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| | |
|---|---|
| **Prepared for:** | Data and Information Committee |
| **Report No.** | OPS1020 |
| **Activity:** | Natural Hazards |
| **Author:** | Sharon Hornblow, Natural Hazards Analyst<br>Jean-Luc Payan, Manager Natural Hazards |
| **Endorsed by:** | Gavin Palmer, General Manager Operations |
| **Date:** | 14 October 2020 |

## PURPOSE

[1] This paper summarises recent South Dunedin geological and seismic hazard work, including on liquefaction, undertaken both by ORC and via external scientific research programmes. Liquefaction hazard findings are of importance to the City's continued investment in the South Dunedin area, and are relevant to informing climate change adaptation. This paper also outlines proposed next steps for continued development of a work programme which focusses on improving the understanding of the ground conditions of South Dunedin and Harbourside.

## EXECUTIVE SUMMARY


[2] Otago Regional Council's understanding of the geological setting of South Dunedin, which helps define the risk from natural hazards, has greatly improved since the publication of the 2016 ORC report, The Natural Hazards of South Dunedin. A wealth of technical data and information, building the scientific knowledge base upon which planning decisions are based, has been made possible thanks to targeted spending on scientific partnership projects.

[3] For example, the 2019 drilling work for the NZSeaRise[1] programme, and geotechnical data gathering (Cone Penetrometer Tests, CPT) initiated by a project led by the Earthquake Commission (EQC) in 2019 and supported by ORC and other partners, have resulted in new geological data across a wide range of sites in the area.

[4] These data have informed a new report on the liquefaction hazard in South Dunedin and variation in ground conditions across the area.


[1] In 2018, ORC joined the NZSeaRise research venture with the research Trust of Victoria University of Wellington and GNS Science. The project objective is to improve sea-level rise projections for New Zealand to better anticipate and manage the impacts of rising sea level on low-lying cities. The project will deliver an authoritative, scientifically-robust set of national probabilistic sea level rise projections to the end of the 21st century and beyond. South Dunedin has been selected as a regional case study as it is a low-lying densely populated urban area likely to be impacted by sea level rise, potentially coupled with land subsidence. The ORC contribution to the project is to improve understanding of groundwater and to work with GNS scientists to collate information about the physical environment of South Dunedin to inform a robust geological model of the area. The NZSeaRise project is due for completion in June 2022.

[5] In addition to this, GNS Science have developed a new 3-dimensional geological model of South Dunedin, utilising the same data as well as recent geophysical surveys undertaken by the University of Otago. This model will inform the South Dunedin groundwater model, which ORC is planning to update this coming year, in partnership with NZSeaRise.

[6] These data and models provide critical information about long-term tectonic deformation in the coastal Dunedin area, which is useful information for seismic hazard research, as well as information on the thickness and position of young sediments beneath the city. This kind of information is necessary in order to form a complete picture of relative sea level rise over time, as, for example, areas of softer, younger sediment may settle and subside faster than other areas. This, in turn, allows for more informed decision-making around climate change adaptation and the future of South Dunedin.

[7] This report focuses primarily on updates to understanding the geology and liquefaction hazard of the South Dunedin area. However, further modelling work is planned for extension around the Harbourside area, pending collation of additional subsurface data.

## RECOMMENDATION

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*That the Council:*

1) ***Receives*** *this report.*

2) ***Notes*** *the current state of knowledge of the geology and ground conditions of South Dunedin and Harbourside.*

3) ***Makes*** *this information publicly available through the National Geotechnical Database and ORC's Otago Natural Hazards Database.*

4) ***Provides*** *this information to Dunedin City Council for incorporation into building control, utility infrastructure and land use planning decisions.*

{recommendation-end}
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## LIQUEFACTION REPORT

[8] In the last 15 years approximately, ORC has undertaken a programme of technical work aimed at providing better understanding of the South Dunedin natural environment, and how the physical environment influences natural hazards and the likely impacts of climate change in South Dunedin. The scope of this programme extends beyond the South Dunedin flat with the plan for encompassing all the low-lying area around the coast of Dunedin's Central Business District (CBD), from the Oval to the University of Otago (Harbourside). The aim of the ORC programme of technical work is progressing the development of a multi-hazard 'Climate Change Adaptation Plan' for South Dunedin and the Harbourside areas. This includes an expanded groundwater monitoring network, a 'next generation' groundwater flood model, a seismic hazard assessment including liquefaction susceptibility, and coastal hazards (erosion and elevated sea level) assessment. A multi-hazard approach recognises that, whilst climate change and sea

level rise are frequently referred to in South Dunedin, any future adaptation plan will need to address all natural hazards and their interactions and cascading effects.

[9] Under the Resource Management Act (1991), regional councils are required to control the use of land for the purpose of the avoidance or mitigation of natural hazards (s30 RMA 1991). This includes the identification and assessment of natural hazards in the region.

[10] Through 2019, ORC worked with several organisations (including EQC, GNS Science, University of Otago and the Dunedin City Council) to fund a variety of subsurface investigations in South Dunedin to determine geotechnical and geological properties and groundwater characteristics.

[11] Sixteen cone penetrometer tests (CPT) were carried out as part of work led by EQC and the University of Canterbury to better understand ground conditions and liquefaction potential in South Dunedin (**Figure 1**). A further eight drill holes were completed around the South Dunedin and Harbourside areas, and core recovered and analysed by GNS Science and University of Otago geologists.


**Figure 1. Cone Penetrometer Testing (CPT) rig taking pressure readings from the soil beneath South Dunedin in 2019.**

[12] Previous work by GNS commissioned by ORC (ORC report Liquefaction Susceptibility of the Dunedin City area, 2014) mapped liquefaction hazard areas based on the potential for liquefaction susceptible materials to be present. The South Dunedin flat and Harbourside areas were classified with a moderate to high liquefaction potential. This reflects the geomorphic history of the area (shallow marine/estuarine) which entails a high likelihood of fine-grained soils and a shallow groundwater across the area.

[13] In July 2020, in order to refine the understanding of the liquefaction susceptibility in South Dunedin, ORC commissioned a report (Review of liquefaction data, GeoSolve Ltd, attached) on the assessment of the raw CPT data from the work carried out by ORC, NZSeaRise, and the consortium CPT and piezometer installations which took place in South Dunedin in 2019. Additional sites from previous CPT work available in South Dunedin were also included in the analysis.

[14] The CPT data from each site has been analysed in relation to theoretical settlement which would occur in standardised earthquake cases (e.g. NZS 1170 Serviceability Limit States and Ultimate Limit States which specify different peak ground accelerations and annual exceedance probabilities). This is an industry standard approach for assessing settlement that may result from seismic shaking, to help determine foundation design for any occupied structures so they are safe and serviceable for a design lifetime with exposure to expected seismic hazards. A Liquefaction Severity Number (LSN) was assigned to the uppermost 10 m of each CPT (sometimes multiple CPTs were completed at a site) which provides a useful summary of relative liquefaction susceptibility across the South Dunedin area.

[15] The LSNs for an earthquake scenario considered to have an estimated annual exceedance probability (AEP) of 1 in 100 years were all below 10, which indicates settlement of only a few centimetres (less than 70 mm, and generally less than 40 mm) is expected at all tested sites in such a seismic event. The LSNs returned for this earthquake scenario are displayed as coloured dots in **Figure 2** to give an idea of the spatial variability of liquefaction susceptibility. 1 in 100 years recurrence event has been chosen as it is commonly used when discussing natural hazard risk. The results from other earthquake scenarios show similar variability across the area.

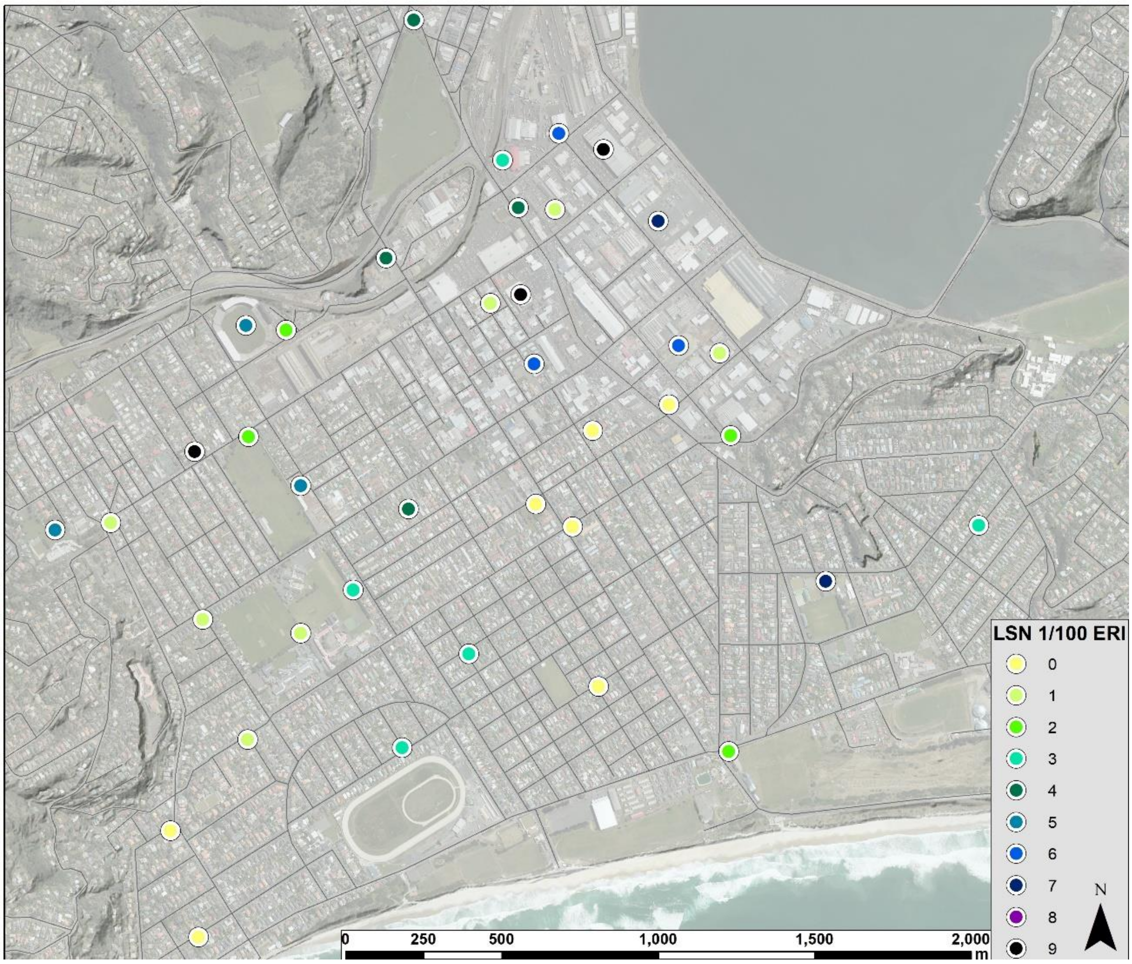


**Figure 2. Locations of sites analysed in the liquefaction susceptibility report. Coloured dots represent the Liquefaction Susceptibility Numbers (LSN), summarising how severely the ground would be impacted by shaking, calculated for a 1 in 100-year AEP (or ERI, estimated recurrence interval) earthquake scenario (Mw5.8, 0.11 g).**

[16] Settlement values and LSN for a maximum scenario with a 1 in 2500 years AEP (see Table 1) were also calculated. This attempts to capture a peak ground acceleration equivalent to the February 22$^{nd}$, 2011 Christchurch event which induced widespread liquefaction there in 2011. Results show the sediments analysed, in the upper 10 m, should not experience severe and widespread liquefaction, nor significant settlement above 70 mm.

[17] The CPT analysis also indicates a high variability in liquefaction potential of soils across greater South Dunedin, with variability in settlement potential observed across single sites. Figure 1 shows how there is not a defined spatial pattern of high vs low LSN and associated settlement. Some areas have groups of CPTs on one building site and results show settlement (and LSN) varies across a single site.

[18] The report does not consider factors such as lateral spreading, which could be an issue near free-faces such as around the harbour edge. It also does not cover other potential hazards from seismic shaking such as specific areas at heightened risk of shaking amplification due to basement geometry, or potential for cyclic softening.

| Annual Exceedance Probability (AEP) | Liquefiable Layers | Reconsolidation Settlement | LSN |
|---|---|---|---|
| 1/25 | Predominately limited liquefiable layers | 0-5 mm (mostly 0 mm) | 0-1 ground damage not predicted or limited |
| 1/100 | Liquefaction starts to occur in layers | 0-70 mm (mostly 0-40 mm) | 0-9 ground damage not predicted or limited |
| 1/250 | Liquefaction occurs in loose sandy and non/low plasticity silts | 0-70 mm (mostly 0-40 mm) | 0-29 (mostly 0-20) Mostly minor expression of liquefaction, some sand boils and potentially some structural damage in places |
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| 1/2500 | Liquefaction occurs in loose to medium dense sandy and non/low plasticity silts | 0-70 mm (mostly 0-40 mm) | 0-46 (mostly 0-25) Mostly minor expression of liquefaction, some sand boils and potentially some moderate to severe expression of liquefaction with settlement that can cause structural damage in places |

**Table 1. Summary of liquefaction results, from the 2020 Geosolve liquefaction susceptibility report to ORC (attachment). Each row gives the results for one of the six earthquake shaking scenarios tested with the CPT data. Most settlement expected in the South Dunedin area is less than 40 mm, even in strong shaking (higher AEP) scenarios.**

[19] CPT data of the sites investigated in this report indicates very fine-grained sediments which are naturally highly plastic and cohesive, and therefore not very liquefiable. This interpretation was supported by the samples recovered during bore hole drilling in 2019 (see the following section of this report on geological modelling). For comparison, assessment of CPT data indicates that settlement under peak ground accelerations up to 0.41 g (1 in 2500 year AEP event) would not match the damage experienced in areas affected by liquefaction in eastern Christchurch during the 2011 earthquakes (grouped as 'TC3 land': moderate to significant land damage from liquefaction is possible in future significant earthquakes).

[20] Based on this dataset and current understandings of liquefaction processes, widespread liquefaction in greater South Dunedin, akin to that experienced during the Christchurch earthquake sequence, is unlikely. However, this does not preclude liquefaction occurring in some places, and does not address the possibility of lateral spreading along unconfined saturated embankments, such as the harbour edge. The ground beneath South Dunedin is very soft and may give rise to other geotechnical issues during an earthquake, such as foundation settlement or shaking amplification.

[21] The report also considers that settlement of up to 100 mm may occur in some areas, without this being considered severe. However, complex flood related, and infrastructural issues can result from even small settlements, such as the ongoing

drainage issues experienced over large parts of Christchurch after the Canterbury Earthquakes and damage to rigid structures. With a low-lying area such as South Dunedin with a high, and rising, water table, small ground settlement would also exacerbate flood hazard.

[22] The findings from the liquefaction data report do not change or replace the need for site-specific geotechnical advice for individual buildings but confirms the variability of ground conditions across the area. The variability of the CPT data indicates the ground conditions are highly variable and does not support more refined mapping of liquefaction risk at this stage given the relatively low spatial density of CPT soundings.

## GEOLOGICAL MODEL OF SOUTH DUNEDIN UPDATE

[23] In addition to the CPT data gathering, deeper boreholes were drilled in the greater South Dunedin area in 2019. These were geologically logged, samples were collected from the drill core for scientific dating purposes, and geotechnical data at each drill site were recorded.  This work was funded by ORC as part of the 2018/2019 Annual Plan.

[24] These data, in addition to that collected by University of Otago geologists and existing bore hole and geotechnical data for the area, form the basis of an updated geological model. The work, briefly presented in this report, summarises geological, geotechnical, and geophysical investigations carried out in 2019 and will be used in modelling the impacts of various sea level rise scenarios on the groundwater and future surface flooding. Results of the investigations and groundwater monitoring can also be used in further seismic hazard analyses which will guide assessments of subsurface infrastructure investment and inform planning decisions.

[25] Geological drill hole logs and CPT data have been collated by GNS Science to create an interpretive 3-dimensional geological model of the South Dunedin subsurface geometry. Figure 3 shows the different kinds of existing geophysical and geotechnical data which were used to support creation of the model. The physical 2019 drill cores were essential in ground-truthing these data.

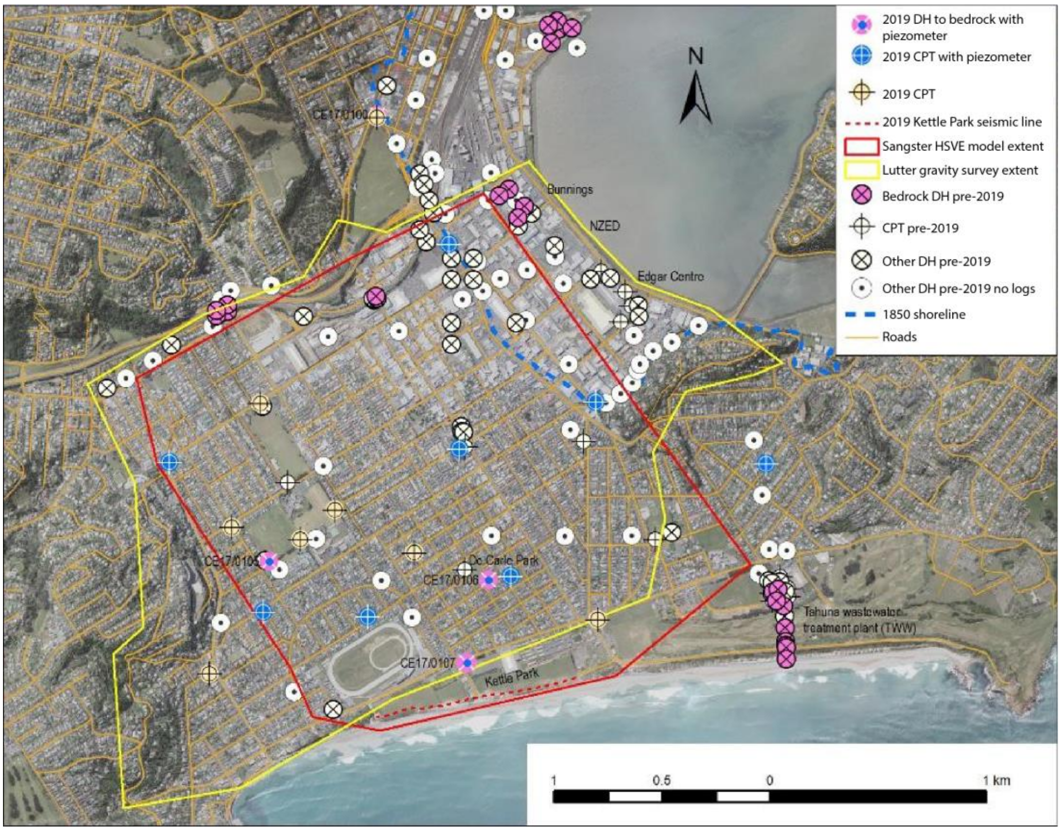


**Figure 3. Subsurface investigation data points used for the update of the South Dunedin geological model.**

[26] Basement rocks, such as the Dunedin Volcanics and Caversham Sandstone (Figure 4), and the younger Holocene sediments, which in-filled the valley beneath South Dunedin as sea level rose after the Last Glacial Maximum (Figure 5), are depicted in the model. A paper was prepared by GNS (Glassey), along with co-authors from University of Otago and ORC, for this week's NZ Geotechnical Society symposium, to report on the geological model and findings of the deep drilling work carried out in 2019. A final GNS report on the modelling and interpretation of results is currently in preparation.

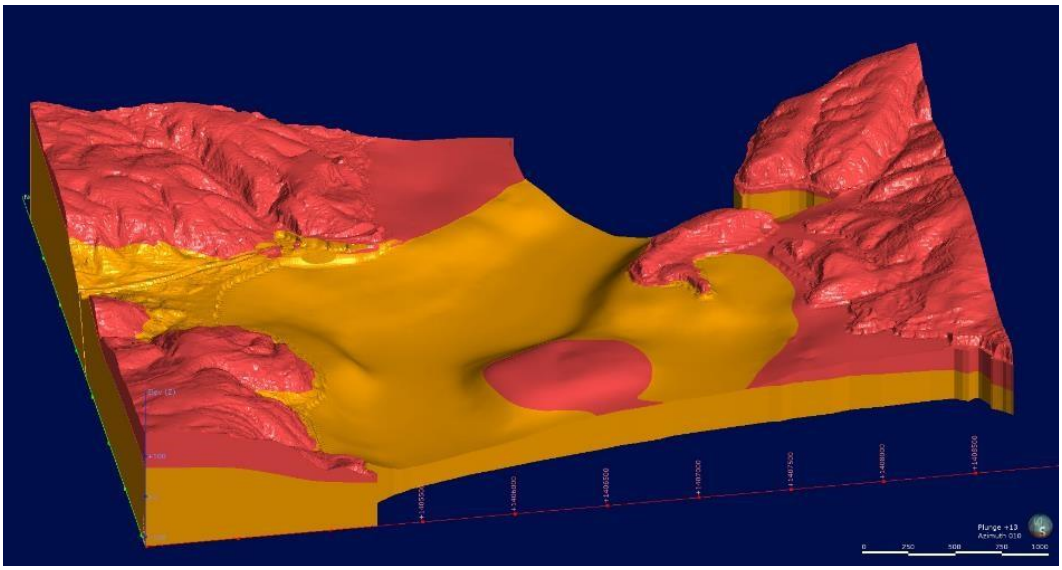

**Figure 4. Perspective view of South Dunedin with the younger sediment infill removed and bedrock surface exposed. Volcanic bedrock is shown in red and Caversham Sandstone in orange. (Glassey et al., in prep)**

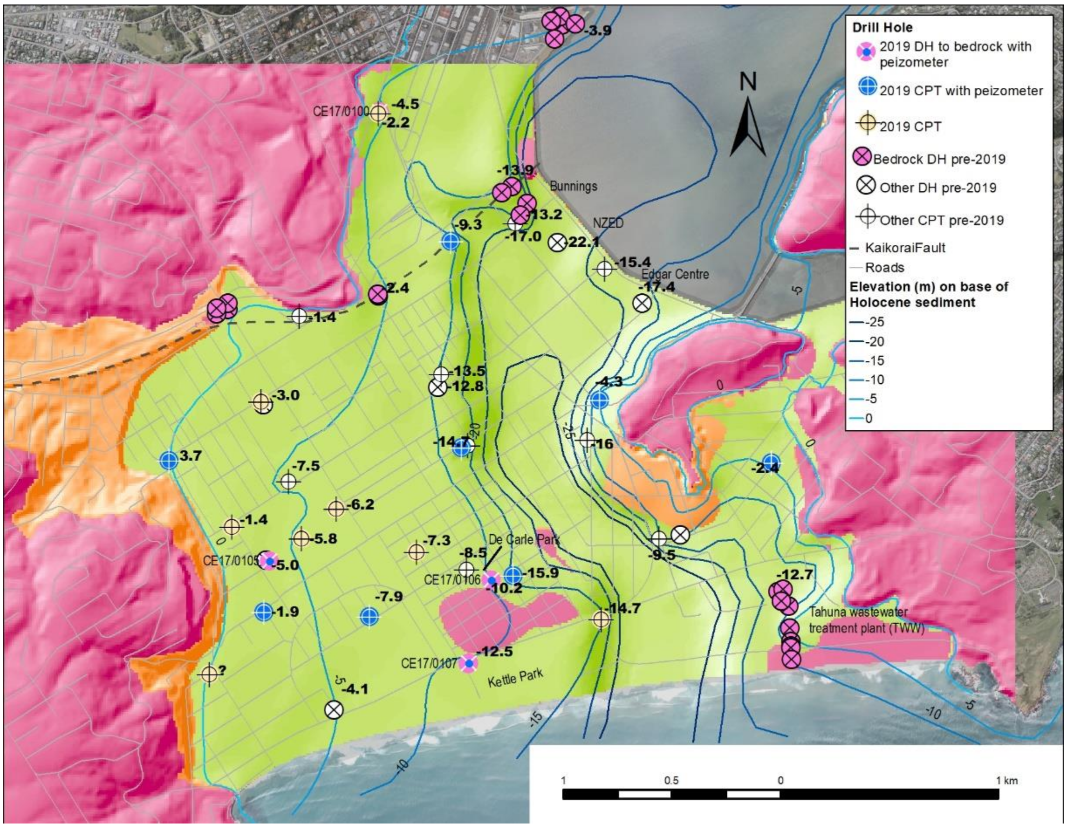


**Figure 5. Plan view showing structure contours on the base of the Holocene sediments (green) beneath South Dunedin based on depth interpretations from drill holes and CPT data. (Glassey et al., in prep).**

## DISCUSSION

[27] This geological model is important to ORC because it will inform the groundwater model which, in turn, will be used to analyse the impacts of various sea level rise scenarios on the groundwater, future surface flooding, and infrastructure in South Dunedin. The new understanding of geophysical properties of the sediment is important for building purposes such as assisting in appropriate building foundation design through informing the depth of the Holocene (recent, softer) sediment at sites through South Dunedin.

[28] The model also has some importance for considering the above liquefaction susceptibility results. As mentioned in the first section of this report, lack of liquefaction susceptibility does not preclude poor ground conditions being present. The clays and fine sediments deposited in an estuarine setting which are in some places quite deep, do not easily liquefy but may be likely to exhibit ground damage of other kinds due to their plastic nature.

[29] In 2019, when the drilling programme commenced, estimates of the depth to bedrock at the drill sites varied from 40 to 70 m. Carrying out the programme and bringing together as much existing geophysical and geotechnical data as possible to support the geological modelling, has highlighted the complexity of the subsurface ground conditions, and the

difficulty of predicting where softer/deeper sediments will be. This shows the importance of investing in invasive, scientific research programmes, along with processing and using pre-existing data, such as existing geotechnical work done for building consents in the area.

[30] The model presented here extends partially into the Harbourside area. It is planned to extend the geological model to fully cover the Harbourside area. This is pending the collation of additional subsurface data and is planned for later in the year.

## CONSIDERATIONS

### Policy Considerations

[31] There are no immediate policy considerations for ORC.

### Financial Considerations

[32] The work described in this paper is part of a multi-year programme. Completion of the programme relies on ORC providing funding in the 2021/31 Long Term Plan and future Annual Plans.

### Significance and Engagement

[33] This paper does not trigger ORC's policy on Significance and Engagement.

### Legislative Considerations

[34] The work described in this paper helps ORC fulfil its responsibilities under sections 30 and 35 of the RMA.

### Risk Considerations

[35] Disclosing the information presented in this paper helps the community understand and manage the risks associated with South Dunedin's multi-hazards.

## NEXT STEPS

[36] It is proposed to make this information publicly available through the National Geotechnical Database and ORC's Otago Natural Hazards Database.

[37] It is also proposed to provide this information to Dunedin City Council for incorporation into building control, utility infrastructure and land use planning decisions.

[38] A paper on collaboration with Dunedin City Council on adaptation for South Dunedin/Harbourside and options for the role ORC should play is in preparation.

## ATTACHMENTS

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GeoSolve Ref: 200038
7 July 2020

Otago Regional Council
70 Stafford Street,
Private Bag 1954,
Dunedin 9054

Attention: Ben Mackey

# Review of Liquefaction Data
# South Dunedin

**Introduction**

The Otago Regional Council is wanting to better quantify the liquefaction risk for the greater South Dunedin area. In accordance with our Agreement dated 25 February we have undertaken a liquefaction analysis of existing cone penetration tests (CPT) data across South Dunedin. This includes the CPTs co-funded by the ORC in 2019 along with other readily available CPTs from the Geosolve database.

This letter shall be read as a whole and in conjunction with the limitations at the end of the letter.

**Cone Penetration Test Data**

16 cone penetration tests have been provided to GeoSolve from the ORC which were undertaken in 2019 as part of other works. To supplement these tests GeoSolve has undertaken a review of readily available CPT data around the South Dunedin area and identified 22 sites. The approximate site locations are presented in Figure 1 in Appendix A.

**Liquefaction Assessment Methodology**

A liquefaction assessment has been undertaken using the CPT data based on the method of Boulanger and Idriss (2014)[1] as follows:

- Six earthquakes scenarios have been assessed in accordance with NZS1170 – Structural Design Actions[2] which are described below;
- Peak horizontal ground accelerations and effective magnitudes were calculated using the procedure from the NZTA Bridge Manual[3];
- The site has been assessed as subsoil category Class C – Shallow Soil site in accordance with NZS1170 – Structural Design Actions, in terms of liquefaction this is conservative for

[1] Boulanger, R.W. & Idriss, I.M. (2014). CPT and SPT Based Liquefaction Triggering Procedures. Department of Civil & Environmental Engineering, University of California.
[2] NZS1170-5 (2004) Structural Design Actions, Part 5: Earthquake Actions – New Zealand.
[3] NZTA Bridge Manual (2014). SP/M/022, third edition amendment 1, Effective from September 2014.


GeoSolve Limited - Dunedin Office:
Level 1, 70 Macandrew Road, South Dunedin
PO Box 2427, South Dunedin 9044
dunedin@geosolve.co.nz

geotechnical purposes, as it is possible areas of South Dunedin will be equivalent to Class D or E.

- Groundwater levels have been adopted at 0.5 m depth. It is likely that parts of South Dunedin will have groundwater levels at greater depths;
- In our analysis the ground level at time of testing has been assumed to be the final ground level.
- A fines content correction ($C_{FC}$) of 0 and a soil classification index ($I_c$) cut off of 2.6 has been adopted as we are not aware of a large enough data set of laboratory testing in the South Dunedin area to better refine these parameters;
- Our assessment is focused on indexed settlement and Liquefaction Severity Number (LSN) considered over the upper 10 m to easily compare liquefaction results. Some tests may have reached early refusal. Therefore, additional layers could liquefy which will result in additional settlement and ground damage potential. Settlement and LSN may not reflect damage especially where deep piles/foundations and/or where liquefiable layers directly interact with foundation.
- We have not carried out a lateral spreading assessment as part of the liquefaction assessment. Therefore, it is possible that liquefaction risk may be greater when in close proximity to the sea, Dunedin Harbour and any other local streams, changes in height or other free faces due to lateral spreading risks.

***Table 1:*** *Earthquakes cases considered with reference to NZS1170*

| Annual Exceedance Probability (AEP) | Magnitude | $a_{max}$ (g) | Notes |
|---|---|---|---|
| 1/25 | 5.8 | 0.06 g | NZS1170 Serviceability Limit State (SLS1) |
| 1/100 | 5.8 | 0.11 g | NZS1170 Ultimate Limit State (ULS) for an Importance Level 1, 50 year design level structure |
| 1/250 | 5.8 | 0.17 g | NZS1170 Serviceability Limit State (SLS2) for an Importance Level 4, 50 year design life structure |
| 1/500 | 5.8 | 0.23 g | NZS1170 Ultimate Limit State (ULS) for an Importance Level 2, 50 year design level structure |
| 1/1000 | 5.8 | 0.29 g | NZS1170 Ultimate Limit State (ULS) for an Importance Level 3, 50 year design level structure |
| 1/2500 | 5.8 | 0.41 g | NZS1170 Ultimate Limit State (ULS) for an Importance Level 4, 50 year design level structure |

*Notes:*

- *NZS1170 Ultimate Limit State (ULS) – to avoid collapse of the structural system*
- *NZS1170 Serviceability Limit State (SLS1) – to avoid damage that would prevent the structure from being used as originally intended without repair*
- *NZS1170 Serviceability Limit State (SLS2) – to maintain operational continuity after the SLS2 earthquake*
- *Importance Level 1 – structures presenting a low degree of hazard to life and other property (e.g. garages)*
- *Importance Level 2 – normal structures and structures not in other importance levels (e.g. houses)*
- *Importance Level 3 – structures that as a whole may contain people crowds or contents of high value to the community or pose risks to people in crowds (e.g. large buildings)*

- *Importance Level 4 – structures with special post disaster functions (e.g. fire stations)*

**Liquefaction Assessment Results**

We have made a summary of liquefaction results attached in Appendix B. These show the following:

***Table 2:*** *Summary of liquefaction results*

| Annual Exceedance Probability (AEP) | Liquefiable Layers | Reconsolidation Settlement | LSN |
|---|---|---|---|
| 1/25 | Predominately limited liquefiable layers | 0-5 mm (mostly 0 mm) | 0-1 ground damage not predicted or limited |
| 1/100 | Liquefaction starts to occur in layers | 0-70 mm (mostly 0-40 mm) | 0-9 ground damage not predicted or limited |
| 1/250 | Liquefaction occurs in loose sandy and non/low plasticity silts | 0-70 mm (mostly 0-40 mm) | 0-29 (mostly 0-20) Mostly minor expression of liquefaction, some sand boils and potentially some structural damage in places |
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**Technical Categorisation Based on Canterbury Criteria (MBIE Guidelines)**

We have used the MBIE guidance (2012) to assess equivalent technical categories for the site based on the calculated liquefaction risk. We have not assessed lateral spreading so it is possible that liquefaction risk may be greater when in close proximity to the sea, Dunedin Harbour and any other local streams, changes in height or other free faces due to lateral spreading risks.

Note that technical categories are for houses in Canterbury Importance Level 2, 50 year design life structures and are not appropriate for other structures.

***Table 3:*** *MBIE liquefaction deformation limits and house foundation implications*

| Technical Category | Index Liquefaction Deformation Limits | | | | Likely Implication for House Foundations (subject to individual assessment) |
|---|---|---|---|---|---|
| | Vertical | | Lateral Spread | | |
| | SLS | ULS | SLS | ULS | |
| TC1 | 15mm | 25mm | Nil | Nil | Standard NZS3604 type foundations with tied slabs |
| TC2 | 50mm | 100mm | 50mm | 100mm | MBIE enhanced foundation solutions |
| TC3 | >50mm | >100mm | >50mm | >100mm | Site specific foundation solution |

As calculated indexed settlements are less than 15 mm in the SLS event and between 0 and 70 mm in the ULS event therefore the testing shows the greater South Dunedin area is likely to be consistent with MBIE TC1 or TC2.

**Discussion**

Total settlement

Total liquefaction induced settlement and area wide settlement may cause other consequences. Examples of these effects were noted in Christchurch include:

- Total liquefaction and tectonic settlement putting areas into or further into flood zones, or increasing liquefaction vulnerability to sites;
- Area wide differential settlement causing issues with drainage through rivers, streams and pipes; and
- Global lateral movement of areas damaging infrastructure.

We note that we have only summarised indexed settlements (i.e. in the top 10 m) but have calculated total liquefaction induced reconsolidation settlements up to approximately 200 mm.

Other Geotechnical Issues in South Dunedin

Often the soils encountered in the CPTs of South Dunedin were too plastic to liquefy (i.e. moderately plastic silts or clays). Notwithstanding this, although these soils may not be susceptible to liquefaction they pose other significant geotechnical challenges for development, such as:

- They are soft and compressible and therefore only provide low bearing capacities with associated high rates of settlement for shallow foundations. Note significant areas in South Dunedin do not meet the definition of 'good ground' as per NZS3604:2011;
- Due to the soil type inferred from the CPTs, the liquefaction assessment indicates that some soils are unlikely to liquefy due to their plasticity. However, it is possible that cyclic softening may occur in this layer in a moderate to major earthquake event. Research on cyclic softening is not as clear as liquefaction effects. So the effects of cyclic softening are more difficult to quantify. But if softening occurs it is likely that the consolidation process will be reset and that long-term settlement will start over. It also can cause soft cohesive soils to lose strength.

Uncertainty of earthquake loading

The seismic hazard in Christchurch is greater than in Dunedin, however even if the level of seismic loading is increased the predicted settlements (in the upper 10 m) do not quite reach MBIE TC3 levels, even at PGA's up to 0.41 g (1/2500 AEP event).

The recent events in Canterbury and Kaikoura have highlighted the challenge that previous unidentified faults and site amplification effects may be very significant factors in the actual seismic risk applying to a site. This concern is most relevant where pre-historic faulting is masked by a persistent mantle of recent deposits (and such terrain dominates both in South Dunedin and Coastal Canterbury).

Data gaps

The testing has a relatively good spacing across the greater South Dunedin area. However, as the ground conditions are variable and can change quickly in the area specific site testing is recommended to better define the liquefaction risk.

**Applicability**

This report has been prepared for the benefit of the Otago Regional Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Yours faithfully,


..................................................

Tim Plunket
Senior Geotechnical Engineer (CPEng)
GeoSolve Limited

..................................................

Colin Macdiarmid
Geotechnical Group Director (CPEng)

# Appendix A – Figures


## Key

CPT1 = Cone Penetrometer Test

Background image aerial photography taken between 2018-2019. Sourced from LINZ

| | | | | |
|---|---|---|---|---|
| CADFILE: | Site Plan.pptx | DRAWN | TJP | 02/2020 |
| SCALE: (AT A4 SIZE) | AS SHOWN | DRAFTING CHECKED | TJP | 02/2020 |
| PROJECT No.: | 200038 | APPROVED | CEM | 02/2020 |

GEOSOLVE
ENGINEERING CONSULTANTS
GEOTECHNICAL
WATER RESOURCES
PAVEMENTS

Otago Regional Council
South Dunedin Liquefaction Assessment
Dunedin
CPT Investigation Locations

FIG No. FIGURE 1

REV No. 1

# Appendix B – Liquefaction Results

## General

Liquefaction occurs when susceptible, saturated soils attempt to move to a denser state under cyclic shearing. In this report, liquefaction is defined as when pore pressures rise to reach the overburden stress. When this occurs, the following effects can happen at flat sites:

- loss of strength;
- ejection of material under pressure to the ground surface; and
- post-liquefaction volumetric densification as the materials reconsolidate.

In addition, sloping sites or sites with a 'free face' may experience lateral spreading or movement.

## Liquefaction Susceptibility

Soils susceptible to liquefaction have the following characteristics:

- Saturated. Below the ground water level;
- Have "sand like" behaviour[4]; and
- Are in loose or medium dense condition.

Soils which are susceptible to liquefaction require a certain level of earthquake shaking (trigger) to cause them to liquefy. Denser soils require more intense and/or longer duration of shaking (higher trigger) than less dense soil.

## Analysis Method

Liquefaction analyses were undertaken on the test data using the Boulanger & Idriss (2014)[7] deterministic method.

## Assessment of Consequences of Liquefaction

The following can be assessed to estimate the consequences of liquefaction at this site:

- Crust thickness.
- Liquefaction severity index.
- Free field settlements.
- Lateral spread.

[4] "Geotechnical earthquake engineering practice: Module 1 Guideline for the identification, assessment and mitigation of liquefaction hazards", Rev 0, July 2010. New Zealand Geotechnical Society. This document states that soil with: Fc <30%, or; Fc >30% and PI < 7% (where Fc= percent passing a 0.075mm sieve and PI=plasticity index) is considered as "sand-like" and is susceptible to liquefaction.

## Crust Thickness

The non-liquefiable upper layer of soils (crust) provides some protection against ground surface damage as a result of liquefaction. The thicker the crust, the less ground surface damage is expected with significant protection provided by thicknesses of more than 5 m.

Empirical correlations have been developed by Ishihara[5] to quantify the thickness of non-liquefiable crust required to prevent the formation of sand boils resulting from the liquefaction of underlying soil layers. These correlations indicate that for a given thickness of liquefiable soil, as the peak ground acceleration increases a greater thickness of non-liquefiable soil is required to prevent liquefaction damage from manifesting on the surface.

## Liquefaction Severity Number

Liquefaction severity number (LSN) is a single value which can be calculated from a liquefaction assessment considering the thickness density and depth of liquefiable layers and the intensity of earthquake shaking. Based on observations of ground surface damage in Christchurch an indicative correlation has been developed between ground surface damage from liquefaction and LSN as described below.

As the LSN increases, so does the risk of severe effects on the land and structure. In general, the following surface effects are considered likely at sites with various LSN values.

**Table 1C - Liquefaction Severity Number**

| LSN | Effects |
|---|---|
| 0 – 10 | Little to no expression of liquefaction, minor effects |
| 10 – 20 | Minor expression of liquefaction, some sand boils |
| 20 – 30 | Moderate expression of liquefaction, with sand boils and some structural damage |
| 30 – 40 | Moderate to severe expression of liquefaction, settlement can cause structural damage |
| 40 – 50 | Major expression of liquefaction, undulations and damage to ground surface, severe total and differential settlement of structures |
| > 50 | Severe damage, extensive evidence of liquefaction at surface, severe total and differential settlements affecting structures, damage to services |

[5] Ishihara, K. (1985). "Stability of natural deposits during earthquakes," Theme lecture, Proc. 11th Int. Conf. On Soil Mechanics and Foundation Engineering, San Francisco, 2, 321-376pp.

## Free Field Settlements

This describes the settlement of ground not occupied by a building, occurring due to dissipation of excess pore water pressure generated during earthquake shaking. Where appropriate, we have estimated reconsolidation settlement of any potentially liquefiable layers using the methodology recommended by Boulanger & Idriss (2014).

A component of building settlement may also occur due to yield of any liquefied founding soils. This component of settlement is very difficult to predict and depends on the interaction of the building and the soil it is founded on.

**Project:** ORC South Dunedin Liquefaction
**Part:** Liquefaction Assessment Summary
**By:** TJP

**Job Number:** 200038
**Date:** 22/06/2020
**Checked by:** CEM

| Test | Test Depth (m) | Predrill (m) (1) | Assumed GWL (m) | 1/25 Event (Mw5.8, 0.06g) | | 1/100 Event (Mw5.8, 0.11g) | | 1/250 Event (Mw5.8, 0.17g) | | 1/500 Event (Mw5.8, 0.23g) | | 1/1000 Event (Mw5.8, 0.29g) | | 1/2500 Event (Mw5.8, 0.41g) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Settlement (mm) (2) | LSN (2) | Settlement (mm) (2) | LSN (2) | Settlement (mm) (2) | LSN (2) | Settlement (mm) (2) | LSN (2) | Settlement (mm) (2) | LSN (2) | Settlement (mm) (2) | LSN (2) |
| CPT118535 | 6.1 | | 0.5 | 0 | 0 | 10 | 3 | 10 | 3 | 15 | 4 | 20 | 5 | 25 | 7 |
| CPT118547 | 5.9 | | 0.5 | 0 | 0 | 0 | 1 | 0 | 1 | 5 | 1 | 5 | 1 | 5 | 2 |
| CPT118552 | 20.5 | 0.6 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CPT118553 | 11.2 | 0.6 | 0.5 | 0 | 1 | 30 | 3 | 30 | 3 | 30 | 3 | 30 | 3 | 30 | 3 |
| CPT118790 | 12.5 | | 0.5 | 0 | 0 | 15 | 4 | 30 | 12 | 35 | 13 | 35 | 14 | 35 | 16 |
| CPT118802 | 16.6 | | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CPT118805 | 5.5 | | 0.5 | 0 | 0 | 0 | 0 | 5 | 2 | 10 | 9 | 20 | 16 | 25 | 21 |
| CPT118808 | 7.1 | | 0.5 | 0 | 0 | 10 | 2 | 15 | 3 | 20 | 7 | 25 | 10 | 30 | 14 |
| CPT118810 | 9.8 | | 0.5 | 0 | 0 | 20 | 3 | 25 | 3 | 25 | 3 | 25 | 4 | 25 | 6 |
| CPT118811 | 10.9 | | 0.5 | 0 | 0 | 10 | 2 | 20 | 7 | 30 | 9 | 35 | 12 | 40 | 13 |
| CPT118812 | 5.2 | | 0.5 | 0 | 0 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 2 |
| CPT118813 | 3.0 | | 0.5 | 0 | 0 | 0 | 1 | 15 | 8 | 25 | 12 | 25 | 15 | 30 | 19 |
| CPT118815 | 22.7 | 0.5 | 0.5 | 0 | 0 | 5 | 2 | 25 | 14 | 35 | 18 | 40 | 20 | 50 | 22 |
| CPT118819 | 7.9 | | 0.5 | 0 | 0 | 5 | 1 | 10 | 2 | 10 | 6 | 15 | 9 | 15 | 11 |
| CPT118821 | 9.1 | | 0.5 | 0 | 0 | 20 | 3 | 25 | 8 | 30 | 11 | 30 | 14 | 30 | 15 |
| CPT118823 | 12.4 | | 0.5 | 0 | 0 | 15 | 4 | 45 | 15 | 55 | 18 | 55 | 19 | 60 | 20 |
| Site A | 10+ | | 0.5 | 0-5 | 0-1 | 5-40 | 1-4 | 10-40 | 1-4 | 15-40 | 3-6 | 20-40 | 4-8 | 20-40 | 5-10 |
| Site B | 7-10+ | | 0.5 | 0 | 0 | 5-45 | 1-7 | 15-80 | 4-13 | 25-85 | 7-16 | 25-85 | 10-20 | 35-90 | 12-23 |
| Site C | 10+ | | 0.5 | 0-5 | 0 | 30-40 | 4-5 | 45-50 | 5-7 | 50-55 | 6-10 | 50-55 | 6-12 | 55-60 | 6-12 |
| Site D | 10+ | | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1-2 | 0-5 | 2-3 |
| Site E | 4-10+ | 0.5 | 0.5 | 0 | 0 | 0-30 | 0-5 | 0-70 | 0-11 | 0-80 | 0-12 | 0-80 | 0-12 | 0-80 | 0-12 |
| Site F | 10+ | | 0.5 | 0 | 0 | 0-20 | 1-6 | 10-65 | 5-29 | 15-80 | 11-41 | 15-85 | 13-44 | 15-85 | 15-46 |
| Site G | 10+ | | 0.5 | 0 | 0 | 0-5 | 0-1 | 5-15 | 3-12 | 5-20 | 3-20 | 5-25 | 3-24 | 5-30 | 3-26 |
| Site H | 10+ | | 0.5 | 0 | 0 | 0 | 0 | 0 | 2 | 5 | 3-7 | 0-5 | 3-9 | 5 | 3-10 |
| Site I | 10+ | | 0.5 | 0 | 0 | 20-70 | 2-9 | 45-90 | 6-12 | 55-95 | 7-13 | 55-95 | 8-15 | 55-95 | 8-16 |
| Site J | 10+ | | 0.5 | 0 | 0 | 0-5 | 0-1 | 0-5 | 1 | 0-5 | 1-3 | 0-5 | 1-3 | 0-5 | 1-3 |
| Site K | 6.5 | | 0.5 | 0 | 0 | 0 | 0 | 5 | 2 | 5 | 2 | 5 | 2 | 5 | 2 |
| Site L | 10+ | | 0.5 | 0 | 0 | 10-15 | 2-3 | 20-30 | 8-11 | 25-40 | 10-15 | 30-40 | 11-18 | 30-45 | 12-21 |
| Site M | 10+ | | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Site N | 8.5-10+ | | 0.5 | 0 | 0 | 10-20 | 2-5 | 30-75 | 6-24 | 35-85 | 8-28 | 35-85 | 9-28 | 35-85 | 9-28 |
| Site O | 10+ | | 0.5 | 0 | 0 | 0-20 | 0-9 | 0-35 | 0-17 | 0-35 | 0-17 | 0-35 | 0-17 | 0-35 | 0-17 |
| Site P | 10+ | 1 | 0.5 | 0 | 0 | 10-20 | 3-6 | 25-30 | 9-14 | 25-35 | 11-15 | 25-35 | 11-17 | 25-35 | 11-18 |
| Site Q | 9-10+ | | 0.5 | 0 | 0 | 5-10 | 1-2 | 5-20 | 1-4 | 10-20 | 4-7 | 10-20 | 8-10 | 10-24 | 9-13 |
| Site R | 10+ | | 0.5 | 0 | 0 | 0-25 | 0-6 | 0-40 | 0-14 | 0-40 | 0-17 | 0-40 | 0-18 | 0-40 | 0-19 |
| Site S | 10+ | 1 | 0.5 | 0 | 0 | 5 | 1 | 10-15 | 4-8 | 20 | 10-11 | 25 | 12-14 | 25 | 14-16 |
| Site T | 2.5-8 | | 0.5 | 0 | 0 | 0-10 | 0-4 | 0-45 | 0-13 | 0-65 | 1-15 | 0-70 | 3-18 | 0-75 | 4-22 |
| Site U | 10+ | | 0.5 | 0 | 0 | 0-20 | 0-9 | 0-35 | 0-17 | 0-35 | 0-17 | 0-35 | 0-17 | 0-35 | 0-17 |
| Site V | 9-10+ | | 0.5 | 0 | 0 | 5-40 | 2-7 | 25-60 | 4-15 | 25-65 | 4-22 | 25-65 | 5-24 | 25-75 | 5-25 |
| Min | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Max | | | | 5 | 1 | 70 | 9 | 90 | 29 | 95 | 41 | 95 | 44 | 95 | 46 |

Notes:
(1) Pre-drill recorded if 0.5 m or greater
(2a) Indexed settlement and LSN calcuated by considering the upper 10 m only, where data avaiable
(2b) Some tests may have reached early refusal. Therefore additional layers could liquefy which will result in additional settlement and ground damage potentail
(2c) Areas in South Dunedin area is underlain soft silts/clays which are prone to ongoing static settlement, low bearing capacities and/or cyclic softening in a moderate to major earthquake event which is not covered in the above liquefaction assessment.
(3) Refer to Figure 1 for location of testing
(4) Range of results are given for sites with more than one CPT