shaking, the perception that liquefiable materials underlie the area and the land and building ownership issues referred to above, there is good cause to more closely examine materials beneath the Whakatane CBD with liquefaction in mind. The purpose of this study is to better understand the distribution of materials beneath the CBD and to understand their geotechnical properties, to better understand liquefaction susceptibility. Once susceptibility has been established, discussion around best practise engineering solutions will clarify the need for seismic strengthening of buildings.

3.0 SUMMARY OF SUBSURFACE MODELLING INFORMATION

Borehole logs, SPTs and CPTs were displayed in Leapfrog Geo (3D geological modelling software), providing information on the overall structure of basement and Quaternary materials beneath the Whakatane CBD. Four major lithological surfaces separate five lithologic units, in order of age, basement greywacke, and four Quaternary units, a lower sandy silt, a dense, sand-dominated unit, a loose sand-dominated unit and an upper silt. Volumes representing these major geological units, along with two gravel/shell lenses are modelled in the 3D Geological Model. Discussion of data and modelling methods are described in Appendix 1.

A surface representing the unconfined groundwater surface was developed from drillhole and CPT data. This surface was used to build a model volume representing surficial unsaturated material and underlying saturated material. Saturation is a vital factor in considering liquefaction susceptibility because unsaturated materials (above the unconfined groundwater surface) cannot liquefy.

Analysis of CPT data using the software CLiq suggests that beneath the saturation zone, all materials to the depth of 20 m are capable of liquefaction. SPTs suggest that liquefaction is unlikely in dense materials beneath c. 5 to 7 m below sea level. Both the drillhole logs and CPT data indicate a clear boundary between loose sands and underlying dense sands. To accommodate the apparent conflict between CPT analysis and SPTs within the dense sands, we have differentiated three subsurface volumes in the model for representing liquefaction susceptibility. One encloses materials that are not susceptible (“Non-susceptible) and two potentially liquefiable volumes, one to the base of the loose sands, named “More susceptible”, and an underlying volume enclosing the denser sands, named “Less susceptible”.

Using the structure defined in the Geological Model, we built an interpolated Geotechnical Model using the geotechnical derivatives FC (fines content), Gamma (soil unit weight), I_c (Soil Behaviour Type Index) and Q_{tn} (normalised cone resistance). The Geotechnical Model provides a rich resource of 3D geotechnical information for engineers.

Finally, we provide an analysis of the reliability of these models in 3D space and a short discussion on its limitations (Appendix 1). The input data is of high quality and the spacing of collars allows confidence in its quality across distances of c. 35 m. Data density and therefore confidence drop off with depth, but adequately covers materials to the limit of liquefaction potential (20 m below the ground surface). Pumiceous materials beneath the Whakatane CBD are unlike materials beneath Christchurch (the origin of the liquefaction function LSN; Tonkin & Taylor 2013) and unlike most materials routinely characterised using CPT data internationally. While the impact of this difference is uncertain at this stage, it is unlikely to significantly change the engineering assessment provided below.

4.0 ENGINEERING USE OF SUB-SURFACE DATA

By Dick Beetham & Hayden Nikolaison, GHD Ltd

CPT data have quite good coverage in parts of the CBD area, but are widely spaced in other parts. They are intended to provide building owners a good indication of the ground conditions in the area of their building. Ground condition data can be used as input for both initial and detailed seismic assessments, but are not intended to replace the requirement for new ground investigations for a new building or significant foundation works. However, where the existing coverage is good, they may be useful supplementary data to new investigations.

New Zealand Site subsoil classes are defined in NZS 1170.5 (2004) with five classes, ranging from Class A (Strong rock) to Class E (Very soft soil) (see Table 1 and Table 2). Soils beneath the Whakatane CBD are considered typically to represent Class C, shallow soils.

Table 1 Site subsoil classes as defined by NZS1170.5: 2004. After Semmens et al. (2011).

Class	Description	Definition
A	Strong Rock	UCS > 50 MPa & Vs30 > 1500 m/s & not underlain by < 18 MPa or Vs 600 m/s materials.
B	Rock	1 < UCS < 50 MPa & Vs30 > 360 m/s & not underlain by < 0.8 MPa or Vs 300 m/s materials, a surface layer no more than 3 m depth (HW-CW rock/soil).
C	Shallow Soil	Not class A, B or E, low amplitude natural period ≤ 0.6s, or depths of soils not exceeding those in Table 2.
D	Deep or Soft Soil	Not class A, B or E, low amplitude natural period > 0.6s, or depths of soils exceeding those in Table 2, or underlain by < 10 m soils with undrained shear strength < 12.5 KPa, or < 10 m soils SPT N < 6.
E	Very Soft Soil	> 10m soils with undrained shear strength < 12.5 KPa, or > 10m soils with SPT N < 6, or > 10m soils with Vs ≤ 150m/s, or > 10m combined depth of previous properties.

Table 2 Maximum depth limits for site subsoil class C.

Soil type and description		Maximum depth of soil (m)
Cohesive Soil	Representative undrained shear strengths (kPa)	
Very soft	< 12.5	0
Soft	12.5-25	20
Firm	25-50	25
Stiff	50-100	40
Very stiff or hard	100-200	60
Cohesionless Soil	Representative SPT N values	
Very loose	< 6	0
Loose dry	6-10	40
Medium dense	10-30	45
Dense	30-50	55
Very dense	> 50	60
Gravels	>30	100

4.1 ANALYSES OF CPT DATA

CPT data allow the application of methods used in Christchurch for site classification to the Whakatane CBD. The CPT data has been processed by GHD using the analysis method of Idriss & Boulanger 2008, with amendments as per the Christchurch MBIE Guidance (October 2013). The SLS and ULS index settlements for the top 10 m of ground are calculated using a NZS 3604 derived ULS earthquake of 0.40 g (for IL2, 1/500yr event, Z=0.30) for Whakatane, Site Subsoil Class C (see Table 1), and a SLS earthquake is 0.10 g for a 1/25yr event with R=0.25. Technically, the index values are defined as the calculated estimates for liquefaction-induced settlement (in mm) of the top 10 m of subsoil. These index settlement criteria for site classification, developed in Christchurch are shown in Table 4.

Table 3 is copied from the Ministry of Education Guidelines document (MoE 2015).

Table 3 Geotechnical site classification.

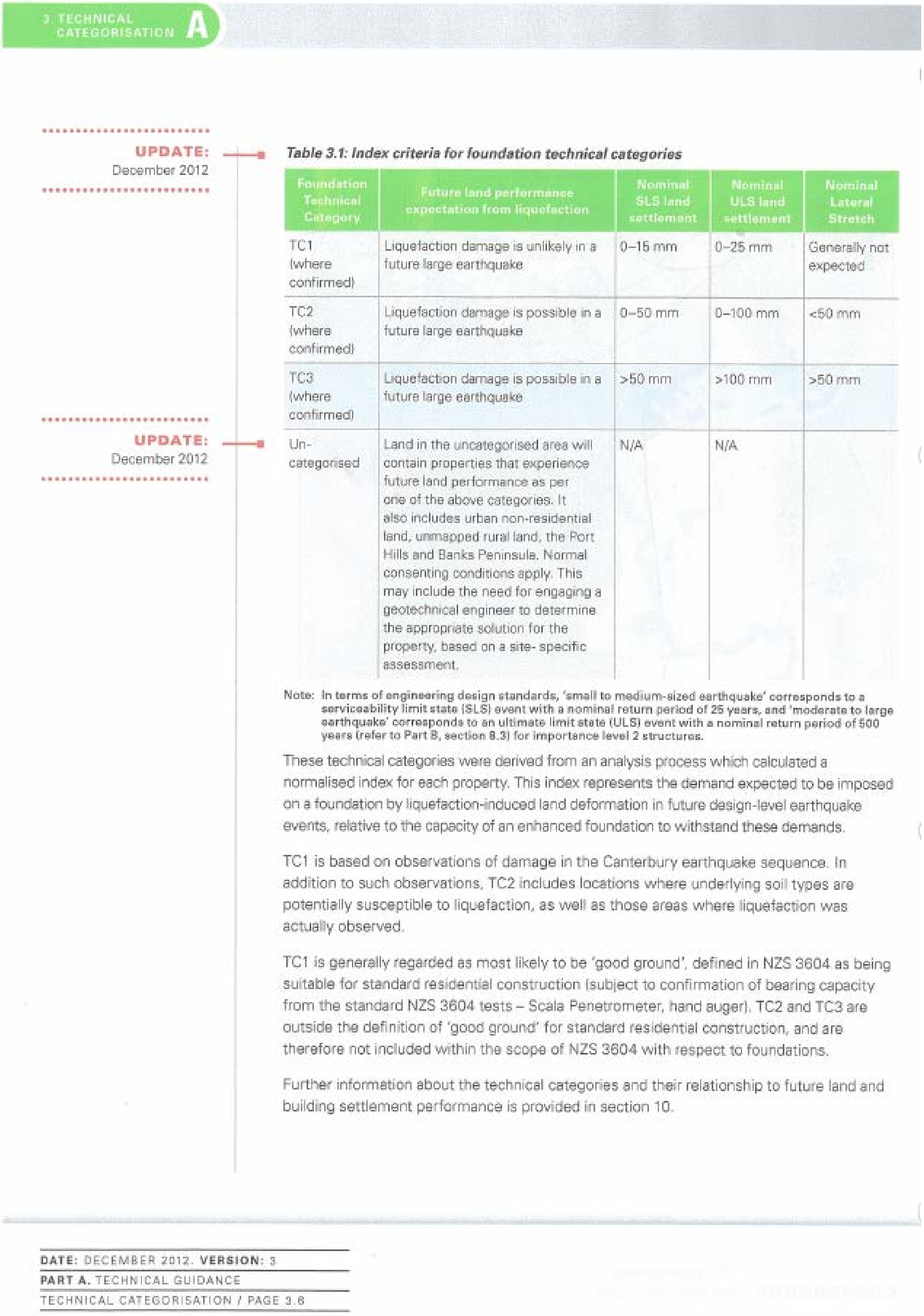
Site classification	Future land performance expectation	Nominal SLS land settlement	Nominal ULS land settlement	Nominal ULS lateral stretch
Good ground	Refer to NZS 3604 Settlement [1] or liquefaction damage from a future large earthquake is **unlikely**	0-15mm	0-25mm	Generally not expected
Poor ground	Settlement [1] or liquefaction damage from a possible future large earthquake **possible**	≤50mm	≤100mm	≤500mm
Poor with lateral spread [2]	Settlement [1] or liquefaction and lateral spread from a future large earthquake **are likely**	>50mm	>100mm	>500mm

Notes:

1. Settlement refers to ground movement that may result under non-seismic “loading” conditions, such as might be expected in compressible or expansive soils (e.g. peat or reactive clays).
2. Lateral spread is the stretching effect that is experienced by some soils during ground shaking, typically in liquefaction-prone areas, and often accompanied by settlement. This is often, but not always, along watercourses.

Table 3 relates a site ground classification, with good and poor ground, and poor ground with lateral spread, to the index SLS and ULS earthquake settlements, and the lateral stretch. Table 3 relates to Table 4 below, copied from MBIE Guidance (MBIE 2012). We propose using the TC Zone index settlements (Table 4) from the MBIE Guidance, together with its correlations to MoE Guidelines (Table 3) for classifying the land in the Whakatane CBD. By doing this, property owners will have access to the extensive, well considered, assessment methodologies and foundation options presented in the two documents.

Table 4 MBIE Guidance Table 3.1, Index criteria for foundation technical categories.



3. TECHNICAL CATEGORISATION **A**

UPDATE:
December 2012

Table 3.1: Index criteria for foundation technical categories

Foundation Technical Category	Future land performance expectation from liquefaction	Nominal SLS land settlement	Nominal ULS land settlement	Nominal Lateral Stretch
TC1 (where confirmed)	Liquefaction damage is unlikely in a future large earthquake	0–15 mm	0–25 mm	Generally not expected
TC2 (where confirmed)	Liquefaction damage is possible in a future large earthquake	0–50 mm	0–100 mm	<50 mm
TC3 (where confirmed)	Liquefaction damage is possible in a future large earthquake	>50 mm	>100 mm	>50 mm
Un-categorised	Land in the uncategorised area will contain properties that experience future land performance as per one of the above categories. It also includes urban non-residential land, unmapped rural land, the Port Hills and Banks Peninsula. Normal consenting conditions apply. This may include the need for engaging a geotechnical engineer to determine the appropriate solution for the property, based on a site- specific assessment.	N/A	N/A	

UPDATE:
December 2012

Note: In terms of engineering design standards, 'small to medium-sized earthquake' corresponds to a serviceability limit state (SLS) event with a nominal return period of 25 years, and 'moderate to large earthquake' corresponds to an ultimate limit state (ULS) event with a nominal return period of 500 years (refer to Part B, section 8.3) for importance level 2 structures.

These technical categories were derived from an analysis process which calculated a normalised index for each property. This index represents the demand expected to be imposed on a foundation by liquefaction-induced land deformation in future design-level earthquake events, relative to the capacity of an enhanced foundation to withstand these demands.

TC1 is based on observations of damage in the Canterbury earthquake sequence. In addition to such observations, TC2 includes locations where underlying soil types are potentially susceptible to liquefaction, as well as those areas where liquefaction was actually observed.

TC1 is generally regarded as most likely to be 'good ground', defined in NZS 3604 as being suitable for standard residential construction (subject to confirmation of bearing capacity from the standard NZS 3604 tests – Scala Penetrometer, hand auger). TC2 and TC3 are outside the definition of 'good ground' for standard residential construction, and are therefore not included within the scope of NZS 3604 with respect to foundations.

Further information about the technical categories and their relationship to future land and building settlement performance is provided in section 10.

DATE: DECEMBER 2012. **VERSION:** 3
PART A. TECHNICAL GUIDANCE
TECHNICAL CATEGORISATION / PAGE 3.6

We note that poor ground in Table 3 has the same index settlements ranges, but smaller lateral stretch of < 50 mm rather than < 500 mm, and the poor ground with lateral spread has equivalent index settlement values to TC3 ground in Table 4, but again the lateral stretch is different. A lateral stretch of > 500 mm in Christchurch would probably be Red Zone, from where all houses are demolished.

The location, collar elevation, depth, and ULS and SLS index settlement values for all CPT's used in the Whakatane 3D ground model are shown in Table 5, and in Figure 3 and Figure 4.

Table 5 Location, collar elevation, depth, and ULS and SLA index settlements for all CPT's used in the 3D ground model.

holeID	Easting	Northing	Elevation	Total depth	ULS Index	SLS Index	Column1	TC Zone
CPT_1	1951618	5792204	2.47	10.56	183	41		2/3
CPT_2	1951418	5792189	1.55	7.66	156	136		3
CPT_3	1951277	5792184	2.11	6.78	189	179		3
CPT_4	1951190	5792174	2.44	8.5	173	153		3
CPT_5	1951099	5792156	3.23	11.08	150	55		3
CPT_6	1950920	5792134	2.19	20.56	188	127		3
CPT_7	1950827	5792132	1.73	18.98	236	179		3
CPT_8	1950728	5792045	1.47	14.56	200	97		3
CPT_9	1950840	5792022	2.75	6.7	107	68		3
CPT_10	1950876	5792028	1.45	33	79	58		2/3
CPT_11	1951148	5792079	2.21	7.2	166	148		3
CPT_12	1951218	5792125	2.28	7.1	160	122		3
CPT_13	1951238	5792137	2.32	4.4	77	55		2/3
CPT_14	1951325	5792151	2.00	7.78	216	182		3
CPT_15	1951284	5792123	2.46	5.14	98	49		2
CPT_17	1951231	5792084	3.03	1.92	14	1	Refused at 1.9m	1
CPT_18	1951175	5792048	2.70	6.22	92	51		2
CPT_19	1951118	5792022	2.72	2.12	32	11	Refused at 2.1m	2
CPT_20	1951069	5792009	2.83	7.9	178	140		3
CPT_21	1951039	5792002	2.68	11.8	231	179		3
CPT_22	1950970	5791985	2.54	16.7	197	133		3
CPT_23	1950900	5791959	2.73	18.12	143	57		3
CPT_24	1950872	5791919	2.58	17.68	177	94		3
CPT_25	1950796	5791860	-0.70	33	163	76		3
CPT_26	1950783	5791911	1.70	17.66	170	64		3
CPT_27	1950745	5791991	1.64	18.42	183	77		3
CPT_28	1950740	5791942	1.27	18.14	219	117		3
CPT_29	1950739	5791912	1.34	12.6	143	55		3
CPT_30	1950734	5791818	2.21	21.66	173	76		3
CPT_31	1950568	5791962	1.73	33	173	46		3
CPT_32	1950538	5791853	1.53	14.52	178	99		3
CPT_33	1950634	5791882	0.43	19	160	74		3
CPT_34	1950523	5791746	1.35	16.7	230	94		3
CPT_35	1950638	5791765	0.65	18.1	168	50		3
CPT_36	1950695	5791783	0.60	21.9	224	118		3
CPT_37	1950731	5791749	1.83	21.7	175	124		3
CPT_38	1950799	5791692	1.80	8.16	188	157		3
CPT_39	1951094	5791774	1.07	6.8	169	135		3
CPT_40	1950965	5791837	0.88	13.5	262	191		3

CPT_41	1950978	5791917	1.48	15.6	248	182		3
CPT_42	1951064	5791921	2.42	9.28	253	210		3
CPT_43	1951131	5791922	2.61	2.94	45	32	Refused at 2.9m	2
CPT_46	1951511	5792066	3.26	8.6	209	136		3
CPT_47	1950057	5791909	0.42	19.5	209	70		3
CPT_48	1950323	5792087	0.64	19	148	56		3
CPT_49	1950675	5792220	0.31	16.3	271	218		3
IRBAHSP001	1949536	5790747	6.37	6.358	66	1		2
IRBAHSP002	1949518	5790731	6.35	5.983	70	53		2/3
IRBAJSL001	1947690	5791112	0.35	10.086	116	6		2/3
IRBAJSL002	1947634	5791114	-0.12	11.128	134	30		2/3
IRBAJSL003	1947574	5791117	-0.10	12.535	169	40		2/3
IRBAJSL004	1947499	5791118	2.51	10.144	182	82		3
IRBAJSL005	1947622	5791440	-0.83	17.17	167	41		2/3
IRBAJSL006	1947667	5791393	2.21	16.421	208	104		3
IRBAJSL007	1947707	5791355	-0.15	13.887	167	33		2/3
IRBAJSL008	1947760	5791302	-0.20	15.123	162	46		3
IRBALRB001	1948972	5791844	0.67	9.118	109	38		2/3
IRBALRB002	1949019	5791882	2.58	12.903	116	16		2/3
IRBALRB003	1949034	5791751	3.27	9.589	138	51		3
IRBALRB004	1949077	5791806	3.49	13.382	166	77		3
IRBALRB005	1948917	5791732	1.34	7.833	147	50		3
IRBALRB006	1949000	5791801	2.00	11.988	169	86		3
IRBALRB007	1949049	5791842	1.69	15.468	137	41		2/3
IRBALRB008	1949093	5791657	0.69	6.029	137	84		3
IRBALRB009	1949093	5791657	-4.75	14.843	45	0	??	2
IRBALRB010	1949087	5791625	0.45	12.892	146	25		2/3
IRBALRB011	1949111	5791583	0.18	11.894	139	77		3
IRBALRB012	1949154	5791716	-0.03	17.819	185	54		3
IRBALRB013	1949209	5791651	-1.18	17.8	157	9		2/3
IRBASPS001	1950304	5792449	0.20	13.526	249	116		3
IRBAWPC001	1948863	5790004	0.15	8.7	150	36		2/3
IRBAWPC002	1948798	5789963	0.46	10.67	127	21		2/3
IRBAWPC003	1948932	5789949	0.83	12.747	116	9		2/3
IRBAWPC004	1948917	5789849	-0.51	12.83	110	7		2/3
WRHSECPT01	1951071	5792125	2.19	12.73	159	101		3
WRHSECPT02	1951100	5792119	2.39	7.21	144	105		3
WRHSECPT05	1951089	5792088	2.39	11.7	198	152		3
WRHSECPT06	1951107	5792089	2.29	8.79	175	148		3
WRHSECPT07	1951093	5792072	2.29	10.59	248	196		3
WRHSECPT08	1951110	5792074	2.19	8.34	174	113		3

Notes on results in Table 5:

- The water table is typically assumed to be 1 m below the ground surface.
- Where there is no sensible CPT data above 1 m, the water level has been adjusted to the first sensible data point, so that realistic results are returned.
- The method follows Idriss & Boulanger 2008, with amendments as per Christchurch MBIE Guidance of October 2013 have been used for the index settlement calculations. This is the method that was used for establishing the TC zones originally in Christchurch.
- Where the CPT has refused shallower than 10 m deep, it has been assumed that underlying soils are too dense to liquefy, and as such, the index values only account for the depth tested.
- Some of the CPTs did not appear to contain all the data (total depth didn’t match.)

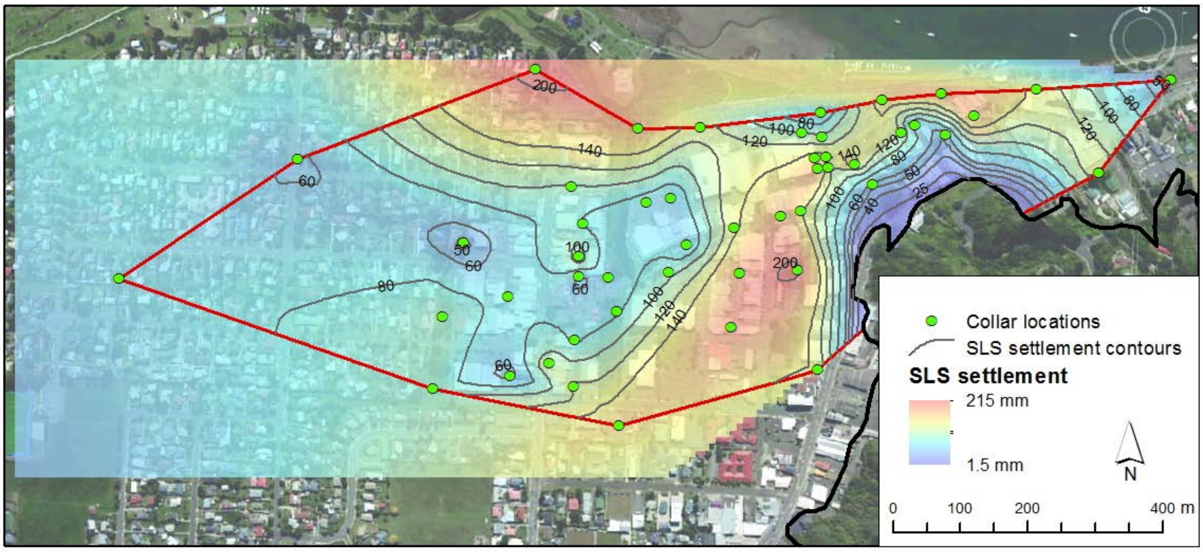


Figure 3 A map grid approximating settlement in an SLS earthquake (0.10 g, 1/25 yr event with R=0.25), contoured within the zone of relative reliability (red polygon) with 25mm, 40 mm, 50 mm, 60 mm, 80 mm, 100 mm, 150 mm and 200 mm contours. CPTs that provide the primary data are displayed as green points. As indicated by the grid, the model extends outside the red polygon, where it is influenced by data points outside the field of view, but the distance between data points is such that confidence in the area outside the red polygon is low. Future geotechnical investigations would assist in reducing the uncertainties that exist outside the polygon. Note that except for a narrow strip beneath the greywacke cliff, settlements are entirely characteristic of TC3 land.

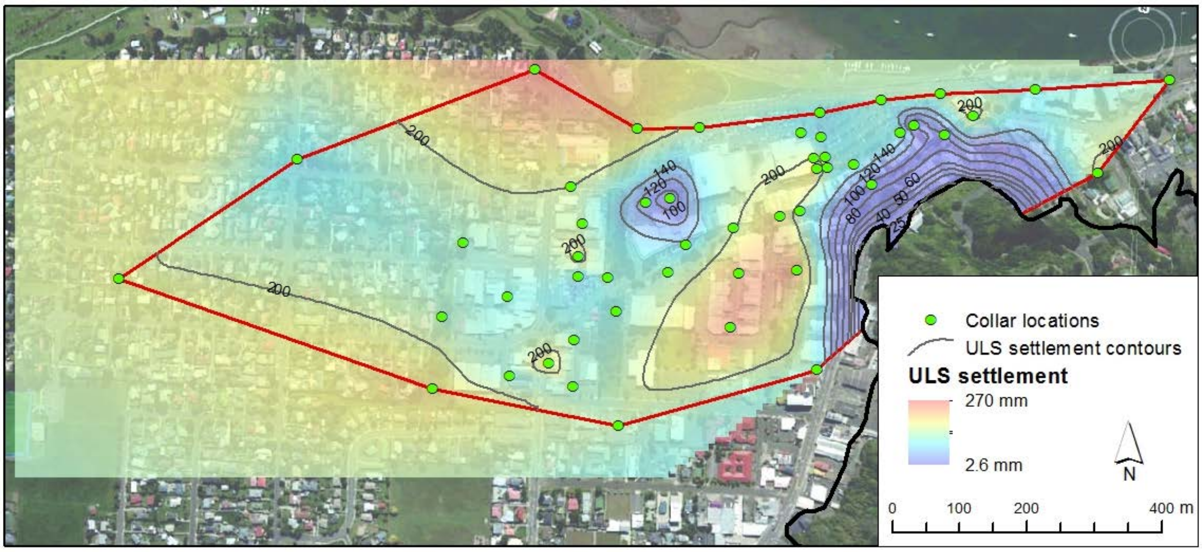


Figure 4 A map grid approximating settlement in an ULS earthquake (0.40 g, 1/500 yr event with Z=0.30), contoured within the zones of relative reliability (red polygon) with 25mm, 40 mm, 50 mm, 60 mm, 80 mm, 100 mm, 150 mm and 200 mm contours. CPTs that provide the primary data are displayed as green points. Comments on reliability in the caption for Figure 3 also apply here.

We also note that the liquefiable soils in Whakatane are likely to contain pumice grains and are different to the soils under Christchurch. However, by using the same analytical process, with the same index settlement ranges that have been established for TC Zones in Christchurch, we are adopting a liquefaction settlement analysis procedure and zoning that can be applied nationally to all parts of New Zealand.

4.2 RESULTS OF THE TC ZONING

As can be seen from Table 5 (see also Figure 3 and Figure 4), most of the land in the Whakatane CBD is classified as TC3 equivalent using the calculated settlement criteria of MBIE Guidance (MBIE 2012). For such TC3 sites in Christchurch there is a requirement for additional subsurface investigations prior to construction of new buildings and foundation design requirements are stringent. The foundation options for houses on TC3 zoned land have just been updated by MBIE (Section 15.3, April 2015; MBIE 2015), while in general the Ministry of Education Guidelines can be followed for commercial buildings. The foundation options may be deep “pile” or a shallow stiff (geogrid reinforced) soil raft and reinforced concrete “slab” that will not deform differentially (they will mitigate flexural distortion) and can be readily re-leveled if required. This stiff foundation has a variety of configurations and options (MBIE 2015).

The TC3 zoning of the CBD is not surprising given its location on a “flood plain” adjacent to the Whakatane River. Experience from Christchurch close to the Avon River indicates that lateral spreading in the worst cases, may extend a distance up to a few hundred metres from the river bank. In Whakatane we expect that lateral spreading might occur close to the Whakatane River bank, particularly during a ULS earthquake.

We note that in the 1987 Edgecumbe Earthquake, judged to be a one in 110 year recurrence event (i.e. greater than an SLS earthquake) there was some lateral spreading at the Landing Bridge, but none was noted along the river banks near the CBD. Observations from the Edgecumbe Earthquake provide reassurance that liquefaction, liquefaction settlement and lateral spreading are unlikely to occur in an SLS earthquake. In this case, the SLS index settlements calculated for Whakatane (Table 5) are over-predicted.

4.3 A WHAKATANE GEOTECHNICAL DATABASE AVAILABLE FOR ALL TO USE

We strongly recommend that new ground investigations data (in the appropriate digital format) is uploaded onto a Whakatane Geotechnical Database and is provided to WDC as part of each building consent application in the Town. In return WDC would ensure that both the Geotechnical Database for the town and the 3D ground model are regularly updated, so that all this data is available online for use by consultants and interested citizens.

The model for this database is the Canterbury Geotechnical Database which is highly appreciated, widely used and endorsed by all engineering consultants working in Christchurch; here, new ground investigations data is uploaded to the database by the consultants working in the city. It then becomes available for all the other consultants registered to use the database. The database currently has data from some 18,000 CPT probes throughout the city, as well as nearly as many drillhole logs, hand augers and Scalas and most recently, Lab Tests data. The Canterbury Geotechnical Database is the envy of cities around the world for its practical utility. Although a 3D ground model has been developed for the city by GNS Science, this model is not yet available as part of the database, whereas in Whakatane, where there is much less data, it is feasible and practical rapidly to include the 3D ground model to illustrate the database.

The Canterbury Geotechnical Database has been administered by CERA (Canterbury Earthquakes Recovery Authority). As CERA winds down, we understand that the Database will be handed to MBIE to administer, with the intention that other cities in New Zealand will in a similar fashion develop their own geotechnical databases administered using systems consistent in format with those established for Canterbury. Currently the only urban areas in New Zealand covered by 3D subsurface modeling are Christchurch (utilizing data collected before and after the 2010-2011 earthquake sequence) and Napier-Hastings. The latter model is currently under development. Palmerston North has been provided with a “two and a half” dimensional model. However, by sponsoring the CBD ground investigations and developing a Town database with a 3D ground model, Whakatane DC are leading most other Councils in New Zealand by developing a resource for the benefit of their citizens.

5.0 DISCUSSION AND CONCLUSION

In the previous sections we have outlined derivatives of the data and modelling. For those interested, Appendix 1 presents information on the data and modelling. But the principal goal of this work is to provide geological and geotechnical information that contributes to an understanding of liquefaction hazard in the Whakatane CBD. In this section, we discuss one earthquake scenario, and using the CPT data available, illustrate the likely extent of liquefaction, what materials may liquefy and what is the vertical distribution of these potentially liquefiable materials.

The example scenario that we have selected to illustrate liquefaction potential is an earthquake of M7 involving groundshaking of 0.3 g. This earthquake approximates a 1/250yr return earthquake that probably exceeds the worst case scenario for earthquakes generated by faults of the Taupo Fault Zone which runs through the Rangitaiki Plains, but is smaller in earthquake magnitude and groundshaking expected for a North Island Fault System (e.g. Whakatane Fault) rupture. The unconfined groundwater surface is set uniformly at 1 m below the ground surface for this example.

We applied these parameters to the suite of CPT data for the Whakatane CBD and calculated LSNs and identified liquefiable horizons for this scenario using CLiq software, using the settings explained in Appendix 1. The calculated LSN values average c. 44, a number representing a high liquefaction potential. Of the 27 CPTs that are deeper than 10 m, the average LSN value is c. 48, 22 exceed 40, and 7 exceed 60. In addition, 4 LSN values for shallower CPTs (CPTs 3, 14, 38 and 39) are 60, attesting to the presence of serious issues at those locations.

Table 6 LSN values for Whakatane CBD CPTs derived from CLiq, set to parameters described in Appendix 1, for an earthquake magnitude M7, with peak ground acceleration of 0.3 g, and with groundwater depth set at a consistent 1 m depth. CPTs are arranged in order of refusal depth.

holeID	Easting	Northing	Elevation	Refusal depth	LSN
CPT_16	1951259	5792087	2.748	0.8	
CPT_44	1951243	5792036	3.287	0.8	
CPT_45	1951319	5792066	3.109	0.8	
CPT_17	1951231	5792084	3.053	1.92	2
CPT_19	1951118	5792022	2.743	2.12	8
CPT_43	1951131	5791922	2.629	2.94	18
CPT_10	1950876	5792028	2.453	4.2	7
CPT_13	1951238	5792137	2.335	4.4	21
CPT_15	1951284	5792123	2.484	5.14	37
CPT_18	1951175	5792048	2.724	6.22	36
CPT_9	1950840	5792022	2.774	6.7	
CPT_3	1951277	5792184	2.125	6.78	60
CPT_39	1951094	5791774	2.274	6.8	60
CPT_12	1951218	5792125	2.297	7.1	48
CPT_11	1951148	5792079	2.234	7.2	46
CPT_2	1951418	5792189	1.572	7.66	26
CPT_14	1951325	5792151	2.016	7.78	60
CPT_20	1951069	5792009	2.852	7.9	42
CPT_38	1950799	5791692	1.822	8.16	60
CPT_4	1951190	5792174	2.463	8.5	31
CPT_46	1951511	5792066	3.28	8.6	51
CPT_42	1951064	5791921	2.436	9.28	47
CPT_1	1951618	5792204	2.486	10.56	31
CPT_5	1951099	5792156	3.248	11.08	38
CPT_21	1951039	5792002	2.703	11.8	49
CPT_29	1950739	5791912	1.36	12.6	27
CPT_40	1950965	5791837	2.082	13.5	60
CPT_32	1950538	5791853	1.547	14.52	58
CPT_8	1950728	5792045	1.485	14.56	
CPT_41	1950978	5791917	2.657	15.6	60
CPT_49	1950675	5792220	1.492	16.3	60
CPT_22	1950970	5791985	2.557	16.7	44
CPT_34	1950523	5791746	1.365	16.7	60
CPT_26	1950783	5791911	1.722	17.66	47
CPT_24	1950872	5791919	2.601	17.68	27
CPT_35	1950638	5791765	1.845	18.1	43
CPT_23	1950900	5791959	2.75	18.12	26
CPT_28	1950740	5791942	1.291	18.14	44
CPT_27	1950745	5791991	1.664	18.42	57
CPT_7	1950827	5792132	1.754	18.98	60
CPT_33	1950634	5791882	1.629	19	52
CPT_48	1950323	5792087	1.843	19	52
CPT_47	1950057	5791909	1.621	19.5	46
CPT_6	1950920	5792134	2.215	20.56	49
CPT_30	1950734	5791818	2.226	21.66	44
CPT_37	1950731	5791749	1.851	21.7	49
CPT_36	1950695	5791783	1.798	21.9	60
CPT_25	1950796	5791860	0.478	33	44
CPT_31	1950568	5791962	1.745	33	43

Using the criteria of LSN value to approximate liquefaction susceptibility (Figure 5), these CPTs more consistently represent high susceptibility to liquefaction than those in the eastern suburbs of Christchurch.

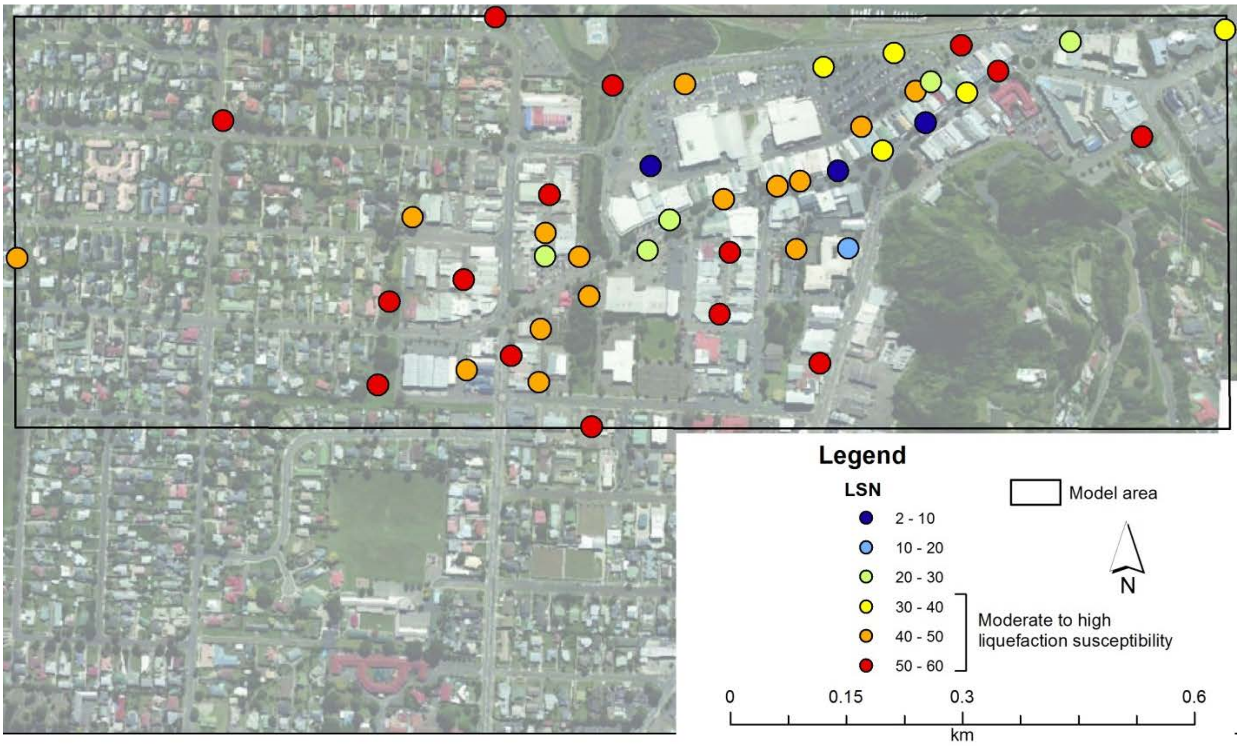


Figure 5 A map of the CBD area with CPT collars coloured according to LSN values for the earthquake scenario discussed above (M7, PGA 0.3 g, unconfined groundwater surface at 1 m depth). Note that LSN values for CPTs shallower than about 10 m are likely to be under-estimates when compared with deeper CPTs, and that LSN values may not represent true liquefaction susceptibility with respect to Christchurch, as the pumiceous materials are so different.

It is possible to take the CPT liquefaction derivative results and display them in Leapfrog Geo to show the distribution of liquefaction susceptible layers throughout the 20 m thickness of the model (Figure 6). An apparent conflict identified between the derivative CPT liquefaction susceptibility data and SPT data, where CPTs suggest liquefaction to significantly greater depths that SPT data is resolved in the modelling by differentiating loose sands from dense sands, and in settlement calculations only the top 10 m of materials are covered by the assessment, meaning that the dense sands contribute very little to the settlements inferred from the CPTs.

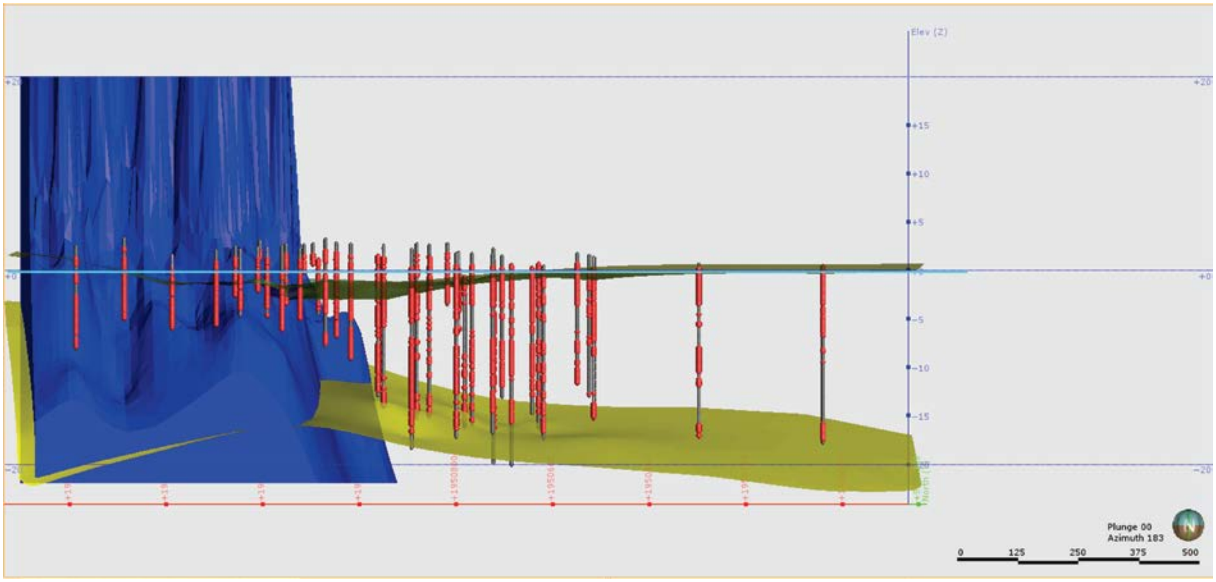


Figure 6 Whakatane CBD, viewed horizontally from the north, showing CPTs coloured as grey vertical lines. The red materials are calculated as having high likelihood of liquefaction for the M7, PGA 0.3 g earthquake in the given scenario, with unconfined groundwater surface at 1 m depth. The base of the upper silt and the base of the sand unit are shown for reference. Note that SPT data contradict CPT analysis, suggesting that materials deeper than up to c. 9 m below the ground surface are unlikely to liquefy.

Some assumptions that are made in these LSN/settlement calculations may not necessarily be valid; notably, that the highly pumiceous materials present beneath the surface at Whakatane behave in a similar way to those beneath eastern Christchurch. The other significant assumption concerns the depth to groundwater (as discussed above).

Lateral spreading may be an issue for sites close to the Whakatane River channel, although its absence close to the CBD during the Edgecumbe Earthquake suggests that it is unlikely to be an issue during SLS earthquakes. Christchurch experience suggests that under severe groundshaking conditions, almost all lateral spreading was within 200 m of significant river channel features and most was within 100 m.

Best use of this report can be gained by reading it in tandem with the IRBA report on data collection and with the Leapfrog Viewer project for the Whakatane CBD (see Appendix 2).

5.1 QUALITY ASSURANCE

The quality of raw and derivative geotechnical data incorporated within this project has been reviewed by a geotechnical and structural engineer (R. Ramilo, GHD). Methods used in geological and geotechnical modelling and interpretations on liquefaction susceptibility derived from the data and models have been internally reviewed (K. Jones and S. Dellow) within the GNS Science quality assurance system.

The GHD contribution on Engineering use of sub-surface data was reviewed internally by S. Webb. The methods applied in this report are entirely compatible with work done in Christchurch, with recommendations of the Canterbury Earthquakes Royal Commission recommendations and are well-aligned with guidelines under development by Tonkin & Taylor, MBIE and GNS Science on managing liquefaction-prone land.

This statement on quality assurance can be read in association with the Section A1.13 on model reliability and Section A1.15 on model limitations for a more complete vision of the work.

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6.0 RECOMMENDATIONS FOR FURTHER WORK

With the addition of new data as it becomes available, this model may be amended, improved and/or spatially extended. A copy of the model is lodged with Whakatane District Council, but the master resides at GNS Science. Some CPTs covering suburban Whakatane have been checked against the data and model reported here and proved comparable. Ultimately these may provide a basis for extending this work across suburban Whakatane, although substantially better data coverage will be necessary before this is possible.

The findings of this report provide a strong indication, with qualification, that materials beneath the Whakatane CBD include some with high susceptibility to liquefaction. As Whakatane is within a zone of relative high seismic hazard, the likelihood of liquefaction susceptibility may leave some current buildings at risk. We recommend that building owners who believe they may be at risk carefully consider the liquefaction susceptibility identified in this report and where appropriate, commission geotechnical and structural engineers to consider carefully their exposure.

For the present study, the record of the unconfined groundwater surface is poorly constrained. We recommend that Whakatane District Council consider the possibility of establishing a network of permanently monitored piezometers in suitable materials to a depth of 5 m to help refine understanding of groundwater surface variability.

Recently collected data suggests that the Whakatane Fault lies west of the CBD area (Meuller pers. comm.). Current knowledge of the fault suggests that the western side subsides during rupture and long term geological indicators suggest the eastern side may be uplifted. Given the CBD’s low elevation and proximity to the Whakatane River, there is good reason to investigate this expectation. Two or three carefully placed drillholes to a depth of 40 m may constrain the location of the fault (and therefore surface rupture hazard) and also provide an estimate of the cumulative vertical slip rate and whether rupture will include uplift on the eastern side of the fault.

7.0 ACKNOWLEDGEMENTS

Razel Ramilo, a geotechnical and structural engineer with GHD, checked the CPT data and derivative data and provided sound advice on the process of eliminating suspect data. We wish to acknowledge the help that Katie Jones provided on use of the modelling software Leapfrog Geo. Mark Stirling provided advice on the earthquake scenario we chose to demonstrate liquefaction susceptibility in the CBD.

GNS Science reviewers Katie Jones and Sally Dellow are warmly acknowledged for their careful reviews and thoughtful suggestions to improve the manuscript. GHD internal reviewer Samantha Webb is warmly acknowledged for her review of the engineering section of the report.

This project has relied heavily on the vision, foresight and coordinating skills of Jeff Farrell of Whakatane District Council. He brought the team together and focussed its vision on providing the best outcome for the council and other stakeholders. He has been an integral part of the team and provided thoughtful comments through to its conclusion.

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APPENDICES

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A1.0 DATA AND MODELLING METHODS

A1.1 DRILLING AND CPT INVESTIGATION DATA

GNS Science provided Whakatane DC with information regarding preferred format for CPT digital data for this 3D modelling project. Ian R. Brown Associates were engaged by Whakatane DC to design, co-ordinate and report on the drilling and geotechnical investigation to provide data for this modelling exercise. The campaign was completed and data with an explanatory text were made available to GNS Science in November 2014 (IRBA 2014). The data provide a sound suite of uniform quality upon which to undertake modelling the materials beneath the Whakatane CBD to a depth of c. 20 m.

Ten drillholes were located across the area of interest, all within 1.2 km of its eastern end (Scene 1). In addition, 46 CPT soundings were completed within the area, each undertaken to conform to the requirements of NZS 4402:1986, Test 6.5.3. All but two CPTs were within 1.2 km of the eastern boundary (Scene 1). CPT collars were located within c. 15 m of seven of the drillhole collars (mostly much less than 15 m), enabling useful comparison between the different data types. The western third of the model area is poorly populated with drillhole and CPT data and thus the reliability of the models here is poor, but is included here because there are two CPTs recorded (CPT47 and CPT48). Three CPTs (CPT16, CPT44 and CPT45) have no recorded data because they encountered refusal at shallow levels, where collars were sited in areas with basement greywacke rock close to the surface (Scene 2). In addition to the CPTs from this round of IRBA investigation, 6 legacy CPTs within the model area were included in the modelling and 27 CPTs across suburban Whakatane.

List of data provided by IRBA (2014):

1. IRBA Delivery Report
2. Daily drillers reports, BH-01 to BH10, pdf format
3. Waste disposal manifest
4. Drillhole and CPT collar data spreadsheet
5. Photography and water levels spreadsheet
6. Drillhole logs, pdf format, BH-01 to BH-10
7. 431 photos
8. SPT test logs, spreadsheet
9. Individual CPT interval data, csv format
10. Individual CPT graphic, pdf format

A1.2 METHOD

Software chosen to complete this work includes CLiq (Geologismiki) for CPT analysis, ArcGIS (ESRI) for spatial information manipulation and Leapfrog Geo (ARANZ Geo) for 3D geological modelling and Leapfrog Viewer for dissemination of the resulting models.

All spatial data is in NZTM projection and elevations are measured from (positive, above and negative below) Mean Sea Level.

The lower boundary of the area of interest is defined as -22 m (m below mean sea level), as the internationally accepted depth limit for liquefaction is 20 m. We draw the upper boundary at 20 m because no part of the CBD other than that underlain by greywacke lies at such elevations.

A1.3 CPT DATA

Properties of materials were derived from raw CPT data using CLiq software. During the input into CLiq the raw CPT data was corrected by converting negative and zero values of cone resistance (q_c) and local friction (f_s) to 0.01. Normalised interpretative derivative data was generated in CLiq by using the calculation method of Robertson (conforming to Youd et al. 2001, NCEER; Robertson & Wride 1998; and Robertson 2009). Fines were calculated according to Idriss & Boulanger (2008) and auto transition layer detection was turned on. Each raw data record was averaged with the measurement above and below, creating a simple running average of 3, so there was no reduction in the number of data points from the original data.

CPT holeID numbers (e.g. CPT_5), eastings, northings and total depth fields were added to output interpretative tables and elevation of each CPT measurement was calculated from the collar elevation stored in the CPT collar data spreadsheet (IRBA) and the depth of the measurement. All tables were concatenated into a single csv format file that was loaded into Leapfrog Geo as x, y, z point data layer. Fields within this file are described in Table A1.

The derivatives included in this table provide a comprehensive geotechnical characterisation of the properties of materials (Scenes 5, 6 & 7), providing base information for more specific liquefaction assessment.

CPT collar table with attributes described in Table A2 was loaded into Leapfrog Geo but purely for display purposes.

Table A1 Attribute fields in CPT point data table.

Field heading	Definition of field
Id	Unique row identifier
X	Easting of CPT measurement
Y	Northing of CPT measurement
Z	Elevation of CPT measurement
holeID	Unique CPT sounding number
Total_depth	Depth of refusal for the CPT sounding, in metres
CPT_No	CPT raw data measured row number
Depth_m	Depth below surface of measurements, in metres
qc_MPa	q_c; Measured cone resistance, in MPa
fs_kPa	f_s; Measured sleeve friction resistance, in kPa
u_kPa	u; Measured pore water pressure, in kPa
qt_MPa	q_t; Corrected cone resistance, in MPa
Rf_pc	R_f; Friction ratio, in %
Gamma_kN_m	Gamma; Soil unit weight, in kN/m^3
FC_pc	FC; Fines content, in %
sigma_v_kPa	Φ_{vo}; In situ total overburden stress, in kPa
u0_kPa	u_0; In situ pore pressure, in kPa
sigma_vo_kPa	Φ'_{vo}; Effective overburden stress in kPa

Field heading	Definition of field
Ic_SBT	Non-normalised Soil Behaviour Type Index
SBT	Soil Behaviour Type
Ic	Normalised Soil Behaviour Type Index
SBTn	Normalised Soil Behaviour Type
Cn	Limit value on stress normalisation factor
N	F_r; Normalised friction ratio
Qtn	Normalised cone resistance
Fr_pc	Normalised friction ratio
Bq	Normalised pore pressure parameter

Table A2 Attribute fields in CPT_Collar point data table.

Field heading	Definition of field
Id	Unique row identifier
X	Easting of CPT collar
Y	Northing of CPT collar
Z	Collar elevation; derived from LiDAR and supplied by IRBA
Total_depth	Depth of refusal for the CPT sounding, in metres

Derivatives for one earthquake scenario were calculated in CLiq to provide an example for liquefaction susceptibility determinations from CPT data, which were loaded into Leapfrog Geo as a point layer and used to highlight liquefiable layers. The specific earthquake scenario chosen was an earthquake of magnitude 7 with peak ground acceleration of 0.3g and groundwater level of 1m below ground surface (see Section 5.0 Discussion and Conclusions).

A1.4 DRILLHOLE DATA

Drillhole data (Scene 2) is presented in Leapfrog Geo using three tables, collar, survey and log table, and was loaded from separate csv files. The attribute fields for each of the drillhole data tables are described in Table A3 to Table A5.

Table A3 Attribute fields in collar drillhole table.

Field heading	Definition of field
Id	Unique row identifier
X	Easting of drillhole collar
Y	Northing of drillhole collar
Z	Collar elevation, determined by IRBA from LiDAR data
holeID	Unique drillhole identifier
maxdepth	Depth of drillhole

Table A4 Attribute fields in survey drillhole table.

Field heading	Definition of field
Id	Unique row identifier
holeID	Unique drillhole identifier
depth	Total depth of drillhole (all drillholes are vertical)
dip	Drillhole inclination (90° for all drillholes)
azimuth	Dip direction (0° for all drillholes)

Table A5 Attribute fields in drillhole log table.

Field Heading	Definition of field
id	Unique row identifier
holeID	Unique drillhole number
from	Depth to top of lithological unit, in metres from collar
to	Depth to base of lithological unit, in metres from collar
Elevation	Collar elevation, in metres above mean sea level; derived from LiDAR by IRBA
td_drill	Total depth of drillhole, in metres
drill_method	Method used in drilling (e.g. vacuum, sonic)
recovery	%age recovery of materials for each interval
lith_col_lith_colour_	Standard descriptor for colour of materials cored
Structure	Standard descriptor for bedding, partings etc.
weathering	Standard descriptor for degree of weathering
Grading	Standard descriptor for spread of predominant grain sizes present
sub1_secondary_lith_	Standard descriptor for secondary lithologies present
lith1_PRIMARY	Primary lithology present
sub2_minor_lith_	Standard descriptor for minor lithologies present
Consistency	Standard descriptor for soil strength for cohesive soils
Density	Standard descriptor for degree of compactness
Moisture	Standard descriptor for moisture of materials cored
Plasticity	Standard descriptor for a material’s ability to be moulded
E	Easting (NZTM)
N	Northing (NZTM)
Datum	NZTM
Total_depth	Depth of drillhole, in metres
company	IRBA
yr_drilled	2014
Comments	Additional special features of the interval

IRBA supplied drillhole logs accompanied by a spreadsheet detailing SPT tests and these were loaded into Leapfrog Geo to be used for validating the developed models (Scenes 2, 3 and 4). SPT table attributes are described in Table A6.

Table A6 Attribute fields in SPT table.

Field heading	Definition of field
Id	Unique row identifier
X	Easting of drillhole collar
Y	Northing of drillhole collar
Z	Elevation of SPT, derived from collar elevation and SPT depth
holeID	Unique drillhole identifier
Z_Collar	Collar elevation
Depth_m	SPT depth bellow collar
N	SPT N value
Comments	Text comments on the test

Drillhole water depth measurements were recorded and provided by IRBA, and these were combined with the estimated CPT water levels to model the depth to unconfined groundwater (Scene 8). Fields within this table are described in Table A7.

Table A7 Attribute fields in GW table.

Field heading	Definition of field
Id	Unique row identifier
X	Easting of drillhole collar
Y	Northing of drillhole collar
Z	Elevation of unconfined groundwater surface
holeID	Unique drillhole/CPT identifier
Collar_Elevation	Collar elevation
Hole_Depth	Total depth of drillhole/CPT
GW_Depth	Depth of unconfined groundwater beneath the ground surface
Date_Time	Date (and time) of measurement

A1.5 TOPOGRAPHY

The base topography used in ArcGIS and Leapfrog Geo modelling is LiDAR data collected for Environment Bay of Plenty (EBoP) in late 2006 by AAMHatch (e.g. Scene 1). The average point separation is c. 1.2 m and the project was designed to provide vertical and horizontal point accuracies of c. 0.15 and <0.55 m respectively. Ground truthing of interpolated point data, using conventional survey methods, indicates a Standard Error (RMS) altitude accuracy of 0.045 m and an error for the horizontal measurements of 0.05 m (AAMHatch, 2007). A 3.5 m DEM derived from last return points was used to generate hillshades to assist in geomorphic interpretation. The DEM was resampled to 10 m resolution on import in Leapfrog Geo.

The Leapfrog-modelled topographic surface differs from that used in assigning elevations for drillhole and CPT collars by IRBA, with point elevation differences between the two topographies up to almost 0.5 m. This results in a mismatch between the 3D model topography and the LiDAR collar heights, and flows into elevation uncertainties in model data. However, given the lateral spatial separation of data points, we deemed this uncertainty to have minor impact on modelled materials and interpolated volumes.

A1.6 COMPARISON OF CLOSELY SITED DRILLHOLES AND CPTS

Seven holes were drilled within 15 m of CPT soundings, providing useful information on the reliability of CPTs to discriminate similar features to those found within drillhole materials (Scene 1).

Table A8 Identification of drillholes and CPT collars within 15 m of each other.

Borehole #	CPT #	Distance apart (m)
BH01	CPT01	3.61
BH03	CPT03	2.24
BH04	CPT04	3.61
BH06	CPT31	2.24
BH07	CPT34	1
BH08	CPT25	12.04
BH09	CPT38	2

In most cases, interpretations of CPT data record similar materials to those identified in drillhole logs. In some cases refusal of CPTs clearly relates to dense and/or gravel horizons depicted in drillhole logs (e.g. CPT4 refusal at 8.6 m probably relates to the top of medium gravel recorded at 9.4 m in drillhole BH4; CPT3 refusal at 6.8 m probably represents the greywacke surface encountered in BH3 at 6.7 m).

In most cases, clean and silty sands are more finely sub-divided in the drillhole logs than in the CPT Soil Behaviour Type Index I_c (henceforth indicated as I_c) results. This is particularly so where thin beds of different lithology are identified in the drillhole logs, but is not recognised in the CPT data. The contrary may be true for silty sand and silt intervals, where it appears that CPT data may be able to distinguish variation in these materials better than visual inspection during logging.

SPTs provide a useful addition to the lithological logs and in many cases major changes downhole in N value are corroborated by q_c changes in CPT records, even where lithologies are consistent through these changes (Scene 9). Curiously, in CPT 31, high q_c values (q_c >200 MPa) are recorded in the interval between 5.6 and 7.8 m, at the same elevation as very low SPT N values in BH6 (N 6, 10, 0).

In some cases, spiky q_c and f_s curves in CPT records are present close to where shellbeds and/or pumice gravels are recorded in drillhole logs (e.g. BH6, 11.7 to 13 m; CPT31, 12 to 13 m).

A1.7 BUILDING A GROUNDWATER SURFACE

Modelling the unconfined groundwater surface is an essential part of liquefaction assessment, as if soil is not saturated, it will not liquefy. Further, it has been clearly established that the thickness and nature of surficial unsaturated materials potentially provides a crust resistant to penetration through which liquefied material (in the event of seismic ground shaking) has to penetrate.

Point data on depth to the unconfined groundwater surface comes from three independent sources (Scene 8), drillhole dip sensor data, interpreted position from CPT pore water pressure data and from a line drawn along the river edge at 0 m elevation.

The drillhole values are the better of the point data sources for estimating the unconfined groundwater surface. Here one or a series of readings is empirically measured. Where a series of measurements are available for a single drillhole, the preferred value is that taken in the morning before drilling started or late in the evening after drilling for the day ceased. This is not the case for BH8, where the evening level is high (1.45 m) and the morning level is low (0.3 m). The value selected for this reading is one taken at 1 pm, 1.1 m depth.

CPT water level data is suspect as it is estimated from the CPT pore water pressure measurements (so a derivative of the data rather than a measurement) and uncertainty is built in from the vacuum clearing of the 1.2 m immediately below the ground surface, a zone in which pore water pressures cannot be assumed to represent *in situ* materials.

A line drawn along the Whakatane River edge at mean sea level provides further control on the elevation of the unconfined water surface. This data, being based on the LiDAR DEM is likely to be more accurate than the CPT data, although the level probably fluctuates up to 2.1 m due to tidal influence. This cyclical fluctuation undoubtedly affects the unconfined groundwater level for some distance inland from the river bank.

The modelled surface (Figure A1; Scene 8) suggests that depth to the unconfined water table is reasonably consistent across the area of interest at between 1 and 1.5 m depth.

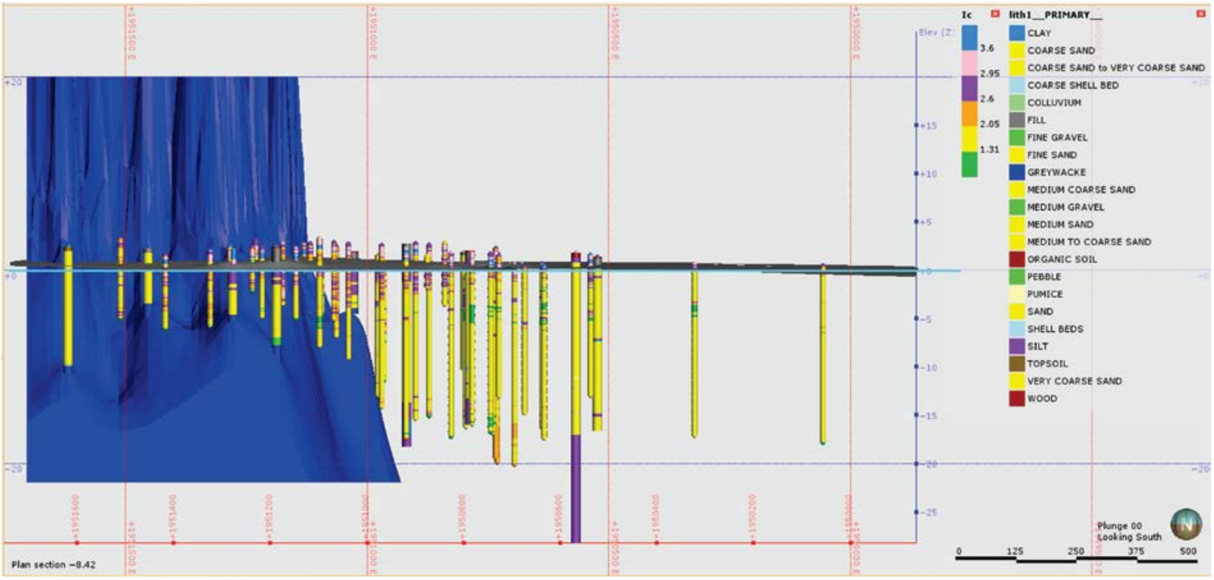

Figure A1 The Whakatane CBD model area, viewed horizontally from the north, illustrating the unconfined groundwater surface as modelled. Drillholes logs are plotted thicker than CPT logs, but both are coloured to illustrate lithology (CPTs are coloured according to Ic). Silt and silty clay are bright and pale pink respectively, sand is yellow, gravel/shellbeds are green and greywacke bedrock is dark blue. Mean sea level is represented in this and the following figures by a horizontal pale blue line. Vertical exaggeration in this and other illustrations in this report is X20.

A1.8 IDENTIFYING AND BUILDING SURFACES REPRESENTING CORRELATIVE HORIZONS

The easiest lithological change to define within the study area is the boundary between bedrock greywacke and Quaternary sediments. Five of the ten drillholes within the investigation phase intercepted greywacke at depth, BH1, BH2, BH3, BH4 and BH10 (Scenes 2 & 3). In addition, the depth of basement was established in the pre-drill stage of three CPT sites, CPT16, CPT44 and CPT45. We defined a GIS line boundary at the surface between Quaternary sediments and greywacke rock exposed in the seacliff behind Whakatane using shaded and slope models derived from the LiDAR DEM. We used topography in the form of GIS line contours from the LiDAR DEM to model the greywacke surface in the cliffs above the town. We added 10 m to the contour value to force this surface above the ground so that clipping of the resulting model with topography left greywacke volume at the ground surface. Additionally, we built a series of subsurface polylines within Leapfrog Geo to represent the location of the greywacke surface using the drillhole data where greywacke was recorded, the slope of the cliff behind the town and the maximum depths of drillholes and CPTs that failed to reach bedrock. These three inputs were used to define the greywacke surface.

We used drillhole logs and CPT soundings within Leapfrog Geo software to visualise lithological changes and define further geological boundaries within the model extent (Scenes 2 & 3). We coloured drillhole logs using the lith1_PRIMARY_ field to represent drillhole lithologies and the I_c to define CPT lithologies. We have not modelled fill, which is widely distributed across the area of interest and up to 1.5 m thick. The upper 1.2 m of CPT soundings represent vacuum clearing, providing no useful information and are not modelled.

An upper interbedded unit of silt, sandy silt and minor sand can be recognised in almost all drillhole and CPT logs to depths ranging from 2 m (west) to -3 m (east). Each log was marked by a point at the elevation considered to represent the base of this upper silty unit across the area and these points were modelled as a surface (Figure A2). This surface, defining the spatial distribution of the base of this surficial silty unit honours most of the data, although silts are present below the modelled surface in a number of areas. The silty unit above the modelled surface is characterised by low $q_t < 4$ MPa and low SPTs (N = 4-20). Silts below the modelled surface are not considered correlative with the lithologies above it.

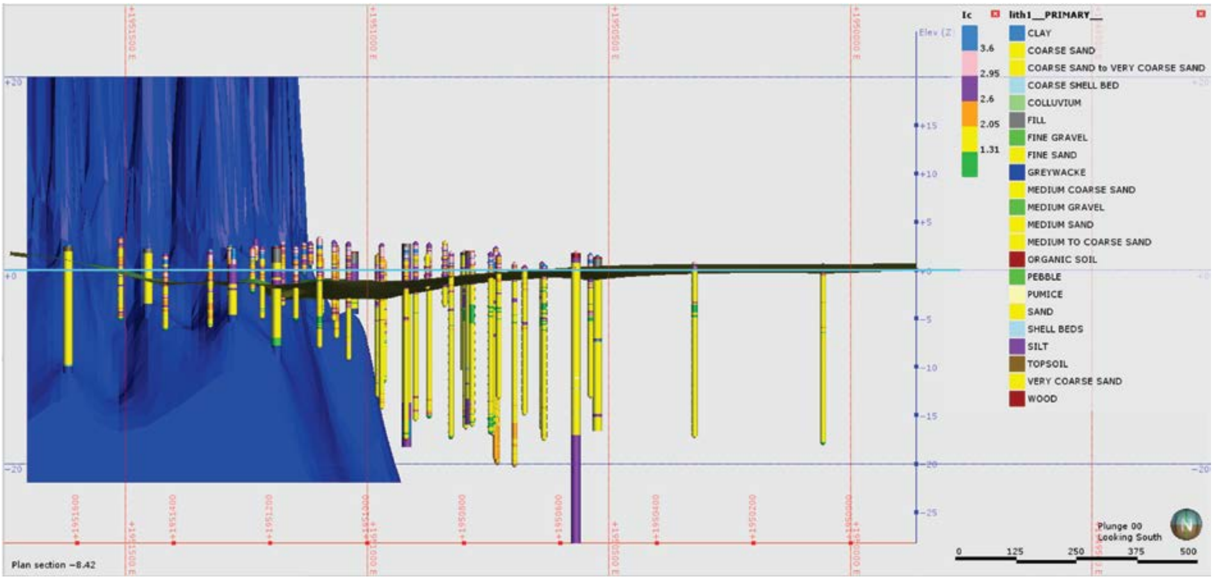

Figure A2 The Whakatane CBD viewed horizontally from the north, illustrating the sub-horizontal surface modelled between fine-grained materials (mostly silt) close to the surface. Note that this surface lies close to modern mean sea level (pale blue line).

Beneath the base of the upper silty unit, lithologies are dominantly sand to a depth of c. -17 m, when a number of the deeper CPTs and drillhole logs indicate the presence of a sandy silt unit beneath the sands. The base of the sand unit was defined using short polylines at each drillhole and CPT where the boundary was recognisable. Additional lines were added to ensure the base of the sand unit continued to the greywacke basement, ensuring that the surface is clipped by the greywacke boundary in the volume-building phase. The resulting modelled surface dips gently to the north (azimuth 335° at c. 0.7° dip; Figure A3).

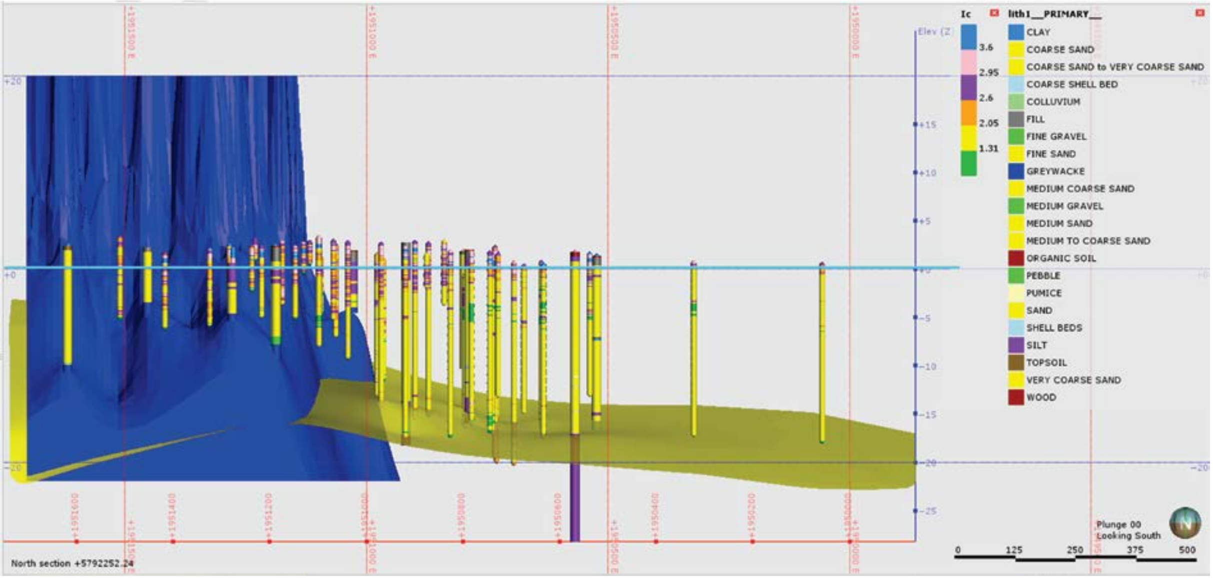

Figure A3 The Whakatane CBD viewed horizontally from the north, illustrating the gently north-dipping surface between sand-dominated material and underlying silt and silty sand.

These two surfaces represent respectively the top and the base of the Holocene marine materials. The top is close to horizontal and lies close to sea level and the dipping basal surface reflects rising sea level prior to sea level stabilisation c. 7000 years ago. They provide guidelines on stratigraphic correlation expected for all materials between.

A1.9 BUILDING 3D GEOLOGICAL MODEL VOLUMES

The modelled surfaces and contacts described above, together with two lenticular gravel/shelly units differentiated within the middle sandy unit were used to construct the 3D Geological Model. The model is composed of the greywacke and five Quaternary volumes (Scene 4).

There is no further discussion about the characteristics of the basement greywacke unit other than that it is important to know that its upper surface is likely to have considerable local relief. Prior to sea level stabilising c. 7000 years ago, streams cut into the bedrock on their route to the shoreline at least 10 km offshore. Since mid-Holocene sea level stabilisation, marine interaction with the seacliff behind Whakatane has undoubtedly resulted in erosion marginal marine benching and landslides that have modified the morphology of the surface. The relict sea stack on the corner of Canning Place, The Strand and Commerce Street is one such irregularity that is exposed at the surface.

The geological units differentiated within the Quaternary volume in stratigraphic sequence are: a lower sandy silt, a sand, with two lensoidal gravel/shelly units, and an upper silt. The base of the upper silt unit lies close to sea level while the base of the sand unit dips gently seaward (Scene 4). These combined surfaces define the geometry of the interpolation ellipsoid for the interpolated Geotechnical Models described in Appendix 1.10.

The upper silt appears to be present consistently across the full extent of the area, with its lower contact lying close to sea level, although locally (e.g. near CPT22), it lies as deep as -3 m. Core photos and logs show that where sampled, the silt is well graded, soft, medium dense and wet. Where it lies above sea level, the unit probably comprises overbank silt and/or swamp deposits, although these may grade into estuarine deposits below sea level in some places. Judging by the presence of abandoned meander loops of the Whakatane River elsewhere in Whakatane, it is reasonable to assume that there may be infilled, buried channels of old river courses through the area of interest, that may be represented by rapid sub-surface inhomogeneity within these materials. No shell materials were recorded in drillhole logs from this unit, corroborating our inference that they are non-marine. SPT (Standard Penetration Tests) N values within the upper silt unit are consistently in the range N = 1 to N = 10 (13 out of 16 SPTs), although three records (BH4, depth 1.5 m; BH5, depth 4.5 m; BH8, depth 3 m) have values N = 17 to N = 23. CPT q_t values are typically in the 0-2 MPa range, although some very thin horizons may be up to 33 MPa. CPT effective unit weight values (Gamma) are generally low to moderate (mostly 13.7 to 17 kN/m^3).

The underlying sand unit is thick and comprises largely of sand and silty sand, commonly pumiceous sand. Shells are commonly recorded in logs and photos, attesting to its marine origins. The two lensoidal shellbeds/gravels differentiated within the unit (see Figure A4; Scene 4) are identified largely using CPTs, although a thin gravel with greywacke and pumice pebbles is recorded in the log of BH9 between 5.9 and 6 m depth and a shellbed is logged lateral to the lower unit in BH6 (16.4 to 16.5 m depth). All shell materials recorded in the drillhole logs are from this unit, with the possible exception of a record in BH7, between 16.5 and 18 m depth, where part of this interval may be in the underlying sandy silt unit. SPT N values are consistently higher in the sand unit than in the overlying silt. Here, N values are generally in the range N = 10 to N = 50 (25 out of 53 tests are N ≥ 30), although 2 individual N measurements of N < 4 are recorded (BH3, depth 4.5 m; BH10, depth 4.5 m) and 7 have N ≥ 4 ≤ 10. A rapid transition in relative density between -4 and -8 m recorded in the drillhole logging (S. Henderson, pers. comm. 11 March 2015) can also be seen in many CPT logs. CPT q_t values are commonly <10 MPa (with some very thin horizons may be as low as <1MPa) in the upper part of the unit, but are commonly in the 15 to 25 MPa in the lower part.

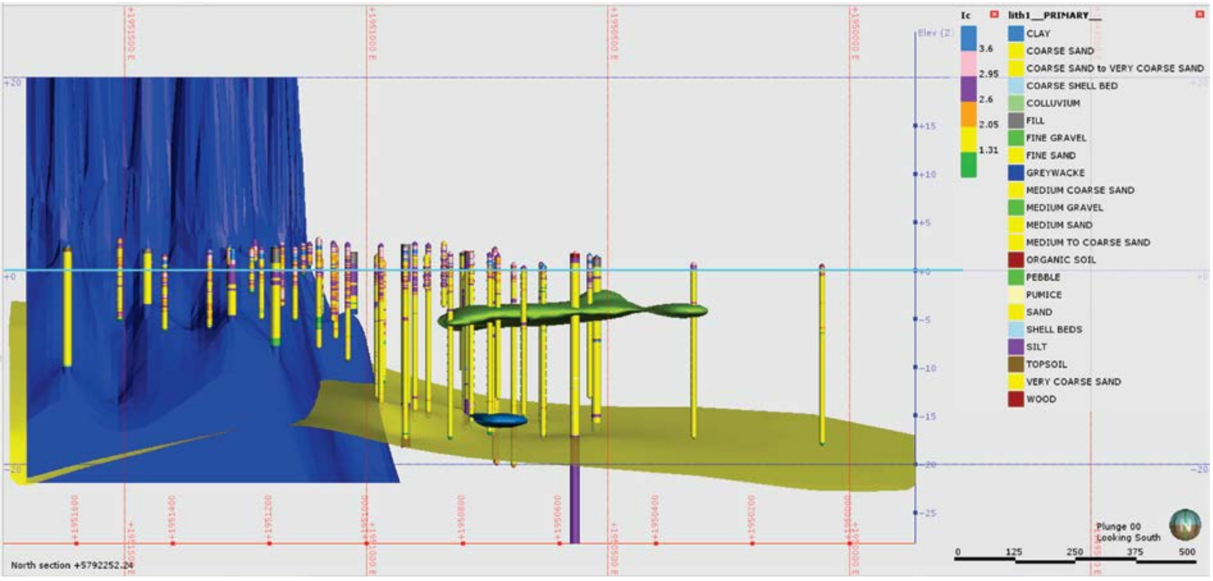

Figure A4 Whakatane CBD viewed horizontally from the north, illustrating the modelled gravel/shellbed lenses. The lower surface of the sand is shown for orientation.

The lowest Quaternary unit modelled lies beneath the north-dipping lower boundary of the sand unit, and it commonly includes silty sand, sandy silt, silt, clayey silt and clay. The elevation of the top of the lower silt unit is c. -14 m along the southern edge of the area and is at c. -20 m at the northern edge. Drillhole logs describe this material as dense to very dense, stiff to very stiff, well graded, dry to moist, homogeneous and of low plasticity. We interpret these materials as non-marine in origin, and they were probably deposited in the period of sea level rise following the last glaciation, as sea level rapidly approached its present elevation. SPTs universally have N values of 50 (total of 6 SPTs), and CPTs show very high sleeve friction values (> 200 to >600 kPa) and high normalised friction ratios (Fr = 2-4%). CPT effective unit weight (Gamma) densities are high, almost exclusively >20 kN/m^3.

A1.10 BUILDING 3D INTERPOLATED GEOTECHNICAL MODELS

The extent of the Geotechnical Models was defined as that volume within the Geological Model that does not consist of greywacke bedrock. That is, the interpolated models encompass the geotechnical properties of Quaternary materials within the model extent.

Using the geometry we established in the 3D Geological Model, it is possible to build interpolated, numerical 3D Geotechnical Models. The data input for building these models are the derivative CPT data, the structural trend derived from the Geological Model and ellipsoid ratios representing the strength of correlation in 3D (Table A9). Spheroidal interpolant function is used for interpolation.

Table A9 Interpolant structural trends.

Global trend	
Dip	0.35°
Dip azimuth	335°
Pitch	120°
Ellipsoid ratios	
Maximum	1
Intermediate	0.9
Minimum	0.003

The same interpolant structural trends were employed in building 3D Geotechnical Models of I_c (Figure A5; Scene 5), effective unit weight, normalised cone resistance, Q_{tn} (Scene 6) and Gamma (Scene 7).

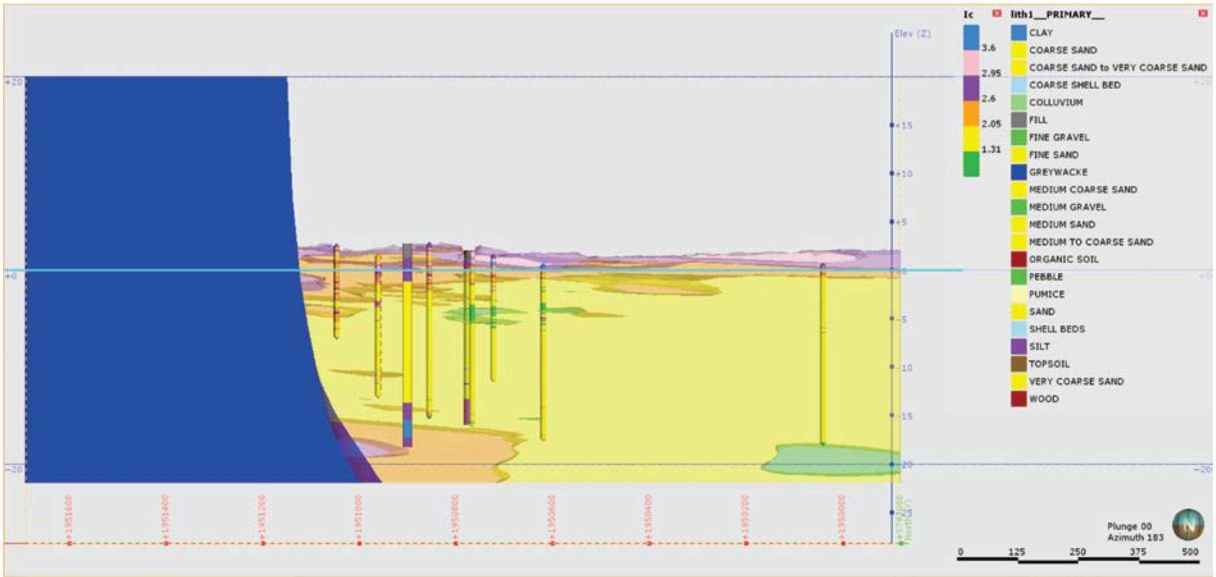

Figure A5 A slice of the Ic Geotechnical Model orientated east (left) to west (right) close to along Pohutu Street. The fine material near the base of this drillhole log (BH6; wide vertical features) indicates a higher change between sand and sandy silt than has been modelled from the CPT data. The Geological Model picks the change recorded in the drillhole as the boundary between the sand and underlying sandy silt. Otherwise, correlations between individual CPT Ic and modelled Ic are compatible.

A1.11 DEFINING A POTENTIALLY LIQUEFIABLE VOLUME

Volumes of potentially liquefiable material (Scene 9) is built by defining an upper extent from the unconfined groundwater surface and a lower surface at 20 m depth, a maximum value for liquefaction that impacts surficial structures identified in literature on liquefaction (e.g. Tonkin & Taylor 2013; Chang et al. 2011). This volume is differentiated into two using the surface drawn between loose sands and dense sands at a depth of c. -6 to -7 m. The upper volume is defined as “More susceptible” and the lower dense sands are defined as “Less susceptible”.

A1.12 LEAPFROG GEO PROJECT

As discussed earlier, Leapfrog Geo is used for 3D modelling and it provides good tools for correlating data, building surfaces and visualising resulting 3D models. All data relevant to the Whakatane CBD is loaded into the Leapfrog Geo project and can be seen in the Table of Contents. Explanations are given in Table A10. An editable copy of the Leapfrog Geo Project for the Whakatane CBD is provided with the report, but the master resides at GNS Science. In addition, a Leapfrog Viewer Project (see Appendix for specific scene information), which contains all the data but cannot be edited, is provided to be placed on the WDC website providing free and easy access through the web.

Table A10 Leapfrog Geo Project Table of Contents.

Data	Description
Topographies	
DEM	2010 AAMHatch LiDAR DEM resampled to 10 m resolution
GIS Data, Maps and Photos	
greywacke_contact3D	Boundary between exposed greywacke rock and Quaternary sediments
greywacke contours	DEM contours with added elevation used for modelling exposed greywacke surface
water_zero_contour	Zero unconfined groundwater contour along the Whakatane River derived from the DEM
QMAP geology	1:250,000 geological map (GNS Science)
BE40	Topographic map (LINZ Topo50 series)
Drillhole Data	
collar	Drillhole collar information
survey	Drillhole survey table
logs	Drillhole downhole interval information
Points	
CPT	CPT data including geotechnical properties of materials
CPT_Collars	CPT collar information
CPT_liq_M7_PGA03_GW1m	CPT data including liquefaction parameters calculated for a specific earthquake scenario
GW	Unconfined groundwater depth and elevation information
SPT	Drillhole SPT data
UpperSilt_CPT	Points derived from CPT data marking the base of ‘Upper Silt’ unit
Meshes	
DEM	LiDAR DEM resampled to 10 m resolution
Greywacke	Greywacke surface used together with topography to create greywacke volume
Groundwater Level	Unconfined groundwater surface extracted from Groundwater Model where the level was modelled from drillhole readings and CPT estimates
Liquefaction Limit	Lower limit of liquefaction, defined as 20 m beneath ground surface and used to define potentially liquefiable volume
Polylines	
greywacke	Lines connecting locations identifying top of bedrock and used for modelling greywacke surface
lower gravel	Short lines created at CPT location marking lower gravel boundaries and used for modelling lower gravel intrusion
lower sandy silt	Short lines created at CPT location marking top of lower sandy silt layer; includes two long lines added to constrain surface in the area of greywacke; used for modelling lower sandy silt surface.
upper gravel	Short lines created at CPT location marking upper gravel boundaries and used for modelling upper gravel intrusion

Data	Description
Geological Models	
Basement Model	3D model composed of greywacke and Quaternary volumes; Quaternary volume used to set extent for 3D interpolated Geotechnical Models
Geological Model	3D Geological Model composed of following volumes: Gravel Upper, Gravel Lower, Silt Upper, Sand, Sandy Silt Lower and Greywacke. Surfaces and intrusions modelled inside this model were used to generate volumes.
Groundwater Model	3D model representing saturated and unsaturated parts of Quaternary volume. Groundwater surface modelled inside model from drillhole readings and CPT estimates.
Potentially Liquefiable Volume	Potentially liquefiable volume created from saturated volume (Groundwater Model) but limited to depth of 20 m.
Interpolants	
FC	3D Geotechnical Model of fines content, FC
Gamma	3D Geotechnical Model of effective unit weight, (
Ic	3D Geotechnical Model of Soil Behaviour Type Index, I_c
Qtn	3D Geotechnical Model of normalised cone resistance, Q_{tn}

A1.13 RELIABILITY OF THE GEOLOGICAL AND GEOTECHNICAL MODELS

Reliability of the 3D geological and Geotechnical Models is dependent upon the quality of data used for modelling and its density and distribution. Data used in the Whakatane CBD modelling is homogeneous and high quality. Drillholes were drilled within a short period of time (c. 2 weeks in late September and early October) by a single rig and driller, core recovery was high (c. 95%), core was logged by one person and is well described in logs and the data includes regular SPTs. CPT data is uniformly good quality, and was completed by a single rig over the period of about five weeks in September and October 2014.

The average distance between a CPT and its nearest neighbour is c. 71 m and the average distance between drillhole collars is c. 170 m. Figure A6 illustrates the location of data used in building our 3D Geological Model and the Geotechnical Models and a qualitative estimation of the reliability of the models across the area of interest based on the horizontal distance between measurements.

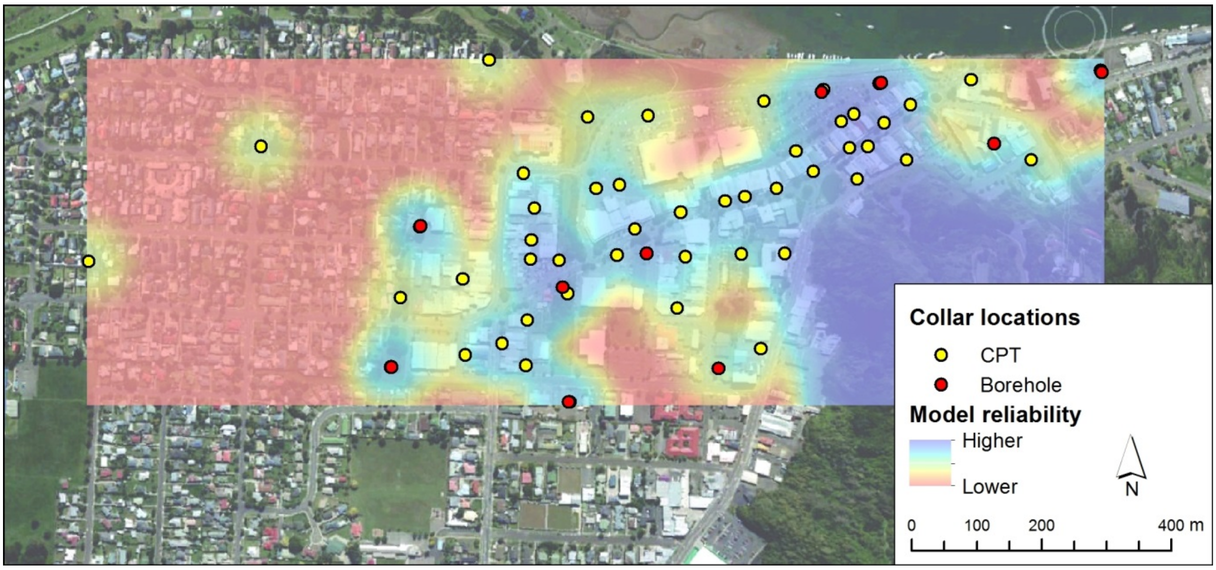

Figure A6 A map illustrating the distribution of CPT (yellow points) and drillhole (red points) collars across the area of interest. Higher model reliability is represented by dark blue shading and lower reliability by red shading.

However, this two dimensional representation applies only at the surface and does not take into account the drop-off in data with depth. With depth, data distribution reduces as different CPTs reach refusal at different depths and total depths of drillholes varies. Figure A7 illustrates the change in data density with depth.

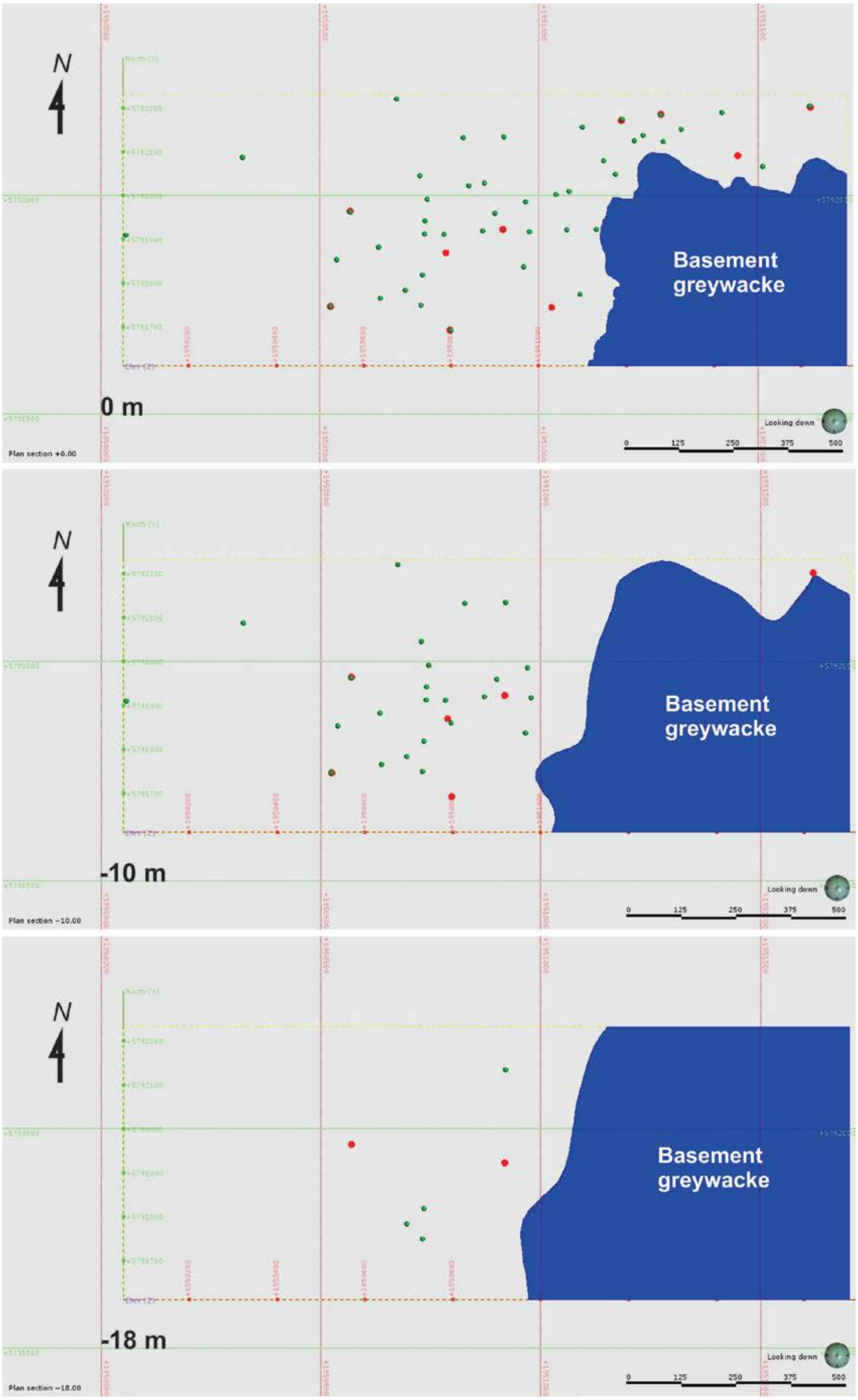

Figure A7 In comparison with the surface data density (Figure A6), these horizontal slices within the Geological Model demonstrating its drop-off with depth. The first map illustrates the presence of CPT (green points) and drillhole (red points) data at 0 m elevation, the second at -10 m and the third at -18 m. North is at the top of the page in each slice.

A1.14 RELIABILITY OF THE UNCONFINED GROUNDWATER SURFACE MODEL

Other than land immediately below the sea cliff behind the CBD, almost the entire area of interest lies at an elevation of < 3 m above mean sea level. Much of the area of interest is within half a kilometre of the Whakatane River which is subject to cyclical tidal fluctuation (the tidal range here may be up to 2 m) and to periodic high flood events. These periodic events undoubtedly influence the unconfined groundwater surface close to the river. The average depth to the unconfined groundwater surface for the 10 drillhole records we use in this report is 1.3 m below the ground surface. The likelihood that the unconfined groundwater surface will drop below sea level is very low. This means that the unconfined groundwater surface has limited scope for seasonal fluctuation and maximum seasonal variation can be little more than 1 m. The unconfined groundwater surface is modelled at elevations between 1 m and 0 m across most of the reliable part of the area of interest.

Given the paucity of data available, our unconfined groundwater surface (Scene 8) has limited accuracy, but is the best possible at this time. This absence of data represents a significant gap in ability to accurately assess liquefaction in Whakatane and we recommend that efforts should be made to establish network of shallow piezometers (< 5 m depth) to provide reliable long term data.

A1.15 LIMITATIONS

Finally, a note of caution should be raised about use of this model to predict ground conditions at sites between existing CPTs and drillholes. The models presented here represent materials present beneath the CBD at the scale of the separation of data points. Extrapolation between data points depends upon certainty of correlation and on continuity of geological features, and thus on distance to the nearest data. With an average CPT collar separation of 71 m, it is reasonable to assume that the resolution of the model is valid at the c. 35 m scale, but care must be taken to ensure that all nearby CPTs and drillhole logs are examined carefully before the models are applied at scales larger than this. The models are designed primarily to provide information on materials below the ground surface. The 3D Geological Model identifies the principle geological units and their boundaries, but users need to understand that the material present in these units is not restricted to the primary lithology. The Geotechnical Models are built from standard derivatives of raw data, the calculations of which are based on materials experienced in a number of parts of the world. Whakatane, with its distinctive pumiceous soils may differ in some ways, and thus derivatives here may not represent exactly the same characteristics to the other locations.

A2.0 WHAKATANE CBD LEAPFROG VIEWER PROJECT

This report is accompanied by a Leapfrog Viewer project that illustrates the data and interpretations discussed in the text. Scenes within the Leapfrog Viewer software may be rotated and viewed from any angle, and elements of each scene may be turned off, on, or made transparent gradationally. Scenes may be sliced in any plane. The purpose of this Appendix is to describe the contents of each of the fourteen scenes in the Leapfrog Viewer project. Vertical exaggeration of each scene is set at X50 and this cannot be altered in Leapfrog Viewer.

Scenes in this project are:

1. Location
2. Major lithological surfaces
3. Supplementary lithological surface
4. Lithological volumes
5. Interpolated geotechnical volumes, I_c
6. Interpolated geotechnical volumes, Q_{tn}
7. Interpolated geotechnical volumes, Gamma
8. Groundwater table
9. Liquefaction susceptibility information and volumes
10. Working

A2.1 EXPLANATION

Scene 1: ***Location***. LiDAR-derived DEM, orthophoto, TOPO50 and QMAP draped on the DEM; Drillholes and CPTs, drillhole collars (red balls) and logs coloured by primary lithology, iillustrating the distribution of drillholes and materials; CPT collars (yellow and green balls) and data coloured by Soil Behaviour Type (I_c).

Scene 2: ***Major lithological surfaces***. DEM or draped orthophoto, TOPO50 or QMAP with drillhole collars, CPT collars, drillhole logs coloured by primary lithology, CPTs coloured by Soil Behaviour Type (Ic); surfaces representing major lithological changes, greywacke volume.

Scene 3: ***Supplementary lithological surface***. DEM or draped orthophoto, TOPO50 or QMAP with drillhole collars, CPT collars, drillhole logs coloured by primary lithology, CPTs coloured by normalised cone tip resistance (Q_{tn}); a further surface representing a change in sand state of packing; greywacke volume.

Scene 4: ***Lithological volumes***. DEM or draped orthophoto, TOPO50 or QMAP with drillhole collars, CPT collars, drillhole logs coloured by primary lithology, CPTs coloured by normalised cone tip resistance ($Q_{tn)}$; illustrating volumes for each of the identified geological units, an upper silty layer, underlain by loose sand, dense sand (with “shelly gravelly sand” lenses), an underlying sandy silt unit and basement greywacke.

Scene 5: ***Interpolated geotechnical volumes (I_c).*** Draped orthophoto with drillhole collars, CPT collars, drillhole logs coloured by primary lithology, CPTs coloured by Soil Behaviour Type (I_c) and interpolated I_c volumes; slice and compare drillhole logs and CPT I_c data against interpolated geotechnical volumes.

Scene 6: ***Interpolated geotechnical volumes(Q_{tn}).*** DEM or draped orthophoto, TOPO50 or QMAP with drillhole collars, CPT collars, drillhole logs coloured by primary lithology, CPTs coloured by normalised tip resistance (Q_{tn}) and interpolated Q_{tn} volumes; slice and compare drillhole logs and CPT Q_{tn} data against interpolated geotechnical volumes.

Scene 7: ***Interpolated geotechnical volumes (Gamma)***. DEM or draped orthophoto, TOPO50 or QMAP with drillhole collars, CPT collars, drillhole logs coloured by density, CPTs coloured by normalised derivative density (Gamma), and interpolated Gamma volumes; slice and compare drillhole logs and CPT Gamma data against interpolated geotechnical volumes.

Scene 8: ***Groundwater table***. DEM or draped orthophoto, TOPO50 or QMAP with unconfined water table point information, the modelled unconfined water table surface and volumes representing unsaturated and saturated materials.

Scene 9: ***Liquefaction susceptibility information and volumes***. DEM or draped orthophoto, TOPO50 or QMAP with drillhole collars, CPT collars, drillhole logs coloured by primary lithology and SPTs coloured by N values; CPTs coloured by Soil Behaviour Type (I_c); a second tier of CPT data is present, visible by turning off the CPT_ALL layer; this CPT layer illustrates calculated liquefiable horizons for a scenario earthquake of M7, with PGA of 0.3 g; liquefiable layers are coloured red; surfaces illustrated are the unconfined groundwater surface, the loose sand-dense sand boundary, the dense sand - sandy silt contact and the greywacke volume; two volumes of liquefaction susceptibility, an upper more susceptible and a lower less susceptible volume.

Scene 10: ***Working***. DEM, draped orthophoto, TOPO50 and QMAP, CPT, drillhole and SPT data, liquefaction information and modelled surfaces and volumes.

GLOSSARY OF TERMS

The following abbreviations and acronyms used within the report are explained here in the form of a glossary.

CBD	Central Business District (of Whakatane)
CERA	Canterbury Earthquakes Recovery Authority; a short term authority set up by central Government to lead and coordinate the recovery effort of the region from the devastating earthquakes
CES	Canterbury Earthquake Sequence; the sequence of earthquakes that commenced with the 4 Sept 2010 M7.1 Darfield Earthquake in the Canterbury area and that includes the earthquakes of 22 Feb 2011 M6.2 Christchurch Earthquake, the M6.013 June 2011 Christchurch 2 Earthquake and the M5.8 23 December 2011 Christchurch 3 Earthquake
CLiq	Proprietary computer software (GeoLogismiki) for analysis of CPT data
CPT	Cone Penetration Test – a method of geotechnical investigation
DEM	Digital elevation model; a DEM defines the variability of modelled data surface, with embedded values (elevations for topography) at regular spacing across the surface
FC	Fines content; a geotechnical parameter derived from CPT raw data that characterises the %age of fine-grained material within that horizon
Gamma	Soil unit weight; a geotechnical parameter derived from CPT raw data that characterises the soil unit weight for each measurement
GHD	International consultant organisation specialising in water, energy and resources, environment, property and buildings and transportation.
GNS	GNS Science; Crown Research Institute; a research organisation, Government-owned, specialising in Earth, geoscience and isotope research and consultancy services.
GW	Groundwater
Ic	Normalised Soil Behaviour Type Index; a geotechnical parameter derived from CPT raw data that characterises the soil grain size characteristics
Interpolant	Applied mathematical analysis for constructing new data points within a range of discrete known points known as “data points”
IRBA	Ian Brown and Associates – a geological engineering consultancy company
LiDAR	Light Detection and Ranging – a very precise aerial scanning laser-based topographic surveying tool

LiDAR	Light detection and Ranging; an aircraft-based laser pulsed scanning and ranging-finding technique used to provide very high resolution, precise digital topographic information on a landscape, allowing development of highly accurate topographic models
Liquefaction	A phenomenon where the strength and stiffness of a saturated soil is reduced, usually by earthquake ground shaking, to a state where it is no longer cohesive but behaves like a fluid.
LSN	Liquefaction Severity Number; a liquefaction index number designed by Tonkin & Taylor following investigation of liquefaction after the Canterbury earthquakes, that reflects calculated vulnerability of flat, confined residential land to liquefaction; the index involves calculated settlement and includes a depth weighting function.
M	Richter magnitude (of an earthquake); an assigned number that represents the amount of energy released in an earthquake on a logarithmic scale
MBIE	Ministry for Business, Innovation and Employment; a central Government organisation
MoE	Ministry of Education; a central Government organisation
NIFS	North Island Fault System; a system of strike-slip faults that bisect the upper plate of the North Island; the Whakatane Fault, that is found beneath Whakatane is the most active of these faults in the Bay of Plenty, and can be followed continuously to the south Wellington coast and into Cook Strait; it changes name (and to some degree, character) southwards to the Mohaka Fault in Hawke's Bay and the Wellington Fault south from Woodville. The NIFS intersects the Taupo Volcanic Zone at the Rangitaiki Plains
PGA	Peak Ground Acceleration; defines maximum ground accelerations, usually expressed in terms of the acceleration of gravity (g), associated with an earthquake
QMAP	Image and digital data from the 1:250,000 scale Geological Map of New Zealand; GNS Science
Qtn	Normalised tip resistance; a geotechnical parameter derived from CPT raw data that defines the resistance to penetration at the CPT tip, defined in a non-dimensional form, taking account of the in-situ vertical stresses
Site subsoil classes	A five-fold system of site soil types established as the New Zealand Standard NZS1170.5:2004; soil classes are differentiated on the basis of the material strength of soils beneath as site and designed to help evaluate the response of a site to earthquake ground shaking amplification.
SLS	Serviceability limit state; a computational limit state of strength for a building beyond which it is no longer serviceable for the purpose for which it was designed.

SPT	Standard Penetration Test – a mechanical drilling (penetrative) method used periodically down-hole to characterise the geotechnical properties of subsurface materials
TC	Foundation Technical Category – a methodology, developed in Christchurch following the earthquakes by the Ministry of Business, Innovation, and Employment, of subdividing habitable land into three zones characterising liquefaction vulnerability
TOPO50	An image of the Land Information New Zealand (LINZ) TOPO50 1:50,000 scale topographic map
TVZ	Taupo Volcanic Zone; a NNE-SSW trending belt of active volcanoes, geothermal features and faults between Ohakune, the Rangitaiki Plains and White Island and beyond that represents a zone of active upper crustal spreading and crustal thinning
ULS	Ultimate limit state; a computational limit state of strength for a building, within the elastic condition zone, far below total collapse of the structure, where all factored bending, shear and tensile or compressive stresses are below factored resistances.
WDC	Whakatane District Council; a local Government territorial authority whose vision is to make Whakatane the place of choice for people to live, work and play.

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