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Wellington's sedimentary basin and its role in amplifying earthquake ground motions: new CBD 3D model and maps

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ABSTRACT

During the Mw7.8 Kaikōura earthquake, ground motions in central Wellington were clearly influenced by both the nature of the earthquake source and local amplification effects due to the sedimentary basin. These effects led to high spectral accelerations at periods of 1 – 2 seconds in deeper parts of the basin that exacerbated damage to midrise structures.

Following these observations, GNS Science and collaborators from the University of Auckland undertook a Natural Hazards Research Platform project to model the 3D basin structure and update the Semmens et al. (2010) geotechnical maps for Wellington CBD. The results contribute to our understanding of the role of the basin structure in amplifying earthquake ground motion.

Our new 3D model utilises the wealth of geological data in the region, modern computing software, a suite of new block-by-block geophysical measurements, surface and subsurface data such as Light Detection and Ranging (LiDAR) and a new borehole database. We model five different geological deposits above the basement rocks and provide new maps of, fundamental site period and NZS1170.5 subsoil classification. These maps can be used as a starting point to guide engineering design. They also provide new insights into the local structure of the Thorndon and Te Aro basins, the newly discovered Aotea Fault, as well as the role of 3D basin effects. One key observation is that the traditional treatment of site response as a 1D problem may lead to underestimation of amplification effects at the steep-sided basin margins.

1 INTRODUCTION

The character of local ground motion amplification depends on the geological structure and local geotechnical soil properties surrounding the site. In sedimentary basins, seismic waves are amplified within softer materials at shallow depths, with the period of amplification primarily related to the shear-wave velocity (Vs) and thickness of the subsoil, as well as the shape of the 3D basin structures. Traditional engineering approaches consider the first two of these factors, estimating the fundamental site period (Tsite) by constructing a 1D soil profile at the site. Site response analyses that also incorporate complementary geophysical measurements and observational records can increasingly provide a more complete picture of ground motion amplification at the site that also consider 3D basin effects.

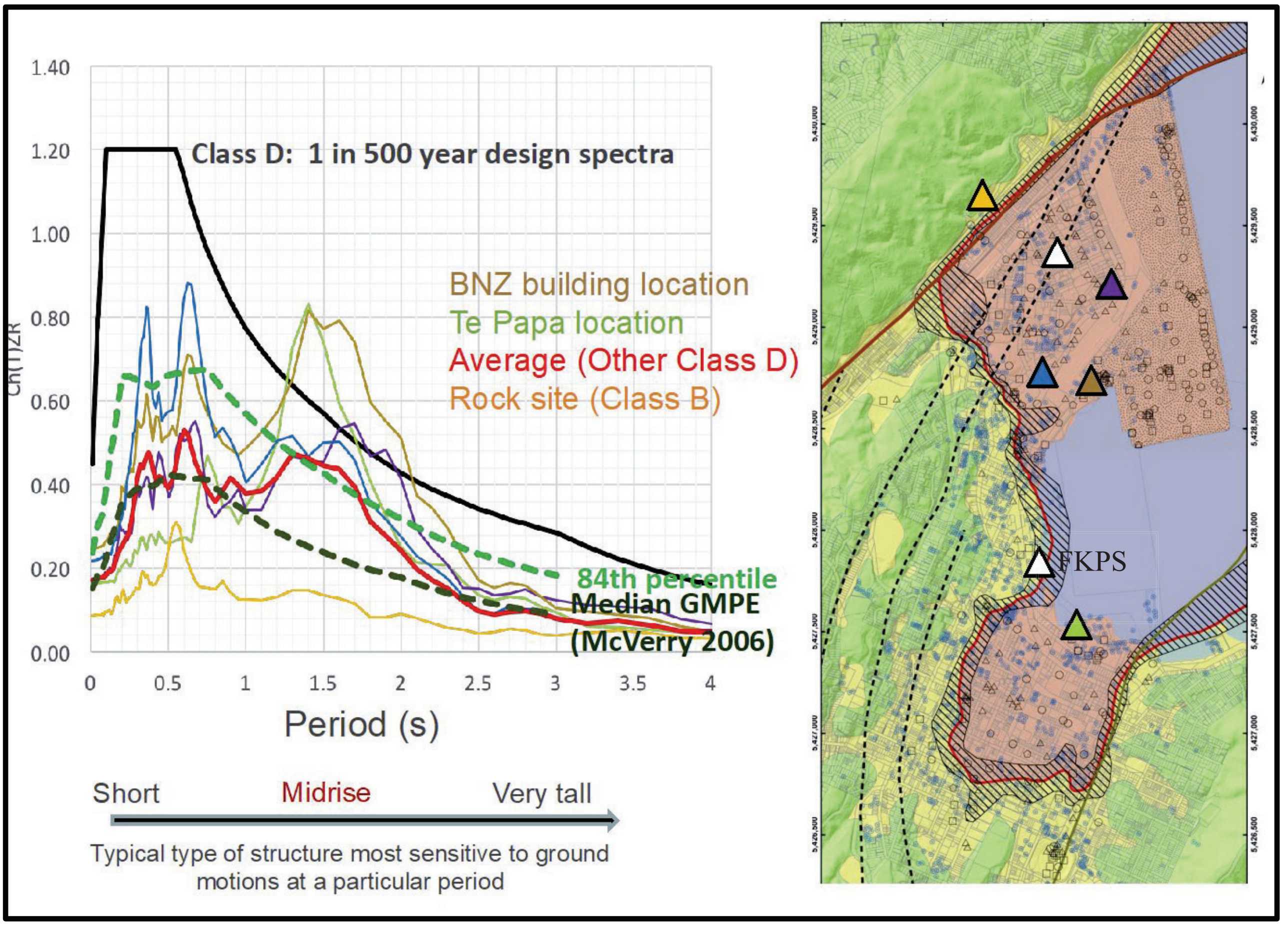


Figure 1: Spectral accelerations during the 2016 Mw 7.8 Kaikōura earthquake recorded at central Wellington Class D subsoil sites compared to (i) Class D 1in 500 year ULS design spectra and (ii) median and 84th percentile ground motion predictions from McVerry (2006) GMPE. Map on the right shows the location of recording sites and the NZS1170.5 subsoil class (orange = Class D, Yellow = Class C and green = Class B).

In central Wellington, significant basin amplification effects were observed during the Kaikōura earthquake (Figure 1), exacerbating damage to mid-rise structures in the downtown area (Kaiser et al. 2017; Bradley et al. 2018). This amplification was observed systematically at all Class D subsoil sites, including those close to the basin margin, but was of greater amplitude at the recordings sites in waterfront areas (e.g. BNZ building location, Te Papa locations, where soils are both deeper and near-surface soils are softer).

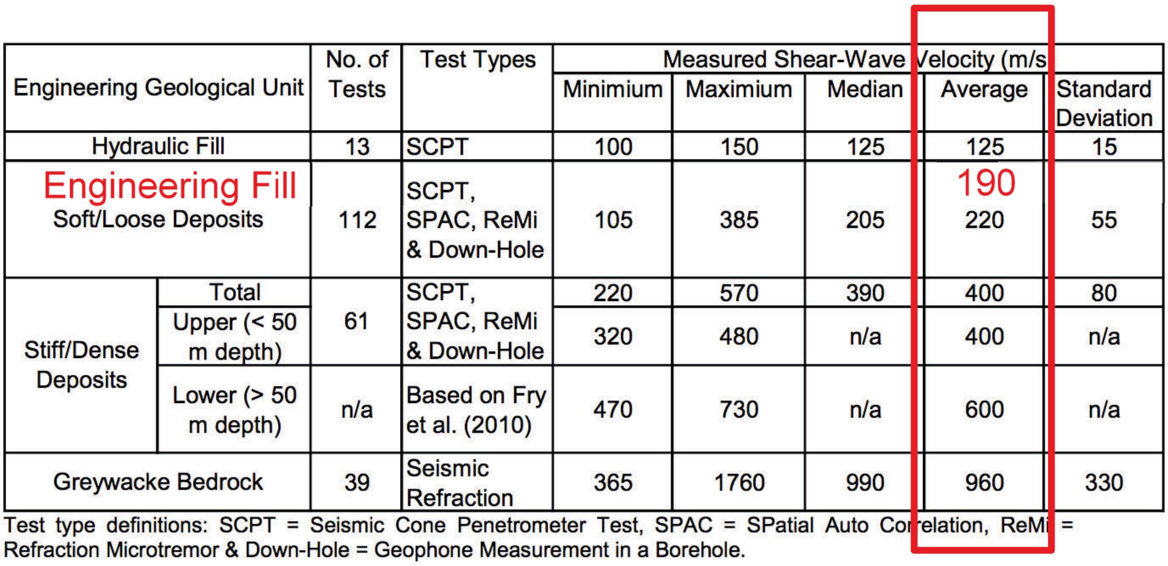
To better understand these ground motion effects, we have undertaken a major revision and update of the Semmens et al. (2010, 2011) 3D basin model and geotechnical maps for central Wellington. This work and follow-on research are summarised here, with further details contained in in Kaiser et al. (2019). The study incorporates information from 700+ new downhole borehole logs analysed together with a new expansive geophysical database of 400+ HVSR (horizontal-to-vertical spectral ratio) measurements. The result is much more detailed knowledge of the subsurface that can be used to understand amplification, 3D basin effects and damage patterns, and as a starting point to guide engineering design.

2 3D GEOLOGICAL MODEL

2.1 Engineering Geological Units

Our updated 3D Wellington geological and velocity model is based on the same geological classification scheme as Semmens *et al.* (2010, 2011) summarised in Table 1. This scheme groups "like" geological deposits into key engineering unit categories based around geological description and SPT N count values (which are a representation of the stiffness in non-cohesive materials). In addition to the Semmens classification, we have used new borehole data to define a new "Engineering Fill" unit, which was previously included within the "Soft/Loose Deposits" category. Furthermore, the delineation of engineering fill helps to define the extent of reclaimed land in waterfront areas and provides further insights into the effect of near-surface sediments on seismic response.

Table 1: Summary of shear-wave velocity measurements by engineering geological unit for the Wellington CBD, modified from Semmens et al. (2010) to include the additional unit of Engineering Fill. The average shear-wave velocities were used in this study to estimate site period from the 3D basin model.



Engineering Geological Unit		No. of Tests	Test Types	Measured Shear-Wave Velocity (m/s				
				Minimum	Maximum	Median	Average	Standard Deviation
Hydraulic Fill		13	SCPT	100	150	125	125	15
Engineering Fill Soft/Loose Deposits		112	SCPT, SPAC, ReMi & Down-Hole	105	385	205	190 220	55
Stiff/Dense Deposits	Total	61	SCPT, SPAC, ReMi & Down-Hole	220	570	390	400	80
	Upper (< 50 m depth)			320	480	n/a	400	n/a
	Lower (> 50 m depth)	n/a	Based on Fry et al. (2010)	470	730	n/a	600	n/a
Greywacke Bedrock		39	Seismic Refraction	365	1760	990	960	330

Test type definitions: SCPT = Seismic Cone Penetrometer Test, SPAC = SPatial Auto Correlation, ReMi = Refraction Microtremor & Down-Hole = Geophone Measurement in a Borehole.

We have adopted the shear-wave velocity characterisation of Semmens *et al.* (2010), assigning an average velocity for each unit in the 3D basin model. A first review of new velocity information collected since 2010, suggest the average velocities assigned to each layer are appropriate to capture first order velocity variations. The new 'Engineering Fill' unit was assigned a velocity of 190 m/s, which is consistent with the approach in Semmens *et al.* (2010) of arbitrarily reducing the velocity of 'Soft/Loose Deposits' by 30 m/s within waterfront reclamation areas, based on known velocity profiles.

2.2 3D Model Overview

We have upgraded and expanded the Semmens *et al.* (2010) borehole database, which now includes 700+ additional boreholes and numerous CPT/SPT and shear-wave velocity measurements. The borehole database now comprises 1,427 boreholes, 429 of which intersect greywacke basement. We also provide an assessment of the quality of each borehole log and its geological profile in the database. The updated 3D basin model utilises these borehole records, surface geological contact enhancements from LiDAR elevations, and new 3D geological modelling techniques to better define engineering geological units and investigate the location of the newly discovered Aotea fault.

The new model interprets a shallower basement contact under the Wellington Stadium and CentrePort region; a deeper basin and possible paleochannel below Thorndon; and a fault-controlled basin west of Te Aro. New interpretations of the sedimentary boundaries between loose and dense sediments and manmade fill are the result of new borehole records.

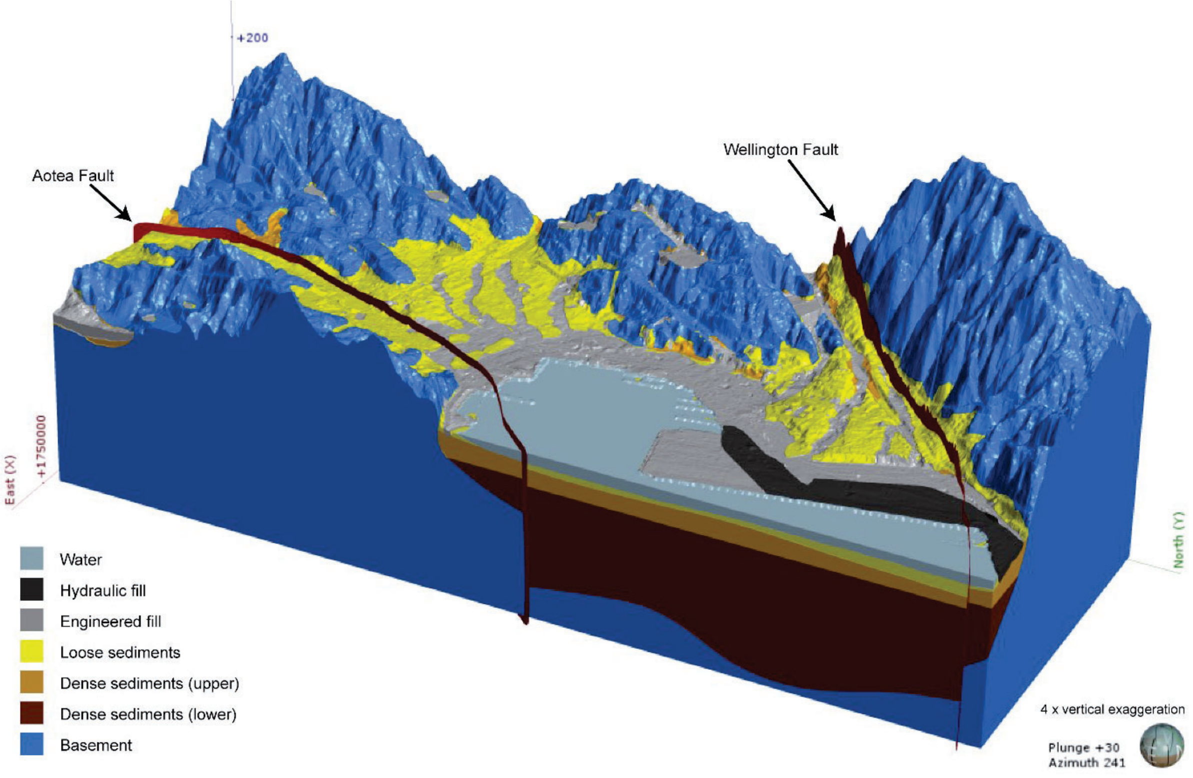


Figure 2: New 3D Geological model of central Wellington, showing the key engineering units and locations of the Wellington and newly mapped Aotea faults.

3 SITE PERIOD

3.1 Site Period Database

GNS Science, the University of Auckland and collaborators from the University of Texas at Austin have collated over 483 geophysical site period measurements in the central city. The majority of these measurements have been derived from analysis of seismometer recordings of ambient noise at closely spaced locations using the horizontal-to-vertical spectral ratio (HVSR) technique (Nakamura 1989). Our geophysical surveys have largely targeted the deeper parts of the Wellington basin (i.e.> 30 m of sediment), where borehole information down to bedrock is sparse. In these locations, clear amplification peaks in the HVSR data are observed in many cases, and these can be used to estimate the site period. Hence the site period database is directly complementary to the borehole database used to construct the 3D basin model.

For each measurement in the site period database, an additional summary measure of overall uncertainty or ‘rand’ is also given where categories are as follows: 0=unusable, 1=very poor, 2=poor, 3=satisfactory, 4=good, 5=excellent. These values enable the relative robustness of each measurement to be captured in a consistent manner and ultimately allow contours of site period to be more robustly drawn and interpreted.

We have developed an innovative strategy to combine complementary site period estimates from the 3D basin model and the geophysical database into a comprehensive site period map, as described in detail in Kaiser et al. (2019). The result is much improved block-by-block mapping of site period in central Wellington (Figure 3).

3.2 Site Period Map

The most significant updates from Semmens et al. (2010) occur in the Thorndon basin, where previous interpretations were based only on sparse site period measurements. The new data suggest that site period is longer in the upper Thorndon area than previously mapped (e.g. between Hill St, Murphy Street and State Highway 1). This also implies that greywacke basement may be deeper here than previously expected. In this area, site period estimates also show some local variability, which most likely reflects the variability in local soft soil deposits and/or basin or basin-edge effects at the steep-sided basin margin.

The longest site periods (>1.2s) are largely confined to waterfront areas including reclaimed land in the CentrePort area, where many high quality measurements now provide robust site period mapping. However, no boreholes-to-basement exist in this area, and the deeper basin velocity structure and bedrock depth estimates are associated with significant uncertainty.

The Te Aro basin site period mapping now suggests a steeper-sided, wider basin shape than that of Semmens *et al.* (2010). The steep eastern basin-edge is compatible with the projected location of the newly discovered Aotea Fault. Geophysical and borehole site period estimates are in excellent agreement throughout the Te Aro basin, and the deeper parts of the basin are well constrained. Furthermore, site period estimates also show smoothly varying changes across the basin which allow us to draw robust site period contours.

It is important to note that there are still large uncertainties associated with many site period estimates within ~100m of the mapped Wellington and Aotea fault traces bounding the western and eastern edges of the Wellington basin. In these areas basement depth is rapidly varying and geophysical measurements are generally of lower quality (e.g. they can be affected by complex 2D/3D effects). Furthermore, 1D assumptions inherent in the common methods to calculate site period may not adequately capture the true ground response. Additional constraints on basement depth would help to better define site period in these areas.

4 NZS1170.5 SUBSOIL CLASS

Based on our results described above, we have updated NZS1170.5 subsoil class map for central Wellington (Figure 4). For the purposes of our mapping, the Class B/C boundary is defined based on the 3m soil depth contour extracted from our 3D model and the Class C/D boundary is defined based on our newly revised 0.6 s site period contour. An estimate of the uncertainty in the C/D boundary is also given based on the site period contours equivalent to ±10% of this value. An area of possible Class E is outlined by the extent of hydraulic fill and observations of historical liquefaction during the Kaikōura and Cook Strait earthquakes (Cubrinovski *et al.* 2018). The original intent of the Class E standard was to capture liquefiable soils, which are clearly present within this area. The extensive liquefaction observed within this outlined area highlights the need for site-specific assessment and mitigation strategies. More details on the site subsoil class mapping can be found in Kaiser et al. (2019).

The new subsoil class maps show that the main features of the original Semmens *et al.* (2010) map are robust. The most significant changes to note are:

- Site period estimates for upper Thorndon consistently indicate it is most likely Class D.
- The Te Aro basin subsoil Class C/D boundary has undergone minor adjustment, and is now better defined.

- Uncertainty estimates associated with the Class C/D boundary have generally been reduced, due to the large number of additional measurements.

Our updated subsoil classification maps are consistent with the 2004 NZS1170.5 standard subsoil classification guidelines. However, current best-practice modern estimates of seismic hazard increasingly rely on alternative site parameters as discussed in the next section.

5 DISCUSSION AND CONCLUSIONS

Following the 2016 Mw 7.8 Kaikōura earthquake, we have undertaken a major update of the Semmens et al. (2010) 3D basin model and geotechnical maps for central Wellington. The new modelling draws on databases of ~1600 boreholes and 400+ geophysical site period measurements as well as new LiDAR mapping to provide much improved constraints. The new maps and 3D model provide greater clarity about the subsurface structure and its implications for future engineering design in Wellington.

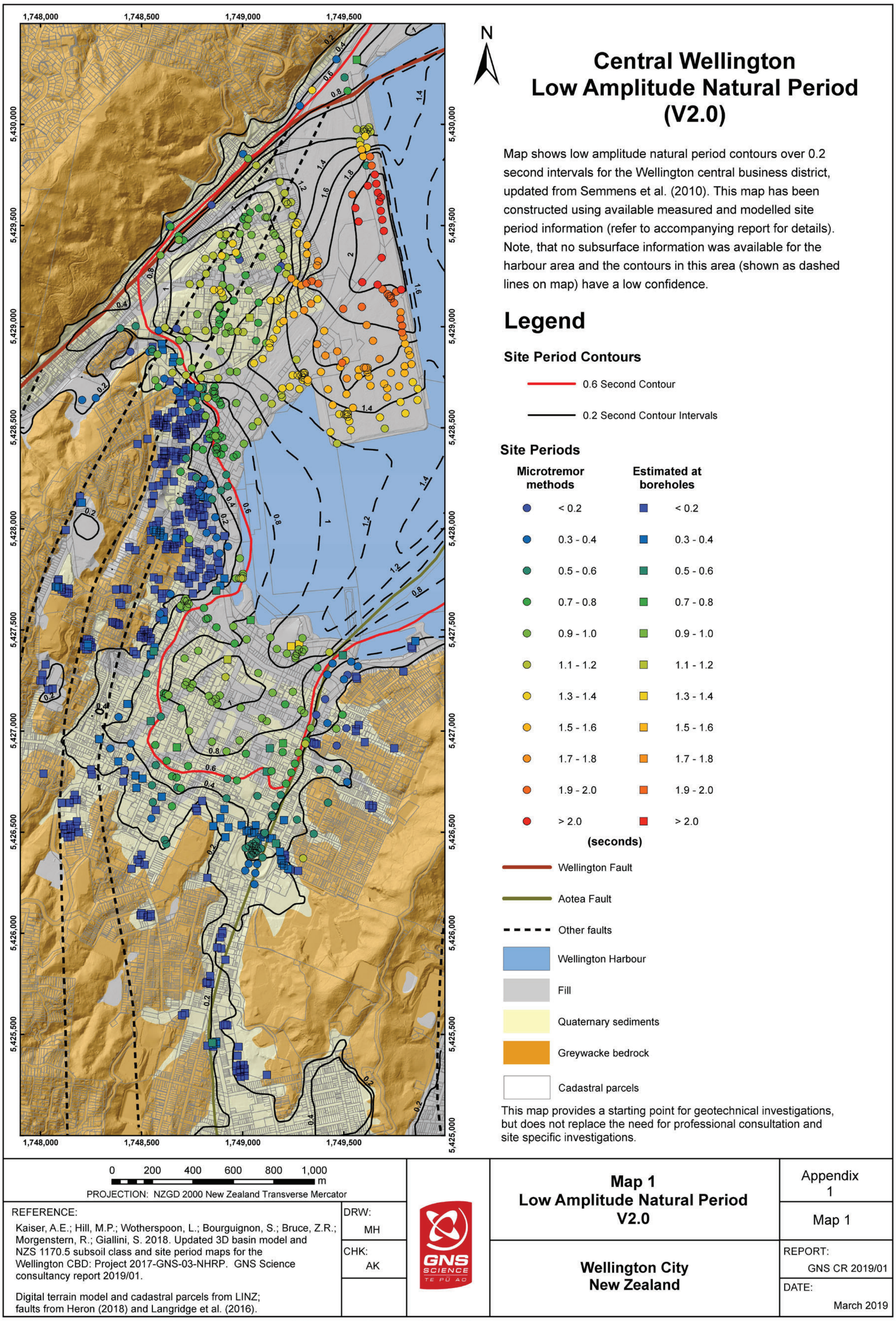
The central Wellington basin is comprised of two sub-basins of greater than 100 m depth. Our results indicate that site period is consistently longer and basement likely deeper than previously thought in the upper Thorndon basin, with the result that the Class D subsoil classification is most appropriate based on current evidence. In areas of reclaimed land, including CentrePort, site period is now much better constrained, ranging from 1.2 s to greater than 2 s. These periods correspond to the 1–2 s period range of large amplifications observed here during the Kaikōura earthquake which exacerbated damage (Kaiser *et al.* 2017; Bradley *et al.* 2018).

The Te Aro basin to the south is now robustly mapped with more steeply dipping basement on its western and eastern flanks. In particular, the steeply dipping eastern basin edge is consistent with the projected location of the newly discovered offshore Aotea Fault (Barnes *et al.* 2018), although the precise onshore character and location of the fault trace has not been determined.

We note that two areas of our 3D model would particularly benefit from further drilling of deep borehole down to greywacke basement to reduce uncertainty in the deeper basin structure: (i) Thorndon – CentrePort where site period estimates are robust, but depth to basement is uncertain and (ii) areas directly adjacent (within 100m) of the Wellington and Aotea faults where geophysical measurements are sparse and/or difficult to interpret and exact fault location cannot yet be confirmed.

One key observation from our study is the tendency of geophysical measurements at the steeply dipping basin margins to yield somewhat longer estimates of site period than those traditionally predicted from 1D soil profiles. This illustrates the need to consider the potential for 3D basin amplification effects at sites directly adjacent to deeper soil deposits, with geophysical estimates of site period potentially better able to capture the expected ground response at these locations.

The subsoil classifications adopted in the current building standard (NZS1170.5, Standards New Zealand 2004) provide one useful measure to understand likely local ground shaking response. However, modern best-practice seismic hazard evaluations increasingly rely on other parameters, including Z1.0 (depth to shear-wave velocity of 1km/s), Vs30 (time-average shear-wave velocity in the uppermost 30 m) and site period. Our 3D model is able to provide initial estimates of each of these parameters, and can serve as a starting point on the information available to guide site-specific assessment for engineering design. The new 3D basin velocity model can also be used to simulate expected ground motions and further investigate 3D basin effects during large earthquakes impacting Wellington (e.g. Benites *et al.* 2005).



Central Wellington
Low Amplitude Natural Period
(V2.0)

Map shows low amplitude natural period contours over 0.2 second intervals for the Wellington central business district, updated from Semmens et al. (2010). This map has been constructed using available measured and modelled site period information (refer to accompanying report for details). Note, that no subsurface information was available for the harbour area and the contours in this area (shown as dashed lines on map) have a low confidence.

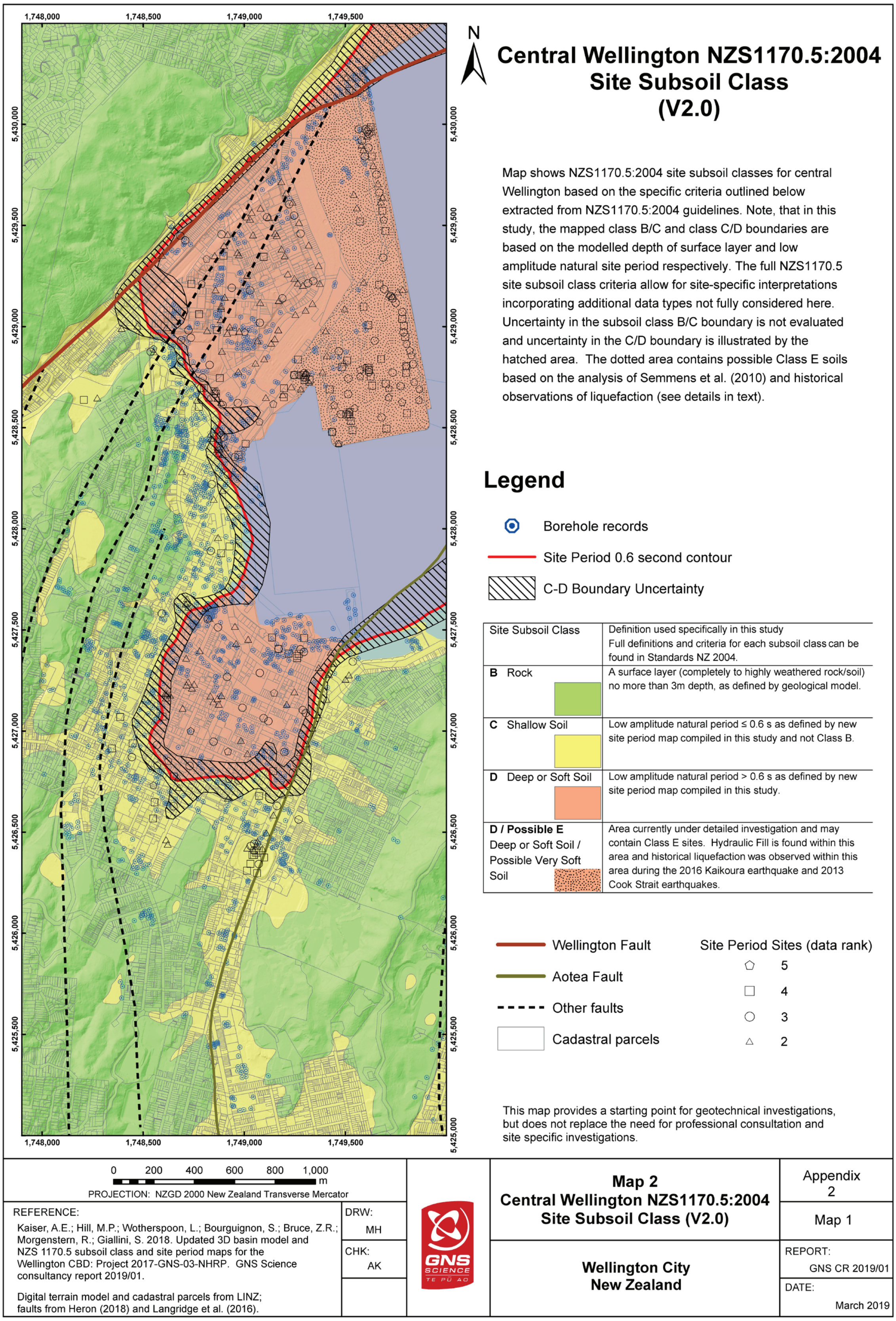
This map provides a starting point for geotechnical investigations, but does not replace the need for professional consultation and site specific investigations.

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

REFERENCE:
Kaiser, A.E.; Hill, M.P.; Wotherspoon, L.; Bourguignon, S.; Bruce, Z.R.; Morgenstern, R.; Giallini, S. 2018. Updated 3D basin model and NZS 1170.5 subsoil class and site period maps for the Wellington CBD: Project 2017-GNS-03-NHRP. GNS Science consultancy report 2019/01.

Digital terrain model and cadastral parcels from LINZ; faults from Heron (2018) and Langridge et al. (2016).

Figure 3: Site period map for Wellington CBD from Kaiser et al. (2019), also showing locations of individual measurements. For estimates of the quality of each measurement, please contact the authors or refer to Kaiser et al. (2019).



Central Wellington NZS1170.5:2004 Site Subsoil Class (V2.0)

Map shows NZS1170.5:2004 site subsoil classes for central Wellington based on the specific criteria outlined below extracted from NZS1170.5:2004 guidelines. Note, that in this study, the mapped class B/C and class C/D boundaries are based on the modelled depth of surface layer and low amplitude natural site period respectively. The full NZS1170.5 site subsoil class criteria allow for site-specific interpretations incorporating additional data types not fully considered here. Uncertainty in the subsoil class B/C boundary is not evaluated and uncertainty in the C/D boundary is illustrated by the hatched area. The dotted area contains possible Class E soils based on the analysis of Semmens et al. (2010) and historical observations of liquefaction (see details in text).

Legend

◎ Borehole records

— Site Period 0.6 second contour

▨ C-D Boundary Uncertainty

Site Subsoil Class	Definition used specifically in this study Full definitions and criteria for each subsoil class can be found in Standards NZ 2004.
B Rock 🟩	A surface layer (completely to highly weathered rock/soil) no more than 3m depth, as defined by geological model.
C Shallow Soil 🟨	Low amplitude natural period ≤ 0.6 s as defined by new site period map compiled in this study and not Class B.
D Deep or Soft Soil 🟧	Low amplitude natural period > 0.6 s as defined by new site period map compiled in this study.
D / Possible E Deep or Soft Soil / Possible Very Soft Soil ▨	Area currently under detailed investigation and may contain Class E sites. Hydraulic Fill is found within this area and historical liquefaction was observed within this area during the 2016 Kaikoura earthquake and 2013 Cook Strait earthquakes.

— Wellington Fault

— Aotea Fault

- - - - Other faults

☐ Cadastral parcels

Site Period Sites (data rank)	
⬠	5
□	4
○	3
△	2

This map provides a starting point for geotechnical investigations, but does not replace the need for professional consultation and site specific investigations.

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

REFERENCE:
Kaiser, A.E.; Hill, M.P.; Wotherspoon, L.; Bourguignon, S.; Bruce, Z.R.; Morgenstern, R.; Giallini, S. 2018. Updated 3D basin model and NZS 1170.5 subsoil class and site period maps for the Wellington CBD: Project 2017-GNS-03-NHRP. GNS Science consultancy report 2019/01.

Digital terrain model and cadastral parcels from LINZ; faults from Heron (2018) and Langridge et al. (2016).

DRW: MH

CHK: AK

GNS SCIENCE TE PŪ AO

Map 2
Central Wellington NZS1170.5:2004
Site Subsoil Class (V2.0)

Wellington City
New Zealand

Appendix 2

Map 1

REPORT: GNS CR 2019/01

DATE: March 2019

Figure 4: NZS1170.5 subsoil class map from Kaiser et al. (2019). Locations of individual site period measurements of quality > 2 are shown (quality indicated by symbol).

ACKNOWLEDGEMENTS

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