AN ENGINEERING GEOLOGICAL INVESTIGATION OF THE SEISMIC SUBSOIL CLASSES IN THE CENTRAL WELLINGTON COMMERCIAL AREA

VOLUME ONE: THESIS

A thesis submitted in partial fulfilment of the requirements for the

Degree of

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by

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Frontispiece: View looking southwest along the Wellington-Hutt Valley segment of the Wellington Fault, Wellington City is located across the harbour at the top of the photo (Photo by L. Homer; GNS 20121-14)

"We learn geology the morning after the earthquake."

Ralph Waldo Emerson
Philosopher & Poet (1803-1882)

ABSTRACT

The city of Wellington has a high population concentration and lies within a geologically active landscape at the southern end of the North Island, New Zealand. Wellington has a high seismic risk due to its close proximity to several major fault systems, with the active Wellington Fault located in the north-western central city. Varying soil depth and properties in combination with the close proximity of active faults mean that in a large earthquake rupture event, ground shaking amplification is expected to occur in Thorndon, Te Aro and around the waterfront.

This thesis focuses on the area bounded by Thorndon Overbridge in the north, Wellington Hospital in the south, Kelburn in the west, and Oriental Bay in the east. It includes many of the major buildings and infrastructural elements located within the central Wellington commercial area. The main objectives were to create an electronic database which allows for convenient access to all available data within the study area, to create a 3D geological model based upon this data, and to define areas of different seismic subsoil class and depth to rock within the study area at a scale that is useful for preliminary geotechnical analysis (1:5,000).

Borelogs from 1025 holes with accompanying geological and geotechnical data obtained from GNS Science and Tonkin & Taylor were compiled into a database, together with the results from SPAC microtremor testing at 12 sites undertaken specifically for this study. This thesis discusses relevant background work and defines the local Wellington geology.

A 3D geological model of the central Wellington commercial area, along with ten ArcGIS maps including surficial, depth to bedrock, site period, Vs30, ground shaking amplification hazard and site class (NZS 1170.5:2004) maps were created. These outputs show that a significant ground shaking amplification risk is posed on the city, with the waterfront, Te Aro and Thorndon areas most at risk.

Key Words

3D Engineering Geological Model, Depth to Bedrock, Ground Shaking Amplification, Liquefaction Potential, NZS 1170.5:2004, SCPT, SPAC, SPT, Site Effects, Site Period, Site Subsoil Class, Surficial Deposits, V_s30, Wellington City.

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VOLUME ONE: THESIS
TABLE OF CONTENTS:

LIST OF FIGURES:

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1.1 PROJECT BACKGROUND

This research has been conducted to better constrain the geological conditions through the collection, correlation and modelling of all available subsurface information within the central Wellington commercial area. A better understanding of the controls of site effects and improved access to all available data will enable local site response parameters to be established faster and more accurately with a greater consistency. The new knowledge and understanding gained from this project will enable more accurate hazard and risk estimates for Wellington City. This will help increase community resilience and preparedness within the central city and provided engineering measures are properly implemented would enable faster recovery in an earthquake event.

By New Zealand standards Wellington City is a densely populated urban area (due to limited building space) with a moderate climate and hilly topography dominated by the harbour. The city's population base is situated in close proximity to 7 major seismogenic sources including the Wellington Fault and subduction interface. Seismogenic risk in Wellington City and the surrounding region is the greatest in New Zealand and is well documented (Van Dissen et al. 1992a; Van Dissen & Berryman 1996; Murashev & Palmer 1998; Stirling et al. 1998; Kerr et al. 2003; Benites & Olsen 2005).

The study area encompasses the major infrastructural elements of the central city and focuses on the area from the Thorndon overbridge in the north, through to Wellington Hospital in the south. Within the study area Holocene and Pleistocene deposits overly the greywacke basement. Reclamation landfill around Wellington's waterfront is also significant with more than 155 hectares added to the city.

The influence of local geologic (site) conditions on the intensity of ground shaking and earthquake damage is well documented. Site conditions can influence amplitude, frequency and duration of strong ground motion. Seismic waves travel faster through hard rocks and compact sediments than through softer rocks and sediments. Generally soft soils amplify earthquake shaking more than shallow soils and rock sites. As sediment thickness increases, so too does the amount of shaking (amplification), which is directly proportional to damage. Local site effects represent one of the most important aspects of geotechnical earthquake engineering and must be accounted for on a case by case basis (Kramer 1996).

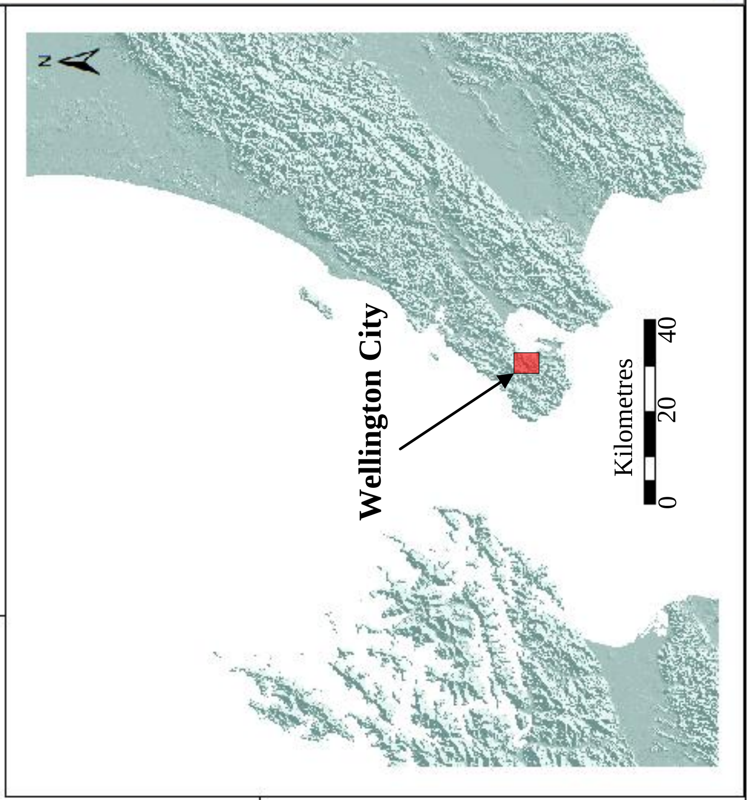
In New Zealand site effects are dealt with in the structural design actions NZS 1170.5:2004. The five site subsoil class categories within this standard consider both the soil type and depth, which determines a site's dynamic stiffness and period. These dynamic response characteristics are in turn used to design code compliant structures. The assigned site subsoil class is also significant as it has a major effect on design and construction costs, with the lower classes (deep soil and very soft soil) requiring greater structural strength. Of the five site subsoil class categories defined by NZS 1170.5:2004, four can be found within the study area including rock, shallow soil, deep of soft soil and very soft soil (Standards New Zealand 2004).

1.2 PROJECT OBJECTIVES

The primary objective of this study was to collate all available information within the study area, then use this data to construct a site subsoil class map based on the New Zealand structural design specifications (NZ S1170.5:2004) at a commercially useful scale (1:5,000).

The major outputs of this project reflect the ultimate goal of better defining the subsurface properties of the central Wellington commercial area. These outputs include:

- A readily accessible database containing all the available borehole information within the study area.
- A 3D geological model for the central Wellington commercial area.
- A surficial deposit map (showing reclamation areas, former swamps and old stream beds).
- The depth to bedrock, low amplitude natural period (site period), Vs30 and ultimately site subsoil class maps (1:5,000 scale).



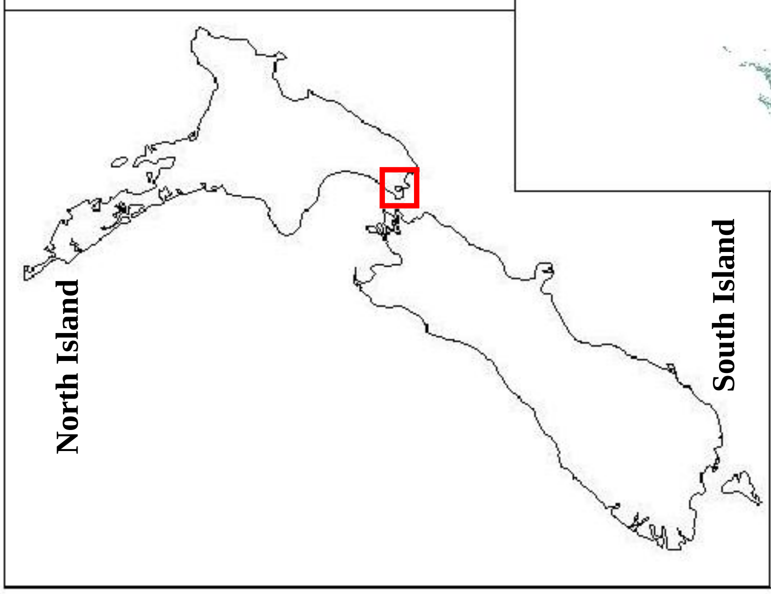


Figure 1.1: Location of the study area (Google 2009). Insert: Maps indicate the location of Wellington City within the North Island, New Zealand (Begg & Johnston 2000).

1.3 STUDY AREA

1.3.1 BOUNDARIES

The study focuses on a 10 km^2 area of Wellington City from the Thorndon overbridge in the north, through to Wellington Hospital in the south, from Kelburn in the west, through to Oriental Bay in the east (Figure 1.1). New Zealand Map Grid (NZMG) coordinates were used with 265,8000-266,0000E representing the western and eastern boundaries respectively and 598,7000-599,2000N representing the southern and northern boundaries respectively.

1.3.2 SIGNIFICANCE

The study area was chosen as many of the major building and infrastructural elements vital to Wellington and the surrounding region are located within the central city, for example rail, road and ferry transportation, water reticulation, telecommunications, electricity cabling, the Earthquake Commission and Parliament. After working as a summer student with Tonkin & Taylor in Wellington it was decided that the information from within the study area could be collated and modelled within the Master’s thesis time frame.

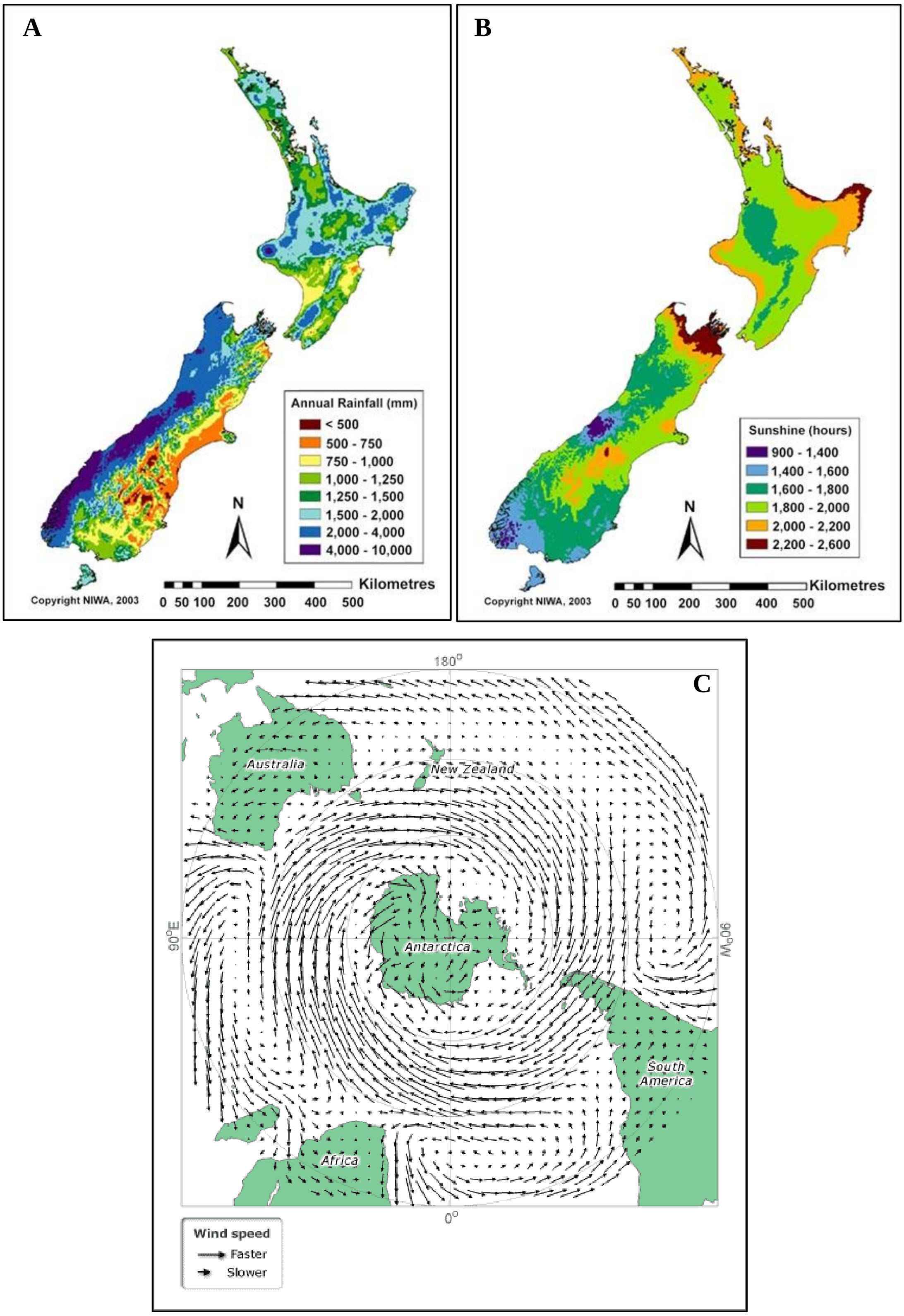
The seismogenic risk in Wellington is very high and well documented, however to date very little in the way of collating and modelling the vast amount of subsurface data (mainly from structural geotechnical investigations held by consulting engineers) from sites within the central city has been done. By modelling the subsurface data and producing outputs that are directly relevant to engineering professionals through their alignment with the structural design actions of NZS 1170.5:2004, accessible knowledge of the site conditions in Wellington will be greatly increased.

1.3.3 PHYSIOGRAPHY

1.3.3.1 CLIMATE

New Zealand's climate is complex and ranges from warm subtropical in the north to cool temperate in the south, with mountainous areas experiencing severe alpine conditions. Mean annual temperatures in New Zealand range from 10 °C in the south to 16 °C in the north, with July generally experiencing the coldest temperatures and January or February the warmest. New Zealand lies in the path of the prevailing westerly winds (Figure 1.2). These winds are deflected by the central ranges running the length of the country and funnelled through Cook Strait, increasing in speed and strength as a result (Mackintosh 2001).

Figure 1.2: New Zealand annual rainfall (A), sunshine hours (B) and prevailing winds over southern hemisphere (C), NIWA 2009.



Wellington's close proximity to Cook Strait and the surrounding rugged terrain lead to frequent gusty winds, with the region one of windiest the country. Channelling of airflow by the hills and surrounding ranges around Wellington generally results in either northerly (summer) or southerly (winter) wind directions with the strongest gusts felt in spring although seasonal variation is not large. Wellington City has a temperate climate, with moderate rainfall and generally mild daytime temperatures but is at risk of severe winds during extreme weather events. Cold gusty southerly winds blast the region during winter months and sometimes leave snow on the higher ranges. In the past, Wellington region experienced a cooler, more severe climate and glacial evidence can still be seen in the Tararua Ranges today (Mildenhall 1993).

Average annual rainfall for the Wellington region (Figure 1.2) is in the range of 1200 to 2400 mm, with an average of 1249 mm slightly less than the national average of 1400 mm recorded in the central city (Kelburn). At the Kelburn meteorological station, average rainfall (Figure 1.3) in February is 62 mm (minimum) while in June it is 147 mm (maximum). Rainfall records extend as far back as the late nineteenth century for Wellington and rainfall distribution throughout the year shows strong variations with lower totals recorded in the summer and higher totals recorded in the winter (NIWA 2009).

Annual sunshine hours for the Wellington region vary from about 1600 to 1700 hours per year in the Tararua Ranges to 2065 hours per year in Wellington City (Figure 1.2). The midday summer solar radiation index (UVI) is often very high throughout New Zealand especially in the northern part of the North Island with Wellington also experiencing high values.

Figure 1.3: Wellington City monthly climate data.

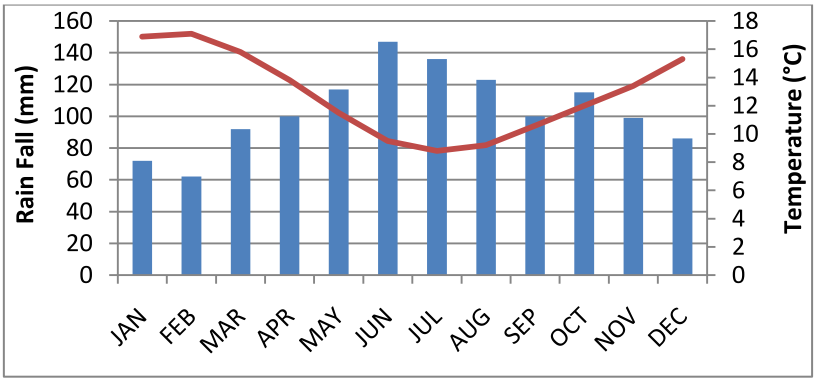


Table 1.1: Climate data for Wellington City, New Zealand (NIWA 2009).

Month	Average Maximum Temperature (^{O}C)	Average Minimum Temperature (^{O}C)	Average Sunshine hours (per day)	Number of Days with at least 0.25 mm Rainfall	Mean Monthly Rainfall
January	20	13	7.9	10	16.9
February	21	14	7.3	9	17.1
March	19	13	6.2	11	15.8
April	17	11	5.2	13	13.8
May	14	9	4.1	16	11.5
June	12	7	3.3	17	9.5
July	11	6	3.8	18	8.8
August	12	7	4.4	17	9.2
September	14	8	5.2	15	10.6
October	15	9	6.2	14	12.0
November	17	10	7.0	13	13.4
December	19	12	7.3	12	15.3
Annual	31.1 (highest)	-1.9 (lowest)	2065 (total hours)	123 (> 1.0 mm)	1249 (mm/yr)

1.3.3.2 ISOLATED PHENOMENA WITHIN THE WELLINGTON AREA

1.3.3.2.1 WILDFIRE

Wildfires are not uncommon in the Wellington region and can result in the burning of large areas of bush and scrubland. Extinguishing theses fires can prove costly from mounting labour and fire fighting equipment costs especially if aerial methods are used. In the Wellington region the greatest fire risk areas are characterised by the presence of gorse and scrub type vegetation, on steep slopes, with relatively low rainfall, strong winds, and close to areas occupied by people. Approximately 20% of land in the Wellington region is at high or extreme risk from wildfire. During January 2001, four significant wildfires in the Wellington region (one in Porirua, one in Plimmerton and two in Silverstream) proved difficult and expensive to battle, stretching local resources (Tait et al. 2002).

Fire risk in the Wellington region is likely to increase in the future as a result of increased fuel (pine plantations, taller trees etc) and development in higher risk areas. Wild fire mitigation measures include maintaining defensible space around buildings, removing flammable objects and designing structures incorporating fire resistant materials (Wellington Regional Council; Tait et al. 2002).

1.3.3.2.2 LIGHTNING STRIKE

Lightning is associated with severe convective storms and poses a health risk to nearby people and animals (electrocution, fire etc). Damage to infrastructure (especially power and communications) is generally localised and is often associated with other damaging storm phenomena such as severe wind, hail and rain. Mean annual lightning flashes in the Wellington region range from 0.18 to 0.6 (lightning flashes/km^2/year). Increased conductivity as a result global warming is likely to increase lightning risk and the severity of thunderstorms (Tait et al. 2002).

1.3.3.2.3 SEVERE WINDS

The average annual wind speed recorded at Wellington Airport is 22 km/h with 42 km/h recorded at the summit of Mount Kaukau (425 m). Mean wind speeds of more than 63 km/h are recorded on average 22 days a year (compared with the national average of 6.5 km/h). During the Wahine storm on 10 April 1968 (severe wind event; Cyclone Giselle) wind gusts of up to 187 km/h were recorded at Wellington Airport (Tait et al. 2002; NIWA 2009).

Lifelines and property can be damaged in severe wind events resulting in lost income and access to services. Wind damage can be mitigated through good structural design considering geographical location and wind microzoning which identifies natural and manmade wind channelling features. One of the advantages of Wellington’s frequent strong winds is their potential to be harnessed for sustainable energy, with a number of wind farms operating west and north of the city. Extreme wind changes associated with natural or human induced climatic variations may become more important for future generations.

1.3.3.3 TOPOGRAPHY

The city of Wellington has a topographically controlled high population density and lies within a geologically active landscape at the southern end of the North Island, New Zealand. The heavily populated central city has been significantly altered by man with buildings or reserves occupying every available space. Early on the need for additional flat building space was recognised and reclamation added more than 155 hectares around the waterfront during the late 19th and early 20th centuries with further works filling in former stream channels and swamp areas.

The topography of Wellington City (Figure 1.4) is dominated by Port Nicholson harbour to the east formed by a fault angle depression, the rugged hills surrounding the city, and the Wellington Fault crossing the north-western central suburbs of Northland and Thorndon. Hills and valleys occupying the area west of the city trend in a northeast-southwest direction and are controlled by the region's major active faults (Ohariu and Shepherds Gully). North-south trending linear ridges and valleys are present, often controlled by secondary faulting. Tinakori Hill is the highest peak within the study area at 303 m with Mt Cook, Brooklyn Hill and the western slopes of Mt Victoria and Mt Albert rising around the central city. Many of Wellington's roads are steep, winding and narrow. These roads, cut into weathered greywacke slopes, are vulnerable to landslides (Begg & Mazengarb 1996).

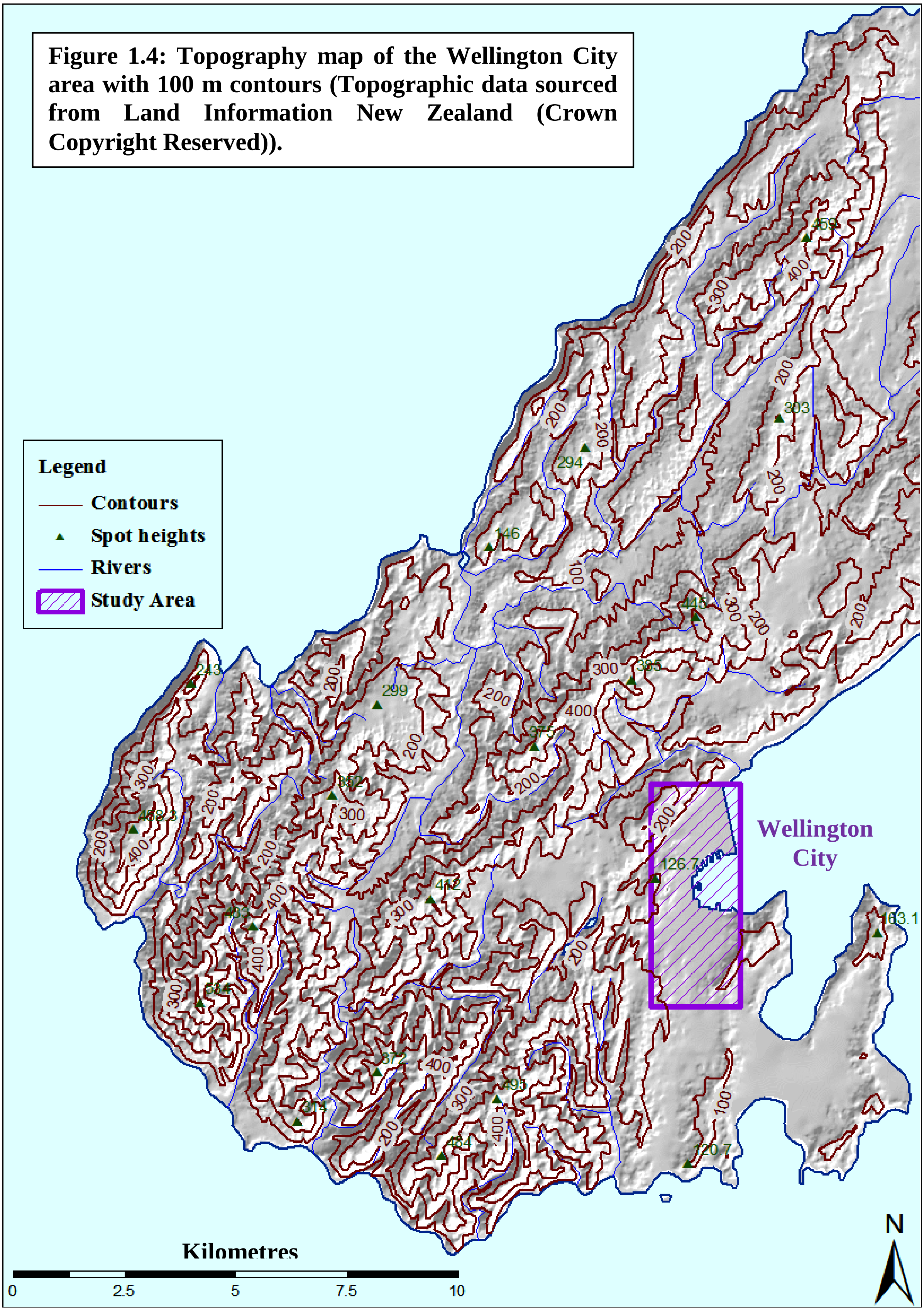


Figure 1.4: Topography map of the Wellington City area with 100 m contours (Topographic data sourced from Land Information New Zealand (Crown Copyright Reserved)).

1.3.3.4 GEOLOGY

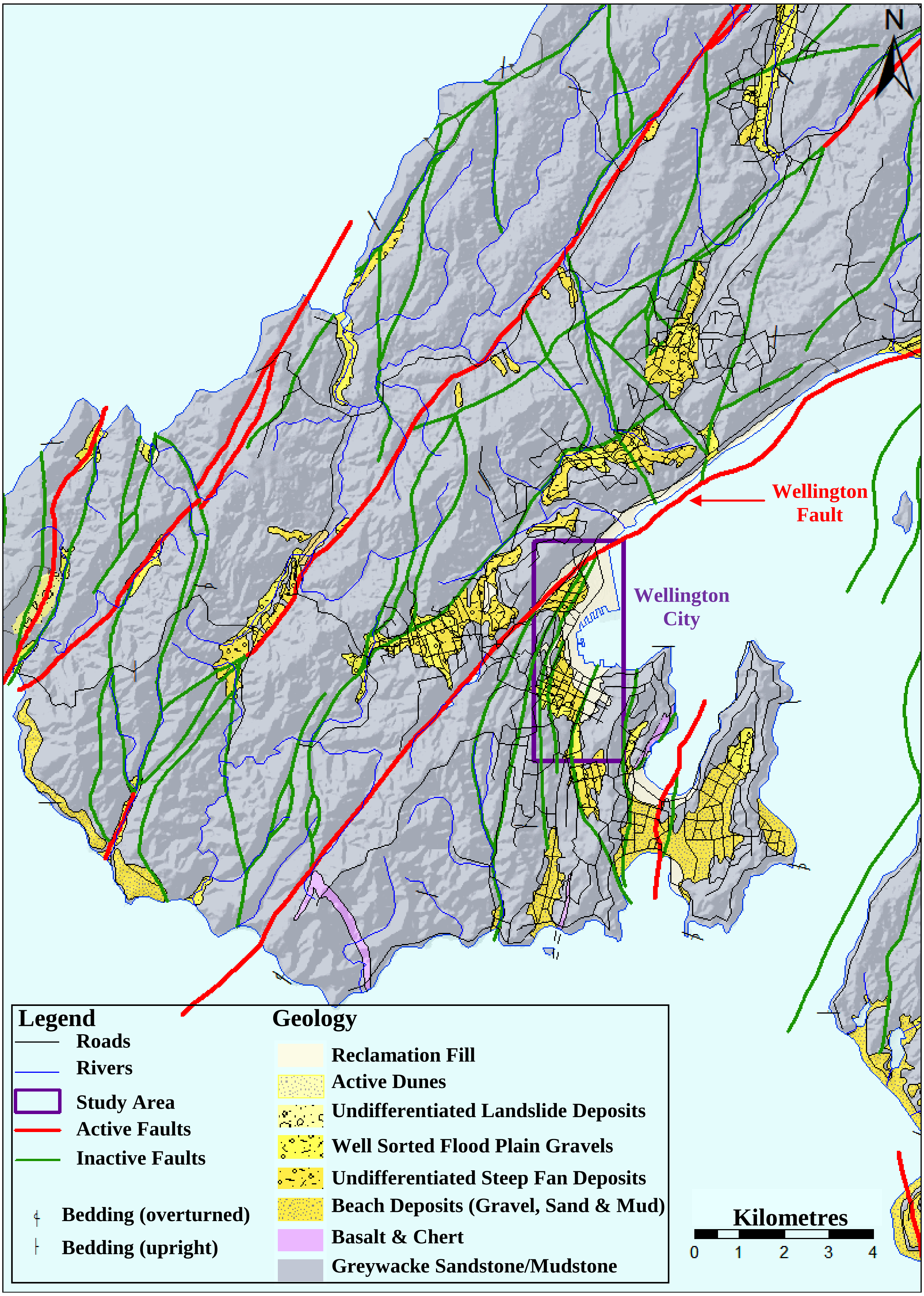
This section contains a brief description of the rock and sediment types found within the central Wellington commercial area (refer to Chapter Two for more detailed information including stratigraphy, tectonics and geomorphology).

Late Triassic to early Jurassic grey brown quartzo-feldspathic sandstone mudstone sequences of the Rakaia Terrane form the basement rock within the study area. These sequences are referred to as greywacke throughout the text, which refers to both the sandstone and mudstone component unless stated otherwise (Begg & Mazengarb 1996; Begg & Johnston 2000).

Pleistocene deposits lie unconformably on top of greywacke bedrock with the deepest recorded sequence of 137 m at Te Papa Tongarewa (Museum of New Zealand). The underlying Pleistocene deposits generally provide suitable founding conditions for piles and consist of weathered alluvium, colluvium and shallow marine deposits. These deposits typically consist of dense silty sandy gravels with interbedded stiff silts and organic clays

Holocene sediments overlie Pleistocene deposits and generally consist of weathered alluvium and colluvium with minor beach, estuarine and swamp deposits. Reclamation landfill is common around the waterfront with two main types, hydraulic (pumped sand and mud from the seabed) and locally sourced end tipped fill (boulders, domestic building and construction waste, spoil etc) used.

Figure 1.5: Simplified geological map of the Wellington City area (Begg & Johnston 2000).

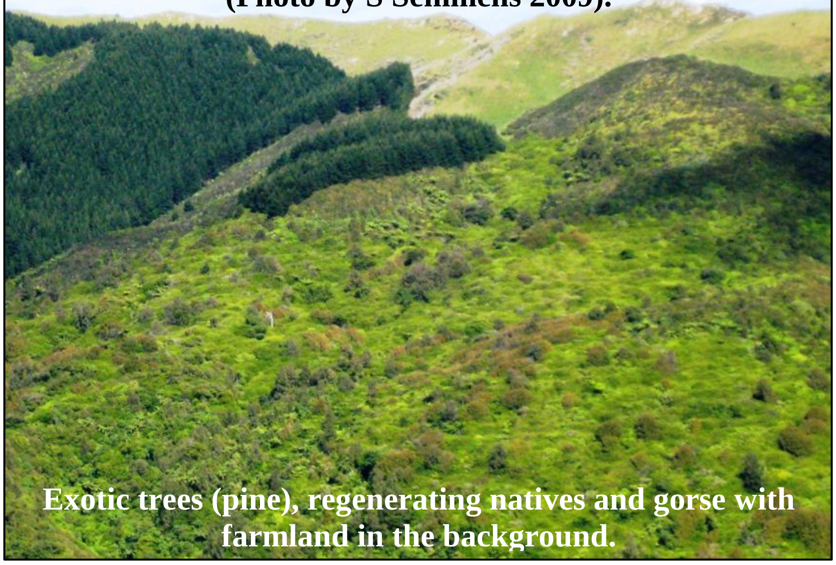


1.3.3.5 VEGETATION

Prior to European settlement, vegetation in the Wellington region consisted of conifer–broadleaf forest including Rimu, Matai, Northern Rata, Titoki, Hinau, Rewarewa, Tawa, Totara and Karaka occupying the fertile and sheltered hillsides with pockets of Kahikatea, Pukatea and Cabbage tree occupying swamps and poorly drained valleys. Maori had cleared vegetation around the harbour and Mt Victoria with the rest of the region remaining relatively untouched. European settlers cleared large tracts of forest and apart from isolated pockets, little lowland native forest remains today (Gabites 1993).

The hills surrounding Wellington were used for farming for most of the 19th century. Reforestation projects, including the planting of exotic species such as Pine and Macrocarpa on the slopes of Mount Victoria and Tinakori Hill, began in the 1930. During the 20th century, large areas of former pastureland reverted back to scrubland. Introduced species such as Gorse and Broom, along with native Manuka and flax, now dominate the landscape. The presence of Gorse and Broom may not be as problematic as first thought because of their ability to provide a nursery environment for regenerating natives provided there are no wild fires. Noxious weed species such as Old Man's Beard, Wandering Jew and Darwin's Barberry are more problematic as they quickly become established and smother large areas of bush. Today vegetation within the study area is limited to that of parks, reserves and private gardens (Gabites 1993).

Figure 1.6: Typical vegetation in the Wellington area (Photo by S Semmens 2009).



1.3.3.6 LAND USE

Wellington City is the southernmost capital city in the world and the third most populous urban area in New Zealand, housing Parliament and many of the government departments and foreign diplomatic missions. More than 60,000 people (Statistics New Zealand) work in the city's central business district (CBD), a higher proportion of the urban population than in Auckland.

Land use within the study area is entirely urban with the exception of scattered reserves, playing fields and parks. These are generally located on school property or on the steeper slopes such as Tinakori Hill and the western slopes of Mount Victoria. The central city is physically contained between the harbour and surrounding hills, resulting in an intensely populated urban centre with numerous multiple dwelling units (apartment blocks, flats, etc.). Redevelopment and intensification is an ongoing process in the city and has taken place on most of the reclaimed land around the Wellington's waterfront.

High-rise buildings in Wellington are generally centred on Lambton Quay, the Terrace, Willis Street and the immediately adjacent city blocks. Medium-rise buildings (< 30 m) are found throughout the central city (e.g. along Waterloo Quay), while low rise structures tend to dominate the rest of the study area. The tallest building in Wellington City is the Majestic Centre (Willis Street) at 116 metres high (Table 1.2). Reinforced concrete and steel structures dominate the CBD while timber framing remains the primary structural component of most residential dwellings. The Colonial Cottage Museum is the oldest building in Wellington. The cottage was built in 1858 and is located on Nairn Street within the suburb of Mount Cook (southern end of study area).

Table 1.2: Tallest buildings in Wellington City (Skyscraper Source Media 2009).

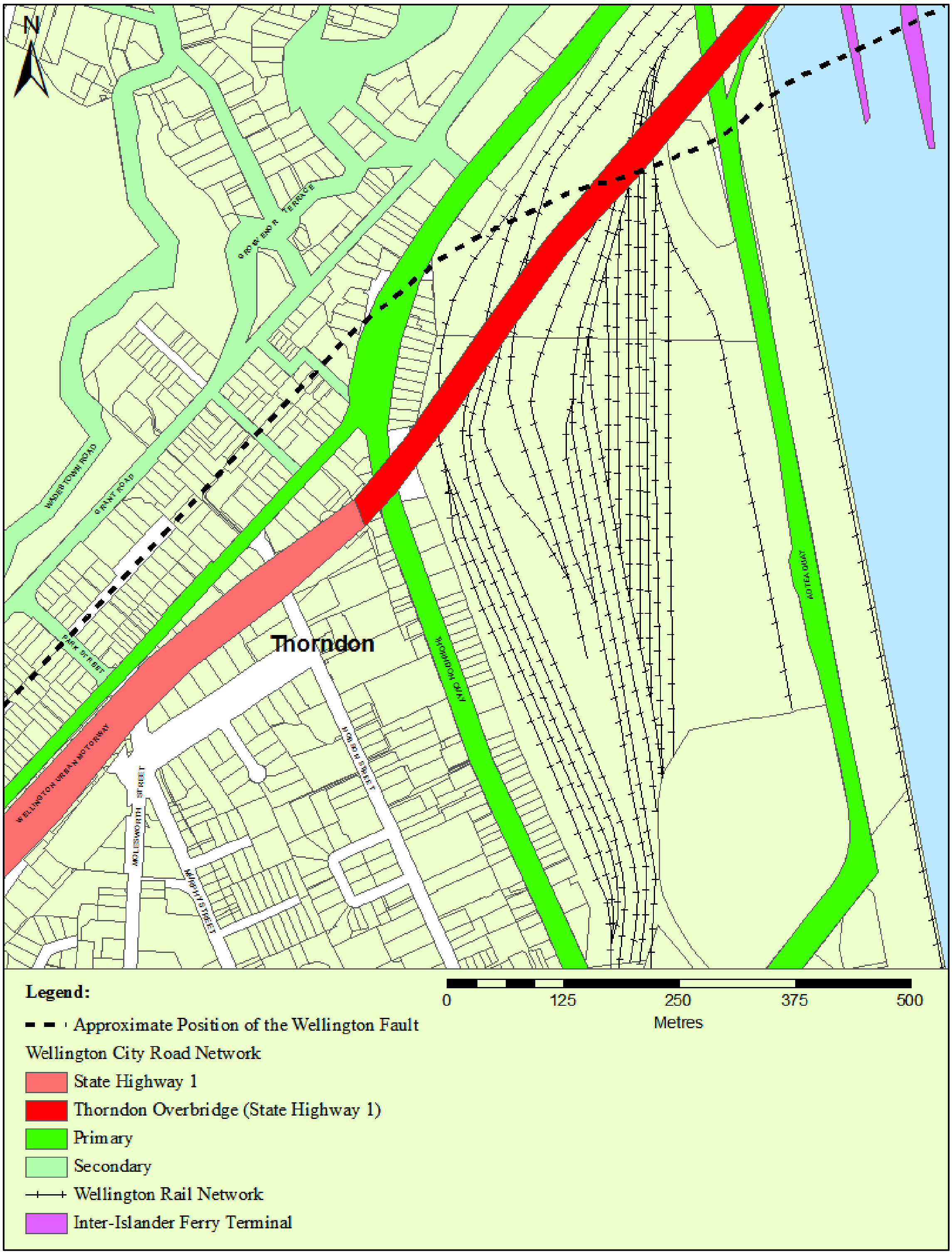
Name	Height (m)	Number of Stories	Construction Date
Majestic Centre	116	29	1991
State Insurance Tower	103	27	1983
HSBC Tower	94	25	2003
Bowen House	90	22	1991
Vodafone on The Park	90	25	1998

Wellington is also renowned for its numerous iconic sculptures and artwork, with the Museum of New Zealand Te Papa Tongarewa located on the waterfront. Victoria University of Wellington and the Wellington Botanic Gardens are located to the west of the CBD in Kelburn. Te Aro and the southern CBD make up one of the largest entertainment districts in New Zealand, with thousands of revellers every week. There are well in excess of 30 large accommodation providers within the study area.

The city is served by a complex network of utilities. Transportation networks including road, rail and Inter-Islander Ferry, feed into the city from the north (refer to Figure 1.8). State Highway 1 runs through the study area from the Thorndon overbridge in the north through the Terrace Tunnel, Te Aro Valley and the Mount Victoria Tunnel to the airport. Electrified rail lines connect Wellington Railway Station to the northern suburbs and beyond. Metlink operate nine trolleybus routes within Wellington, while the remaining areas are serviced by diesel buses.

Figure 1.7: View looking south-east of the Wellington commercial area from Tinakori Hill (Photo S Semmens 2009).

Figure 1.8: Wellington City transportation networks in the vicinity of the Thorndon overbridge.



1.4 PREVIOUS WORK

The Wellington region has been the subject of countless geological investigations since the time of early European settlement in the nineteenth century. Extensive literature related to both the central city and the surrounding region can be accessed through GNS Science's New Zealand Geoscience Bibliography database. The Geological Society of New Zealand's Bibliography of New Zealand Earth Science Theses (Leaming 2009) also provides information on all postgraduate research within New Zealand (up to December 2007).

Research relating to the geology, geomorphology and active tectonics of both the Wellington region and that of New Zealand forms the basis for Chapter Two. Current significant research directly related to this project is also mentioned. Previous work relating to site effects within the study area can be found in Chapter Three. In addition to this a case study of the 1985 Michoacan (Mexico City) Earthquake with relevance to site effects and the Wellington City study area can be found in Appendix 3B. A comparison involving previous site effects and hazard zonation research within the Wellington City area together with the results from this study can be found in Chapter Six.

1.5 RESEARCH METHODS

The research objectives list the production of an accessible database, geological model and accompanying maps as key outputs from this study. These outputs were created through a sequential process where one completed output generally forms the basis of the next. For example information from the database was used to construct the model, which in turn fed into the depth to bedrock, site period and ultimately site class maps.

Initially a feasible study area was finalised after consultation with staff at Tonkin & Taylor, Wellington City Council and GNS Science. These meetings were necessary to determine the type and volume of data held by these organisations. Other important issues including access, commercial sensitivity and the time period for data retrieval were also discussed. The data compiled from these organisations forms the foundation of this research project. It was important to set a suitable study area that could be thoroughly investigated within the required time frame.

From September 2008 to March 2009 files at GNS Science and then Tonkin & Taylor Wellington office were thoroughly searched, and flagged if they were likely to contain relative information within the study area. Once all the appropriate files were identified, all useful subsurface information (generally in the form of borelogs) was extracted and manually entered into an Excel database. In the case of Tonkin & Taylor Wellington, all appropriate files held off site (generally jobs from 1996 or older) were identified and retrieved from Crown archives when required. A significant portion of the data held by both GNS Science and Tonkin & Taylor was found to be common and duplicates were subsequently eliminated. Upon the completion of data gathering from these two organisations Wellington City Council (Building Consents and Licensing Services) was informed and asked to provide any additional subsurface information from their files. At the end of April 2009 Clair Stevens (Wellington City Council) confirmed that they held no additional information. During this time period, in addition to the data gathering and entry process, ESRI's ArcView 9.2 software was learned. This was done by completing a series of both online campus courses and book tutorials. In addition, Mark Rattenbury (GIS Specialist, GNS Science) provided assistance with map construction. A comprehensive literature review was also started at this time focusing on site effects and classification along with previous related work within the Wellington City area.

New Zealand and Wellington City Council Archives and the Alexander Turnbull Library (National Library of New Zealand) were extensively searched intermittently during October and November 2008 for original maps, drawings and photographs of the Wellington city area. These were used to help locate reclamations, streams and former swamp positions within the study area.

During the first week of December 2008, three boreholes were logged within the study area after access was arranged by Tonkin & Taylor Wellington (refer to Chapter Four, Section 4.6.2.1 for more detailed information). This task provided additional borehole information within the study area and further enhanced the author's personal knowledge of the deposits through the logging of recovered material from the boreholes (all of which penetrated weathered bedrock). A walk over of the study area was also conducted at this time and any notable geological feature or rock outcrop (very limited exposure in the heavily modified landscape of Wellington City) was later mapped with the aid of aerial photographs.

During the fourth week of January 2009 seismic cone penetration testing (SCPT) was observed at one site near the waterfront within the study area. The SCPT test was conducted to a depth of twenty metres. This involved pushing a sensor which measures seismic wave speeds directly into the ground, whilst generating shear waves from a nearby source (hammer beam). The real information obtained from this testing helped to better characterise the subsurface conditions at this location. In addition the effectiveness of the test in typical Wellington City deposits could be gauged.

In February 2009 SPAC (SPatial Auto Correlation) microtremor testing was carried out at twelve sites within the study area. Initially a desk study and a meeting with the appropriate staff at GNS Science were arranged to determine the best areas to target within the study area. SPAC works best where there is a relatively thin, shallow dipping, flexible layer of soil over a stiff substrate. Sites were chosen keeping this in mind as well as consideration of access, existing data and the proximity to the estimated site class C/D boundaries. After a number of target areas were agreed on in the office and possible arrays for these areas were determined, the sites were then visited to confirm their suitability for testing. Testing took place in the early morning, evening or on weekends to avoid traffic, pedestrians and noise from nearby construction. SPAC microtremor results were confirmed during the second week of October 2009 and generally provide an indication of site period and an estimate of rock depth.

From May to November 2009, Earth Research was used to produce a simplified 3D geological model of the study area. Earth Research allows the construction of 3D geological volumes from scattered borehole data using 3D interpolation technology and was chosen for its user friendly interface. Information from the compiled database was used to construct the model which is one of the major outputs to this study. Upon the completion of modelling reclamation, surficial deposits, depth to bedrock, site period, Vs30 and site class maps were then constructed from the available information (database, 3D geological model, field notes, SPAC testing, etc) using ESRI’s ArcMap software, thereby completing the other study outputs.

1.6 THESIS FORMAT

The thesis is divided into seven chapters. Chapter One provides an introduction. Chapter Two summarises the geology and geomorphology of the area in both a regional and local context. Lithological differences between formations are noted and active tectonics are described in detail. Chapter Three discusses site effects and how they are implemented in the building code. Other earthquake shaking effects are introduced and previous work within the study area is introduced. A case study of the 1985 Michoacán earthquake (Mexico) is used to illustrate site effects (refer to Appendix 3B). Chapter Four focuses on the collated data and discusses database objectives, construction and limitations. Data sources are listed and summary of fields discussed with the database itself included in Appendix 4A (on DVD). Chapter Five discusses the study outputs and their derivation. Chapter Six discusses project applications such as site class determination and foundation assessment. Chapter Seven summarises all data and interpretations discussed within the preceding chapters, and makes recommendations for future investigations.

CHAPTER TWO

GEOLOGY & GEOMORPHOLOGY

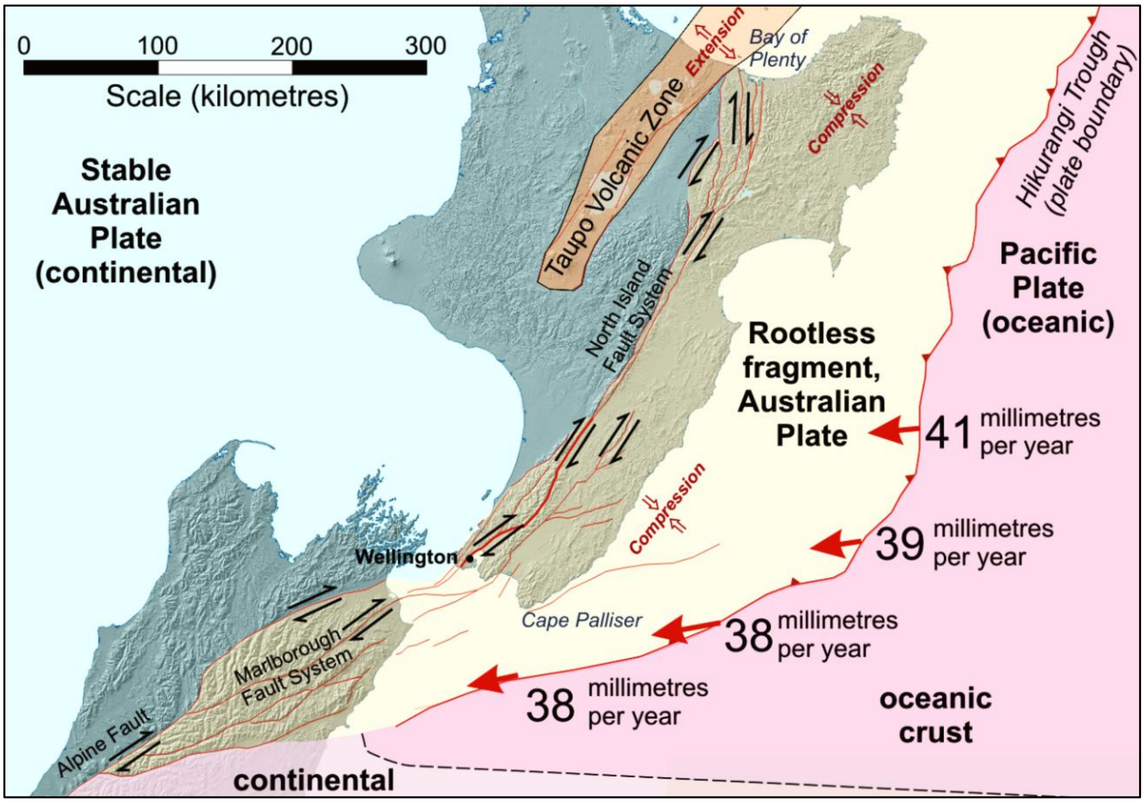
2.1 INTRODUCTION

The geology of the study area within Wellington City is primarily based on mapping from various sources, mainly the "Geology of the Wellington area" (Begg & Mazengarb 1996; Begg & Johnston 2000), with limited field mapping and site observation. Details of the geological units at depth are based on information collated from drill holes and test pits logged during various geological and geotechnical investigations. Personal observations in the field and discussions with GNS Science staff were also used. The stratigraphy of the study area within the Wellington region is summarised, with emphasis on the Recent and Quaternary deposits which are vital to understanding site effects. Where possible photographs have been used to illustrate typical Wellington City deposits (note there is very little bedrock or sediment exposure in the urbanised central city). Geomorphology and active tectonics focusing on the regions active faults are also discussed in detail to provide evidence for the high earthquake risk in Wellington.

2.2 NEW ZEALAND TECTONIC SETTING

New Zealand is a tectonically active landmass that sits astride the active boundary zone between the Australian and Pacific tectonic plates (refer to Figure 2.1). The Australian-Pacific plate boundary trends in a northeast-southwest direction along the length of the country, with plate motion characterised by oblique convergence (Beavan et al. 2002). Relative plate motions in New Zealand are approximately 41 mm/year in the north, 40 mm/year in the Wellington region and 35 mm/year in the South Island. The rate of plate motion decreases southward, whilst the obliquity of convergence progressively increases (Begg et al. 2008).

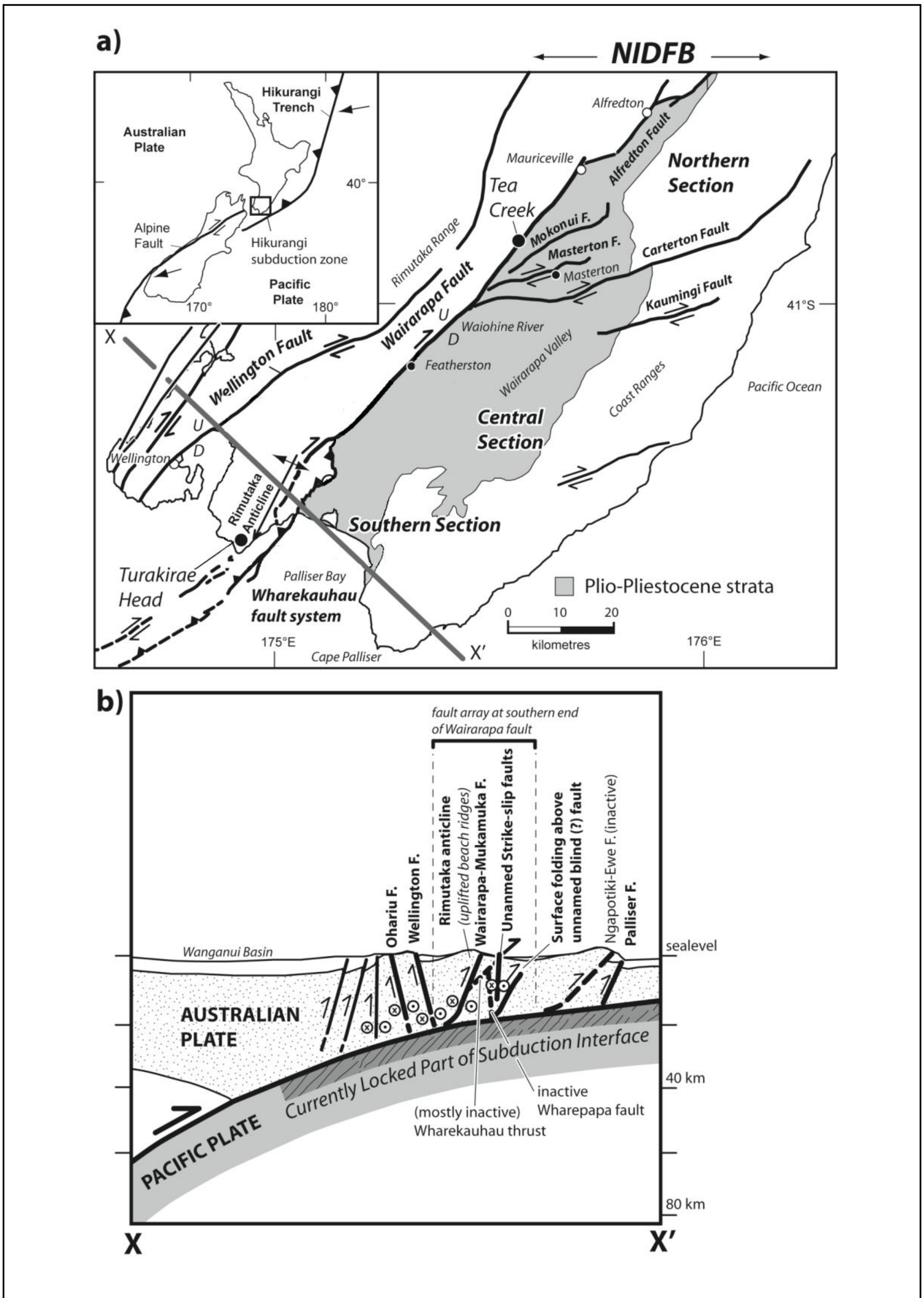
Figure 2.1: The tectonic setting in central New Zealand (Begg et al. 2008).



In the North Island of New Zealand plate motion is accommodated by the offshore subduction of the oceanic Pacific Plate beneath the Australian Plate in the Hikurangi subduction zone. Onshore movement is accommodated along large strike-slip faults. Faults in the southern part of the North Island occur in a transition zone between the two plate boundaries as a series of north-east oriented strike-slip faults known as the North Island Dextral Fault Belt (NIDFB). Faults located within the NIDFB (refer to Figure 2.2) show evidence of repeated movement during the Quaternary (Beanland 1995). A number of the faults within the NIDFB including the Wellington and Wairarapa faults are thought to propagate from the surface to the gently north-west dipping subduction interface at a depth of 20-30 km beneath the southernmost part of the North Island (Beanland 1995; Van Dissen & Berryman 1996; Reyners 1998; Little et al. 2009). The interaction between the subduction interface and the NIDFB is poorly understood. In the southern North Island, GPS geodetic data modelling indicates that the subduction interface is currently locked and is accumulating elastic strain to be released in future large earthquakes (Walcott 1998; Wallace et al. 2004). The largest historic earthquakes in New Zealand have occurred within the 100 km wide Axial

Tectonic Belt that extends from the eastern North Island to the central and southern South Island (Walcott et al. 1981).

Figure 2.2: a) Active faults of the NIDFB, b) cross section through the southern North Island (X-X') (from Little et al. 2008 and references therein).



Both the Australian and Pacific plate margins consist of continental crust in the central South Island of New Zealand. The oblique continental plate motion parallel to the plate boundary occurs along the dextral strike-slip Alpine Fault. Uplift of the Southern Alps (up to 11 mm/yr) is a result of crustal thickening accommodating motion perpendicular to the plate boundary (Walcott 1998). In the southern South Island, beneath Fiordland, oceanic crust of the Australian Plate is subducted beneath the Pacific Plate in the Puysegur Subduction Zone.

2.3 STRATIGRAPHY

A generalised surficial deposit map for the Wellington City study area is contained in Appendix A8 (in the back pocket). A generalised stratigraphic column has been compiled from various sources which relate directly to the Wellington City area (Figure 2.3). A description of each formation is contained in the following text. There are two main stratigraphic units within the Wellington area:

- Late Triassic to early Jurassic sedimentary rocks.
- Quaternary sediments.

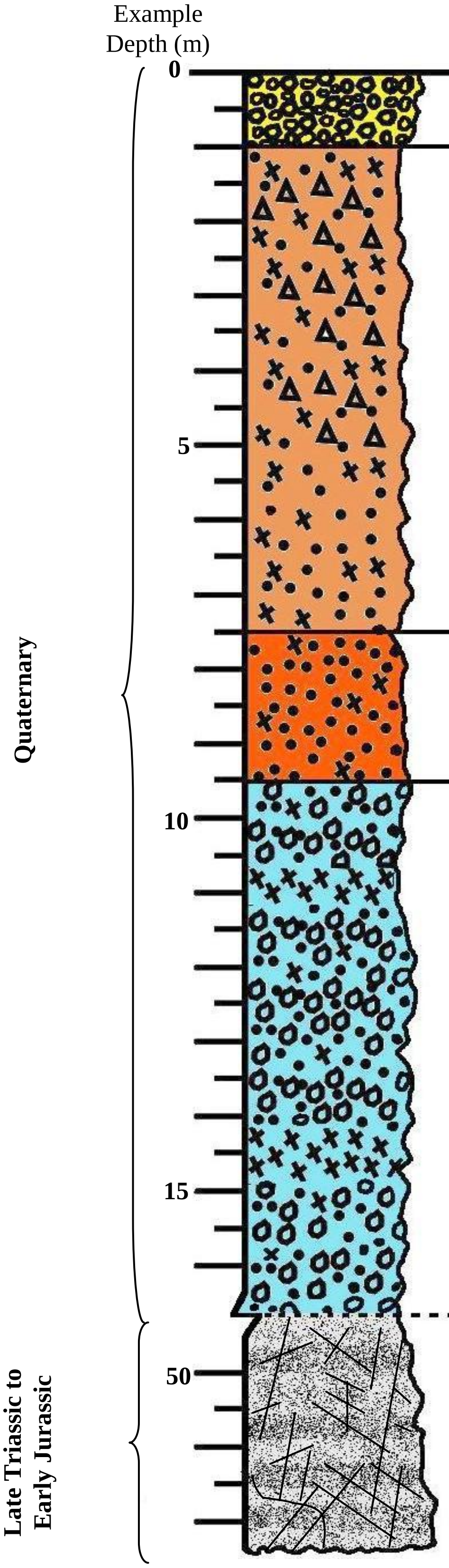
2.3.1 TORLESSE - BASEMENT ROCK

Late Triassic to early Jurassic (refer to Appendix 1A: New Zealand Geological Timescale) sedimentary rocks (greywacke) of the Torlesse composite terrane form the basement rock within the Wellington region. Torlesse rocks are the most widespread in New Zealand forming the North Island’s axial ranges and the Southern Alps. The Rakaia sub-terrane (defined by age, composition and structure) occurs in the western Wellington area and outcrops in the hills surrounding and within the Wellington City study area (refer to Figure 2.4). In the Wellington area rocks of the Rakaia sub-terrane consist of “quartzo-feldspathic sandstone mudstone sequences” (Begg & Johnston 2000), with minor basalt, chert, conglomerate and very rare limestone. Proportions of the alternating sandstone mudstone beds vary throughout the area. Rocks range from thinly bedded sandstone and mudstone sequences with similar proportions to massive sandstone deposits (several metres thick) with little or no interbedded mudstone. Greywacke rocks were deposited by a series of submarine turbidity currents washing layers of sandy and silty sediment down slope into deeper water, gradually building up alternating sandstone mudstone beds (Begg & Mazengarb 1996; Begg & Johnston 2000).

The greywacke rocks of the Wellington region were eroded to a horizontal surface of low relief (Kaukau Surface), possibly by coastal or shallow marine process during the period from the end of the Miocene to c. 1 Ma. Sedimentary features including graded bedding, laminations and flute casts are present, however the occurrence of fossils is rare. Tracks, burrows and tube fossils are the most widespread, with isolated recovered Radiolaria indicating late Triassic depositional ages (Begg & Johnston 2000). Weathering (refer to Appendix 2A, NZ Geotechnical Society Field Guide Sheet) of greywacke rocks is highly variable and ranges from completely weathered, generally yellow-brown sandy silts and gravels to grey/dark grey unweathered well indurated rock at depth. These greywacke rocks have a complex structure as the result of multiple folding and faulting events, ranging from unfoliated to weakly foliated (Begg & Johnston 2000). Jointing in Wellington greywacke is generally very intense, with weaker sandstone beds broken by large numbers of joint sets perpendicular to bedding. Argillite beds are often intensely shattered. Veining is better developed in the sandstone beds although it does occur within the argillites. Vein minerals are predominantly quartz, calcite and zeolite (Begg & Mazengarb 1996; Begg & Johnston 2000).

Sand grains within the greywacke rock mainly consist of angular quartz and feldspar with some lithic metamorphic and dark igneous fragments. The binding matrix consists of clay or the equivalent altered metamorphic minerals formed from the response to differing heat and pressure regimes (Begg & Johnston 2000).

Figure 2.3: Generalised stratigraphic column for the study area within Wellington City, based on information compiled from various sources (Begg & Mazengarb 1996; Murashev & Palmer 1998; Begg & Johnston 2000). The thicknesses are examples only and not all formations are present in all areas.



Description:

Compacted Gravel Fill (basecoarse)

Reclamation Fill:

End dumped Fill: locally quarried weathered greywacke sandstone, mudstone and spoil, domestic waste (bricks, glass, wood etc), sand, boulders and engineered fill loose to medium dense.

And / Or

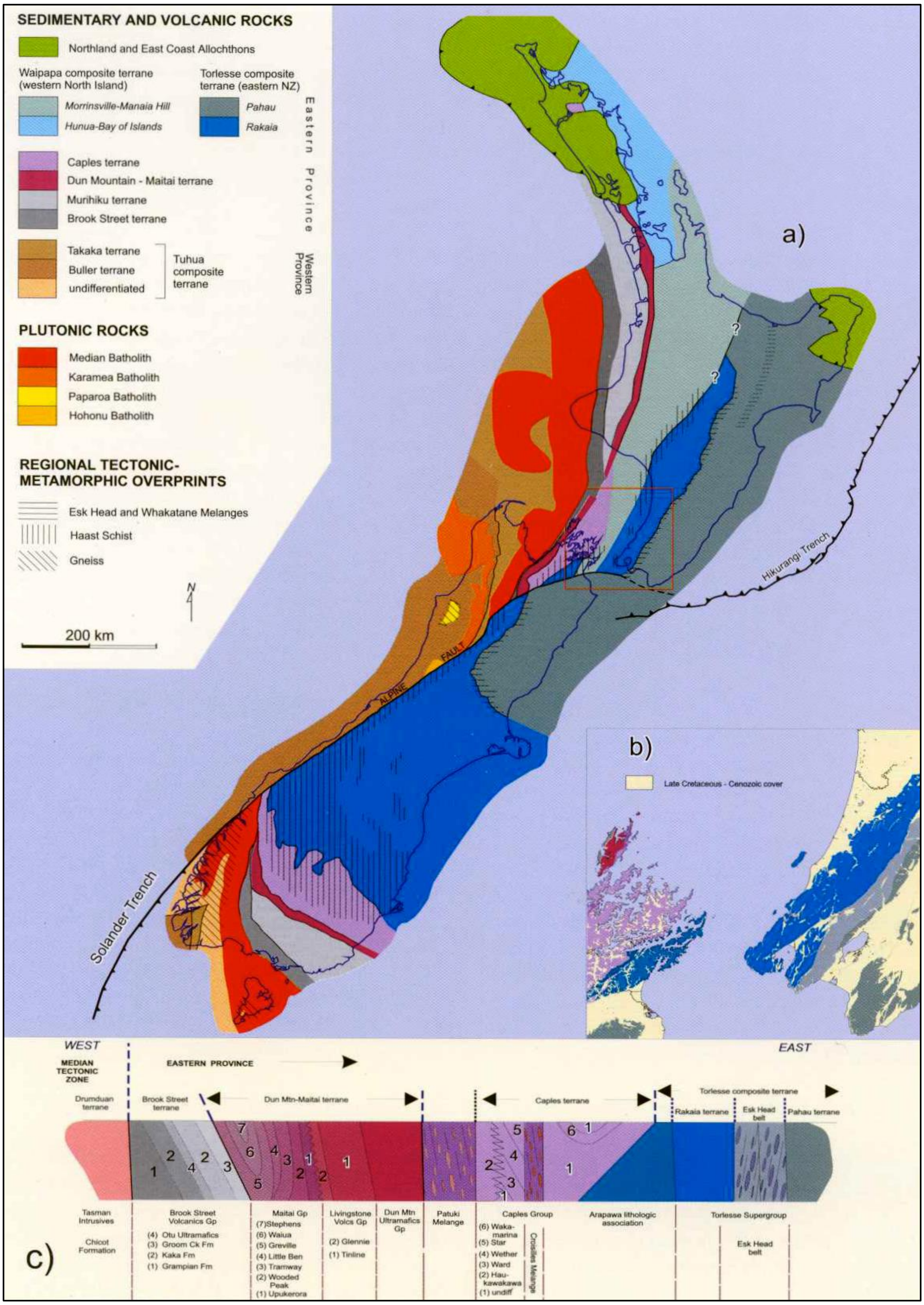
Hydraulic Fill: Dredged sand mud and silt from the seabed, soft/very loose to loose.

Holocene Marginal Marine Deposits: Sand (dominant), silt and gravels with shells. Loose/soft to medium dense.

Pleistocene Alluvium/Colluvium: Alluvial and colluvial deposits consisting of sands, silts, weathered gravels and clays. Poorly sorted to well sorted, medium dense to dense/stiff (silts).

Greywacke Bedrock: Rakaia Sub-terrane; grey/brown (becoming yellow brown with increased weathering) quartzo-feldspathic sandstone mudstone sequences, dominated by quartz, albite, muscovite, chlorite. Sandstone poorly bedded, fine to medium grained (rare), lithic grains have some roundness, intense jointing.

Figure 2.4: a) Basement geological map of New Zealand, b) tectonostratigraphic terranes of the Wellington area, c) cross section cartoon of Marlborough/Wellington basement rocks (from Begg & Johnston 2000 and references therein).



Aggregate is vital for construction and is the most valuable natural geological resource in the Wellington region (Begg & Johnston 2000). It is mined at hard rock quarries throughout the area, with lesser amounts of river alluvium used. Wellington greywacke sandstone is desirable for use as a general purpose aggregate as it is strong and durable. Large greywacke sandstone boulders have also been used as riprap, however extensive jointing within the Torlesse rocks means high quality rip is scarce. Wellington argillite ranges in colour from dark grey-brown to black and consists of hardened layers of silt and clay. Argillites are generally softer and weaker than neighbouring sandstone beds and are not desirable for use as aggregate due to their slaking properties (Rowe 1980).

Greywacke bedrock outcrops in the hills surrounding Wellington City. The deepest recorded depth to basement occurs at Te Papa Tongarewa, observed during foundation investigations in the early 1990's (refer to Appendix 4A & 4B on CD). Bedrock was interpreted to occur at 137 m below ground surface (~3 m above MSL). Whilst this is the deepest recorded sequence within the study area, far greater depths are proposed from modelling, in the Thorndon area north of Wellington's CBD (refer to Appendix 8D, depth to bedrock contour map).

2.3.2 EARLY PLIOCENE (OPOITIAN) DEPOSITS

Rocks older than the Quaternary sediments and younger than the Late Triassic to early Jurassic Torlesse terrane are found onshore only at Makara. This sequence to the north west of Wellington City consists of weakly indurated, shallow to deep water marine, sandstone, siltstone and mudstone deposits, which are preserved in a down-faulted block along the Ohariu Fault (Begg & Mazengarb 1996; Begg & Johnston 2000).

2.3.3 QUATERNARY SEDIMENTS

Quaternary deposits rest unconformably on top of Torlesse greywacke bedrock within the Wellington City area. No single borehole or surface section from Wellington City preserves a continuous sequence of sediments for the past 80 ka. Lithostratigraphic names used by Grant-Taylor et al. (1974) were not used in this study to describe and subdivide the Quaternary sediments around Wellington. These names (Kaitoke, Mowbray, Emerald, Guildford, Whiteman, Trentham, Hutt, Petone and Lambton formations) are defined from sedimentary sequences within Hutt Valley (with the exception of the Lambton formation) and as such cannot be correlated to Wellington

City (Perrin & Campbell 1992). Additionally Wellington City and Hutt Valley have experienced two very different depositional regimes. In Wellington City terrestrial periglacial deposition dominates whereas the Hutt Valley is dominantly a fluvial sedimentary system. Quaternary deposits have been divided into Pleistocene and Holocene sediments for discussion in this thesis. This was done as the two exhibit very different geotechnical properties, therefore they will respond differently in an earthquake event.

2.3.4 PLEISTOCENE SEDIMENTS

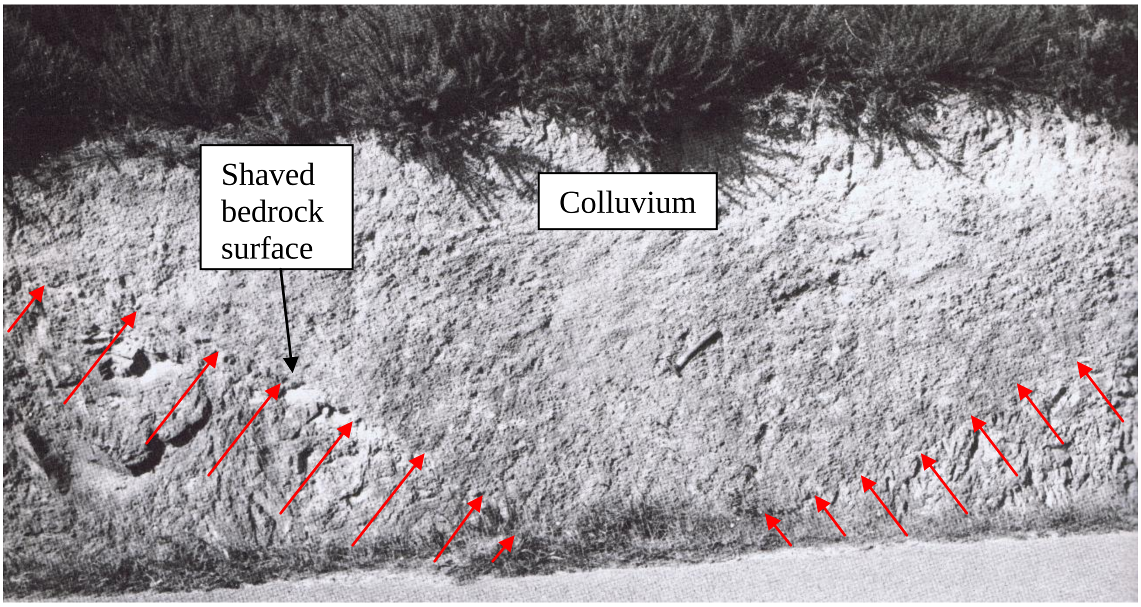
Throughout the Pleistocene, Wellington was subjected to several cycles of cold (glacial) and warm (interglacial) periods. Deposition of Waimaunga Glacial (300-240 ka) sediments containing cold climate pollen assemblages may have occurred in the Thorndon area as a result of active uplift along the Wellington Fault. By the Karoro Interglacial (240-180 ka) Port Nicholson became inundated during high sea level stands, forming an alluvial plane or lake during sea level retreat. Waimea Glacial (180-130 ka) sediments were deposited in the Thorndon and Te Aro areas. During the Kaihinu Interglacial (Last Interglacial, 125-80 ka) beach sediments were deposited in the Thorndon and Te Aro areas (Begg & Mazengarb 1996; Begg & Johnston 2000).

Last glacial and post glacial deposits including lacustrine and swamp deposits are preserved within the Wellington City study area. During the height of the Last Glacial, temperatures in the Wellington region averaged c. 5 °C lower than today. This cold, dry climate meant snow probably lay on the ground for extended periods resulting in the tree-line lowering to below present day sea level. Conditions were too cold for the development of podocarp forests and as a result their pollen assemblages are absent in glacial deposits. During the last Postglacial, temperatures rose 2 °C higher than today, with much higher rainfall. This climate was favourable for podocarp forest which quickly became established. As droughts and frosts became more frequent towards the present day, beech forest gradually returned and replaced the podocarp forest (Mildenhall 1993, 1994).

During the Pleistocene increased sediment load from frost shattered rock was mobilised by seasonal warming and lead to rapid deposition. Thin (< 1 m) layers of loess, organic soil and volcanic ash were deposited between these depositional cycles, indicating former ground surfaces. Within the study area Pleistocene sediments generally consist of weathered alluvium and colluvium along with minor shallow marine deposits. These sediments include medium dense to very dense silty sandy gravels with beds of stiff to hard silt and organic clays. There are no large river catchments in Wellington City and as a result gravel clasts tend to be smaller and more angular than those found in the Hutt Valley. Thorndon and Te Aro Pleistocene sediments are derived from a series of debris fans, flows and landslide deposits, partially transported by small streams at the time of deposition (Perrin & Campbell 1992).

Numerous fossil valleys occur within the Wellington City area (refer to Figure 2.5). The periglacial valleys were cut out from weakened bedrock during glacial periods. These valleys were subsequently in filled with angular gravels during periods of rapid deposition at times of rising sea level. Fossil valleys are often encountered during earthworks within the city and can add significant costs to a project if not planned for. Pleistocene gravels provide bearing stratum for piled foundations. Paleosol properties need to be considered in terms of settlement and bearing capacity (Murashev & Palmer 1998). In general the dense nature of the Pleistocene sediments will result in lower levels of amplification than that of the overlying younger less dense Holocene deposits. Pleistocene deposits will experience greater levels of shaking than the denser underlying greywacke bedrock (Grant-Taylor et al. 1974; Kingsbury & Hastie 1993).

Figure 2.5: A typical "fossil valley" in the Wellington area (Stevens 1975).



2.3.5 HOLOCENE SEDIMENTS

Holocene sediments include terrestrial, marine and post-glacial fan, stream, reclamation fill and soil deposits. Sea level rose rapidly toward the end of the last glaciation reaching its present day level around 6500 years ago (Begg & Johnston 2000). Post glacial sediments range from very soft to stiff for fine sediments to very loose to medium dense for coarse, non-cohesive sediments. These deposits are less dense than the underlying Pleistocene sediments indicated by a sharp contrast in standard penetration testing (5 < SPT N <60, but predominantly equal to 20). A number of dateable ash layers (tephra) overly many of the Holocene terraces in the region. Fresh glass shards from the rhyolitic Kawakawa Tephra have been observed in a number of boreholes within Wellington City. The Kawakawa Tephra has been assigned an age of 22.6 ka (Begg & Johnston 2000). Holocene sediments have variable susceptibility to earthquake initiated ground subsidence, lateral spreading and liquefaction. The less dense Holocene deposits will contribute higher levels of ground amplification than the underlying bedrock and Pleistocene deposits (Grant-Taylor et al. 1974; Kingsbury & Hastie 1993).

2.3.5.1 COLLUVIUM/ALLUVIUM

Thin isolated Holocene alluvial deposits are present within the city and occupy former stream channels. These deposits generally consist of silty sandy sub-rounded gravels. Alluvial fan and landslide deposits are also present within the area but are generally very small. These deposits generally consist of poorly sorted, silty clayey gravels. Holocene alluvial and colluvial gravels can be distinguished from older Pleistocene sediments by their smaller clast weathering rind and their less compact nature. These deposits generally have variable liquefaction and subsidence potential for both large distant, shallow earthquakes and Wellington Fault centred ruptures (Kingsbury & Hastie 1993).

2.3.5.2 BEACH & SHALLOW MARINE DEPOSITS

Holocene estuarine, beach and marginal marine deposits occur within Wellington City. These sediments consist of sands, sandy gravels and marine silts. Shell fragments help distinguish these deposits from alluvial sediments. The thickness of these sediments varies but is typically less than 5 m. The Holocene beach deposits are generally quite dense, but locally have been found to have a moderate to high liquefaction potential, with the potential for lateral spreading and subsidence during large damaging earthquakes (Kingsbury & Hastie 1993; Murashev & Palmer 1998).

2.3.5.3 SWAMP DEPOSITS

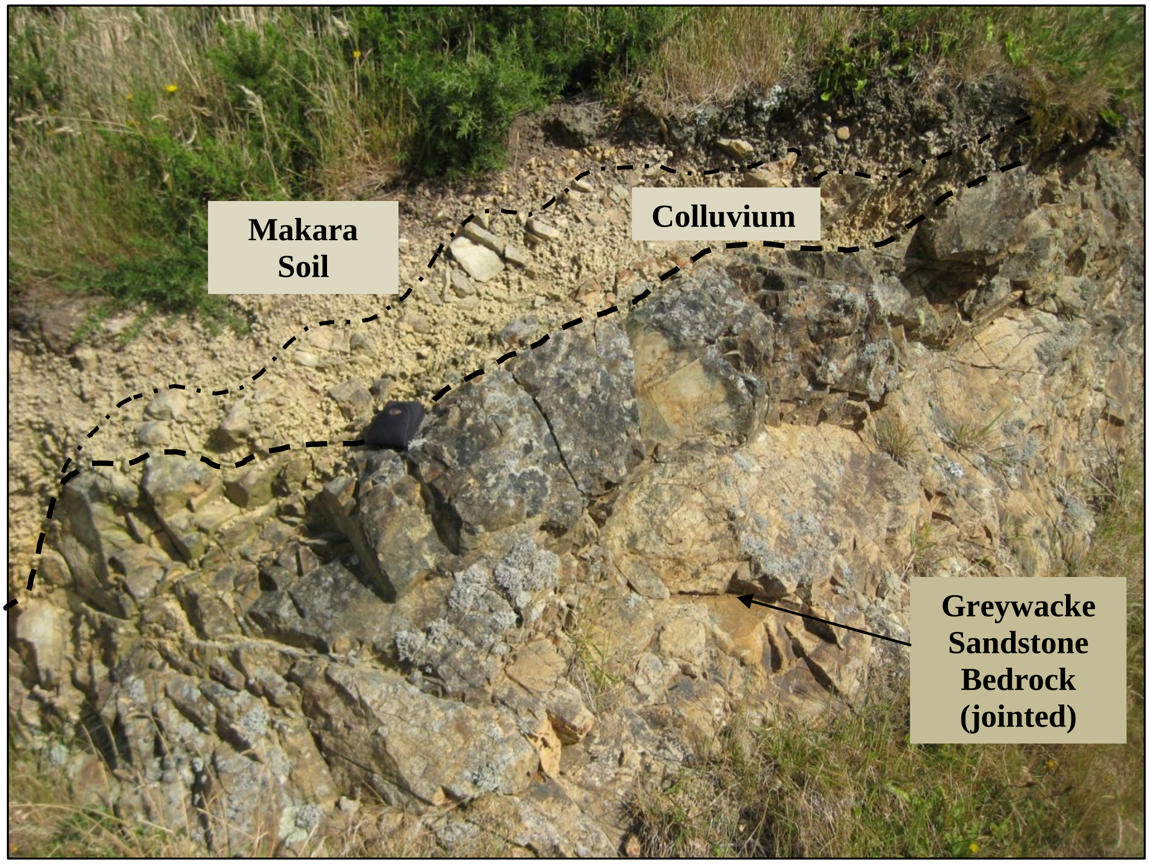
Isolated Holocene swamp deposits are present within the Te Aro Valley, where the former Te Aro swamp once extended from the Basin Reserve north to the original shoreline. These deposits generally consist of silty gravels, muds, peat and organic clays. These deposits generally have both high liquefaction and subsidence potential (Kingsbury & Hastie 1993).

2.3.6 SOILS

The majority of natural soils covering the Wellington region are classified as brown soils (brown earths). Brown Soils are the most extensive in New Zealand covering 43% of the country (Landcare Research 2009). They are derived from sedimentary rocks and occur in places where the climate keeps the soil sufficiently moist throughout the year preventing them from drying out. Parent material in the Wellington region includes loess, colluvium and weathered greywacke bedrock. Brown soils are identified by a yellow-brown subsoil layer which occurs below the dark grey-brown topsoil. This brown soil colour is caused by iron oxides derived from the weathered parent material. Brown soils contain high populations of soil organisms and usually have well developed polyhedral or spheroidal structure (nut structure). Dominant clay minerals found in brown soils are typically illite and vermiculite.

In the Wellington City area Belmont soils (brown soils) occur on the hilly remnants of the ancient peneplain (Kaukau surface). On the steeper slopes where much of the soil has been eroded away, Makara (refer to Figure 2.6) and Korokoro soils dominate. These brown earths are similar to the Belmont soils but are much shallower. The Makara and Korokoro hill soils are suitable for supporting road foundations and cut and fill landscaping (Molloy 1988).

Figure 2.6: Makara soil and colluvium overlying greywacke bedrock.



2.4 ACTIVE TECTONICS

2.4.1 WELLINGTON TECTONIC SETTING

Wellington City is located in a geologically active landscape near the southern end of the Hikurangi subduction zone. The Wellington region sits astride the active transpressional boundary zone between the colliding Australian and Pacific plates. Plate convergence in the region is about 40 mm/yr at an azimuth of approximately 260° (Begg et al. 2008; Little et al. 2009), with the oceanic Pacific Plate being subducted beneath the continental Australian Plate at the Hikurangi Trench (around 150 km east of Wellington). Dominant plate motion in the region is accommodated on the strike-slip faults of the NIDFB, with faults in the east generally having a higher lateral slip rate than those located further to the west (Berryman 1990; Van Dissen et al. 1991). The NIDFB consists of six major active strike slip faults, including Ohariu, Otaki Forks, Shepherds Gully-Pukerua, Wairau, Wellington and Wairarapa Faults in the Wellington region. Movement along these faults is predominantly dextral strike-slip, which accommodates for some 60-90% of motion parallel to the plate boundary (up to ~18 mm/yr (Van Dissen & Berryman 1996)). A small vertical movement component also occurs with exposed marine terraces (Turakirae Head) indicating net uplift over the region (Begg & Mazengarb 1996). Upper-plate deformation offshore to the east and west of Wellington is inferred to be dominantly contractional (Barnes 1998; Little et al. 2009).

There are numerous seismogenic sources in the Wellington region including the subduction interface and faults contained within the NIDFB. Frequent earthquakes associated with the subduction interface (some 20-30 km beneath the city) are generally small, with the most damaging earthquakes (e.g. 1855 Wairarapa Fault Earthquake) appearing to be centred on one of the major active faults within the NIDFB (Little et al. 2009).

2.5 FAULTING & SEISMOTECTONICS

2.5.1 WELLINGTON PALEOSEISMIC RECORD

There are numerous laterally offset stream channels, ridges and terraces in the Wellington area indicating recent fault movement. Paleoseismic investigations involve the detection and interpretation of geological evidence associated with previous fault movement. Generally the aim of these studies is to characterise a specific fault's rupture history (Cochran 2002). This is usually done, where feasible, by trenching across a fault scarp and directly measuring offsets. Dating techniques such as radio carbon can then be used to constrain the timing of previous rupture events. Alternatively, where trenching is not suitable, offset geomorphic features such as terraces and stream channels may be used. Many of the known active faults in the Wellington region have been characterised by various paleoseismic studies (Van Dissen et al. 1992a; Van Dissen & Berryman 1996; Litchfield et al. 2004; Mcsaveney et al. 2006; Langridge et al. 2007; Barnes et al. 2008).

2.5.2 GEODETIC AND GPS STUDIES

Global Positioning Studies (GPS) involve measuring the displacement from accurate survey marks over time and deducing their relative velocities. Wallace et al. (2008) have created an updated model for subduction coupling and crustal block rotations for the Wellington region. This was done using information from a 2007 re-survey of the

Wellington region GPS network, combined with earlier GPS data collected in the area, and fault slip rate and location data. The new model is consistent with fault slip rates and the geodetic data and indicates that strain is accumulating on at least some parts of the subduction interface between the Australian and Pacific plates.

2.5.3 ACTIVE FAULTS

An active fault is one that has moved in recent geological time and is considered to be likely to move again in the future. The two main hazards associated with active faulting are ground rupture and strong ground motion. While ground rupture generally only affects a localised area (the immediate vicinity of the fault), strong ground motion is generally more damaging and can affect areas much further afield. Progressive research has led to a better understanding of the active faults within the Wellington region, with recent significant findings indicating that faulting in the North Island is discontinuous with faulting in the South Island (refer to Figure 2.7 (Barnes et al. 2008)). This has very important implications for understanding the characteristics of the region's earthquake sources. There are around 50 active faults in the Wellington region, many of which are capable of producing a damaging earthquake (GNS Science 2009), thus the earthquake hazard is high. There are 6 major fault systems within the Wellington region (refer to Figure 2.8) capable of producing large earthquakes: the Ohariu (including the Northern Ohariu Fault), Otaki Forks, Shepherds Gully-Pukerua, Wairarapa, Wairau and Wellington faults. The Hikurangi Subduction Zone is also capable of producing strong ground motion as the result of large earthquakes. The Wellington Fault accounts for more than 50 percent of the risk in generating a NZ$ 1 billion earthquake, with 7 percent for the Wairarapa fault, 5 percent for the Ohariu Fault and New Zealand's remaining faults making up the rest (Cousins 2008). Properties of these 7 major earthquake sources are summarised in the following text.

Figure 2.7: Faulting in Cook Strait (Barnes et al. 2008).

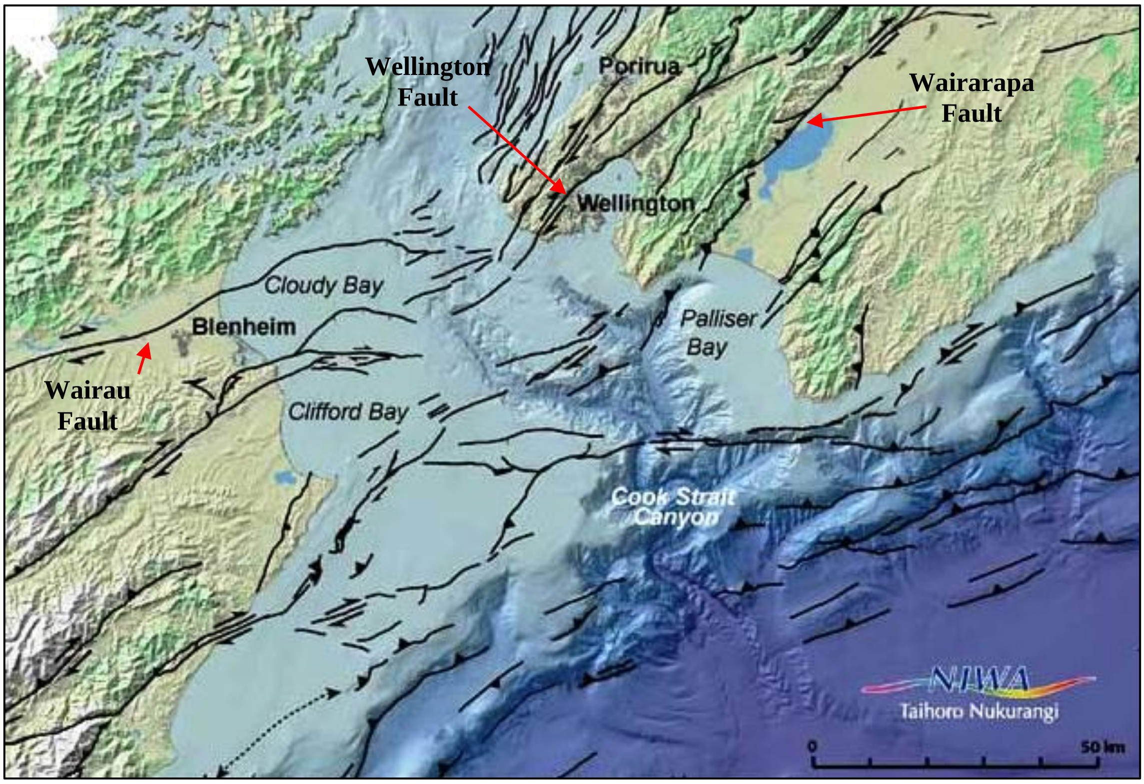
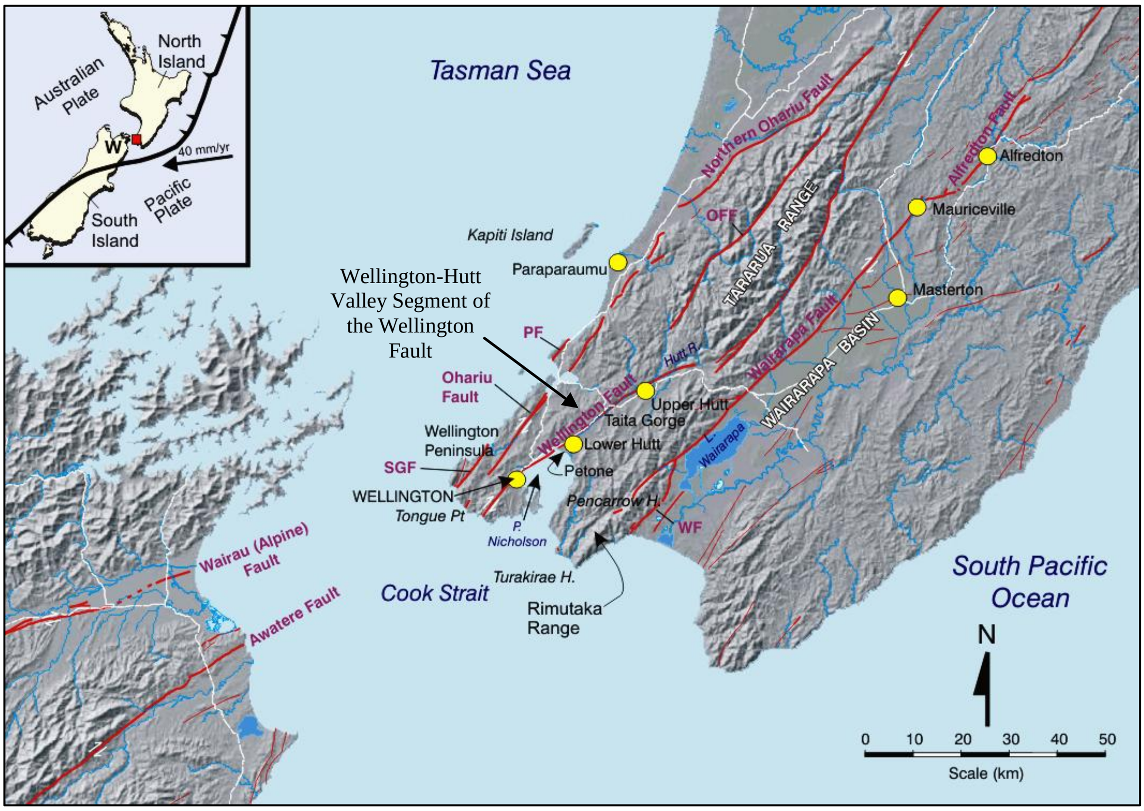


Figure 2.8: Major active faults within the Wellington area (Begg et al. 2004).



OFF = Otaki Forks Fault, SGF = Shepherds Gully Fault, PF = Pukerua and WF = Wharekauhau Fault.

2.5.4 WELLINGTON FAULT

The Wellington Fault is a major active northeast-southwest trending dextral fault of the western strand of the NIDFB (Beanland 1995). It is a class I active fault (Kerr et al. 2003) and as such is capable of generating a strong earthquake within a time period relevant to human occupancy and construction of urban engineering projects (Murashev & Palmer 1998). The Wellington Fault is one of the longest laterally persistent active onshore faults in New Zealand (refer to Figure 2.8). From its southernmost known location in Cook Strait (based on bathymetry and geophysical data), the fault trace can be followed for some 420 km more or less continuously. The fault runs north eastward through the northern end of Wellington City, the Hutt Valley through the Tararua Range to the Manawatu River. The fault then continues northwards to the Bay of Plenty coastline as the Mohaka Fault (Begg et al. 2008). Location of the Wellington Fault within Wellington City has been constrained from a number of offset and fault-related geomorphic features (Ota et al. 1981) and more recently in the Thorndon area using the correlation of borehole sediments (Perrin 1993). The fault passes to the west of Glenmore Street, along the base of Tinakori Hill to the harbour and beyond. The fault's offshore position in Wellington harbour was established as a fault scarp beneath the wharf north of the Interislander ferry terminal (Lewis 1989).

The Wellington fault was discovered after the settlement of the then Wellington Township. In 1892 (McKay 1892) the first map of the Wellington fault was published. Further work in 1910 (Bell), 1912 and 1914 (Cotton) also recognised the fault but it was not determined until 1921 that the Port Nicholson-Lower Hutt Basins occupied a fault angle depression (Cotton 1921). Cotton (1951) was also the first to show that the fault had an important strike-slip component. Further work confirmed this (Lensen 1958). The dominant sense of movement on the Wellington Fault is now shown to be the horizontal strike-slip component (Berryman 1990; Begg & Mazengarb 1996; Begg et al. 2008).

Fault plane properties are known from relatively few exposures, but are indicative of a steeply dipping to vertical fault plane. The upthrown side of the fault is generally to the west, but locally traces and scarps are upthrown to the east (Thondon Seabed (Begg et al. 2008)). Palaeoseismological studies including trenching at a number of sites along the Wellington Fault have been used to investigate the fault’s characteristics, including slip rate which is vital in evaluating the conditional probability of fault rupture (Berryman 1990; Van Dissen & Berryman 1996; Berryman et al. 2002; Langridge et al. 2007; Begg et al. 2008).

The southernmost segment of the Wellington Fault (approx. 80km long), from Cook Strait passing through Wellington City and the Hutt Valley to where the fault undergoes a 2 km wide side-step at Kaitoke, is known as the Wellington-Hutt Valley segment (refer to Figure 2.8 (Berryman 1990)). The fault along this segment has a high lateral slip rate with varying rates of throw. Little et al. (2010) inferred a best fit average moment magnitude (M_w) of 7.5 (7.3 to 7.6 1σ), with a late Holocene dextral-slip rate of ≥ 4.5 ± 0.4 mm/yr (1σ) and a mean earthquake recurrence interval of ~610-1100 years for this fault segment.. Recent results from 'It's Our Fault' studies have shown that the probability of rupture in the next 50 years on the Wellington Fault is around 5%, with an average recurrence interval to date of 900 years (approx.) and the most recent rupture event occurring approximately 300 years ago (GNS Science 2009). Evidence suggests that the Wellington Fault has experienced differing periods of activity over time.

A large surface rupturing earthquake centred on the Wellington Fault (M_w 7.5) is considered to be New Zealand's greatest seismic risk. A mean single event slip displacement of 5.0 ± 0.24 m (95% confidence) is calculated for the Wellington-Hutt Valley segment of the fault (Little et al. 2010). Strong ground motion generated from an earthquake of this magnitude would have a devastating effect on Wellington City and the surrounding area, with structures or lifelines located on or near the fault being severely damaged or destroyed. Depending on the timing of such an event, hundreds of deaths and billions of dollars of damage could be expected (Cousins 2008).

2.5.5 WAIRARAPA FAULT

The Wairarapa Fault is a major reverse dextral fault within the NIDFB (Beanland 1995). The Wairarapa fault strikes northeast and dips steeply northwest. It runs along the western flank of the Wairarapa Basin in the southern North Island and is the easternmost strike-slip fault in the NIDFB. The length of the well-defined onshore Wairarapa Fault trace is approximately 88 km (Rodgers & Little 2006). Seismicity data suggests that the Wairarapa fault intersects the subduction interface at depths of 20-30 km beneath the southernmost part of the North Island (Rodgers & Little 2006). It is interpreted that the Wairarapa fault was initiated in the Pliocene as a reverse fault and then reactivated as a strike slip fault approximately 1-2 Ma in response to a changing tectonic regime (Beanland 1995; Kelsey et al. 1995).

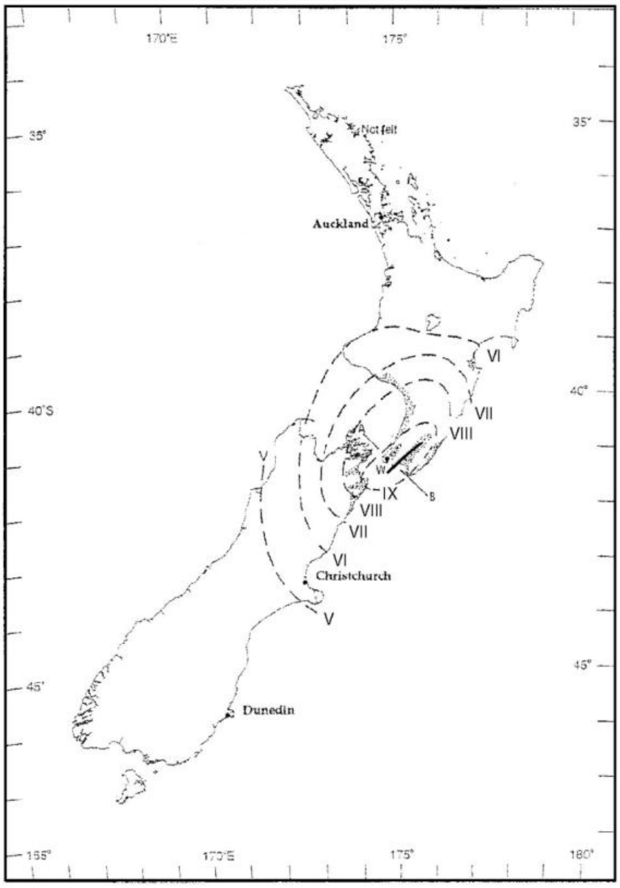
The Wairarapa fault can be divided into three sections based on geometry (central, southern, and northern sections). Based on seismic and bathymetric information, at least two strands of the southern section extend some 35-40 km offshore into Cook Strait from Palliser Bay (Barnes & Audru 1999). Near the southern coast the fault cuts across the eastern foothills of the Rimutaka Ranges marked by a topographic step between the hills and alluvial plain. Further north, the fault is located within the alluvial plain. The central Wairarapa fault segment has a complex surface relationship. It generally consists of a zone of en echelon left-stepping fault segments and/or deformational bulges that are typically 1-2 km long (Little et al. 2008). This results in the warping of alluvial terrace surfaces in this area (Rodgers & Little 2006). The northern Wairarapa fault section consists of a series of dextral-slip splays (including the Carterton and Masterton Faults) that branch off to the east away from the main trace to the west (Little et al. 2008). The main fault trace extends northward as far as Mauriceville (20 km north of Masterton) in the northern Wairarapa basin.

There have been no large earthquakes on the Wairarapa fault since the 1855 rupture event. The southern part of the Wairarapa fault has a late Quaternary dextral slip rate of 11 ± 3 mm/yr. Five surface rupturing earthquakes on the southern part of Wairarapa fault since ca. 5.2 ka have been dated, resulting in a mean earthquake recurrence interval of 1230 ± 190 yr (Little et al. 2008).

2.5.5.1 THE 1855 WAIRARAPA EARTHQUAKE

On January 23rd 1855 Wellington was severely shaken by the Wairarapa Earthquake (estimated $M_w > 8.1$), resulting in the largest documented strike-slip offset measured worldwide. The earthquake was felt throughout New Zealand (refer to Figure 2.9) with a maximum intensity of MM IX-X in the lower North Island (Grapes & Downes 1997). This resulted in extensive damage within Wellington City and the lower North Island with one person killed. Numerous landslides (particularly in the Rimutaka Range), tsunami and ground rupture (approx 145 km) were reported. In the surrounding region at least four people (and possibly as many as eight) were reported to have died during the earthquake. An extensive rebuild following the 1848 Marlborough earthquake using predominantly wooden structures in combination with a relatively sparse population probably resulted in far fewer casualties than expected. Regional uplift (up to 1.5 m) of some 5000 km^2 rendered many of the harbours jetties unusable. Raised beaches provided land for a new rail and road route north.

Figure 2.9: Shaking intensity (Modified Mercalli Scale) of the 1855 Wairarapa Earthquake (Grapes & Downes 1997).



2.5.6 OHARIU FAULT

The Ohariu Fault is one of the major active dextral strike-slip faults within the NIDFB, in the western Wellington region. The fault trace extends north eastwards from Wellington's southern coast at Tongue Point (near Waiariki Stream) through to Waikanae (Heron et al. 1998). Just north of Waikanae the Northern Ohariu Fault appears to be the along-strike continuation of the Ohariu Fault (Litchfield et al. 2004).

The fault runs directly through the urban area of Porirua and is traversed by a number of major lifelines. The total on-land length of the fault is approximately 70 km, with an average strike of 030-050° (Williams 1975; Heron et al. 1998; Van Dissen et al. 1999; Litchfield et al. 2004; Litchfield et al. 2006). The fault can also be followed offshore from Tongue Point for some 20 km across the continental shelf to central Cook Strait as a series of discontinuous traces. The Ohariu Fault is assumed to be a continuous feature although, except for the 7 km long trace between Waiariki Stream and Makara, the surface traces are intermittent (Heron et al. 1998).

Ohariu Fault rupture history has been determined from various paleoseismic investigations e.g., Van Dissen & Berryman 1991; Heron et al. 1998; Litchfield et al. 2004; Litchfield et al. 2006. The slip rate for the Ohariu Fault has been determined through land based studies. Heron et al. (1998) calculated a late Quaternary horizontal slip rate of 1-2 mm/yr, with a single event surface rupture displacement of 3-5 m (mean 3.7 m) measured at seven sites. The most recent fault rupture on the Ohariu fault is well constrained and occurred approximately 1025 yrs B.P. (1050-1000 cal. yr BP (Litchfield et al. 2004; Litchfield et al. 2006)). Evidence of coseismic subsidence in the nearby Taupo Swamp during this period further supports the timing of the most recent rupture event (Cochran et al. 2007). The Ohariu Fault has a best estimate mean recurrence interval of 2200 yr (Litchfield et al. 2006). The Ohariu Fault is capable of generating an earthquake of M_w 7 and higher (Heron et al. 1998 determine a range of M_w 7.1-7.5). In such an earthquake rupture event, 3-5 metres of right-lateral displacement at ground surface can be expected, with smaller vertical displacements varying along the length of fault. Strong ground motion would be felt in the greater Wellington area and any lifelines or structures located on the fault would be severed and destroyed.

2.5.7 OTAKI FORKS FAULT

The Otaki Forks Fault was discovered in 2000 and is located within the NIDFB at the southern end of the North Island. The fault extends for approximately 70 km, running from northeast Cloustonville, north through to the headwaters of the Mangahao River (around 15 km ESE of Levin (GNS Science 2000)). The fault is regarded as active as it is linked to the active Akatarawa and Wellington Faults. The characteristics of the Otaki Forks Fault are poorly understood. In 2000, trenching across the fault found evidence for either two or three rupture events in less than 10,000 years, with each one producing a large earthquake. The fault has produced horizontal displacements of several metres, indicating that it is capable of generating an earthquake of M_w 7 or higher. It has been concluded that the Otaki Forks Fault ranks as comparable with the neighbouring Ohariu Fault to the west, with a similar recurrence interval and ability to produce a major earthquake (Begg & Van Dissen 2000; GNS Science 2000; Van Dissen et al. 2001).

2.5.8 SHEPHERDS GULLY-PUKERUA FAULT

The Shepherds Gully and Pukerua Faults are located on the western edge of the Wellington Peninsula. Van Dissen and Berryman (1996) consider the two faults to be part of the same structure based on the linear continuity of their trends obtained from a seismic profiling study. The surface trace of the Shepherds Gully Fault is poorly expressed in the landscape (Ota et al. 1981) and can be traced from the North Island's south coast in a north easterly direction to Porirua, where it is assumed to join with the Pukerua Fault on the northern side of Porirua Harbour. This suggests a long recurrence interval and a considerable time period since the last rupture event, especially when compared to other active faults in the region. No data is available on the timing of previous rupture earthquakes. Due to the relatively poor preservation of the onshore Shepherds Gully Fault trace, the fault is assumed to have ruptured prior to the most recent primary fault rupture event on the nearby Ohariu Fault (which has a well defined fault trace (Van Dissen & Berryman 1996)). This suggests that the elapsed time since the last rupture event is greater than 1050-1000 years BP (Litchfield et al. 2004). Ota et al. (1981) measured horizontal displacements of 3.5-4 m (probably representing a single displacement event) on the Shepherds Gully Fault. A slip rate of 0.4-1.4 mm/yr has been estimated from an offset right lateral strike slip displaced fluvial channel on the Pukerua Fault. Based on the assumed single event displacement size of 3.5-4 m a very poorly constrained recurrence interval of 2500-5000 years can be estimated. An earthquake of M_w 7.3-7.9 centred on the Shepherds Gully-Pukerua Fault system would generate strong ground motion over the wider Wellington area. The associated lateral and vertical displacements along the fault would severely damage structures and lifelines built across the fault.

2.5.9 WAIRAU FAULT

The Wairau Fault is an active right lateral strike-slip fault, located within the Marlborough Fault System (MFS) in the northern South Island of New Zealand. The MFS transfers slip from the Alpine Fault in the South Island through to the Hikurangi subduction zone of the eastern North Island. The MFS comprises of several major active faults including the Wairau, Awatere, Clarence, Kekerengu, and Hope Faults, with numerous smaller faults also present within the system (Zachariasen et al. 2006). These faults strike in a north easterly direction and together accommodate almost all of the relative Australian-Pacific plate motion (Holt & Haines 1995). The 100 km (approx.) long Wairau Fault is considered to be the north eastern extension of the Alpine Fault. It can be traced on land from the northern end of the Alpine Fault ("The Bends") near Lake Rotoiti through to Cloudy Bay in the north east and possibly some distance offshore (Suggate 1979). The fault consists of a single trace from Lake Rotoiti through to Wairau Valley township where it branches and continues as two strands through to Renwick, approximately 15 km from the Cloudy Bay coast (Lensen 1976). Only the southern strand of the fault trace can be followed from Renwick through to the coast (Grapes & Wellman 1986; Zachariasen et al. 2001; Zachariasen et al. 2006).

The slip sense of the Wairau Fault is predominantly right-lateral. A small vertical component varies along the length of the fault and has been found to have reversed over time (Lensen 1968). Zachariasen et al. (2006) excavated three trenches across the Wairau Fault near Wairau Valley township. Radiocarbon dating of organic material was used to deduce the timing of previous late Holocene surface rupture events on the Wairau Fault. Results indicate that the last surface rupture event on the Wairau Fault occurred more than ~1290 years ago and as much as ~2740 years ago, with the preferred range 1810-2300 cal. yr BP. A penultimate rupture event was found to have probably occurred between ~ 2350 and ~3400 yr BP. A maximum slip rate of 3.5-4.8 mm/yr was estimated for the northern strand of the fault near Wairau Valley, which is consistent with previously determined average Holocene strike-slip rates of 3-5 mm/yr for the Wairau Fault (Grapes & Wellman 1986). The average recurrence interval for the Wairau Fault was found to be ~ 150-1400 yr, which is similar to the time elapsed since the last earthquake event. Given that the accumulated strain and the elapsed time since the last rupture event is similar to the estimated recurrence interval, the Wairau Fault may be nearing the end of its interseismic period. An earthquake centred on the Wairau

Fault can be expected to have a maximum magnitude of M_W 7.6 (Zachariasen et al. 2001; Zachariasen et al. 2006). Thus, the earthquake hazard in Marlborough and the surrounding regions is high. A surface rupture earthquake centred on the northern section of the fault will have serious implications for Wellington City.

2.5.10 HIKURANGI SUBDUCTION ZONE

Offshore subduction of the oceanic Pacific Plate beneath the Australian Plate occurs in the Hikurangi Subduction Zone. The subduction interface is located approximately 30 km below Wellington and is a potential source of damaging earthquakes. No large earthquakes have occurred on the Hikurangi Subduction Interface since European settlers arrived (ca.1840). Earthquakes associated with the subduction interface are frequent in Wellington but are generally small (Van Dissen & Berryman 1996; Stirling et al. 1998). The release of accumulated elastic strain in a large subduction interface earthquake would have a severe detrimental effect on Wellington City and the surrounding region.

2.5.11 INACTIVE FAULTS

In addition to the seismogenic sources mentioned above, there are numerous inactive faults located within Wellington City. An inactive fault poses little risk, as the result of very long movement intervals or lack of activity evidence. In Wellington City, these generally north-south orientated faults include the Lambton, Happy Valley and Terrace Faults (Begg & Mazengarb 1996). Intervals of movement on these faults are large and as a result they have little planning importance. Although these faults are classified as inactive, indirect evidence for late quaternary displacement of the Lambton fault may exist (Perrin & Campbell 1992). Geomorphological evidence also suggests late Quaternary displacement on the Terrace and Happy Valley Faults (Begg & Mazengarb 1996). The Lambton Fault cuts Pleistocene deposits and runs through the commercial and government centres of central Wellington, along the western side of Lambton Quay south to Newtown (Stevens 1975). By definition inactive faults pose little risk, however they may be associated with poor founding conditions and ground failure as a result of rock weakening (Perrin & Wood 2003). Inactive faults can also become reactivated through a change in tectonic regime.

Table 2.1: Summary parameters of the major faults in the Wellington area.

Fault	Slip Rate (mm/yr)	Single Event Displacement, Horizontal Component (m)	Recurrence Interval (years)	Timing of Most Recent Event (cal. yr BP)	Estimated Characteristic Magnitude
Wellington	4.5-4.9	4.75-5.25	900	300	7.5
Wairarapa	10.7-11.3	9-13.5	1140-1420	155 *(Last Ruptured in 1855)*	8-8.3
Ohariu	1.0-2.0	3-5	2200	1025	7.1-7.5
Shepherds Gully-Pukera	0.4-1.4	3.5-4	2500-5000	> ca. 1000yrs *(or > Ohariu Fault)*	7.3-7.9
Otaki Forks	c. 1	2.5-3.5	<4000-9000	?	7.3-7.6
Wairau	3.0-5.0	5-7	150-1400	1810-2300	7.2-7.6

Note best fit values have been used where applicable and all values are approximate (with the exception 1855 most recent Wairarapa Earthquake). These parameters come from a number of sources: Begg & Johnston 2000; GNS Science 2009; Grapes & Wellman 1986; Heron et al. 1998; Litchfield et al. 2004, 2006; Little et al. 2008, 2010; Rodgers & Little 2006; Zachariasen et al. 2001, 2006.

2.6 FOLDING

The underlying Torlesse Greywacke basement rock is both faulted and folded. Cotton (1921 & 1956) illustrated deformation of the K-surface and Ota et al. (1981) defined north-south trending folds on their K-surface isopach map. Generally folding in the Wellington area is related to movement on the region's major faults. Development of the Upper and Lower Hutt basins appears to be directly related to Wellington Fault activity and localised folding immediately east of the fault. The gentle warping of the K-surface on the western side of the Wellington Fault is probably related to the active faults in this area (e.g. Ohariu, Shepherds Gully and Wellington Faults). Folding and uplift in the far east of the southern North Island is related to activity on the Wairarapa Fault, the Wharekauhau Thrust and the eastern Rimutaka faults. This in turn is related to the subducting Pacific Plate beneath the region (Begg & Mazengarb 1996).

2.7 GEOMORPHOLOGY

The landscape in Wellington City has been heavily modified as a result of urban development and few geomorphic features remain. Unlike the Hutt Valley to the northeast of Wellington City there are no large streams or rivers. As a result fluvial deposits are generally much more angular as they have travelled less distance. Streams for the most part in Wellington City are drained by a series of culverts to the coast.

Most valleys within the Wellington region are V-shaped, indicative of an active landscape with rapid uplift. River terraces raised by river cutting and tectonic uplift are preserved within the Hutt Valley, and a number of these (e.g. Emerald Hill) have been used to determine displacement along the Wellington Fault (Berryman 1990).

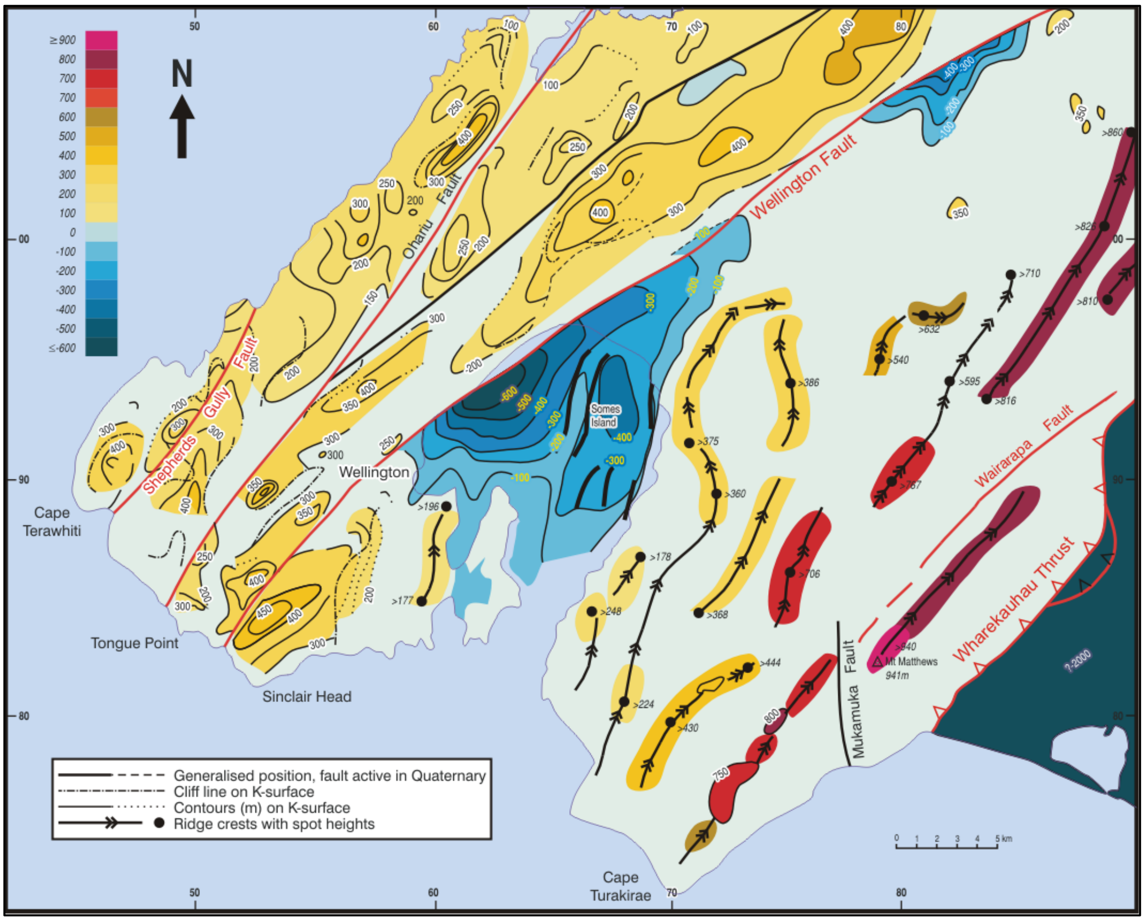
Mass movement of soil, regolith and rock down slope has been observed within the study area (Grant-Taylor et al. 1974; Begg & Mazengarb 1996), but in general these processes are more likely to occur on the steeper hills and suburbs surrounding the city. Mass movement processes can be triggered through both human induced events (roading and foundation construction etc.), and natural phenomena (earthquakes, extreme weather events etc.).

The rugged Wellington region is surrounded by sea to the east, south and west, where large waves and strong winds are common. As a result the coast is generally steep and rocky, with towering coastal cliffs a common site. Uplift from the 1855 Wairarapa earthquake raised the wave-cut platform, which now supports numerous road and rail networks. A number of marine terraces and fossil sea cliffs cut during previous high sea level stand are found within the region, particularly along uplifted sections of the coastline, such as the area to the east of Pencarrow Head (Begg & Mazengarb 1996; Begg & Johnston 2000).

2.7.1 K-SURFACE:

Many of the hills and ridges on the western side of the Wellington Fault are flat or shallow dipping. These are relics of what was once an almost featureless gently undulating plain (peneplain) that existed more or less intact until about 1 million years ago (Begg 1999). The term Kaukau surface (K-surface), which refers to this ancient peneplain, was first coined by Cotton during the twentieth century (Cotton 1912; Cotton & Te Punga 1955; Cotton 1956, 1957). The genesis of the K-surface is uncertain but it was likely formed by marine or coastal processes (Begg & Mazengarb 1996). This c. 5 million year old erosion surface truncates the older basement rocks in the area and was the end result of weathering and erosion of a stable landscape over millions of years. A minimum age of c. 1-0.5 Ma for the development of the K-surface is provided by the deposition of the Kaitoke Gravel (Quaternary sediments (Begg & Mazengarb 1996)). Whilst K-surface is generally well preserved to the west only a few isolated remnants remain on the rugged terrain to the east of the Wellington Fault due to greater rates of erosion and uplift. Erosion in local stream valleys has dissected the K-surface leaving only these isolated remnants behind, which are often in areas of more resistant (less jointed) greywacke bedrock. K-surface altitudes (refer to Figure 2.10) over most of the western hills range from 450-200 m suggesting extensive and significant uplift of the region since the surface was formed (Begg & Mazengarb 1996; Begg et al. 2004).

Figure 2.10: K-surface structural contours (Begg et al. 2004).



Elevations are generally similar on the north-western side of the Wellington Fault. Ridge crest elevations to the southeast of the Wellington Fault are given, providing a minimum K-surface altitude (refer to Figure 2.11 for basement profiles along the Wellington Fault).

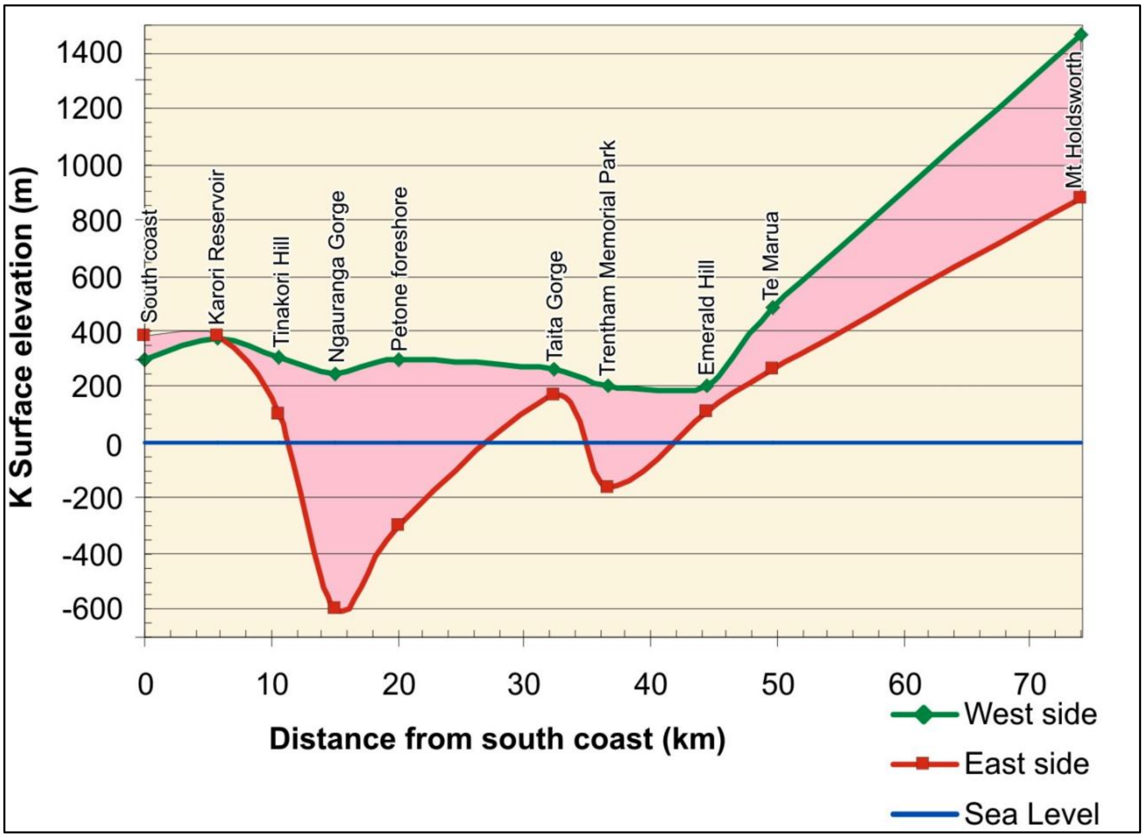
2.7.2 LANDSCAPE DEVELOPMENT

Large scale movement of land took place in the Quaternary and is reflected in the region's physiography (Begg & Mazengarb 1996). During the Quaternary (approximately 500-350 ka ago) the first extensive sediment deposition in the region occurred with basin development and the probable onset of vertical displacement along the Wellington Fault (Begg & Mazengarb 1996). The Cook Strait seaway opened during this time through the linkage of five extensive sedimentary basins by strong tidal scour (Lewis et al. 1994).

Glacial and Interglacial sediments were deposited in the region along with the 350 ka Rangitawa Tephra (Begg & Mazengarb 1996). Further deposition and uplift occurred along the Wellington Fault. During the Last Interglacial beach sediments were deposited in the Thorndon and Te Aro areas. Post glacial deposits including beach alluvium and swamp deposits are preserved within the Wellington City study area (Begg & Mazengarb 1996). The Pleistocene and Holocene sediments have in-filled the area's extensive basins and have become desirable flat areas on which to build. Te Aro Valley, within Wellington City is an example of this. Numerous gullies and small valleys were buried by solifluxion debris during the Last Glacial (Cotton & Te Punga 1955).

The landscape surrounding Wellington has been progressively altered over time through active tectonic and erosion processes. The Wellington Fault is the key control in basin development and deposition in the area, with varying degrees of uplift and subsidence along its length (refer to Figure 2.11 (Begg et al. 2008)). Initially a relatively flat gently rolling landscape, the Wellington region has been heavily dissected by streams and uplifted as a series of fault bounded blocks resulting in its present day rugged terrain. The region's most extensive flat alluvial planes (particularly the Hutt Valley) have been formed by river aggradation and are now heavily populated (Begg & Mazengarb 1996). In more recent times the landscape has been altered by man reclaiming land and creating road and rail transport networks. As a result, little unaltered geomorphic evidence remains in the city today, although features can be observed in the surrounding region.

Figure 2.11: Approximately NE-SW trending basement profiles along the Wellington Fault (Begg et al. 2008).



The two profiles illustrate the vertical offset of the K-surface on either side of the Wellington Fault. The profiles extend parallel along the fault from Wellington's south coast (left of figure) to the southern Tararua Ranges.

2.8 RECLAMATION LANDFILL

Wellington waterfront reclamations were constructed in stages between 1852 and 1972 (refer to Table 2.2, Figure 2.12 & Appendix 8B) to expand the central business district and port facilities. Both hydraulic (pumped sand and mud from the seabed) and locally sourced end tipped fill (boulders, domestic waste, spoil etc) were used. Reclamations overlie thin sequences of Holocene beach, estuarine and marine sediments with isolated colluvium and alluvium also present. These sediments typically consist of sands, sandy gravels and silts and often contain shell fragments. The thickness of these sediments varies between 0-4 m. The original shoreline followed from north to south along Thorndon Quay, Lambton Quay, and along the seaward side of Manners Street and Courtenay Place. Reclamation depths generally increase towards the shore (following the slope of the original seabed) up to a maximum depth of 17 metres (Murashev & Palmer 1998). Redevelopment has occurred on a large portion of the land reclaimed by local port, city and railway authorities. Reclamation around Wellington's waterfront has added more than 155 hectares to the central city area (Kelly 2005).

2.8.1 RECLAMATION HISTORY

The remnants of the old K-surface peneplain surround Wellington City. Over time this flat land has been heavily dissected by watercourses and as a consequence of this erosion there is little flat land available in and around Wellington City. Early European settlers (New Zealand Company) arriving in 1839 quickly settled what little available land there was near the harbour. These flat areas included Thorndon and Te Aro which were linked by a very narrow path on the seashore. The land at Te Aro was swampy and as a result was less attractive for residential development than Thorndon and consequently it became more industrialised. Lambton Quay was named after Lord Durham (family name Lambton) who was the chairman of the New Zealand Company. The buildings constructed along Lambton Quay (refer to Figure 2.13) were sited on one side of a muddy track with the sea on the other side (Baillie 1924).

Table 2.2: Wellington Reclamations (Wellington Harbour Board 1936; Murashev & Palmer 1998; Wellington Waterfront Limited 2009).

Reclamation No.	Date	Reclamation No.	Date	Reclamation No.	Date
A	1852	J	1882	S	1901-1903
B	1857-1863	K	1882	T	1901-1914
C	1859	L	1884	U	1902-1925
D	1864	M	1886	V	1904
E	1865	N	1886	W	1904-1916
F	1866-1867	O	1889	X	1906
G	1875	P	1893	Y	1910-1913
H	1876	Q	1893-1901	Z	1924-1932
I	1882	R	1895	α	1965-1972

Figure 2.12: Wellington waterfront reclamation map. Reclamation zones A-Z from Wellington Harbour board (1936), α from Murashev & Palmer (1998).

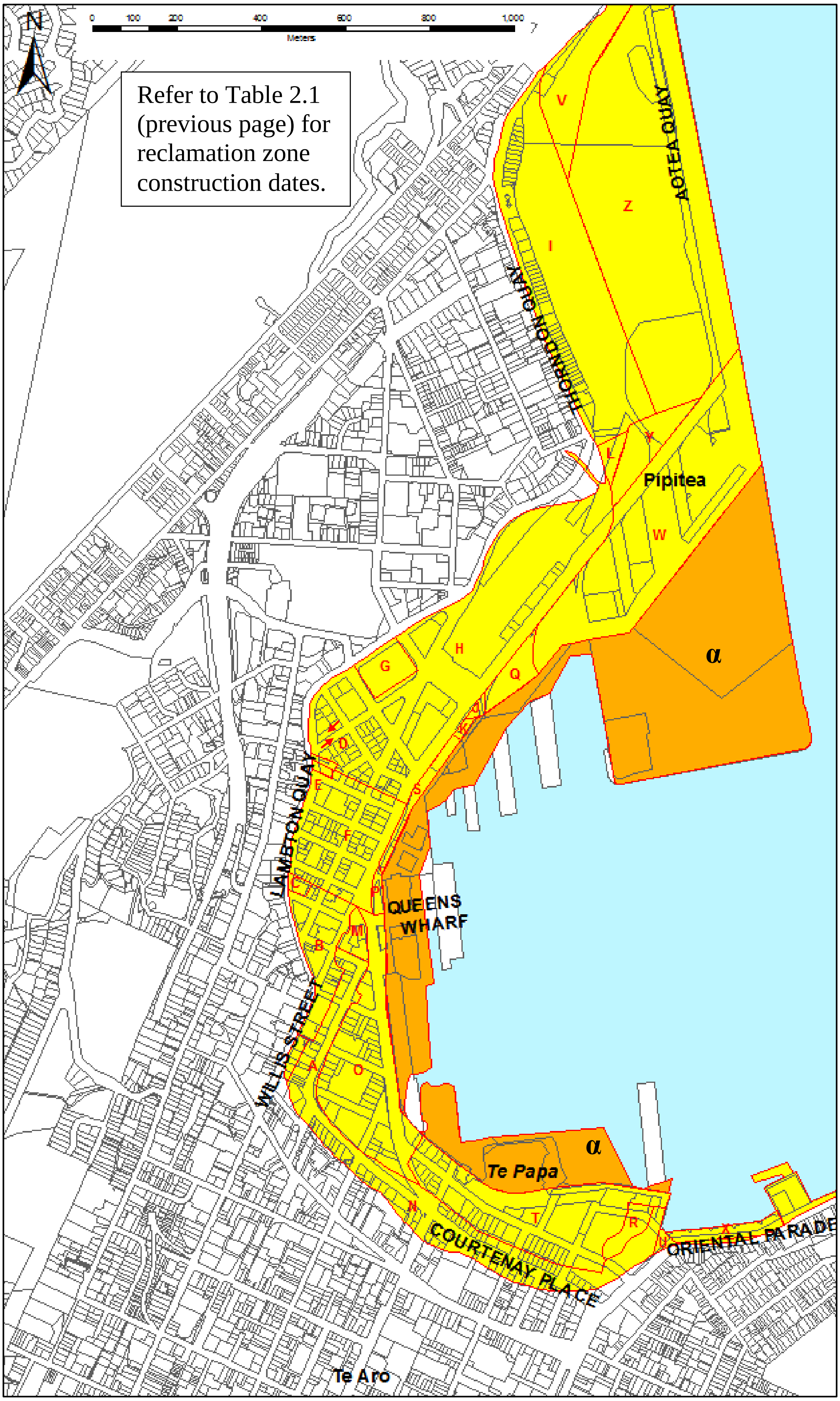


Figure 2.13: Lambton Quay 1863 (Cyclopedia Company Limited 1863).

The absence of building space in Wellington, particularly north of the Te Aro flats led to the first significant reclamation in 1852 consisting of an extension below Willis Street built by C. R. Carter (who did much of the early reclamation and seawall work in Wellington), using spoil from nearby excavations and the hills behind Lambton Quay. Although the 1852 extension below Willis Street was the first significant reclamation in Wellington, George Bennett can be attributed with carrying out the first reclamation works. He arrived in the Berenicia in 1848 and purchased a hilly section at Clay Point (present day Stewart Dawson's corner). He excavated the site with pick-axe, shovel and barrow, dumping the spoil on the beach and widening the roadway that connected the Te Aro flats (Baillie 1924; Anderson 1984).

In 1855 Wellington was severely shaken by the Wairarapa Earthquake (refer to Section 2.5.5.1). Uplift on the north-western side of Port Nicholson rendered many of the existing jetties and wharfs unusable draining the Te Aro swamp (Anderson 1984) and facilitating reclamation. The inland shipping basin planned for this area was abandoned with the land used for a cricket ground (present day Basin Reserve). Cambridge and Kent Terraces were positioned to run along either side of the shipping canal connecting the basin to the sea. The Waitangi Stream (now drained by culvert) originally flowed from the present day Basin Reserve down the centre of Cambridge and Kent Terraces to the sea. Construction on the first deep water wharf (Queens Wharf) started in 1862 (Baillie 1924).

By 1880 further reclamations using spoil from the hills behind Lambton Quay and from Wadestown Hill had been completed with the new sea walls running from Pipitea Point to the bottom of Willis Street (Baillie 1924). Reclamation at Te Aro did not start until the early 1880s due to a greater availability of building space in the area. In 1882 a railway line was constructed to carry fill from quarries in Oriental Bay (Fitzgerald point and Roseneath Hill) to reclamation sites in Te Aro. The reclamation was completed in 1886 adding some nine hectares to the Te Aro foreshore (Anderson 1984). The period from the late 1880’s to the start of the 20th century saw major reclamation developments take place around Wellington’s waterfront and the disappearance of the original 1840 shoreline. Included in these reclamations were those completed by the Wellington Harbour Board, Wellington-Manawatu Railway Company and the General Government. The material used for the reclamation of the present day Wellington Railway Station was sourced from the face of a hill along Hutt Road, close to Pipitea Point (Anderson 1984).

Further reclamations for Wellington Harbour Board and the railway department were constructed and completed by the early 1930’s, the most significant of these being the Thorndon rail yard reclamation (~28 Hectares). This unique reclamation was built behind a seawall using hydraulically pumped seabed sands and muds from the harbour (refer to Figure 2.14). Little reclamation work took place between the early 1930’s and the 1960’s, a situation partly attributed to the effects of the Great Depression. The final significant phase of reclamation took place in the 1960's and 1970's with the construction of the Thorndon container terminal, with the first container ship berthing on 19 June 1971. Containerisation requiring more handling space also saw reclamations carried out on both sides of Queens Wharf (Anderson 1984).

Figure 2.14: a) Thorndon reclamation under construction (Evening Post ca. 1925), b) Present day (S Semmens 2009)

Dashed red line indicates approximate position of the Wellington Fault.

2.8.2 RECLAMATION MATERIALS

2.8.2.1 ENGINEERED FILL

Engineered fill refers to suitable rock, gravel or similar materials that have been used as fill and compacted to specified densities. Early reclamation (before 1930's) in Wellington did not use engineered fill and it was not until modern construction practices were developed that foundations were improved using various compaction techniques. Any compaction during early reclamations was generally the result of the construction process at the time (for example horse and cart travelling over reclaimed land to dump fill and extend the reclamation), as opposed to using specific compaction methods. The Thorndon container terminal reclamation was constructed using engineered fill and completed in 1972. Provided the correct standards are met, engineered fill is likely to perform well in a large earthquake.

2.8.2.2 END TIPPED FILL

End tipped fill used in the reclamation works surrounding Wellington Harbour came from a number of sources. These included quarried rock from Oriental Bay and Wadestown Hill, spoil from the cliffs and hills behind Lambton Quay, nearby road and building excavation material and building debris (bricks, stone, masonry etc). Fill was either brought to site by cart or Ballast train, and in some cases (particularly very early on) was moved by shovel and barrow (Baillie 1924; Anderson 1984). Today this end tipped fill can be distinguished generally as silty or clayey gravels containing various amounts of building debris including wood and glass fragments. End tipped gravels are generally free draining and have low to moderate liquefaction potential and settlement potential (Kingsbury & Hastie 1993; Murashev & Palmer 1998). Although relatively thin, these deposits are likely to amplify earthquake vibrations, especially where they occur in conjunction with loose Holocene or deep sediments (Grant-Taylor et al. 1974).

2.8.2.3 HYDRAULIC FILL

The use of hydraulically pumped sands and muds from the sea floor as reclamation fill material was generally limited to the Thorndon rail yard reclamation (refer to Figure 2.12, WHB Reclamation No. Z) and the area east of Aotea Quay, although it is possible that it was used sparingly at other sites. Today hydraulic fill can be distinguished as silts and silty sands which may contain broken shell pieces. Hydraulic fill sands have a high liquefaction potential. The potential for settlement and lateral spreading is also high (Kingsbury & Hastie 1993; Murashev & Palmer 1998). Hydraulic fill sediments are likely to amplify earthquake vibrations, especially in conjunction with other deep loose deposits.

2.9 CHAPTER SUMMARY

Two major geological units occur within Wellington City. Late Triassic to early Jurassic quartzo-feldspathic sandstone mudstone sequences (greywacke) of the Rakaia Terrane form the basement in the western Wellington region. Quaternary deposits consisting of alluvium, colluvium, terrestrial and shallow marine sediments lie unconformably on top of the basement. The largest recorded Quaternary sequence within the Wellington City study area is 137 m, measured at Te Papa Tongarewa along the Te Aro foreshore. Quaternary deposits generally increase in density with increasing age and a sharp contrast is observed in standard penetration testing between the Pleistocene and Holocene sediments. Waterfront reclamation in Wellington has added more than 155 hectares to the city, including large parts of the central business district. End dumped and hydraulically pumped fill have been used, however compaction was coincidental rather than attempting to reach a set standard (engineered fill). Engineered fill was used in the construction of the Thorndon container terminal and in recent developments.

The Quaternary sediments have vastly different properties to the underlying basement and would be expected to behave differently during an earthquake event. Amplification, subsidence and liquefaction potential are greatest in the younger Quaternary sediments. Increasing density of the progressively older Quaternary sediments will result in reduced levels of amplification from these deposits.

The Wellington region sits astride the active Australian and Pacific Plate boundary zone. Dominant plate motion is accommodated on the strike-slip faults of the NIDFB. There are numerous seismogenic sources in the Wellington region with around 50 active faults capable of producing damaging earthquakes. There are six major active faults within the NIDFB, the Ohariu, Otaki Forks, Shepherds Gully-Pukerua, Wairau, Wellington and Wairarapa Faults. The subduction interface is also capable of generating large damaging earthquakes. The Wellington Fault accounts for more than 50 percent of the earthquake risk in the region, which is the greatest in New Zealand. The properties of these seismogenic sources have been characterised through paleoseismic studies.

CHAPTER THREE

SITE EFFECTS AND CLASSIFICATION

3.1 INTRODUCTION

This chapter provides background information on site effects and site classification. Three earthquake induced hazards are discussed with emphasis on ground shaking amplification. The effect and basic theory behind ground amplification is discussed, with the closely related phenomena of topographic effects also mentioned, providing the necessary technical background for this thesis. Existing legislation including the Resource Management Act 1991, The Building Act 2004 and the New Zealand Structural Design (Earthquake) Actions are mentioned in terms of their relevance to this thesis. Site classification according to the structural design standards is discussed. Site subsoil classes are described in terms of NZS 1170.5:2004 specifications, with methods for their determination given. The evolution of New Zealand's loadings code is summarised along with previous work that is considered directly relevant to this thesis.

3.2 EARTHQUAKE INDUCED PHENOMENA

Whilst earthquakes can trigger a number of hazardous phenomena including fault rupture, land sliding, lateral spreading, liquefaction, settlement, tsunami and ground shaking amplification, only the latter which is directly related to the topic of this thesis is discussed in detail. Wellington City is located directly adjacent to Port Nicholson in a zone of high seismicity (refer to Chapter Two, Section 2.5) and is surrounded by steep hills. As such it is at risk from all of the previously mentioned earthquake phenomena. It is important that the risk of land sliding and tsunami is noted, however they are mentioned in this text only for completeness and are not addressed again elsewhere as they fall outside the scope of this thesis. Liquefaction and lateral spreading are directly related to ground shaking and as such are briefly mentioned. It should be noted that the aim of this thesis was not to address these issues outright and they are included for completeness. As the Wellington Fault crosses the north western central city, fault rupture is also briefly mentioned.

3.2.1 FAULT RUPTURE

During an earthquake centred on one of Wellington's major active faults (refer to Chapter Two, Section 2.5) lateral displacements in the order of 2-6 m could occur on the Wellington, Ohariu, Shepherds Gully-Pukera and Otaki Forks Faults and over 9m on the Wairarapa Fault. Displacements of this order would cause severe damage to lifelines and structures built on, crossing, or positioned near these faults. As an example the Wellington Fault poses a significant risk to the city with half of the water supply carried through pipes crossing the fault (Begg & Mazengarb 1996).

3.2.2 LIQUEFACTION, LATERAL SPREADING AND SETTLEMENT

Liquefaction:

Strong ground motion from earthquakes induces increased pore water pressure which in turn reduces the effective stress of a soil. This reduction in effective stress results in lower shear strength and the soil behaves as a liquid. Liquefaction generally occurs in sandy soils, requiring undrained conditions in conjunction with strong earthquake shaking. Liquefaction resistance increases with increasing fines content, gravel clast size and angularity and stratigraphy depth. Deposits most susceptible to liquefaction are young well sorted sands of Holocene age. These sediments occur within beach, reclamation and stream deposits within the Wellington area (refer to Chapter Two, Section 2.3.5). The effects of liquefaction have been long understood and were observed with disastrous effects in the 1964 magnitude 7.4 Niigata earthquake in Japan and in the 1999 magnitude 7.6 Chi-Chi earthquake in Taiwan (amongst others).

The Niigata earthquake caused extensive damage to the town despite its location being approximately 50 km south of the earthquake epicentre. Structural damage was great with over 3500 houses destroyed, 10,000 damaged and 36 people missing or dead. The earthquake occurred 57 km below the Sea of Japan near the island of Awa-shima. A tsunami generated by the earthquake ravaged the west coast of Honshu, and reached a height of 1.8 m at the town of Niigata. In general the damage at Niigata was caused by perturbation of the subsoil rather than as a result of direct structural vibration. The lower part of Niigata town was built on a thick layer of recent sand deposits. Ground motion affected the dynamic properties of these deposits initiating liquefaction, subsidence and lateral spreading. This lead to a reduction in foundation support and a number of modern multi-storey buildings toppled over with their foundations still intact (refer to Figure 3.1). A number of bridges spanning the Shinano River were also destroyed as a result of pier splaying. Dramatic deformation of railway lines and roads were also observed as a result of subsoil alteration.

Kingsbury & Hastie (1993) reported that liquefaction potential of sediments in Wellington City during a large distant earthquake is variable (from high to low). High liquefaction potential of sediments (especially in the hydraulic fills) is expected from a large Wellington-Hutt valley segment fault rupture on the Wellington Fault (Kingsbury & Hastie 1993).

Figure 3.1: Toppled apartments, Niigata 1964 (US National Geophysical Data Center (NGDC) 1964).

Lateral Spreading:

Lateral spreading is the permanent displacement of ground along a weak or liquefied soil layer toward a free edge, such as a reclamation edge, as a result of strong earthquake shaking. As such, lateral spreading is likely to occur adjacent to the harbour and stream areas in Wellington City. Lateral spreading has been observed in a number of earthquakes including the 1989 Loma Prieta event (San Francisco). Some ground remediation works have been undertaken to mitigate the potential for lateral spreading along Wellington's waterfront (Murashev & Palmer 1998).

Settlement:

Settlement (or subsidence) involves the downward movement of sediment (refer to example given in Figure 3.2). There is a high potential for earthquake induced settlement to occur within the Wellington waterfront reclamations. Murashev and Palmer (1998) report that settlements up to 200 mm per 5 m of fill have been predicted.

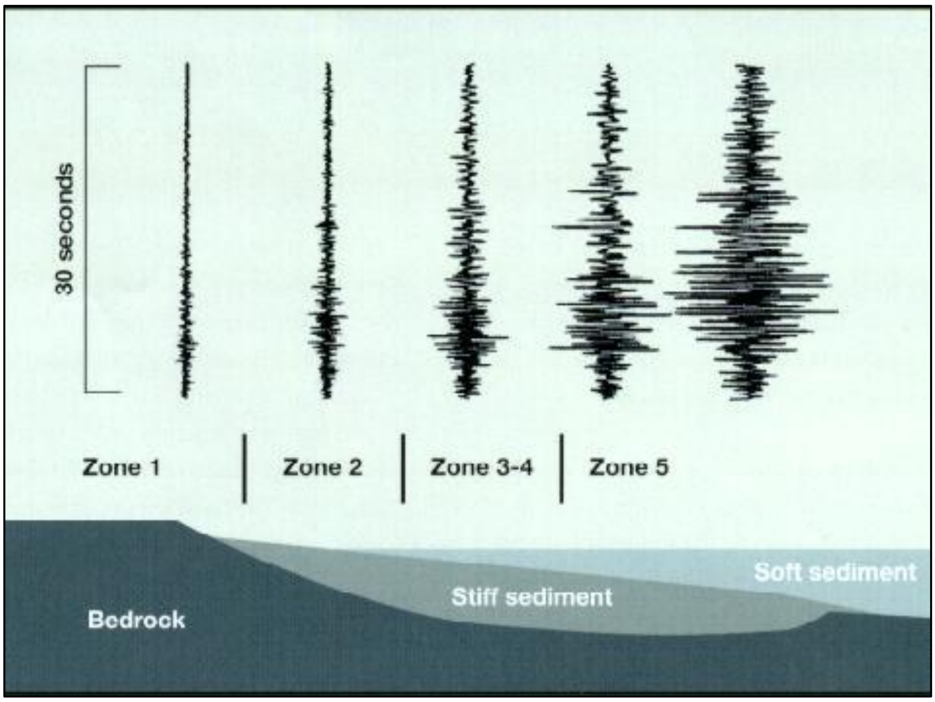
Figure 3.2: Tipped residence due to differential settling, Caracas, Venezuela (US National Geophysical Data Center (NGDC) 1967).

3.2.3 GROUND SHAKING AMPLIFICATION - SITE EFFECTS

Seismic waves radiate out from the source of an earthquake and move rapidly through the earth. These waves cause ground shaking when they reach the earth's surface. This shaking can last from a fraction of a second to minutes and is greatly influenced by the local geology. Ground shaking is the most important seismic hazard as it is the mechanism for all other earthquake hazard phenomena (excluding fault rupture).

Local geologic conditions (site conditions) influence the amplitude, frequency and duration of strong ground motion. This variation in geotechnical properties governing a soil's seismic response characteristics is often referred to as "site effects" (refer to Appendix 3A for basic site effect theory). It should be noted that "soil" in this context refers to the sub-surface geology consisting of fill, unlithified sediments and soft rock that overlies bedrock. The influence of local site conditions depends upon the earthquake motion characteristics, the distance from the fault, site topography and the geotechnical properties of the soil and rock. Local site effect behaviour can be illustrated by simple theoretical calculation and observed by measuring ground motion at geologically varying sites within close proximity (refer to Figure 3.3).

Figure 3.3: Seismograph traces illustrating the influence of local geological conditions on ground shaking (Taber et al. 1998).



The effects of local site conditions on strong ground motion intensity have been known for a number of years with historical references dating back some 200 years. For example, it was noted that shaking intensity in the 1906 San Francisco Earthquake was related to local geologic conditions (Wood 1908). Quantitative measurements of local site effects have only recently been done with the development of strong ground motion recording instruments (Kramer 1996). Specific provisions accounting for local site effects did not appear in New Zealand's loading code until 1976.

Amplified ground motions can cause excessive damage to structures located at considerable distances (100 km$^+$) from earthquake epicentres. The larger the amplitude of ground motion, the greater the forces acting on the structure. Damage tends to be greater where softer sediment layers are present. Ground shaking amplification (particularly for motions ~ < 0.4g) generally increases with increasing sediment thickness. Buildings founded on differing soils will suffer differing levels of damage during earthquake shaking especially from far-field sources (Davenport & Stephenson 2005). Varying levels of structural performance will also lead to variation in damage during earthquake. The frequency of ground motion governs the size of structure that is most likely affected. Taller buildings tend to be damaged by slow vibrations (low frequency/low stress drop) whereas shorter buildings are more at risk from rapid ground motion (high stress drop). The longer the duration of earthquake shaking, the more likely a structure is to be damaged. This results because continuous flexing causes columns and beams to yield, and eventually fail at the limit of the elasto-plastic range where the steel becomes brittle. Most earthquake fatalities and damage generally occur when structures fail during violent shaking caused by seismic waves. Recorded damage patterns conclusively illustrated the effects of local site conditions on ground amplification. It should be noted that magnitude of damage is also a function of building form, with some inverted pendulum structures (e.g. water towers) particularly prone to damage. Amplification of ground motion contributed to the widespread damage in Mexico City during the 1985 earthquake (refer Appendix 3B). The Marina District of San Francisco was also heavily damaged during the 1989 Loma Prieta earthquake. In both cases the epicentre was located more than 100 km from the affected areas. Earthquake damage in Wellington from the 1942 Masterton earthquake clearly demonstrated ground motion amplification. Damage was much more severe in the central city (located on soft sediments) than in the surrounding hilly (greywacke bedrock) suburbs.

3.3 EXISTING LEGISLATION

3.3.1 HAZARD CLASSIFICATION

Definitions of hazard, risk and disaster are outlined below. There is some ambiguity over how these terms are defined and as a consequence they have been appropriately specified for use in this thesis.

3.3.1.1 HAZARD

A hazard is a situation that poses a level of threat to life, health, property or the environment. A hazard does not exist when it is happening and once active can create an emergency situation.

3.3.1.2 RISK

Risk = Likelihood of occurrence of a hazardous event multiplied by the seriousness if the incident occurred (i.e. severity of injury, ill health, building damage etc.).

3.3.1.3 DISASTER

A disaster is the tragedy of a natural or man-made hazard that exhibits a negative effect on society or environment and may occur as the consequence of inappropriately managed risk (can include events such as earthquakes, landslides, floods, and tsunami).

3.3.2 THE RESOURCE MANAGEMENT ACT 1991

The Resource Management Act 1991 covers land use issues in New Zealand including the placement of buildings and their intended use. Under the Resource Management Act 1991, regional councils must coordinate investigations into, and maintain information about, natural hazards within the region. Territorial authorities also have responsibilities for natural hazards and must prepare and maintain a district plan managing the effects of land use. They must also gather the appropriate information on hazards associated with that land use. The Resource Management Act 1991 requires regional councils and territorial authorities to agree on their respective responsibilities to adequately manage the region’s hazards (New Zealand Government 2009b).

3.3.3 THE BUILDING ACT 2004

The Building Act 2004 contains legal requirements for a building's construction including the safety and integrity of that structure. The building act applies to the construction of new buildings and the alteration and demolition of existing buildings. Under the Building Act, all construction work must comply with the mandatory Building Code which prescribes functional requirements for buildings and the performance criteria with which buildings must comply in their intended use. A code of compliance certificate is issued when a building (or part thereof) is in compliance with the particular provisions of the building code (New Zealand Government 2009a).

3.3.4 NZS 1170.5:2004 STRUCTURAL DESIGN (EARTHQUAKE) ACTIONS

NZS 1170.5:2004 sets out the procedures and criteria in relation to the earthquake actions for the limit state design of structures (and parts thereof) to be applied by suitably qualified professionals. All structures must comply with the standards (i.e. the Building Code), which aim to prevent (amongst other things) the total collapse of structures (limiting the loss of life) and enable critical post earthquake structures (e.g. hospitals) to remain in an operational state. These standards are implemented by the Department of Building and Housing and supersede NZS 4203:1992 (General structural design and design loadings for buildings). New Zealand has a well respected loadings code which is periodically reviewed and updated reflecting the progress in science and technology. It should be noted that the term loading(s) code also refers to the structural design actions/standards and is used throughout the text.

3.4 NEW ZEALAND EARTHQUAKE ACTIONS AND SITE CLASSIFICATION

As previously mentioned, in New Zealand site conditions are dealt with in Section 3, site hazard spectra within the earthquake structural design actions (NZS 1170.5:2004). Site classification is required to calculate both horizontal and vertical loading. (Note: NZS 1170.5:2004 uses SI units of kilograms, metres, seconds, Pascals and Newtons unless stated otherwise).

3.4.1 HORIZONTAL LOADING

The elastic site hazard spectrum for horizontal loading C(T) for a given return period is given by Equation 3.1 (NZS 1170.5:2004):

$$\mathbf{C(T) = C_h (T)\, Z\, R\, N(T, D)}$$

Where

$C_h(T)$ = the spectral shape factor determined from NZS 1170.5:2004 Table 3.1 for a defined site subsoil class (refer to Table 3.1).

Z = the hazard factor. Z = 0.40 for Wellington CBD (north of the basin reserve) with $D \leq 2$ km (given by Table 3.3 in NZS 1170.5:2004).

R = the return period factor for the appropriate limit state determined. R=1 for 1/500 required annual probability of exceedance.

N(T, D) = the near-fault factor which accounts for the effects of earthquake ground motions within a few kilometres of the earthquake rupture surface. Wellington Fault requires a near fault factor >1.

3.4.2 VERTICAL LOADING

The elastic site hazard spectrum for vertical loading $C_v(T)$ for a given return period is given by Equation 3.2 (NZS 1170.5:2004):

$$\mathbf{C_v (T) = 0.7\, C (T)}$$

Where

C (T) = the elastic site hazard spectrum for horizontal loading (determined form equation 3.1 for the modal or time history method of analysis).

Table 3.1: Spectral Shape Factor, C_h (T), Standards New Zealand (2004), NZS 1170.5:2004 Table 3.1.

	Spectral Shape Factor, C_h (T) (g)			
Period, T (seconds)	Site Subsoil Class			
	A & B	C	D	E
	Strong Rock & Rock	Shallow Soil	Deep or Soft Soil	Very Soft Soil
0.0	1.89 (1.00)	2.36 (1.33)	3.00 (1.12)	
0.1	1.89 (2.35)	2.36 (2.93)	3.00	
0.2	1.89 (2.35)	2.36 (2.93)	3.00	
0.3	1.89 (2.35)	2.36 (2.93)	3.00	
0.4	1.89	2.36	3.00	
0.5	1.60	2.00	3.00	
0.6	1.40	1.74	2.84	3.00
0.7	1.24	1.55	2.53	3.00
0.8	1.12	1.41	2.29	3.00
0.9	1.03	1.29	2.09	3.00
1.0	0.95	1.19	1.93	3.00
1.5	0.70	0.88	1.43	2.21
2.0	0.53	0.66	1.07	1.66
2.5	0.42	0.53	0.86	1.33
3.0	0.35	0.44	0.71	1.11
3.5	0.26	0.32	0.52	0.81
4.0	0.20	0.25	0.40	0.62
4.5	0.16	0.20	0.32	0.49

3.4.3 SITE SUBSOIL CLASS

NZ has five site class categories: A (strong rock), B (rock), C (shallow soil), D (soft or deep soil) and E (very soft soil) (refer to Table 3.2 and 3.3 for their definitions). These "consider both the soil type and depth, which determine a site's dynamic stiffness and period" (NZS 1170.5:2004 Standards New Zealand 2004) which are the primary factors in determining the response characteristics of a site. The site class definitions are generally descriptive due to the lack of subsurface information available within New Zealand (reliable measurement of shear wave velocity is seldom made). It should be noted that in this thesis class "A" is referred to as a "high" subsoil class decreasing alphabetically to class "E" which is considered a "low" subsoil class.

Table 3.2: Site Class Definitions from NZS 1170.5:2004 (Standards New Zealand 2004).

Class	Description	Definition
A	**Strong Rock**	UCS > 50 MPa & V_s 30m > 1500 m/s & Not underlain by < 18 MPa or V_s 600 m/s materials.
B	**Rock**	1 < UCS < 50MPa & V_s 30m > 360 m/s & Not underlain by < 0.8 MPa or V_s 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 Have depths of soils not exceeding those in Table 3.3.
D	**Deep or Soft Soil**	Not class A, B or E, Low Amplitude Natural Period > 0.6s, or Have depths of soils exceeding those in Table 3.3, or Underlain by < 10 m soils with undrained shear strength < 12.5 KPa, or < 10 m soils SPT N < 6.
E	**Very Soft Soil**	> 10 m soils with undrained shear strength < 12.5 KPa, or > 10m soils with SPT N < 6, or > 10 m soils with Vs ≤ 150 m/s, or > 10 m combined depth of above properties.

- The preferred method for site classification in New Zealand uses the low-amplitude natural period (site period) parameter. The site period (when not measured directly) is defined as four times the estimated travel time of shear waves from the surface to bedrock. This approach addresses the effects of deeper softer soils which exhibit longer period site response characteristics.
- The next most preferred methods are from the use of borelogs (which include the measurement of geotechnical properties), or the calculation of site periods from Nakamura ratios or recorded earthquake motions.
- The determination of site class using borelogs containing only geological descriptions is the second least preferred method of site classification.

- The least preferred method is from surface geology with estimates to underlying bedrock NZS 1170.5:2004 (Standards New Zealand 2004).

Layered sites are evaluated by estimating and summing the contribution to natural period for each layer whereby all material above bedrock is included in the evaluation. An unconfirmed compressive strength of 1 MPa delineates the rock-soil boundary. In general, the classification of a site will be dependent on the surficial sediments present even when piles extend below to stiffer stratum.

Table 3.3: Maximum depth limits for site class C from NZS 1170.5:2004 (Standards New Zealand 2004).

Soil Type & Description		Max. Depth (m)
Cohesive Soil	**Representative Undrained Shear Strength (KPa):**	
Very Soft	< 12.5	0
Soft	12.5-25	20
Firm	25-50	25
Stiff	50-100	40
Very Stiff/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

It can be seen from equation 3.1 and 3.2 that both horizontal and vertical loading will increase as a result of an increased spectral shape factor value arising from a lower subsoil class (e.g. class D & E). Increased loading requires an increase in the amount of reinforcement used within a structure, which in turn requires more construction materials and longer build times. Therefore it can be seen that a lower site class will require greater design strength which will be reflected by an increase in a structure's design and construction costs.

3.5 EVOLUTION OF NEW ZEALAND'S LOADINGS CODE

Seismic loading requirements have become better defined with the increase in understanding of New Zealand's seismicity and structural performance.

Provisions considering seismic loading in structural design were first drafted after the disastrous 1931 Hawke's Bay earthquake. This draft made recommendations for improving building construction standards, especially for important public services. Site conditions were mentioned but their behaviour was not yet clearly understood. The draft contained provisions with the intent of avoiding structural collapse in an earthquake (Davenport 2004).

In 1935 the New Zealand Standard Model Building By-Law was developed, drawing from the 1931 draft as well as British and American work. This by-law also contained provisions relating to construction materials, in particular masonry, reinforced concrete and structural steel. The by-law had to be adopted by each local authority with not all doing so (New Zealand Standards Institute 1935).

Revisions were made to the 1935 by-law and in 1965 the revised New Zealand Standard Model Building By-Law (NZSS 1900) was introduced. As with the previous 1935 by-law it did not apply automatically and needed to be adopted by the local authorities (New Zealand Standards Institute 1965; Davenport 2004).

Another major revision of the loading requirements was introduced in 1976 titled the "Code of practice for general structural design and design loadings for buildings" (NZS 4203:1976). A significant alteration in the new code was the introduction of metric units. The aim of the 1976 code was to provide an economically feasible level of protection to life and property, and emphasised the ultimate strength design method (with load factors based on western United States practices). The code introduced specific requirements for different soil types using higher coefficients for softer/looser soils (Standards Association of New Zealand 1976). However, “the two subsoil classes were defined in general terms and required some judgement to apply” (Davenport 2004). Another revision of the loadings code was made in 1984 (NZS 4203:1984), which was essentially a minor update of the 1976 code with the basic coefficients, seismic zones and soil types remaining unchanged (Standards Association of New Zealand 1984).

A major revision of the earthquake loading code was introduced in 1992 (NZS 4203:1992). The code aimed for the design of symmetrical structures with the philosophy that structural configuration played an important part in earthquake resistant design. The 1992 loadings code introduced limit state design, with both a serviceability and ultimate limit state (Standards New Zealand 1992). Three soil classes were given (rock/stiff soil, intermediate soil and flexible/deep soil) and although better defined than in the previous 1984 revision, they still required considerable judgement to apply in practice (Davenport 2004).

The current loadings code was introduced in 2004 (NZS 1170.5:2004) and is based on New Zealand probabilistic seismic hazard analysis (PSHA). Seismic hazard in New Zealand was assessed using PSHA with the main aim of updating the previous hazard maps (NZS 4203:1992) which were considered outdated. Using the code, an elastic site hazard spectrum for horizontal loading is calculated for a given earthquake return period. The spectral shape factor which is one of the key parameters of the site hazard spectrum depends on subsoil class. Attenuation relationships were developed for five site classes namely strong rock (A), rock (B), shallow soil (C), deep/soft soil (D) and very soft soil (E). Site classification is based on site period and the code gives a hierarchy for site classification involving different methods for estimating site period (Standards New Zealand 2004). Some geotechnical understanding of the site is required to determine the appropriate class which can be difficult if there is a lack of site data at depth.

3.6 PREVIOUS WORK

3.6.1 HISTORIC EARTHQUAKE DAMAGE IN WELLINGTON

The following earthquakes are known to have affected Wellington City (refer to Table 3.4; Modified Mercalli Scale):

- **1848 Marlborough Earthquake (MMVII)**

  In Wellington City, almost all buildings made from brick or stone were significantly damaged including the colonial hospital. Ground cracks and sand boils were observed in the central city. Wooden buildings were generally undamaged although most lost their brick chimneys. Three people were fatally injured as a result of building collapse triggered by one of the aftershocks (Grant-Taylor et al. 1974; Murashev & Palmer 1998).

- **1855 Wairarapa Earthquake (MMX)**

  Wellington experienced severe ground shaking in the 1855 earthquake (refer to Chapter Two, Section 2.5.5.1 for more information). The resulting damage was limited as the city had been extensively rebuilt following the 1848 Marlborough earthquake, primarily using timber frame construction. One person was killed in Wellington City and at least another four people (possibly as many as eight) were reported to have died during the earthquake. Fissures were observed in the central city "erupting white mud", and numerous landslides and extensive uplift also occurred (Grapes & Downes 1997; Murashev & Palmer 1998).

- **1929 Murchison Earthquake (MMVI)**

  Cracks were observed in the asphalt surfacing in the area adjacent to Pipitea Wharf after the 1929 Murchison Earthquake (Murashev & Palmer 1998). Severe local damage to houses was reported with no injuries or loss of life.

- **1942 Masterton Earthquakes (MMVI-MMVII June & MMVI August)**

  Structural damage in Wellington City and the surrounding region was extensive in part due to the cumulative effects of the two earthquakes (the second occurred while damage was still being repaired). In Wellington City at least 5,000 houses and 10,000 chimneys were damaged by the two large earthquakes. Subsidence of reclaimed land along the waterfront was reported, along with cracks in many of the city's masonry structures and sand boils in the vicinity of the Aotea Quay on ramp (possible liquefaction). One person was killed in Wellington by coal gas escaping from a fractured pipe. In the surrounding region the earthquakes caused numerous landslides, and damaged many roads, bridges and railway lines (Grant-Taylor et al. 1974; Murashev & Palmer 1998).

- **1968 Wellington Earthquake (MMVI)**
  Grant-Taylor et al. (1974) reported cracking in beams, columns, concrete, block and brick panel walls, and the ceilings of buildings in central Wellington City.

Table 3.4 Modified Mercalli Scale (United States Geological Survey 1990; Begg & Johnston 2000).

MMI	Description of Effects	
I	Instrumental	Generally not felt by people (unless conditions are favourable).
II	Feeble	Felt only by a few people at best, especially on the upper floors of buildings. Delicately suspended objects may swing.
III	Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV	Moderate	Felt indoors by many people, outdoors by few people during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rock noticeably. Dishes and windows rattle alarmingly.
V	Quite Strong	Felt outside by most, may not be felt by some outside in non-favourable conditions. Dishes and windows may break and large bells will ring. Vibrations like large train passing close to house.
VI	Strong	Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
VII	Very Strong	Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by people driving motor cars.
VIII	Destructive	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.
IX	Ruinous	General panic; damage considerable in specially designed structures, well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Disastrous	Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundation. Rails bent.
XI	Very Disastrous	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Catastrophic	Total damage - Everything is destroyed. Total destruction. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock move position.

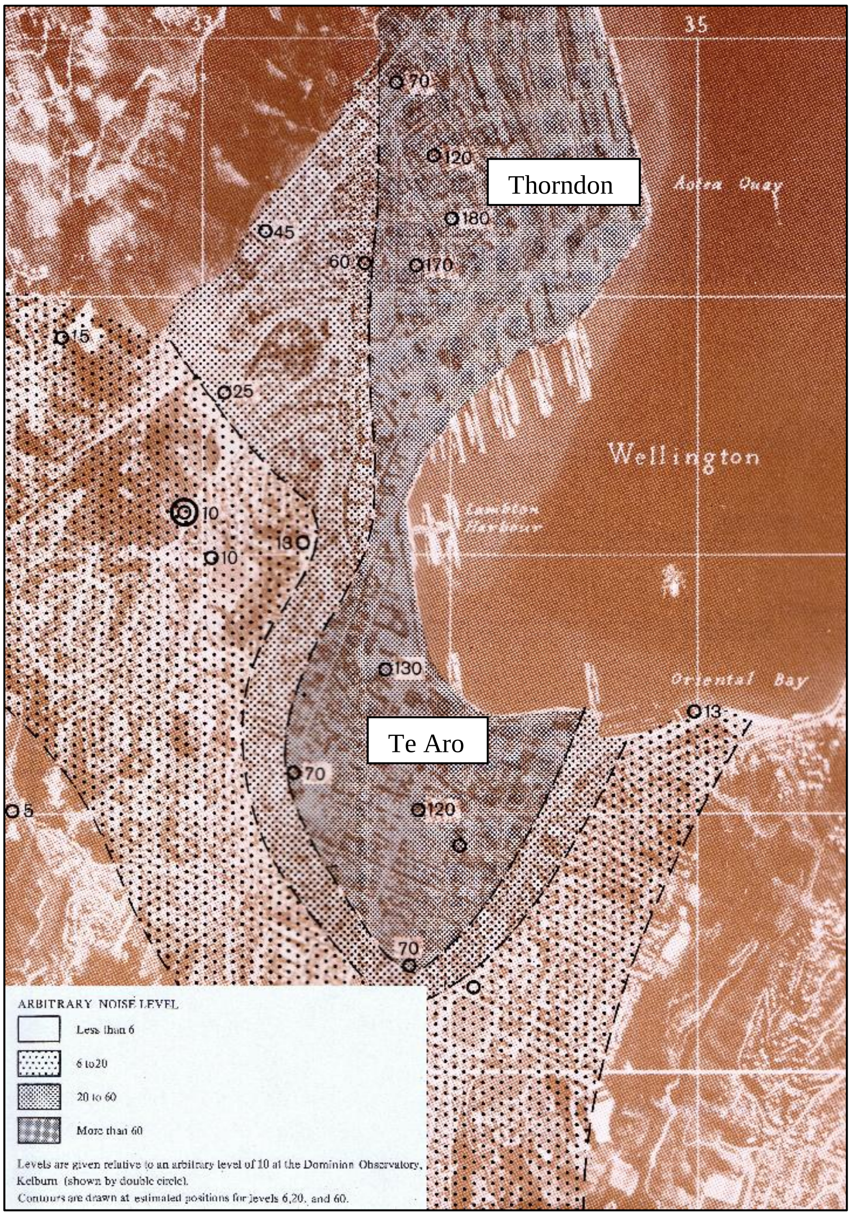
3.6.2 RELATED STUDIES

There have been numerous geological and engineering related studies in Wellington and the surrounding region since the city's seismic risk was first realised. Hundreds of studies have focused on the seismic risk in Wellington City and the related earthquake triggered hazards. This section covers the most significant accessible research in relation to site effects and microzoning within the city. It is divided into three subsections based on time intervals associated with the evolution of New Zealand's loading code (refer to Section 3.5). These intervals are namely pre-1976, 1976 to 2004 and post-2004 studies. The pre 1976 interval was chosen as it represents a time before previsions were made addressing subsoil conditions in the loadings code. The 1976 to 2004 interval represents an extensive period of time where two notable revisions were made to the loadings code (1984 and 1992), after the 1976 version (first containing provisions directly addressing site conditions) was adopted. The implementation of the Resource Management Act in 1991 triggered a series of hazard related studies as regional authorities moved to comply with their requirements. The post 2004 period represents the time since the current loadings code was first implemented. Results from this thesis are compared with some of the previous research in Chapter Six.

3.6.3 PRE-1976 STUDIES

Adams & Orr (1970) conducted a microseismic noise survey in Wellington City between 1968 and 1970. The aim of the study was to determine microseismic noise levels as an aid to understanding the general vibrational response of soil deposits within the city. Measurements were made for approximately 5 minutes at 107 different sites, with approximately 20 of those sites located within the Wellington City study area (defined in Chapter One). A map was constructed highlighting the broad pattern of noise within the city (refer to Figure 3.4), which was later published in the 1974 Microzoning Bulletin (Grant-Taylor et al. 1974). The results showed that in general, measurements on greywacke bedrock sites had lower microseismic noise levels than those sites positioned above colluvium/alluvium. Noise levels along the waterfront, Thorndon and within the Te Aro Valley were the highest, although it was noted that man made noise (traffic etc) may have had an influence on the results (Adams & Orr 1970).

Figure 3.4: Microseismic noise in Wellington City (Grant-Taylor et al. 1974).



Microzoning for earthquake effects in Wellington, NZ was published in 1974 (Grant-Taylor el al.) and at the time provided a comprehensive guide to the geology and seismological study results for Wellington City. The report covered in detail the geology and soils of the city, gravity and microseismic surveys (using information from Adams & Orr 1970), soil dynamics (including amplification, rotation and stretching under earthquake vibration), factors influencing earthquake risk, felt earthquakes in the Wellington area and related damage patterns. In addition to the 62 page report, maps detailing the geology, soil, bedrock depth (isopach map), residual gravity anomalies, relative microseismic noise levels, damage distribution from the 1968 earthquake (refer to Section 3.6.5) and microzone map of Wellington were produced. The report drew information from numerous sources; in addition 13 boreholes specific to the study were drilled to a combined depth of more than 550 m (Grant-Taylor et al. 1974).

Residual gravity anomalies indicated a north east trending basin in the Te Aro area with an easterly dipping bedrock surface in the Thorndon area. The depth to bedrock (isopach) map was constructed using information from more than 30 boreholes along with the residual gravity results in the central city. This map has been very useful in providing an indication of bedrock depth in Wellington City, vital for foundation investigations, and still finds use today some 35 years on. The damage distribution map (from the 1968 earthquake) clearly shows evidence for increased damage in Te Aro, Thorndon and the waterfront areas. The microseismic noise map is a remake of the 1970 Adams & Orr map (refer to Figure 3.4) and shows higher noise levels in Te Aro, Thorndon and the waterfront areas. The accompanying geological map indicated fill, marine deposits and gravel in Te Aro, Thorndon and waterfront areas, where damage from the 1968 earthquake was greatest. A microzone map for Wellington City was constructed with the central business district assigned either zone 2 or zone 3 classification. Zone 3 was defined as high porosity sediment, with significant amplification of incident vibration expected. Zone 2 was defined as compact sediments with small amplification of incident vibration expected. Zone 1 (assigned to the hills surrounding the central city) was defined as basement rock, with no amplification of incident vibration expected (Grant-Taylor et al. 1974).

Now largely outdated, as a result of progressive research and numerous site investigations in Wellington City, the 1974 microzoning report provides a good indication of ground conditions in Wellington City as understood in the early 1970's.

3.6.4 1976 TO 2004 STUDIES

The most significant studies from the 1976-2004 period are discussed in chronological order in the following text.

The 1992 "Report on cone penetrometer and seismic cone penetrometer probing in Wellington City, Kapiti Coast and Upper Hutt Valley" (Stephenson & Barker 1992) explored the likely locations of flexible sediment in these areas. These sediments were targeted as they are likely to amplify earthquake ground motions, thus increasing damage. The report concluded that in the Wellington hospital and possibly the Te Aro areas, earthquake induced forces would be multiplied by five for earthquakes magnitude ≥ 6, centred more than 60 km from Wellington City.

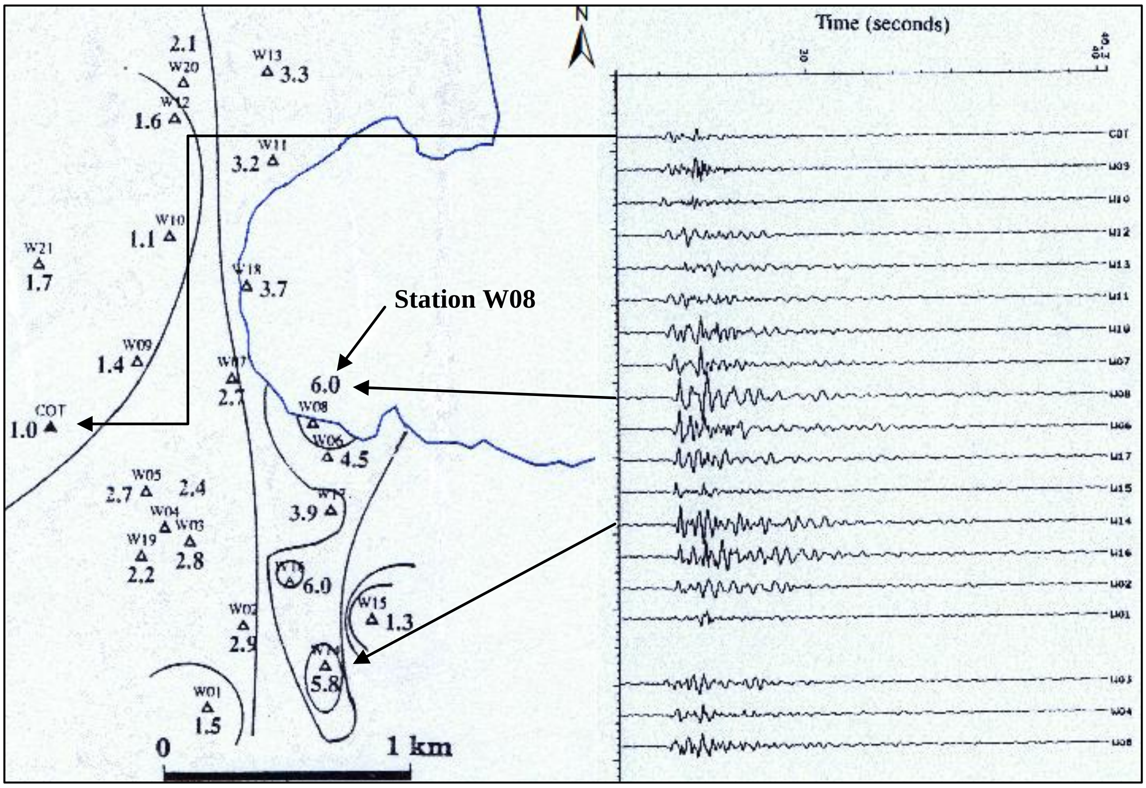
The “Compilation of geological data, Wellington area report” (Perrin & Campbell 1992) provides a useful indication of Pleistocene and Holocene geology and bedrock depth in the Wellington City area. The report and accompanying maps were compiled from 804 borelogs (or composite logs from several holes at one site) and archival data. Of these 804 borelogs, approximately 700 occur within the Wellington City study area and have been used for this study. Pleistocene and Holocene geological deposits were mapped at a scale of 1:10,000 for the central city; this data was also used to construct an earthquake shaking hazard (microzone) map. Contouring of the depth to bedrock and the thickness of soft and loose near-surface sediments was also undertaken and, due to the much larger input data set, a far greater level of confidence was obtained than that of the maps published by Grant-Taylor et al. (1974). A significant change in the depth to bedrock map from the one published by Grant-Taylor et al. (1974) was the doubling of the depth to bedrock (approximately 70 to 140 m) in the Taranaki St Wharf-Clyde Quay area, which was confirmed by drilling at the then Te Papa Tongarewa (Museum of New Zealand) site. Another significant finding from this study was that Wellington City Pleistocene and Holocene sediments could be differentiated using Standard Penetration Test results. The maps from this study have a good fit with the gravity map published in Grant-Taylor et al. (1974). Areas of soft sediment also correspond well with areas of greater building damage during the 1942 and 1968 earthquakes (Grant-Taylor et al. 1974).

The 1992 report titled “Earthquake ground shaking hazard assessment of the Wellington area, New Zealand” identified and quantified the local variations in strong ground motion expected during a damaging earthquake in Wellington City. Four hazard zones were identified and mapped, using geological, microseismic and strong motion data, with the response of each zone determined for two earthquake scenarios (Van Dissen et al. 1992b).

In 1993 Kingsbury & Hastie compiled a liquefaction hazard map for Wellington City at a scale of 1:50,000. The map was published by Wellington Regional Council as part of the seismic hazard map series, and provided information on the earthquake induced hazards in the Wellington City area. The map and accompanying notes highlighted liquefaction potential and related phenomena for two earthquake scenarios. These scenarios were 1, a large distant shallow earthquake and 2, a large earthquake centred on the Wellington Fault. Their map showed that the central city, Thorndon and Te Aro areas had moderate to high liquefaction potential under scenario 1. They also showed that the area surrounding the harbour (reclamation) had the highest potential for lateral spreading and large scale subsidence during both earthquake scenarios.

Taber (1993) presented a paper titled “Instrumental recording of microzonation effects” at the 1993 New Zealand Society for Earthquake Engineering conference. This paper was based on the report prepared for Wellington Regional Council titled “frequency dependent amplification of weak ground motions in Wellington City and the Kapiti Coast”. The main aim of this study was to provide a clear picture of ground shaking in the Wellington region. Seismographs at 27 sites in Wellington City, covering the range of representative soils, were deployed in the city with the reference site (COT) located in the seismic vault 10 m beneath the Cotton building at Victoria University of Wellington. Thirty earthquakes ranging from M 2.5-6.1 were recorded and used for this study, with between four and ten used to determine the average response at each site. The results showed greater amplification near the harbour with the highest shaking recorded at Taranaki St Wharf. High amplifications were also recorded at Kent Terrace, Te Aro and one site at Wellington Hospital, while smaller amplification levels were recorded in the central city and Thorndon (refer to Figure 3.5). Taber concluded that microearthquake recording of ground motion was best for determining areas of greater shaking rather than absolute values (Taber & Richardson 1992; Taber 1993). Results from this study fit in well with others e.g. Taylor et al. (1974), Perrin & Campbell (1992) and Van Dissen et al. (1992b).

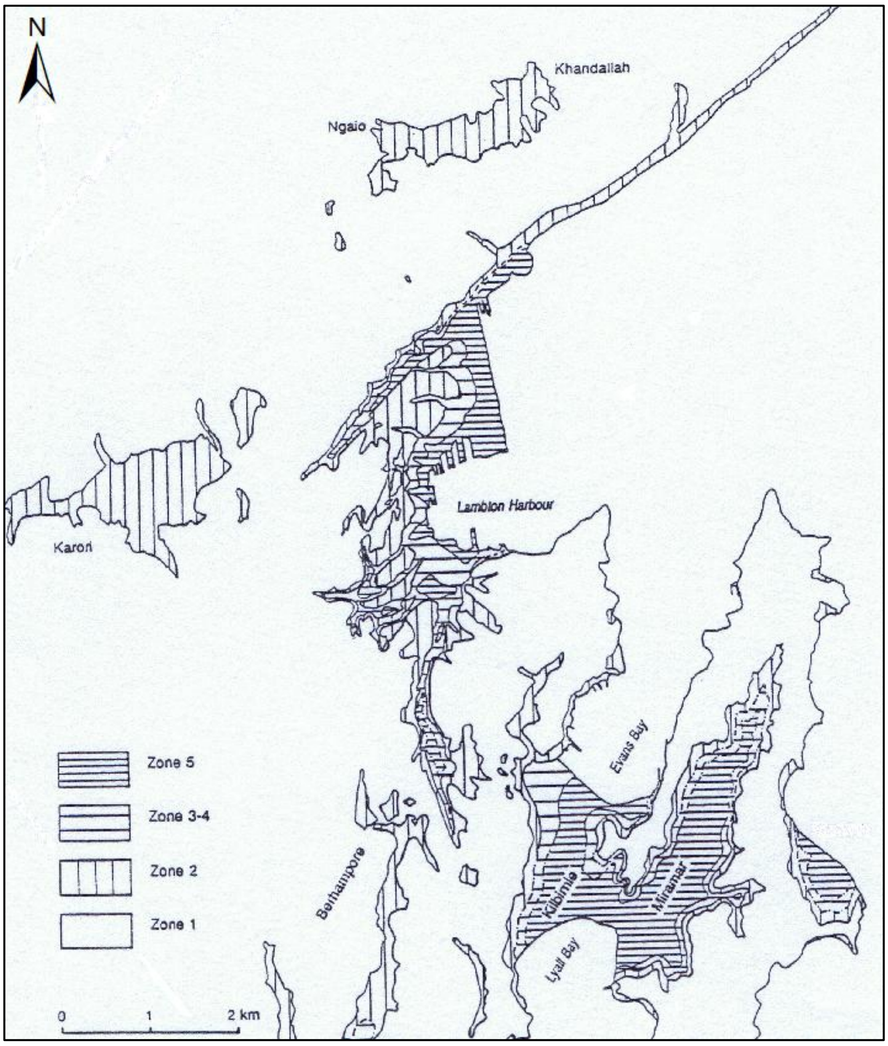
Figure 3.5: Velocity seismograms for a magnitude 3.7 earthquake centred 40km from Wellington City. (Taber 1993).



The solid triangle shows the reference site (COT). Maximum velocity of 1.2 mm/s recorded at station W08 (Taranaki St Wharf). Contours are plotted at 1 unit intervals.

Van Dissen et.al (1993) presented a paper titled “Ground shaking hazard zonation for Wellington city and suburbs, New Zealand” at the 1993 New Zealand Society for Earthquake Engineering conference. The Wellington area was mapped into four ground shaking hazard zones (refer to Figure 3.6) based on the combination of ground motion and geological data for two distinct earthquake scenarios. The zones ranged from 1 to 5, with zone 5 expected to experience the highest levels of shaking (soft and loose sediment), zone 3-4 forming a transition between zone 2 and 5, zone 2 (stiff sediment), the second least shaking and zone 1 (bedrock), the least shaking. This study presents a more refined map (due to a large increase in available geological and geotechnical data) than that published by Grant-Taylor (1974). However, with the exception of better constrained boundaries (especially bedrock), in general the results compare well (Van Dissen et al. 1993).

Figure 3.6: Ground shaking hazard map of the Wellington area (Van Dissen et al. 1993).



Clitheroe & Taber (1995) presented a paper titled "Assessing earthquake site response using microtremors: a case study in Wellington City" at the 1995 Pacific conference on earthquake engineering. They used microtremor data to investigate two methods of assessing the ground shaking hazard in Wellington City. The first involving the isolation of site response from source and path effects, the second using the technique proposed by Nakamura (1989). They found poor correlation between the results using the first method with those obtained from an earlier study using weak motion. Using Nakamura's method they found the results compared well with those obtained from weak motion, providing further evidence that Nakamura's method for approximating site response from microtremors is valid (Clitheroe & Taber 1995).

The Greater Wellington Regional Council produced a combined earthquake hazard map in 1996. This map highlighted five earthquake induced hazards, namely fault movement, ground shaking, liquefaction, slope failure and tsunami. As the map title suggests, a hazard index was used to show the combined hazard from the five specified hazards ranging from low (cool colours) to high (warm colours). Four reduced maps indicating the individual hazards were also included alongside the main map. The map sheet provides a good summary of the main earthquake hazards in the Wellington City area (Greater Wellington Regional Council 1996).

The 1996 GNS Science Report (Cousins et al. 1996) titled "Ground conditions at strong-motion recording sites in New Zealand" describes the ground conditions at 41 accelerograph sites in Wellington City. Details of a sites topography, subsurface conditions and available subsurface data are given (Cousins et al. 1996).

Van Dissen & Berryman (1996) published a summary paper detailing the paleoseismicity of the region's most hazardous faults.

Murashev & Palmer (1998) published a paper highlighting the geotechnical issues associated with development on Wellington's waterfront with examples of recent developments and how issues were addressed. The paper concluded that the area of reclaimed land along the waterfront has the potential for ground damage as a consequence of strong ground motion. Ground damage resulting from strong shaking in the area would include settlement, possibly liquefaction and lateral spreading.

Stirling et al. (1998) published the paper titled "Probabilistic seismic hazard analysis of New Zealand". Probabilistic seismic hazard (PSH) maps for New Zealand were constructed using information from 154 active faults combined with observations of earthquake magnitudes and rupture length for historic earthquakes in New Zealand. Maps of the peak ground accelerations show that the highest levels occur in a zone that extends from the south-western end of the country to the north-eastern end, along the faults that accommodate plate motion between the Australian and Pacific plates. Wellington City lies within the zone of high PSH with accelerations of > 0.4g predicted (Stirling et al. 1998). This study concluded that Wellington is subject to the highest seismic hazard in New Zealand.

Stirling et al. (2002) published a paper titled “A new seismic hazard model for New Zealand”. Their probabilistic seismic hazard analysis (PSHA) model combines seismicity data with geological data for the location and earthquake recurrence behaviour of 305 active faults, with new attenuation relationships for peak ground acceleration developed specifically for New Zealand. The PSH maps from this study were used in the development of the 2004 loadings code, which was previously based on PSHA models that did not specifically include individual faults as earthquake sources (Stirling et al. 2002).

McVerry (2003) presented a paper at the Pacific conference on earthquake engineering titled “From hazard maps to code spectra for New Zealand”. This paper highlighted the development of the New Zealand seismic coefficients which are part of the New Zealand Loadings Standard, derived from a probabilistic seismic hazard analysis (PSHA).

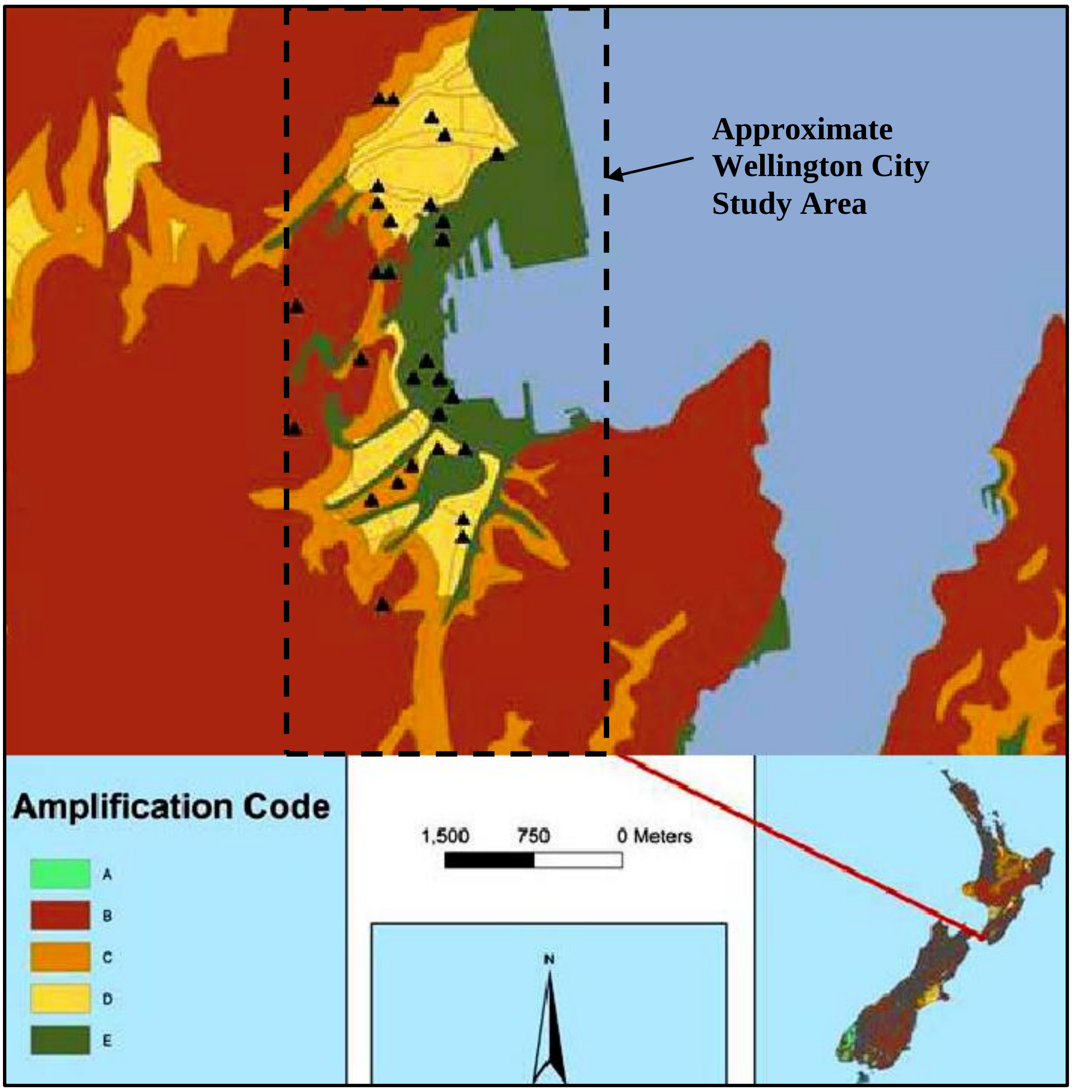
Two significant geological maps were published in the 1976-2004 time period. In 1996 the 1:50,000 scale geological map of the Wellington area was published (Begg & Mazengarb 1996). In 2000 the 1:250,000 scale geological map of the Wellington area (Begg & Johnston 2000) was published as part of the quarter-million map (QMAP) series, with the former proving more useful for engineering purposes (due to scale).

3.6.5 POST-2004 STUDIES

Benites & Olsen (2005) modelled strong ground motion in the Wellington region as a result of a pseudo M 6.7 rupture on the Wellington Fault. Their findings indicated amplification factors between 0.5 (deamplification) and 2 for Wellington City, with the exception of one site located on reclaimed land (Pipitea) giving an amplification factor of 9 (Benites & Olsen 2005).

There has been one significant, publically available study involving site classification in Wellington since the adoption of the 2004 loadings code, although it is likely that others may exist in the private sector, especially in the form of commercial reports assigning NZS 1170.5 site class. Destegul et al. (2009) produced a ground shaking amplification map for New Zealand. The map was constructed by assigning one of the site classes described in NZS 1170.5:2004 to every geological polygon within the national geological map. The resulting map (refer to Figure 3.7) provides a generalised indication of the likely encountered site classes which are based on geological rather than geotechnical information (Destegul et al. 2009). Numerous studies focusing on the seismogenic sources in the Wellington region have better constrained the earthquake risk in Wellington City (refer to Chapter Two, Section 2.5). Microtremor and seismic cone penetrometer testing (SCPT) studies have also been conducted with varying levels of success in the city. SCPT and microtremor measurements used for this study are discussed further in Chapter Four, Sections 4.4.3 and 4.4.4).

Figure 3.7: Ground shaking amplification (site class) map for the Wellington area (Destegul et al. 2009).



3.7 CHAPTER SUMMARY

Earthquake engineering is a relatively young field of expertise and is constantly evolving through advancing research and observation of earthquake induced hazards.

Wellington City is at risk from a number of earthquake induced phenomena including fault rupture, liquefaction and most significantly ground shaking amplification (reflecting the scope of this thesis). The geological setting of Wellington City is the cause of such high risk, as a large portion of the central city is founded on sediments expected to amplify strong ground motion, with Wellington City experiencing the highest seismic risk in New Zealand in terms of its proximity to active faults capable of producing a large damaging earthquake. Damage patterns from historic earthquakes support this.

Ground shaking is the most important earthquake hazard as it is the cause of all other earthquake induced phenomena (excluding fault rupture). The effects of ground shaking amplification have been observed in a number of catastrophic earthquakes (e.g. 1985 Michoacán Earthquake, refer to Appendix 3B) with the theory behind this phenomena becoming better understood. Ground shaking amplification depends on a number of factors including amplitude, frequency and duration of motion, distance from the epicentre, site topography and local site conditions (geological and geotechnical properties of the soil). Structural design in New Zealand considers site conditions which are assigned a site class based upon geological and geotechnical properties. A lower site subsoil class (soft/loose sediment) is more susceptible to ground shaking amplification and as a result will require greater design and strengthening to accommodate higher earthquake loads, resulting in increased construction cost. Sites assigned a higher site subsoil class (bedrock sites) will experience lower levels of ground shaking, requiring less strengthening. The preferred method for site subsoil determination is the calculation of site period from shear wave velocity measurements. However, as accurate shear wave velocity measurements are seldom made, engineering professionals often rely on borehole information and/or microtremor measurements to classify a site.

New Zealand has a current, well respected loadings code which is periodically reviewed and updated with the results from advancing research. New Zealand's loadings code has evolved over time, with major revisions in 1935, 1965, 1976, 1984, 1992 and 2004.

These revisions reflect the constantly evolving understanding of geology, seismology and engineering through research and damaging earthquake events. Historic catastrophic earthquake events have highlighted the need to have both a modern building code and systems in place to make sure it is enforced. There have been no severe damaging earthquakes in New Zealand since the adoption of the current earthquake loadings code, thus the provisions within the code remain untested for such an event.

Previous research concludes that Wellington City will experience varying levels of ground shaking amplification during a large damaging earthquake. Areas most susceptible to liquefaction (and related phenomena) and ground shaking amplification are the reclaimed areas surrounding Wellington's waterfront, Thorndon and Te Aro valley. The 1985 Michoacán (Mexico) Earthquake (refer to Appendix 3B) provided clear evidence for site effects and was well constrained by geological and strong motion data.

CHAPTER FOUR

GEOTECHNICAL DATABASES

4.1 INTRODUCTION

A vast amount of subsurface data has been gathered by various organisations in Wellington City. The data generally consists of geotechnical borehole logs and accompanying reports with limited test pit and site observation notes (e.g. presence of rock in-situ). A borehole geotechnical database has been constructed and designed to bring this information together and make it available in a readily accessible format.

This chapter describes the borehole geotechnical database and its construction (refer to Appendix 4A and 4B). The database contains information from 1025 individual boreholes, test pits and site observations and consists of three main spreadsheets containing information on lithology, geotechnical parameters and SPT N count. Inputs into the database are discussed including the three different geotechnical techniques that were used to gather additional and refine existing data. Data limitations and availability are also discussed and a summary of the information held within the database is given.

4.2 DATABASE OBJECTIVES AND CONSTRUCTION

4.2.1 OVERALL AIMS

The primary objective of this study was to collate all available information within the study area and construct a database containing this information. The aim was then to use information from this database to construct various outputs associated with this thesis.

4.2.2 DATABASE SOFTWARE AND DESIGN

The database has been designed with the primary objective in mind. It is likely that the information stored within this database will be used by a wide range of people with different output requirements. A suitable software package was therefore required, which needed to be readily available, easy to use and compatible with map and modelling software such as ArcMap and Earth Research. Microsoft Excel best fits these requirements.

4.2.3 DATA SOURCES

Data used for this thesis came directly from files held by Tonkin & Taylor and GNS Science. Staff from both organisations are kindly thanked for arranging and allowing access to their files. The data compiled from these organisations forms the foundation of this research project. Borelog, test pit and site observation information has been extracted from reports and related studies. A total of 322 borelogs, test pit and field observation notes were collated from Tonkin & Taylor while the remaining 703 records were obtained from GNS Science. It should be noted that a significant portion of the data held by GNS Science and Tonkin & Taylor was the same and duplicates needed to be eliminated. Since GNS files were collated and entered into the database first, more records appear from GNS Science as the duplicates were omitted from Tonkin & Taylor files (both organisations held a similar number of records within the study area). Where available, copies of a significant portion of bore log information held by GNS Science were obtained from the Perrin & Campbell (1992) “Compilation of geological data, Wellington region” report and the associated working files. This was because a number of the bore logs used for this study were lost, never copied or only existed as rough notes. From this the benefits of having an electronic database can be seen. A copy of the information used from this study is included in the PDF borehole database (Appendix 4B: GNS Science Data/GNS 1992 Perrin & Campbell Study Appendix Data).

4.2.4 DATABASE CONSTRUCTION

The database has been constructed with three main Excel spreadsheets. These spreadsheets contain information on lithology (“Lithology” Spreadsheet), geotechnical testing (“Geotech” Spreadsheet) and standard penetration testing (“SPT” Spreadsheet). The three spreadsheets are relatable to one another as each contains the unique borehole identification values in the first column (when data is available to be entered on that spreadsheet). The database has been constructed so that even users with limited knowledge of the operation of Excel can easily enter additional information.

The “Lithology” spreadsheet contains “as recorded on the log” lithological information. The spreadsheet also records other non-lithological information including location and borelog notes (refer to Section 4.5.1). The spreadsheet has been designed with individual lithological units entered across a row so that each individual borehole’s lithology is represented by only one row. This has been done to allow the user to manipulate location and ID data and then refer to the lithology of a log as required.

The “Geotech” spreadsheet contains all “as recorded on the log” geotechnical information for each borehole, excluding SPT data. Some of the parameters included are dry density, porosity and void ratio (refer to Section 4.5.1 for full list). The spreadsheet has been constructed so that all information from one test depth for one individual borehole is recorded per row. This allows the user to manipulate the data using the inbuilt sort and filter functions in Excel. It also allows the user to easily see what geotechnical parameters were tested for at a particular depth.

The “SPT” spreadsheet contains more than 5000 SPT N count measurements. Where a bore log has recorded additional information associated with an SPT, this information has also been recorded. Additional information includes recovery (R) and blow count, and the lithology that the test was undertaken in has also been recorded (based on the description of the sample returned). The standard penetration test is also defined with an explanation of SPT N count given. The “SPT” spreadsheet has been constructed so that information for one individual SPT test is recorded per row. This again allows the user to manipulate the data using the inbuilt sort and filter functions in Excel.

To increase the accessibility of the information stored within the database compiled for this thesis, it has also been entered into GNS Science’s PETLAB database (refer to Section 4.6). One advantage the database compiled for this thesis has over PETLAB is that data can be entered into any one spreadsheet in any order (after initially entering ID and coordinates, the remaining data can then be entered in any order). Additionally, all the compiled data is directly available for the end user, whereas the PETLAB database needs to be queried in order to obtain the required information. By keeping the database independent of PETLAB it also allows the marker to refer back to it when needed.

4.3 DATABASE DETAILS

4.3.1 SPREADSHEET FIELDS

This section provides a brief description on the fields contained within the database and explanation is also given on the fields themselves within the database spreadsheets. The following fields contain (as recorded on the bore log if given):

Lithology Spreadsheet:

- **Borehole ID** – Unique value assigned to each entry.
- **NZMG Coordinates** – Lists New Zealand Map Grid coordinates for each entry with E reference to easting, N to northing and Z to elevation.
- **Location Error/Precision** – A value based on the location error associated with the borehole position (higher error larger value).
- **Units** – Notes whether imperial (I) or metric (M) units were used when logging the borehole.
- **Unit Error** – Relates to borelogs that do not have depth measurements for each individual lithological layer. The error is based on calculating these depths by measuring thicknesses off to scale with a ruler.
- **Location Comment/Site Description** – Lists useful location details including street address.
- **Drill Method** – Lists the method used (e.g. wash-bore).
- **Company /Contractor** – Lists the driller or engineer.
- **Borelog Notes** – Lists other useful information that is not entered elsewhere (e.g. casing)
- **Data Notes/Site Plan** – Lists whether or not a site plan was present in determining borehole coordinates and the software used to obtain those coordinates (e.g. Tumonz).
- **Date Drilled** – Lists the date the borehole was started.
- **Depth** – Lists the borehole depth (m).
- **Water Level** – Lists the water level depth (m).
- **Date Water Level Recorded** – Lists the date on which the water level was recorded.
- **Rock Tagged** – Lists whether or not a borehole struck bedrock.

- **Rock Depth** – Lists the depth at which rock was struck (m).
- **Stratigraphic Age** – Lists the minimum (Quaternary) and maximum (Quaternary or Triassic) stratigraphic ages.
- **Data Source** – Lists the data source (GNS Science or Tonkin & Taylor).
- **Surface Layer etc From/To** – Lists ground level (0m) to the next lithological layer.
- **Unit Description** – Describes the lithological unit that falls between the "To" and "From" value range given in the preceding field.
- **Origin, Mineral Composition, Defects, Structure** – Lists material origin, mineral type, defects and structure.
- **Classification Symbol** – USCS (Unified Soil Classification System) symbol.
- **Moisture Condition** – Lists the moisture condition of the soil (e.g. W = wet, M = moist etc).
- **Shear Strength/Relative Density** – Lists the relative density or shear strength of the soil by symbol (e.g. MD = medium dense, VSt = very stiff etc).
- **Estimated Shear Strength** – Lists the estimated shear strength of the soil.
- **From/To –** Follows on with the next lithological unit in sequence to the end of the log.

SPT Spreadsheet:

- **Borehole ID** – Unique value assigned to each entry.
- **From/To –** Lists the from/to depth from where the measurement was taken.
- **Blow Count** – Lists the number of blows per division (usually 75 mm).
- **R-** Lists the recovery of the SPT sample (mm).
- **N Value**– Lists the SPT N value.
- **Test Lithology** – Lists the test lithology using a USCS symbol when given. When no symbol is given a G (gravel), S (sand), M (silt), CW R (completely weathered rock) and HW R (highly weathered rock) symbol has been assigned.

Geotech Spreadsheet:

- **Borehole ID** – Unique value assigned to each entry.
- **Dry Density** - kg/m^3
- **Natural Moisture Content** - %
- **Shear Strength** - MPa

- **Test Moisture Content** - %
- **Type of Strength Test Used** – Lists the type of strength test used to obtain the shear strength e.g. direct shear.
- **Test Surcharge Pressure** - Lists the test surcharge pressure used in the shear strength test (MPa).
- **Plasticity Index** – As per field name.
- **Liquid Limit** (%) – As per field name.
- **Fines % (no. 200) 74 µm** – Lists percent fines passing through a No. 200 (74 µm sieve).
- **Void Ratio (e)** – As per field name.
- **Porosity (n)** – As per field name.
- **Saturation** (%) – As per field name.

4.3.2 BOREHOLE IDENTIFICATION AND COORDINATE DETERMINATION

Individual boreholes have been assigned a unique identification value. This number has been based on the original file that the borelog was extracted from. For example GM-1 refers to borehole 1 from GNS Science's "M" data set (used in the 1992 Perrin & Campbell study). This identification number allows an individual record to be selected and can be used to refer back to the location of the original file the log came from.

The vast majority of the boreholes entered into this database do not have coordinates assigned to them. Generally, a site map is given with the borehole positions marked out and this appears to be common practice, unless there is a specific requirement requiring the borehole positions to be accurately surveyed.

Accurate coordinate positions are required to enable mapping and modelling of the borehole information. Where site maps accompanied the bore logs the process of assigning coordinates was a relatively simple one. This process involved measuring the location of each borehole off to scale. Then using either Tumonz or Terraview these locations were used to obtain New Zealand Map Grid coordinates. It was felt that this method was the only feasible way of obtaining the most accurate possible coordinates for each borehole position. There are errors associated with this coordinate determination process. Obviously the poorer the condition of the site map, the less accurate the coordinates representing the location of a particular borehole on that site will be. A minimum error of ± 2 m has been assigned to boreholes when coordinates have been defined using this method. This error is realistic provided care is taken in measuring borehole positions as accurately as possible.

For 12 sites neither a detailed site description or location map is given with the borelogs. Instead theses borelogs have been positioned based on expert opinion (Nick Perrin GNS Science) as to their most likely location considering infrastructure at the time (i.e. if a building was located on a particular site at the time of drilling then the borehole must have been located outside of the perimeter of that building). Once the most likely location was established the borehole was then assigned coordinates using Tumonz. Where borehole positions have been located by this method, large errors ($10m^+$) have been assigned (the "Location/Precision" field in the lithology spreadsheet). These logs have then only been used for indicative purposes in mapping and modelling and bear no weight in the final outputs (e.g. GM-22 has an error of ± 400 m as it may be located anywhere along or within the vicinity of Aotea Quay). By doing this the errors associated with accurately positioning the boreholes were kept as close to a minimum as possible.

4.3.3 ELEVATION

The majority of the boreholes used to construct the database do not contain elevation information (which is required to complete the 3D geological model output). Where elevation information is given the datum is often not recorded or no reference could be found to convert this information into a useable format (e.g. feet from Mt Cook coordinate system).

Elevation values are required to project borehole information in three dimensions (3D). It was decided the best and easiest way of obtaining elevation values was to overlay a DEM (digital elevation model) on top of the borehole positions and then have ArcInfo compute Z-values (elevations) for each borehole. It should be noted that Mark Rattenbury (Geologist/GIS Specialist, GNS Science) completed this step, which the author is most grateful for.

There are obvious errors in using this method to compute Z-values. The ground surface in Wellington City has changed markedly since the first log was recorded (1909). This combined with the errors already associated with the DEM (inherent errors associated with digital elevation data) need to be considered. Once Z-values were obtained for the boreholes they were plotted in ArcScene to check that the values positioned the boreholes correctly.

4.3.4 DATA ERRORS AND LIMITATIONS

Every effort has been made to ensure that the data within the database is accurate and correct. However, as with the nature of data entry, mistakes can be made, so by referring to the borelog appendix users are able to check the information against its primary source. Aside from typing errors made when the data was entered it must be noted that some bore logs are very old and are subsequently in poor condition making them difficult to read. When this is the case a note has been made in the database directing the user to the original log.

Another source of error arises from the fact that approximately 35% of the bore logs were recorded using imperial units (before New Zealand adopted the metric system). Where this is the case units have been entered as recorded using imperial units into one column then converted into metric values in another column. The columns containing the imperial measurements have been hidden in the spreadsheet but can be referred back to (right click column/unhide). The conversion values are also stated for reference. Location errors are discussed in Section 4.5.3 (Coordinate Determination).

The use of SPT data is limited and should be used with caution, especially in gravels and saturated fine sands. The SPT test was designed to determine the relative densities of sands and as such can lead to ambiguous result if conducted in other materials. For example SPT results in gravelly soils typically give false high penetration resistance values because of interference from gravel clasts.

Bore logging standards have changed markedly over the years undergoing a major leap with the adoption of the metric system in the late 1970’s. It can be stated that in general older borelogs are more prone to interpretive errors than those logged to modern standards. This is because older logs generally contain less lithological information or terms which may be unfamiliar. For example “soft metal and pug” can be hard to interpret on its own. Where interpretation was difficult, a professional engineering geologist was consulted, namely Nick Perrin (GNS Science) who has considerable experience in all things geological in Wellington City.

4.4 DATABASE INPUTS

4.4.1 NEW AND EXISTING DATA

The main borehole database contains information from 1025 boreholes, test pits and site observations. In addition to the main database, subsurface information obtained from SCPT and SPAC microtremor testing has also been compiled.

During the course of this study, three different geotechnical techniques were used to investigate the subsurface geology within the central Wellington commercial area. The three methods used were: borehole investigations, microtremor testing (SPAC) and seismic cone penetrometer testing.

The primary objectives of the geotechnical testing performed during this study were to:

- Investigate the weathering of greywacke basement bedrock (borehole investigations).
- Investigate the composition of Quaternary and fill sediments.
- Define and later refine depth to greywacke basement and sediment thicknesses.
- Directly measure shear wave velocities (SCPT).
- Obtain site period and shear wave velocity information (SPAC).
- Observe the effectiveness of these tests under Wellington geological conditions.

4.4.2 BOREHOLE LOGGING

4.4.2.1 INTRODUCTION

Geotechnical borehole investigations are an expensive, but proven method for use in the characterisation of subsurface conditions. Due to funding limitations it was not possible to undertake drilling and logging of boreholes specifically for this thesis. Boreholes for use in this thesis were logged from suitable sites where Tonkin & Taylor were performing site investigations and access was granted. From the 1st to the 3rd of December 2008 three boreholes were logged at the Wellington City Council Central Park Flats (refer to Appendix 4C for bore logs), located off Nairn Street south-west of

Te Aro valley. Central Park Flats are owned by Wellington City Council and were occupied at the time of testing. The purposes of logging these three boreholes were:

- To provide additional information on depth to bedrock and sediment thickness within the Central Park Flats area.
- To enhance the author's personal knowledge of the sediments encountered, their likely Standard penetration test (SPT) value range and to gain experience in borehole logging. Note the standard penetration test is a standardised (NZS 4402.6.5.1:1988) in-situ dynamic penetration test (refer to Glossary or standard for full description). The standard penetration resistance or N count from an SPT is used to determine the relative density of a soil. The N count refers to the sum of the number of blows required for 300 mm of penetration.

4.4.2.2 METHODOLOGY

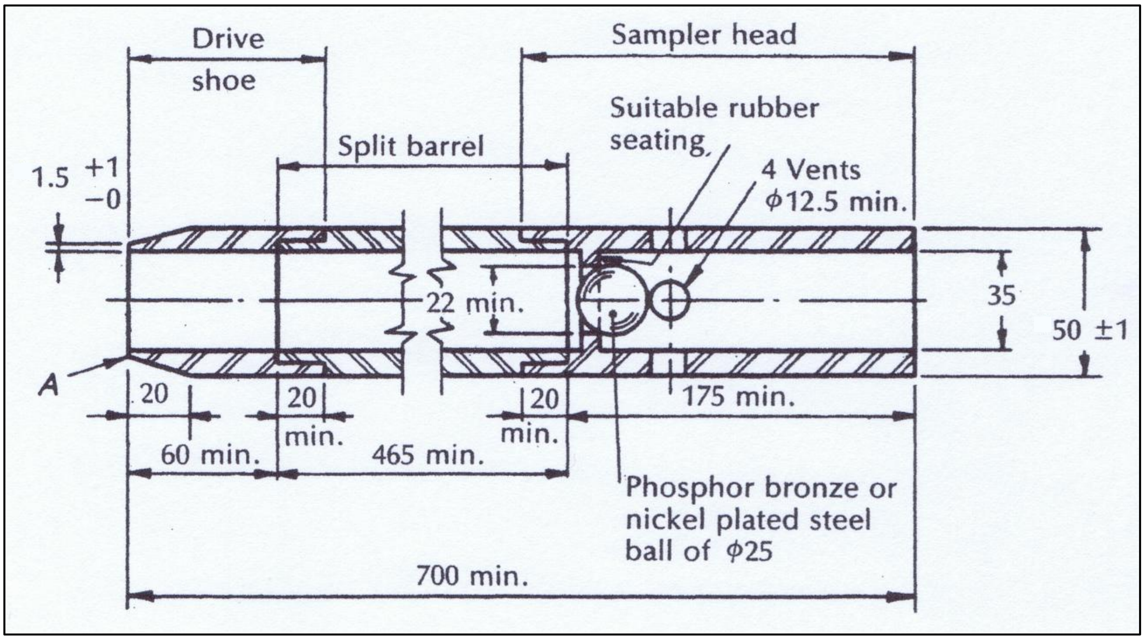
The locations of the boreholes were predetermined by Tonkin & Taylor (refer to site plan on page 2 of bore log 3, Appendix 4C). Borehole 1 was started on Monday 1st December 2008 and completed Tuesday morning. Borehole 1 was located on the grass verge adjacent to Brooklyn Road. Borehole 2 was started after the completion of Borehole 1 and was completed on Wednesday morning. Borehole 2 was located in the Central Park Flats car park off Nairn Street. Borehole 3 was started Wednesday morning and completed that afternoon with the installation of a piezometer and flush mounted toby box (covering of the piezometer tube). Borehole 3 was located adjacent to Nairn Street near the entry to Central Park Flats. It should be noted that owing to the location of the boreholes (security and safety issues associated with leaving the rig unattended) the drill rig had to be removed and reset over the holes each day, requiring a longer time on site.

- A health and safety briefing was held prior to meeting on site. This was done to identify and mitigate against the risks associated when working near a drill rig. Personal protective equipment (PPE) including steel cap boots, Hi-Vis clothing, hard hat and hearing protection was worn at all times while the machinery was operating on site.
- For all three boreholes a jet-vac system was used to start the hole to a depth of 1.5-2 m. Jet-vac refers to the industrial high suction vacuum system that is used in combination with pressurised water to loosen and remove material (in this

case sediment). Jet-vac was used as it is a relatively safe method of starting a borehole when there is a risk of encountering buried services. It should be noted that a pipe was unexpectedly discovered in borehole 2 at a depth of approximately 1.5 m, thus the jet-vac was used to clear out the hole to two metres to allow safe access for the drill rig to continue.

- After the jet-vac had been used the holes were advanced vertically using a combination of wash-bore drilling with SPT measurements taken at 1 m centres. Wash-bore drilling uses water or a similar drilling fluid (in this case water, bentonite and CR650 polymer mix) to lift the cuttings to the surface while advancing the drill bit down the borehole. The washings were constantly monitored noting any change in colour or grain size. Any deviation in drill speed or inclination was also noted. The recovered material from the split spoon sampler (refer to Figure 4.1 for a typical split-tube sampler assembly) after the completion of each SPT was bagged and labelled noting location (sample identification), date, depth and SPT N count.

Figure 4.1: Typical split spoon sampler assembly (Standards New Zealand 1988).



- Upon recording an SPT "N" count of more than 40, drilling was stopped and the method switched to triple-tube coring, as instructed by the senior engineer.

- The hole was advanced for another 2.5-3.5 m and drilling was stopped, as per instruction from senior engineer.
- The triple-tube wire-line system was then used to extract the core. Triple-tube wire-line core barrels have a second inner split-tube (split lengthwise) inside the standard inner tube. When retrieving the core a grabbing device is lowered by a wire down the hole, where it connects to the sample tube. The tube containing the core is then retracted via the wire line winch from within the drill rods and the core is ejected using the core ejection piston.
- The retrieved core was then measured and placed in a core box (refer to Figure 4.2) where it was washed, photographed and inspected.
- Upon satisfactory core material (completely weathered greywacke bedrock) being recovered, the drillers were then instructed to reinstate the hole and move on to the next one.
- The recovered core and SPT samples were then analysed and logged in the lab to the New Zealand Geotechnical Society specifications (refer to Appendix 2A & 2B). After the draft logs were checked by a Tonkin & Taylor staff member, electronic copies were produced using gINT (geotechnical and geoenvironmental bore logging software).

Figure 4.2: Retrieved core from Borehole 1 (S Semmens 2008).

Completely (CW) to Moderately Weathered (MW) Greywacke Sandstone

4.4.2.3 RESULTS AND DISCUSSION

A layer of fill material (> 1.4 m) was encountered in all three boreholes (refer to bore logs in Appendix 4C for exact depths and geologic descriptions). Beneath the fill material a layer of alluvium was encountered. Weathered greywacke bedrock was encountered in all three boreholes directly below the overlying alluvium layer. Greywacke bedrock was interpreted to occur at 9.25 m for both boreholes 1 and 2 and 9.95 m in borehole 3. The weathering of this rock ranged from completely to highly weathered in boreholes 2 and 3, while some moderately weathered rock was recovered in borehole 1. In borehole 3, weathering was more intense and a layer of residual soil was found above the completely weathered bedrock.

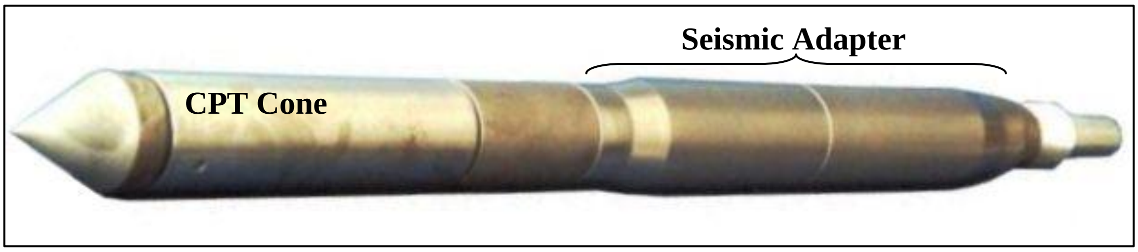
The borehole investigation set out to determine the depth to basement and sediment thickness in the Central Park Flats area. All three boreholes were successful as sediment thickness, relative density, composition and depth to basement was determined. Geotechnical borehole investigations are a valuable method for characterising the subsurface geology. If required, boreholes can be used to provide samples from depth for analysis. Additionally water levels can be monitored by installing a piezometer. Provided caution is used, the SPT allows the relative density of sediments to be calculated and provided recovery is good, a virtually unaltered sample is obtained.

4.4.3 SEISMIC CONE PENETROMETER TEST

4.4.3.1 INTRODUCTION

The Seismic Cone Penetrometer Test (SCPT) is a valuable geotechnical tool used to determine accurate in-situ compression (P) and shear (S) wave velocities. An SCPT involves pushing a probe containing sensors (refer to Figure 4.3) which measure seismic wave speeds directly into the ground. The SCPT probe consists of a seismic adapter threaded to a standard CPT probe. Tip resistance, sleeve friction, pore pressure, tilt angle and shear wave velocities are recorded and transmitted to the surface via cable. The amount of data measured is too big for cordless transmission so the SCPT probe is run with a data cable through the rods. As with most geotechnical testing methods, SCPT is relatively inexpensive tool ($2150.00 inc. GST for 1 site to 20 m depth) compared to geotechnical borehole investigations ($300 per m inc. GST), but due to funding limitations it was not possible to undertake specifically for this thesis.

Figure 4.3: SCPT Probe (GeoMil Equipment B.V. 2009).



From the 20th to the 21st of January 2009 I was invited by staff at GNS Science to observe an SCPT at one site within the study area near the waterfront. The test was planned to be conducted to a depth of 20 m. The purposes of the SCPT at this site were:

- To obtain real measured shear wave velocities for the subsurface sediments (these measurements can be used to determine the subsoil class of a site).
- To observe the change in shear wave velocity travel time with depth.
- To determine the effectiveness of the SCPT in typical Wellington City deposits (SCPT has limited use in gravelly or hard sediments as the cone is pushed through the ground rather than drilled).

4.4.3.2 METHODOLOGY

The location of the SCPT was near the waterfront in Wellington City and the exact position was predetermined by GNS Science. A health and safety briefing was held prior to meeting on site. As the SCPT was conducted at a working construction site and due to the large heavy machinery involved, awareness had to be maintained at all times and PPE worn. The SCPT rig was set up over the predefined location. This involved extending the roof to allow the hydraulic ram to drive the SCPT rods into the ground. A hammer beam (specially designed plate used to generate shear waves when struck by a hammer) was then positioned directly underneath the stabilizer foot at one end of the rig. The rig was then hydraulically raised off the ground (refer to Figure 4.4).

Shear wave velocity measurements were then recorded every 200 mm. This involved the operator striking the hammer beam (shear plate) with a specially designed sledge hammer to generate shear waves (refer to Figure 4.5). The sledge hammer is constructed so that data acquisition begins automatically when it has been struck against the plate.

The hammer beam is designed to generate dominant SH waves (shear waves that are polarised parallel to the ground surface). SH waves only generate SH waves at boundaries and therefore simplify the analysis (shear waves perpendicular (SV) to the ground surface generate both SV and P-waves at a boundary interface, complicating the analysis). Accelerometers in the seismic cone adaptor recognise the arrival of the SH waves generated at the ground surface, and this information is sent back up to the surface via the data cable within the rods. Specialised software then plots the wave amplitude versus travel time, and wave velocities are then calculated.

Figure 4.4: Sketch of the seismic cone penetrometer test (SCPT).

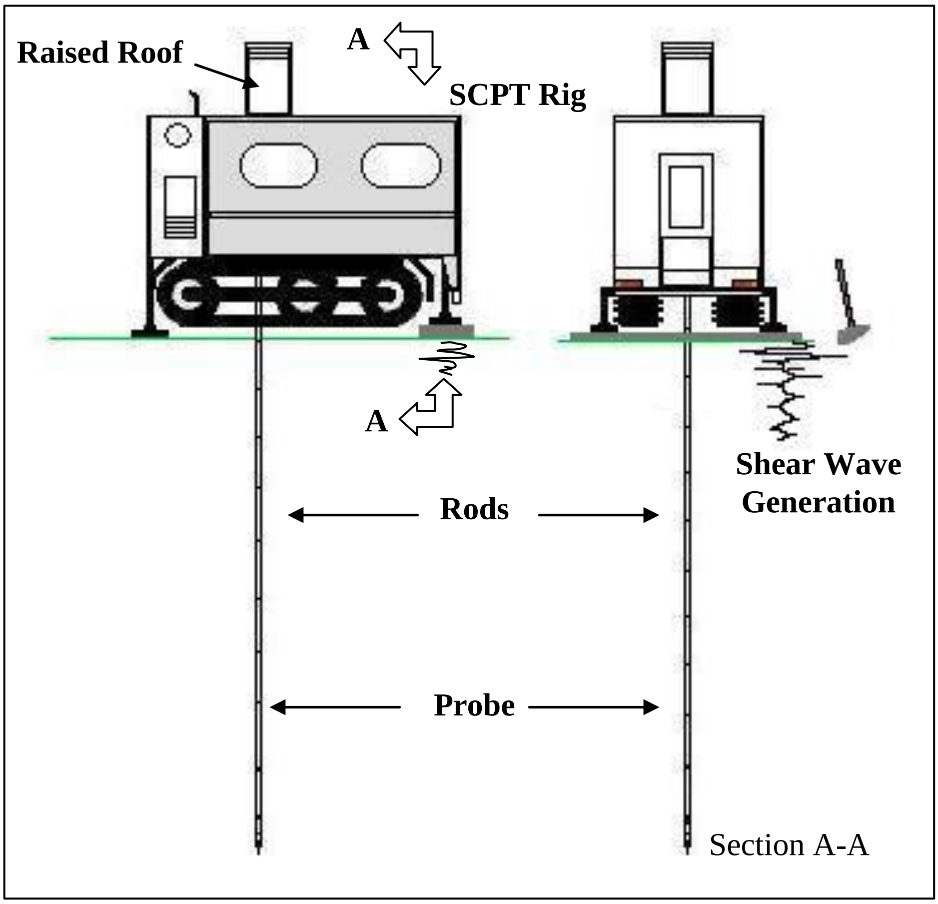


Figure 4.5: Shear wave generation (S Semmens 2009).

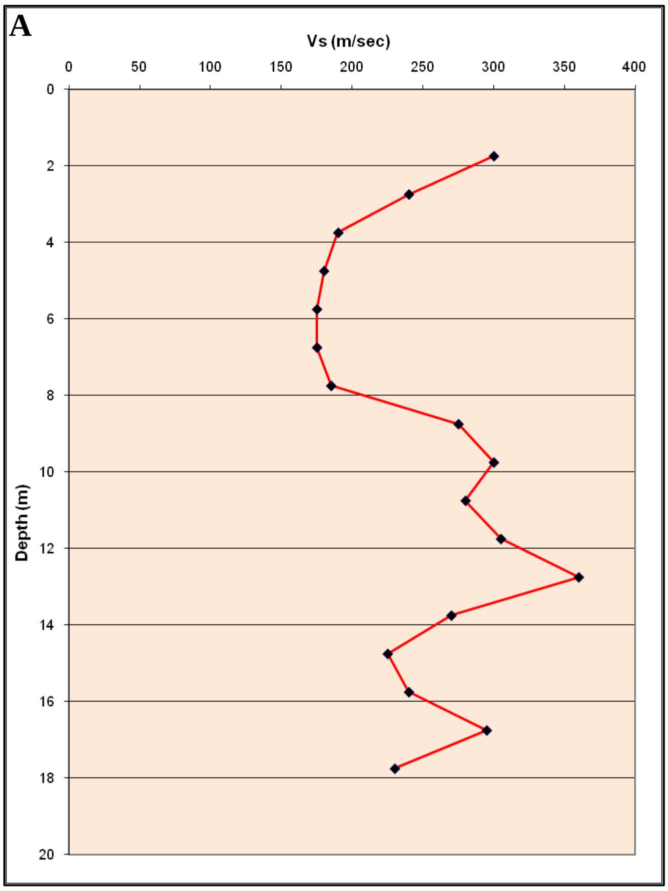
After each successful measurement was recorded the cone was advanced to the next test depth, with a new measurement recorded. The probe unexpectedly hit refusal at approximately 13 m (the test was to be conducted to a depth of 20 m). It was decided to remove the probe from the hole, auger through the impenetrable layer then continue with the test. The hole was advanced for approximately 0.5 m at which point the auger was removed from the hole and the SCPT continued. This interval was determined by the rapid increase in the rate at which the auger was advanced indicating that the hard layer had been passed. The test was then resumed with measurements at 200 mm intervals. At 17.75 m the probe once again hit refusal so the test was stopped and the rods extracted from the hole. A permanent accelerometer was then connected to the rods and pushed to refusal at approximately 18 m (at the request of the client), completing the test.

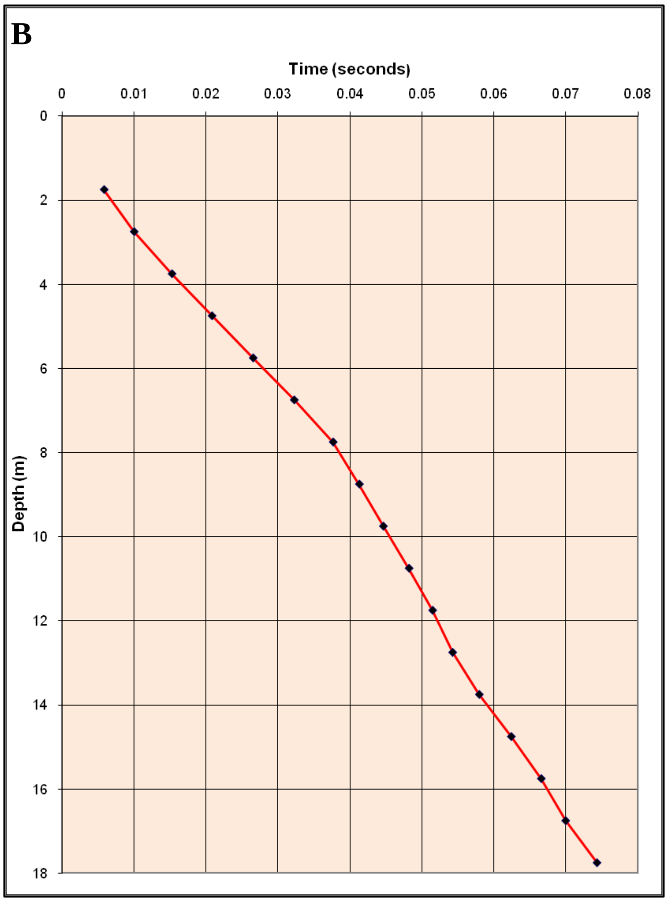
4.4.3.3 RESULTS AND DISCUSSION

The measured shear wave velocities can be found in the "Waterfront SCPT" spreadsheet (Appendix 5A, on DVD). It should be noted that as this was a commercially funded project external to GNS Science, the actual printout of the results from this test are not included in this thesis nor is the exact location given. Instead the measured shear wave velocities over 1 m intervals have been plotted using Excel. Two profiles showing shear wave velocity vs depth (A) and shear wave travel time vs depth (B) can be seen in Figure 4.6. Accurate shear wave velocities for the subsurface to a depth of 17.75 metres were obtained. The average shear wave velocity to a depth of 17.75 was approximately 240 m/s with a minimum value of 175 m/s and a maximum value of 360 m/s. The minimum value was recorded in soft sandy silt with traces of gravel (confirmed as a result of augering). The maximum shear wave velocity value was recorded at a depth of 12.75 m (probe refused at approximately 13 m), in what was inferred to be dense silty gravels (observed as a result of augering). Shear wave travel time steadily increased (linear) with depth.

Conducting an SCPT in Wellington conditions can be difficult especially if dense or large gravels are present. A viable way of extending the SCPT when the probe reaches refusal was found. This involved extracting the SCPT assembly, auguring through the impenetrable layer then continuing the test as required. One advantage of this method is that sediments can be visually inspected after their shear wave velocities have been measured. The SCPT provides a very useful way of obtaining real measured shear wave velocities which can be used to determine a site's subsoil class.

Figure 4.6: Waterfront SCPT, A) shear wave velocity vs depth & B) shear wave travel time vs depth.





4.4.4 SPAC MICROTREMOR TESTING

4.4.4.1 INTRODUCTION

Research and field testing has shown that both the Nakamura and SPAC (Spatial Auto Correlation) techniques are useful non-invasive geophysical methods, which can be used to determine subsurface sediment and rock properties (Teves-Costa et al. 1996). These properties include shear wave velocity, layer thickness and Vs30 which can be used to determine the subsoil class of a site. Simple sites consisting of a soft sediment layer overlying a stiffer layer of material can be investigated using these geophysical techniques, which are based on microtremor (refer to Section 4.4.4.2) recordings. The Nakamura technique can be used to determine site period, while the SPAC technique can be used to obtain subsurface shear wave velocities and layer depth. For complicated sites, analysis becomes more complex and time consuming and can yield no result. SPAC microtremor testing was conducted at 12 sites in Wellington City as part of this thesis, with funding coming from the "It's Our Fault" programme. "The goal of the "It's Our Fault" programme is to see Wellington positioned to become a more resilient city through a comprehensive study of the likelihood of large Wellington earthquakes, the size of these earthquakes, their effects and their impacts on humans and the built environment" (Van Dissen et al. 2009).

4.4.4.2 MICROTREMORS (MICROSEISM)

Microtremors are low amplitude (typically in the range of 0.001-0.1 mm) ambient vibrations of the ground caused by cultural or atmospheric disturbances and are unrelated to earthquake activity. Generally microtremors with a frequency greater than 1 Hz are produced by cultural sources (traffic, trains etc), while frequencies below 1 Hz result from natural phenomena such as wave action and wind. Microtremors are recorded by a seismometer and their observation can give useful information on a site's dynamic properties. Microtremors are predominantly travelling surface waves and both Rayleigh and Love waves may be present. Love waves do not have a vertical component, thus only Rayleigh waves are of interest when using microtremor measurements for the SPAC and Nakamura techniques. By using only the vertical component, Rayleigh wave effects can be investigated without complications arising from the presence of Love waves. Rayleigh waves are dispersive, and as such their phase velocity at any frequency is a function of the local shear wave velocity profile. When Rayleigh waves travel within a sediment layer lying upon a substrate, there is a frequency at which their ellipticity changes from retrograde to prograde, undergoing purely horizontal motion at that frequency. This frequency is very close to that associated with the quarter-wave travel time within the layer. Thus, there is a concentration of Rayleigh wave energy at that frequency, and a lack of energy associated with the vertical component of motion at that frequency (Chavez-Garcia et al. 2006).

4.4.4.3 NAKAMURA TECHNIQUE

If microtremors are recorded for a sufficient period of time, and the ratio of the horizontal and vertical spectra is computed, there will be a single sharp peak at what is known as the site period. This method was popularised by Nakamura in 1989 (Nakamura 1989). Generally the method will show the natural frequency of a site, but differing views are held on whether HVSR (Horizontal to Vertical Spectral Ratio) peak heights are indicative of amplification (Stephenson 2007). The Nakamura ratio can be obtained from SPAC data which has been recorded using three-component geophones.

4.4.4.4 SPAC TECHNIQUE

The acronym SPAC stands for Spatial AutoCorrelation and was first proposed by Aki in 1957 (Aki 1957). SPAC testing is a non-invasive technique and uses an array of sensors (geophones) to make simultaneous records of the vertical component (Rayleigh waves) of microtremor motion. Provided conditions are favourable the microtremor records can then be processed to obtain a shear wave velocity profile for the site. In order to do this the array must have pairs of sensors separated by a constant distance, and the directions between pairs of sensors must approximate a uniform azimuthal distribution (a compass is used in the field to orient the sensors). The microtremor records are then converted to the azimuthally-averaged coherency of the vibrations as a function of station separation and vibration frequency. This information is then used to construct a dispersion curve. If the dispersion is a result of Rayleigh wave propagation then the dispersion curve can be used to determine a shear wave velocity profile. The inter-station distance (distance between geophones) determines the depth to which useful subsurface information is obtained. If r is equal to the radius of the array used then subsurface information can be obtained over the range 0.1r-2r.

Depth to Rock:

For sites where there is a clear peak observed in the HVSR, and where the coherency curve allows for good characterisation of the topmost layer with a good velocity estimate for the next layer, the thickness of the second layer may be determined. This is done by varying the estimation of thickness of the second layer until a good match is obtained between the theoretical model and the observed frequencies for the horizontal particle orbit. When a “good match” second layer thickness is obtained the shear wave velocity profile down to rock has been determined. This only works where good HVSR values are acquired (a good clear HVSR peak will be sharp with a trough at twice the frequency of the peak).

Vs30:

When the top layer is well defined and greater than 10 metres thick, the coherency curve can give an accurate depth and velocity for that layer. This is achieved by matching of the coherency at frequencies above the first zero crossing. Knowing the properties of the top layer and the approximate velocity of the substrate, the value of Vs30 can then be determined.

The SPAC technique was conducted at 12 sites in the Wellington City study area during the week of the 19th to the 26th of February 2009 (refer to Appendix 8A for location map). The purpose of using the SPAC technique was:

- To obtain new subsurface information (site period, shear wave velocity and approximate depth to rock) for sites that had little or no additional subsurface data nearby.
- To confirm and correlate between existing data points.
- To refine the depth to bedrock, site period and Vs30 maps.
- To observe the effectiveness of conducting SPAC testing in Wellington City.

4.4.4.5 FIELD METHOD AND EQUIPMENT

The following equipment is used to conduct SPAC/Nakamura testing:

- Taurus portable digital seismographs incorporating a three-channel 24-bit digitizer.
- GPS receiver and system clock and removable storage (recordings are made at 100sps and stored on a removable compact flash card).

- Lennartz Seismometer (LE-3Dlite MkI & MkII) 1 second period.
- Batteries -12v gel cell.
- Measuring tapes - 100 m, 50 m.
- Measuring wheel.
- Compass.
- Spray paint & traffic cones (for marking out positions).
- Small concrete pads (used underneath each sensor if working on grass).

The location for each SPAC test was predetermined by desk study which considered the following:

- SPAC works best where there is a relatively thin, shallow dipping, flexible layer of soil over a stiff substrate.
- Access.
- Proximity to existing data.
- Proximity to possible site class C/D boundaries.

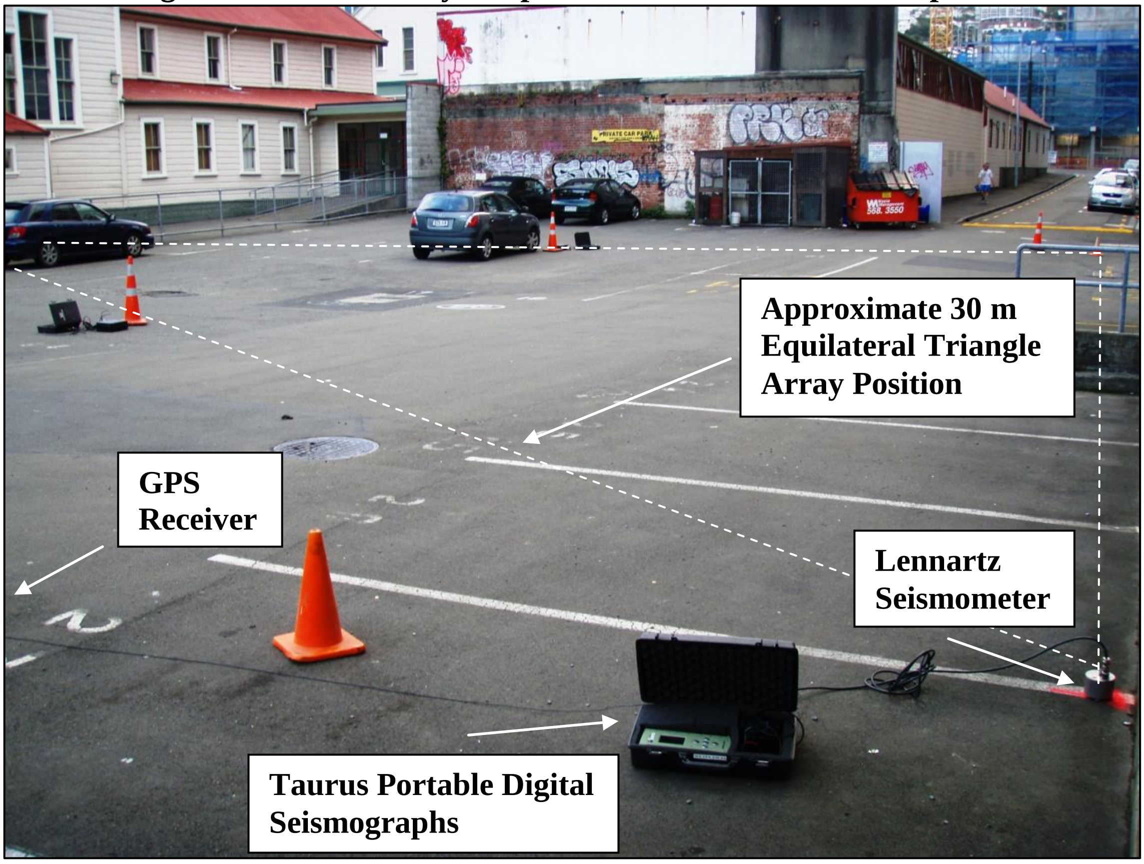
The possible layout of each array for each individual site was then selected and drawn out on air photographs (Google Earth). Equilateral triangle arrays were used (although other geometries can be used) as they are the simplest to set up and require the least amount of space (which is in short supply in the heavily urbanised central city).

The sites were then visited to confirm access, array size and location and to mark out instrument positions. The Wellington Girls College playing field and the Lorne Street sites were not marked out in advance. This is because access to the playing field was only granted for the weekend and the Lorne Street site was a working construction site, and it was considered too dangerous to be there at the time.

When on site the most appropriate layout was selected and the maximum sized triangle array was measured out first (using tapes and a measuring wheel), marking instrument positions with spray paint and/or traffic cones. If additional different sized arrays were to be used at a particular site the positions for the additional instruments were marked out second, keeping one point of the triangle common to each array (recordings from more than one array can be made simultaneously). Thus if two arrays were to be used at a site, 5 instrument positions were marked out, and if three arrays were to be used at a site, 7 positions were marked out.

As all measurements (with the exception of Wellington Girls College playing field) were either taken in car parks, over roads or in a construction site it was important to watch traffic at all times and wear Hi-Vis clothing. Once the sites had been marked out the order and time at which the microtremor measurements were to be made was decided on. This needed to consider both safety (i.e. when traffic volume was low and construction had stopped for the day) and access (as many of the sites selected were car parks, it was necessary to conduct the measurements at times when these were not in high use e.g. early morning or evening in order to position the instruments).

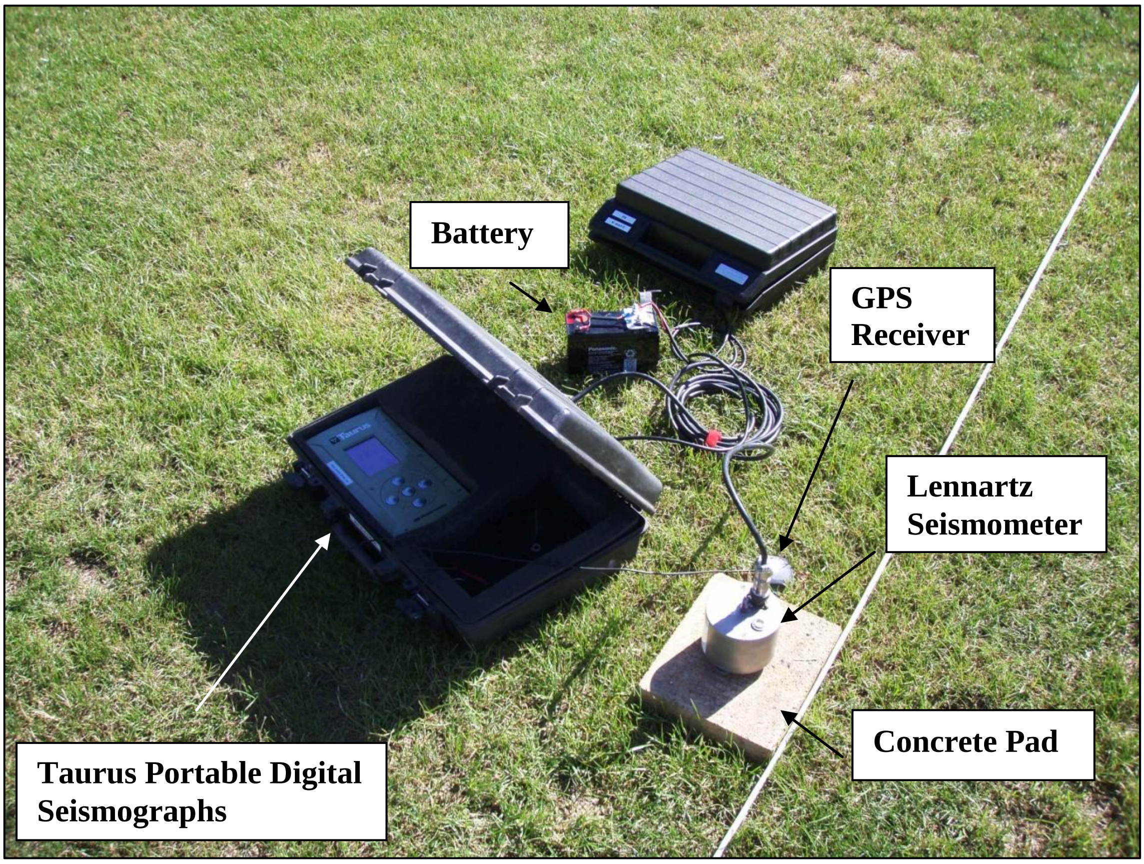
Figure 4.7: SPAC array setup in the St James Theatre car park.



Array apertures of 15 and 30 m were used. Note one instrument position is obscured. GPS receiver moved out from tall buildings to obtain satellite lock.

Prior to measurement the Lennartz sensors were set up and their positions rechecked (refer to Figures 4.7 and 4.8). Set up of the sensors involved them being levelled, aligned to magnetic North, and connected to the Taurus loggers. When the sensors were used on a grass surface (Wellington Girls College playing fields and the Law School car park) they were placed on a small concrete pad ((to ensure good contact with the ground) refer to Figure 4.8). The GPS receiver was then placed as close as possible to the sensors however it had to be moved out in some cases to allow a satellite lock when the site was surrounded by tall buildings. A 12 volt battery was then connected to each logger to provide power. When all the instruments and their components had been set up and connected, the Taurus loggers switched on.

Figure 4.8: SPAC array setup on the playing fields (grass) at Wellington Girls College.



Array apertures of 20, 40 and 60 m were used.

Once all the instruments were checked to see if they were working properly the start up time and instrument details for each logger was noted and the instruments were left to record for approximately 40 minutes (refer to Figure 4.9). After the 40 minute recording period was complete, finish times were recorded for each instrument and they were packed up. When recordings for all 12 sites were complete the records were then given to a seismic microzoning specialist at GNS Science to analyse (SPAC coherency, and

HVSR plots, field sheets and tabulated results can be found in Appendix 6A, 6B, 6C & 6D).

Figure 4.9: Lennartz Seismometer and Taurus portable digital seismograph recording (S Semmens 2009).

4.4.4.6 MICROTREMOR RECORD ANALYSIS

It should be noted that the analysis of microtremor records is a complicated process requiring specialist skill to complete. This was beyond the skill level of the author, therefore specialist staff at GNS carried out the analysis of the microtremor records. This section provides brief detail into that analysis and the reader is referred to the papers by (Aki 1957; Chavez-Garcia et al. 2004; Chavez-Garcia et al. 2005; Okada 2006) should further background be required.

Location and site conditions of the 12 sites were not given to the analyst prior to processing and interpretation. This is done to prevent bias arising from prior knowledge. The microtremor records are converted to the azimuthally-averaged coherency of the vibrations as a function of station separation and vibration frequency by GNS staff. This is done by dividing the recordings into 40 second segments. The coherency for each segment is then computed, and the average coherencies among all time windows and all (three) azimuths are determined. The coherencies are then inverted with a Simplex algorithm being used to get the best match between layering and coherency. This information is then used to construct a dispersion curve, which in turn is used to construct a shear wave velocity profile.

4.4.4.7 RESULTS AND DISCUSSION

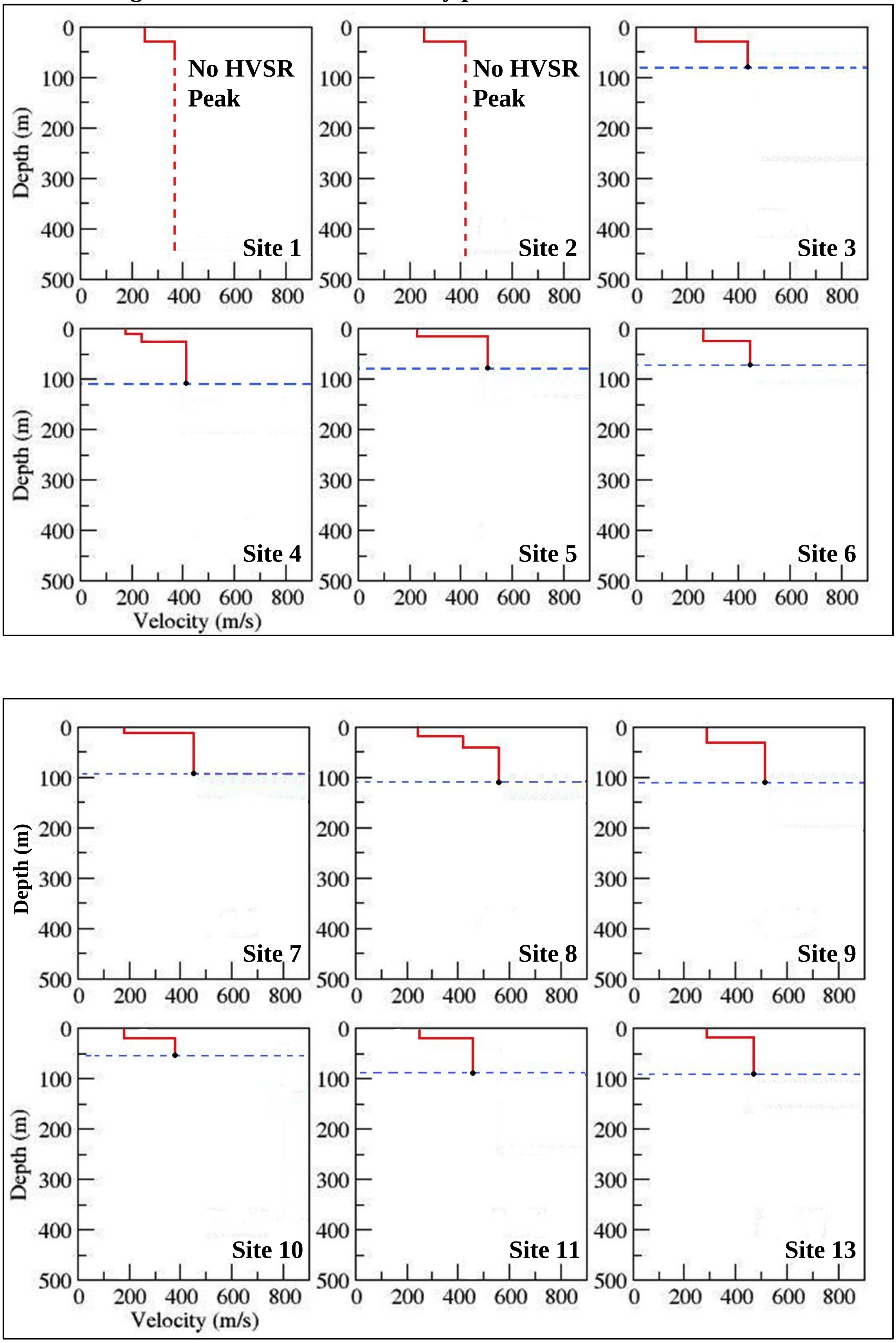
The results of the 12 SPAC tests are shown in Table 4.1 below:

Table 4.1: SPAC Results.

Site ID	Location Name	Period (seconds)	Esimated Rock Depth (m)	V_S30 (m/s)
1	VTNZ CPK	5	no_HVSR	252
2	WGC Field	5	no_HVSR	263
3	Railway Station	0.91	80	234
4	Bluebridge CPK	1.14	107	235
5	Law School CPK	0.67	75	325
6	Shell Station RD	0.73	70	294
7	Te Papa CPK	0.93	117	265
8	Reading CPK	0.87	110	292
9	St James CPK	0.97	111	290
10	Lorne St CN Site	0.71	52	211
11	Ebor St CPK	0.83	88	324
13	Cuba St CPK	0.77	92	347

Note: testing at 13 sites was planned originally, however site 12 was found to be unsuitable and was abandoned. CPK denotes that the site was a car park, CN a construction site and RD a street intersection.

Figure 4.10: Shear wave velocity profiles for the 12 SPAC sites.



Dashed blue line indicates estimated bedrock depth.

10 of the 12 sites measured by SPAC analysis returned favourable results that were consistent and credible when compared with other nearby subsurface information. HVSR peaks could not be obtained for sites 1 and 2 and therefore the depth to rock could not be estimated (refer to Figure 4.10). This may be because bedrock is located at a much greater depth than expected in this area. A more likely scenario is that the bedrock and the overlying Pleistocene deposits do not have a sufficient impedance contrast (i.e. the Pleistocene deposits are very dense and could be considered "effective bedrock"). This scenario is more likely, as very dense sediments were logged at great depth for one of the foundation investigation boreholes for Te Papa Tongarewa. However, there is no deep subsurface information in the vicinity of sites 1 and 2 so this scenario is only speculative (refer to Chapter Seven for recommendations of further work).

Shear wave velocity profiles for the 12 sites have been plotted (refer to Figure 4.10). Based on site period all 12 sites were assigned a "D" site subsoil class (period > 0.6s). Shear wave velocities (V_s30) were found to be relatively high (average approximately 240 m/s) in Wellington City (compared to approximately 170 m/s in the Hutt Valley). The general trend observed is that velocities decrease near the waterfront, which may be partly attributed to the reclamation fill material in this area. Site 10 (Lorne Street) returned the lowest shear wave velocities which may be due to the fact that the site is located on the former position of the Te Aro swamp. Soft swamp materials were found in the foundation investigation boreholes on this site which adds weight to this theory. Higher observed Vs30 values in Wellington when compared to the Hutt Valley and Wainuiomata suggest that microzone effects may not be as high in Wellington City as these areas.

4.4.4.8 INTERPRETATION

The SPAC technique was successfully used at 10 out of 12 sites in Wellington City, with good subsurface information being obtained for these sites. The combined use of HVSR and SPAC gave credible estimates of rock depth for 10 of the 12 sites. Where nearby subsurface information was present it correlated well with the SPAC results. Data from the SPAC testing was used to further refine the depth to bedrock, site period and Vs30 maps, which in turn influenced the site class maps (refer to Chapter Five).

Advantages of the SPAC technique are that it is non-invasive and data on site response can be gathered quickly in the field with little or no access limitations. Provided the subsurface geology is relatively simple, SPAC testing can be a convenient, economical tool to estimate the effect of subsurface geology on seismic motion without needing additional geological information. As with all microtremor methods, the deeper the depth to bedrock the greater the uncertainty

The major disadvantage with the SPAC technique (and for that matter any other microtremor technique) is that if a site has a very complicated subsurface geology (i.e. the stratigraphy lacks a clear interface or contrast between the soft and firm layers) or other mitigating factors are present (such as incoherent noise) then no result may be returned. The SPAC technique is especially limited in the case of shear wave velocity profiles that increase gradually with depth. The resonant character of nearby structures can also be picked up and if unexpected can lead to ambiguous results. For research purposes this may present a lesser problem than if the analysis was for a client who was expected to pay for no result. By screening out sites (either based on prior knowledge or by other testing means) it may be possible to reduce the likelihood of no result being returned, however it can never be eliminated completely.

4.5 DATA AVAILABILITY

To fulfil the primary objective of this study it was necessary to create a readily accessible database using all the available borehole information from within the study area. The database was created in Excel which allows the information to be viewed, printed and imported into other software such as ArcMap and Earth Research. Additionally, where available, PDF copies of the borelogs are also included in a borelog appendix accompanying the database (refer to Appendix 4B, on DVD). This allows the original logs to be viewed.

4.6 PETLAB DATABASE

PETLAB is a New Zealand rock catalogue and geoanalytical database operated by GNS Science (http://pet.gns.cri.nz). Contributors to this database include GNS Science and Auckland, Waikato, Massey, Victoria, Canterbury and Otago universities. The database contains locations and descriptions (PET) and analytical and geotechnical properties (LAB) of rocks, soils and minerals collected from New Zealand and Antarctica.

Information has been sourced from journal articles, theses and open file reports. As of 18 January 2010, PETLAB contains 154938 sample records, of which 40561 have accompanying geotechnical and analytical data. PETLAB has been designed to make previous collected data readily available to the academic and professional community while simultaneously involving users to grow the database. PET data can be queried and downloaded by anyone free of charge (limited to 250 records). LAB (geochemical, isotopic, age, volumetric, petrophysical and geotechnical) data requires registration to obtain a username and password for unrestricted query results.

As part of the conditions for access to the data held by GNS Science it was required that all data from this thesis be uploaded into PETLAB. After discussions with staff at GNS Science new parameters as a direct result from this thesis have been added into PETLAB with the aim of making it a national depository for all geological and geotechnical data. The parameters added to the PETLAB database include:

- **penet_norm_n_per_300mm** – This is the SPT N value normalised to 300 mm.
- **shear_strength_MPa** – This is the shear strength measured by the direct shear test.
- **test_surcharge_P_MPa** – This is the surcharge pressure that was used in the direct shear test.
- **moisture_content_pct** – This is the laboratory measured moisture content (a parameter for test moisture content has also been added).
- **density_dry_SI** – This is the laboratory measured dry density (SI units).
- **void_ratio_0_1** – This is the void ratio (0_1 indicates the range the value should fall into i.e. the ratio is between 0 and 1).

By uploading the database into PETLAB it becomes available to everyone, thus it is readily accessible and the first half of the primary objective of this thesis (refer to Section 1.2; “the primary objective of this study was to collate all available information within the study area”....) has been met.

4.7 ADDITIONAL DATA

It is highly likely that additional information within the study area exists. This information may be held by the engineering consulting companies that were not approached for this thesis. These organisations were not approached simply due to the timing constraints of a Master's thesis as the retrieval and entry of data for the database is a time consuming process.

The database is designed so that anyone can add additional information including new boreholes. This is simply a matter of assigning the new holes a unique borehole identification name/number and then proceeding with entry as you would any other spreadsheet.

4.8 DATABASE OPERATION

The database has been designed to be used in conjunction with mapping software or the maps accompanying this thesis. Individual boreholes have all been assigned New Zealand Map Grid (NZMG) coordinates which allows their positions to be accurately plotted in any mapping software capable of using the New Zealand Map Grid Coordinate system.

For new geotechnical investigations it is envisaged that the user will be able to locate the site to be investigated in NZMG coordinates. Then either creating or viewing one of the existing maps the user will be able to identify and select boreholes that are located within the vicinity that may be of use to the investigation.

Alternatively, should the maps or mapping software be unavailable users can filter and sort the data using the functions built into Excel. If the user is unfamiliar with Excel operations the detailed tutorials on how to manipulate the data can be found by searching the web. If the user is more comfortable manipulating data in another spreadsheet programme then the spreadsheets from this database can be exported into that software and used as required.

4.9 SUMMARY BOREHOLE DATABASE INFORMATION

The borehole database contains information from 1025 individual boreholes, test pits and site observations. Table 4.2 lists some of the database statistics.

Table 4.2: Borehole database statistics.

Statistic	No. Of Holes/Records
Deeper than 100 m	5
50 m or Deeper	18
30 m or Deeper	117
Tag Bedrock	366
SPT N Count Measurements	5340
Average SPT N Count	53
Average Borehole Depth	16.5 m
Arerage Bedrock Depth	8.6 m
Average Borehole Depth with No Bedrock	17.2 m

Bore logs used to construct this database range in age from 1909 to December 2008. Borehole depths range from 1 to 152 m (rock at 137.1 m) with 18 holes deeper than 50 m. Some 36% of the boreholes within the study area tag bedrock, 5 of these at depths greater than 100 m. Of the boreholes within the study area, 89% are less than 30 m deep. This is because most of the boreholes in this database have been used for geotechnical foundation investigations either targeting bedrock or the dense Pleistocene gravels at these depths.

The SPT N count spread sheet contains 5340 individual measurements. The SPT N count ranges from 0 (rods and hammer sink into sediment) to 300^+ in Wellington City. The average SPT N count from these 5340 measurements is 53. This statistic could be misleading if taken on face value as an N count of 53 would indicate very dense material (Refer to Appendix 2A, NZ Geotechnical Society Field Guide Sheet). This high number arises from the fact that SPT measurements are usually concentrated at depth when investigating founding conditions. Thus, this number is not representative of the subsurface in Wellington. In addition to SPT N count, geotechnical data including density, void ratio, shear strength, porosity and natural moisture content for 90 boreholes has been entered into the geotech spreadsheet.

4.10 CHAPTER SUMMARY

A readily accessible Excel database containing lithological and geotechnical information from 1025 bore logs, test pits and site observations has been constructed. The construction of this database partially fulfils the primary objective of this project by entering the collated data into a database that can be accessed by a large number of users. Increased accessibility to the information held within this database has been achieved by developing new parameters and uploading the information into GNS Science's PETLAB Database.

The non-invasive SPAC technique has been used successfully at 10 out of 12 sites to quickly gather site response information. Provided the subsurface geology is relatively simple, SPAC testing can be economically used to determine sub-surface geology and its likely effects on seismic motion.

Three boreholes were logged within the study area and were successfully used to determine sediment thickness, relative density, composition and depth to basement. The standard penetration test was used successfully to determine the relative density of sediments.

The SCPT provides a useful economical way of obtaining real measured shear wave velocities, which can be used to determine a site's subsoil class. The technique was used successfully near the waterfront to obtain shear wave measurements of the subsurface to a depth of 17.75 m. The SCPT is limited to penetrating soft-stiff materials and can be problematic where there are alternating layers of soft and dense deposits (as is the case in Wellington City).

Geotechnical borehole investigations, whilst more costly than the other two techniques used to obtain additional subsurface information for this thesis, provide a more accurate insight into the subsurface geology, providing samples that can be used for further analysis. One disadvantage of borehole investigations compared to SPAC and SCPT is that they do not provide direct shear wave velocity information (unless this geophysical test is specifically done e.g. down-hole or cross-hole seismic profiling), which is vital in determining a site's response characteristics.

CHAPTER FIVE

PROJECT OUTPUTS

5.1 INTRODUCTION

This chapter discusses the production of the modelling and mapping outputs for this thesis. The software used to create the 3D geological model and maps is briefly mentioned. Each individual output is described including inputs, construction methodology and results. Applications relating to the use of these outputs are discussed in detail in Chapter Six.

The outputs discussed in this chapter are (in chronological order of construction):

Model:

- Wellington central commercial area 3D geological model.

Maps:

- Data location map.
- Waterfront reclamation map.
- Surficial deposit map.
- Depth to bedrock contour map.
- Cross section calculations and location map.
- Low amplitude natural period (site period) map.
- NZS 1170.5:2004 site subsoil class map.
- V_s30 Map.
- Ground shaking amplification hazard map.
- Liquefaction potential map.

5.2 WELLINGTON CENTRAL COMMERCIAL AREA 3D GEOLOGICAL MODELLING

One of the major outputs of this thesis was to create a three dimensional (3D) geological model from the borehole information that was compiled into the geotechnical borehole database (refer to Chapter Four). The aim of creating this model was to allow the user to visualise the geological relationship at depth within the study area.

A suitable modelling software package was required, which needed to be user friendly, compatible with ESRI’s ArcMap software, and available for the duration of this thesis. After discussion with a mapping specialist from GNS Sciences it was decided that Earth Research best fitted these requirements.

Earth Research is a user-friendly 3D geological modelling software programme that is currently under development (ARANZ). The software facilitates the rapid construction of 3D geological volumes from scattered drill hole data using 3D interpolation technology. The software is simple to learn and, provided the input data is correctly formatted, a basic 3D geological model can be created within a few hours.

The following software and computer was used to create the 3D geological model:

Software:

Earth Research version:	1.3.0.76 (trunk)
Build date:	2009-05-14--02-30-03

Computer System (laptop):

Operating system:	Windows Vista Service Pack 2
Python version:	2.6 (r26:66721, Oct 2 2008, 11:35:03)
GTK+ version:	2.14.4
Aview version:	2.11.0 (r0)
CPU:	AMD Turion(tm) 64 X2 Mobile Technology TL-64
Speed:	2.20 GHz
Total Memory:	2046 MB

5.3 MODEL INPUTS

5.3.1 REQUIRED FILES

Borehole data is entered into Earth Research by importing the three required Excel .cvs (comma delimited) files. The three required files are:

- Collar
- Survey
- Lithology

5.3.2 COLLAR FILE

The collar file (refer to Figure 5.1 and Appendix 7C) contains coordinate and elevation information so that the boreholes can be projected in 3D space. The collar file (and survey and lithology files) also contains a unique borehole identification value (refer to Chapter Four, Section 4.3.2) for each individual bore log. The collar file was constructed by copying the first four columns of the lithology spreadsheet from the geotechnical borehole database, namely borehole ID, New Zealand Map Grid easting (x) and northing (y), and elevation (z). The collar file is designed so that Row One contains the column titles Borehole ID, x, y and z. Each row after the first then contains x, y and z information for all 1025 unique borehole IDs.

5.3.3 SURVEY FILE

The survey file can contain information on the orientation and inclination of boreholes entered into the model software. For the model produced as part of this thesis, the survey file was left blank as all boreholes are assumed to be vertical (which is the software default by leaving the survey file blank). This was done as there is no information regarding inclination on the bore logs and thus all were assumed to be vertical. This is a valid assumption as the bore logs collated for this study are all from geotechnical investigations of founding conditions in Wellington City. Thus, the holes are likely to be vertical.

Figure 5.1: A) Screen capture image of the model collar file, B) screen capture image of the model lithology file.

Model_Collar_File.csv **A**

	A	B	C	D
1	Borehole_ID	NZMG_E	NZMG_N	Z
2	GB-1	2658618	5988383	19.67
3	GB-2	2658681	5988376	16.93
4	GB-3	2658796	5988315	19.89
5	GB-4	2658932	5988323	16.5
6	GB-5	2658910	5988279	17.84
7	GBH101	2659469	5991813	2.34
8	GD-1	2659199	5988079	7.2
9	GD-2	2659162	5988134	5.69
10	GD-3	2659131	5988203	5.49
11	GD-4	2659015	5988242	14.79
12	GD-5	2658653	5988415	18.13
13	GD-6	2658490	5988489	18.99
14	GD-7	2658435	5988516	20.01
15	GD-8	2658308	5988667	23.5
16	GD-9	2658308	5988806	26.66
17	GD-10	2658318	5988867	25.2
18	GD-11	2659256	5988022	12.42
19	GD-101	2658934	5988182	17.06
20	GD-102	2658950	5988236	15.7
21	GD-103	2659004	5988389	14.5
22	GD-104	2658792	5988327	20.18
23	GD-105	2658819	5988362	18.41
24	GD-106	2658588	5988321	20.72
25	GD-107	[illegible]	[illegible]	[illegible]

Model_Collar_File

Model_lithology_File.csv **B**

	A	B	C	D	E
1	Borehole_ID	From	To	Unit	Groups
2	GB-1	0	2	FE	Loose_Deposits
3	GB-1	2	3	LU	Loose_Deposits
4	GB-1	3	10.2	SI	Stiff_Deposits
5	GB-1	10.2	18.2	SU	Stiff_Deposits
6	GB-1	18.2	22.5	RU	Greywacke
7	GB-2	0	2.4	FE	Loose_Deposits
8	GB-2	2.4	8.7	LU	Loose_Deposits
9	GB-2	8.7	31.24	SU	Stiff_Deposits
10	GB-3	0	1.6	FE	Loose_Deposits
11	GB-3	1.6	3	LU	Loose_Deposits
12	GB-3	3	3.5	SI	Stiff_Deposits
13	GB-3	3.5	19.8	RU	Greywacke
14	GB-4	0	0.3	FE	Loose_Deposits
15	GB-4	0.3	3.5	LU	Loose_Deposits
16	GB-4	3.5	23	SU	Stiff_Deposits
17	GB-4	23	30.2	RU	Greywacke
18	GB-5	0	2	FE	Loose_Deposits
19	GB-5	2	6.5	LU	Loose_Deposits
20	GB-5	6.5	16.5	SU	Stiff_Deposits
21	GB-5	16.5	29.4	RU	Greywacke
22	GBH101	0	7.4	FE	Loose_Deposits
23	GBH101	7.4	8	LB	Loose_Deposits
24	GBH101	8	15	SU	Stiff_Deposits
25	GD-1	[illegible]	[illegible]	[illegible]	[illegible]

Model_lithology_File

5.3.4 LITHOLOGY FILE

The lithology file (refer to Figure 5.2 and Appendix 7C) contains lithological information that has been derived from the lithology spreadsheet of the geotechnical borehole database. Each individual lithological unit from each borelog was assigned one of seventeen unit codes based upon their lithological description, grain size, SPT N count, weathering condition and depositional setting as recorded in the geotechnical borehole database (refer to Table 5.1 for individual lithology properties). The lithological units recorded in the geotechnical database needed to be assigned a unit code to allow the software to process the data and create the model.

In addition to the assigned unit code for each lithological unit, Earth Research requires the user to assign a "stratigraphic order" to the individual lithologies to enable the construction of geological volumes (a mesh connecting points with the same lithology) from the borehole lithology. It should be noted that in a perfect world where sample deposits were taken from each individual geotechnical investigation borehole and dated, a model could be constructed based on stratigraphic ages. However, with rare exceptions, material recovered from geotechnical boreholes is never dated as this is not required when determining founding conditions. Although the crude approximation can be made that soft/loose deposits are generally of Holocene age and younger and stiff/dense deposits are generally of Pleistocene age, because of the lack of supporting data this deposit age relationship cannot be modelled. It was found that there was not enough weathering information on all of the borelogs to successfully differentiate the greywacke bedrock by weathering grade (i.e. most were defined as RU) and therefore the three weathering grade based units (defined in Table 5.1) were grouped together. The greywacke bedrock was not divided into either mudstone or sandstone as the modelling software requires a stratigraphic order to be assigned to each unit in order to create a model (you cannot assign a stratigraphic order to rocks that are the same age).

The naturally interbedded relationship of the assigned units was found to be complex and required simplification for modelling. The simplification process involved grouping “like” units together, resulting in four different lithology groups which could then be modelled. The four groups are:

Hydraulic Fill:	Unit FP.
Loose/Soft Deposits:	Units FE, LS, LF, LB, LA, LC, and LU.
Stiff Dense Deposits:	Units SL, SS, SI, SA, SC and SU.
Greywacke Bedrock:	Units RW, RU and RR.

Before arriving at this final grouping, the model was run with loose/soft deposits separated into loose (LA, LB LC and LU) and soft (LS and LF) groups. The results can be seen in Wellington 3D Geological Model - Primary Scene File - Scene 10 in Appendix 7A. This was found to produce inconsistent results. It can be seen that the model software has placed and divided these two groups where no data exists (e.g. in the area of the harbour).

Table 5.1 Model Lithologies.

Model Groups	Model Units	Unit Description	SPT N
Hydraulic Fill	FP	Hydraulic fill (sea bed sand and mud pumped in behind retaining walls) e.g. West of Aotea Quay.	1<N<15
Soft Deposits	FE	End dumped fill and spoil materials comprised mainly of weathered bedrock (greywacke and argillite) and building debris.	1<N<60
	LS	Swamp deposits, generally very silty and contain large amounts of organic matter.	2<N<35
	LF	Undifferentiated silts and clays.	5<N<35
Loose Deposits	LB	Beach or shallow marine deposits (granular/non-cohesive loose sediments). The presence of shell material helps to differentiate from LS, LA & LC.	5<N<35
	LA	Alluvial deposits (rounded gravels, sands etc), includes Holocene post-glacial stream deposits.	5<N<60
	LC	Colluvial deposits (angular gravels etc).	5<N<60
	LU	Undifferentiated granular deposits, generally gravels and sands that cannot be distinguished as colluvium or alluvium due to insufficient information.	5<N<60
Stiff/Hard Deposits	SL	Clays.	10<N<70
	SS	Silts.	10<N<70
Dense/Very Dense Deposits	SI	Interbedded fine and granular deposits (silts/clays with gravels).	30<N<120
	SA	Dense to very dense alluvial deposits (very compact rounded granular materials).	30<N<120
	SC	Dense to very dense colluvial deposits (very compact angular granular materials).	30<N<120
	SU	Undifferentiated alluvial and colluvial deposits (granular materials).	30<N<120
Greywacke Sandstone/ Mudstone (Basement)	RW	Rock that is of a weathering grade CW-HW.	5<N<100+
	RU	Rock that is of an undifferentiated weathering grade (weathering grade not recorded).	N>25
	RR	Rock that is of a weathering grade UW-MW.	N>25
	Σ = 17		

5.3.5 MODEL CONSTRUCTION METHODOLOGY

Once the two (no survey file was used) required .cvs files were created they were imported into Earth Research. Next, the bounding box for the model was set using the study area boundary coordinates and an elevation of ± 400 m was set. A mesh was then imported, representing the topography (note this was created by GNS Science). A new geological model was then created by defining the model groups to be used with their relative stratigraphic order. By setting the stratigraphic order the software is told which geological volumes can overly one another.

Pseudo points were then created (using the edit on object tool) for each of the four groups to correct their positions where the modelling software had obviously placed them incorrectly. An example of one of the corrections made was to confine the hydraulic fill to the area in the vicinity of Aotea Quay. As the hydraulic fill was assigned the youngest stratigraphic order the modelling software automatically placed it on high points (such as Tinakori Hill and Mt Victoria) where there was no additional data in addition to its correct position along Aotea Quay. It should be noted that only obvious errors such as these were corrected for and other may exist. Similarly pseudo points representing greywacke bedrock were also created so that the hills surrounding Wellington City are shown as such (which is known but not represented by drill hole data).

Once the model was satisfactorily completed additional elements were added to enhance it. A plane representing the position of the Wellington Fault (assumed to be vertical) was created. Shapefiles representing various features including cadastral boundaries, depth to bedrock contours fill zones and the 12 SPAC sites were then added to orient the user and allow different features to be viewed in relation to one another. Upon completion of the geological model it was then exported so that it could be viewed in Earth Research Viewer.

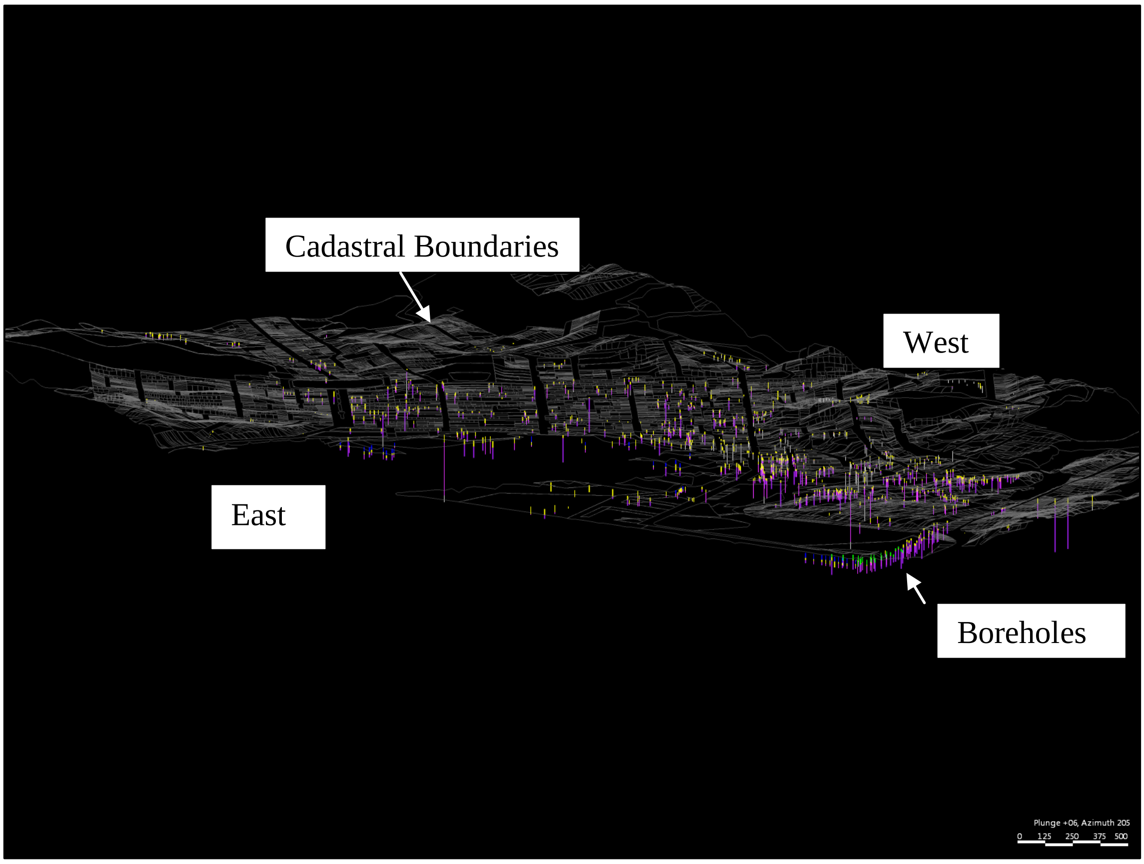
5.3.6 MODEL OUTPUTS

Three different "Scene Files" were created which can be viewed using Earth Research Viewer (software located in Appendix 7B, on DVD). The primary Earth Research Scene File contains 10 different individual geological scenes. In addition to the Primary Scene File a secondary scene file has also been created. This file contains one scene (reduced version) and is designed to be run on computers with poor graphic and memory performance. A short video containing images of the 3D model is also given (in Appendix 7A) should the user be unable to install/view or manipulate the model in the viewer software.

A DVD containing a copy of the model along with the Earth Research viewer is located in the back pocket of this thesis. The software is easy to install although it may take several minutes depending on the computer type. The software is freeware and as such can be freely distributed provided the conditions at installation are met. Please refer to the Earth Research Model Scene Help & Manipulation.docx file in Appendix 7B for model manipulation commands.

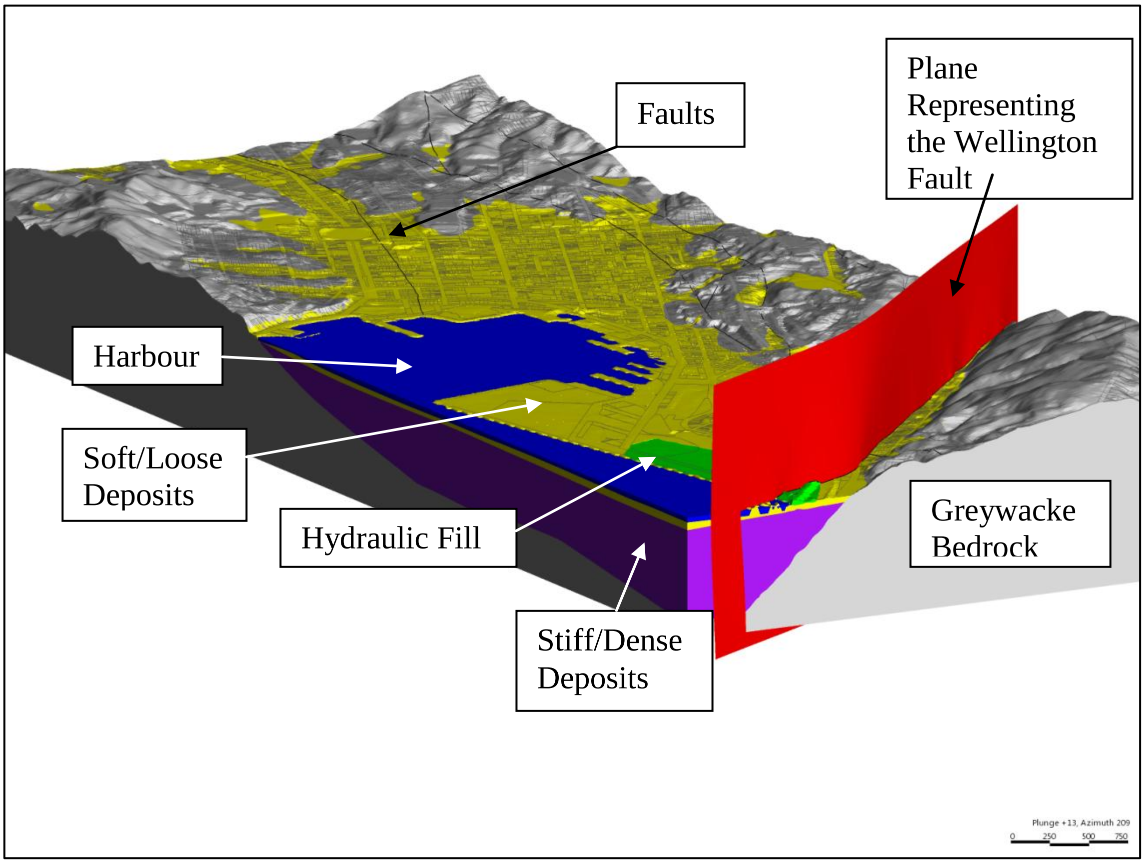
A simplified 3D geological model has been created for the study area based on borehole information (refer to Figures 5.2-5.7). The model contains four lithological groups, namely hydraulic fill, loose/soft deposits, stiff/dense deposits and greywacke bedrock. This simplified grouping was required to model Wellington City's naturally complex geology.

Figure 5.2: View southwest of the distribution of the 1025 boreholes, test pits and site observations used in this study.



Hydraulic fill deposits have been modelled. They are shown to occur in the Thorndon area in the vicinity of Aotea Quay. A "possible" hydraulic fill zone has also been created to highlight the area along the waterfront where additional unconfirmed hydraulic fill materials may occur.

Figure 5.3: View to the southwest of the complete Wellington City 3D geological model.



Loose/soft deposits have been modelled and are shown to occur at the surface throughout the study area where greywacke bedrock does not outcrop. The model indicates that the loose/soft deposits are less than 30 m thick, and overlie stiff/dense deposits. Stiff/dense deposits have been modelled and are shown to occur beneath loose/soft deposits within the study area. Stiff/dense deposits have a maximum confirmed thickness of approximately 122 m and are shown to extend to depths greater than 300 m off shore in the northeast corner of the study area.

The “best fit” greywacke bedrock surface for the Wellington City study area has been created. This surface shows a deep (150 m) basin in Te Aro which shallows as it extends southward towards the Basin Reserve, Mt Cook and the Brooklyn Hills. A maximum depth of 137 m has been confirmed by drilling to bedrock at the site of the

Museum of New Zealand. Greywacke bedrock is shown to occur at approximately -100 m below Wellington Girls College, with the bedrock surface in the Thorndon area sloping to the west. The Wellington Fault is shown to occupy a steep sided valley which deepens in a north-easterly direction. Four boreholes in this area (along the line of George Street) help to constrain this feature. Two boreholes (GM14-1 and GM14-2) strike bedrock at approximately 35 m and 46 m and occur on either side of the Wellington Fault. Another two boreholes (GM14-3 and GM14-4) extend to approximately 122 m and 117 m without striking rock and also occur on either side of the Fault but inside the positions of the two boreholes previously mentioned. The existence of this valley feature is also consistent with the maximum K-Surface offset at Ngauranga Gorge (approximately -600 m, refer to Figure 2.11) assuming a steeply dipping profile that gradually flattens out.

Figure 5.4: Hydraulic fill and reclamation zones around the Wellington City waterfront.

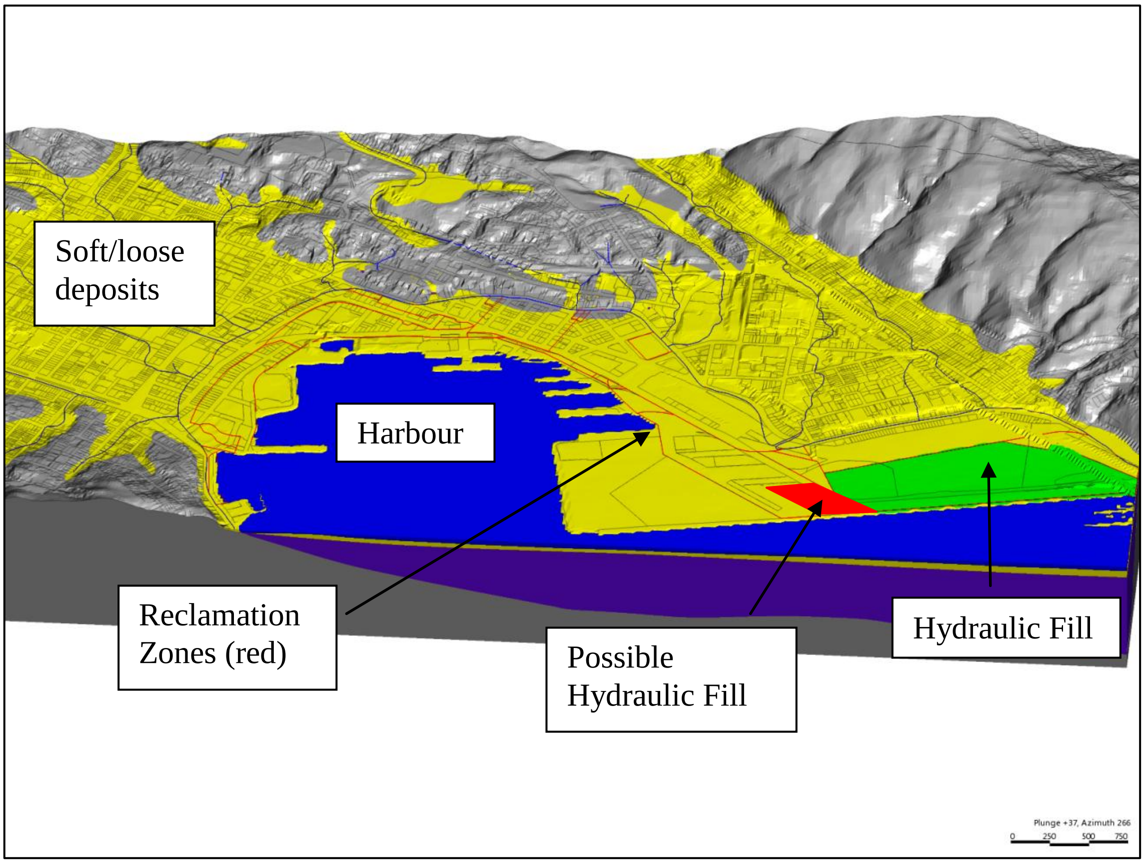


Figure 5.5: Soft/loose and stiff/dense deposit distribution in Wellington City.

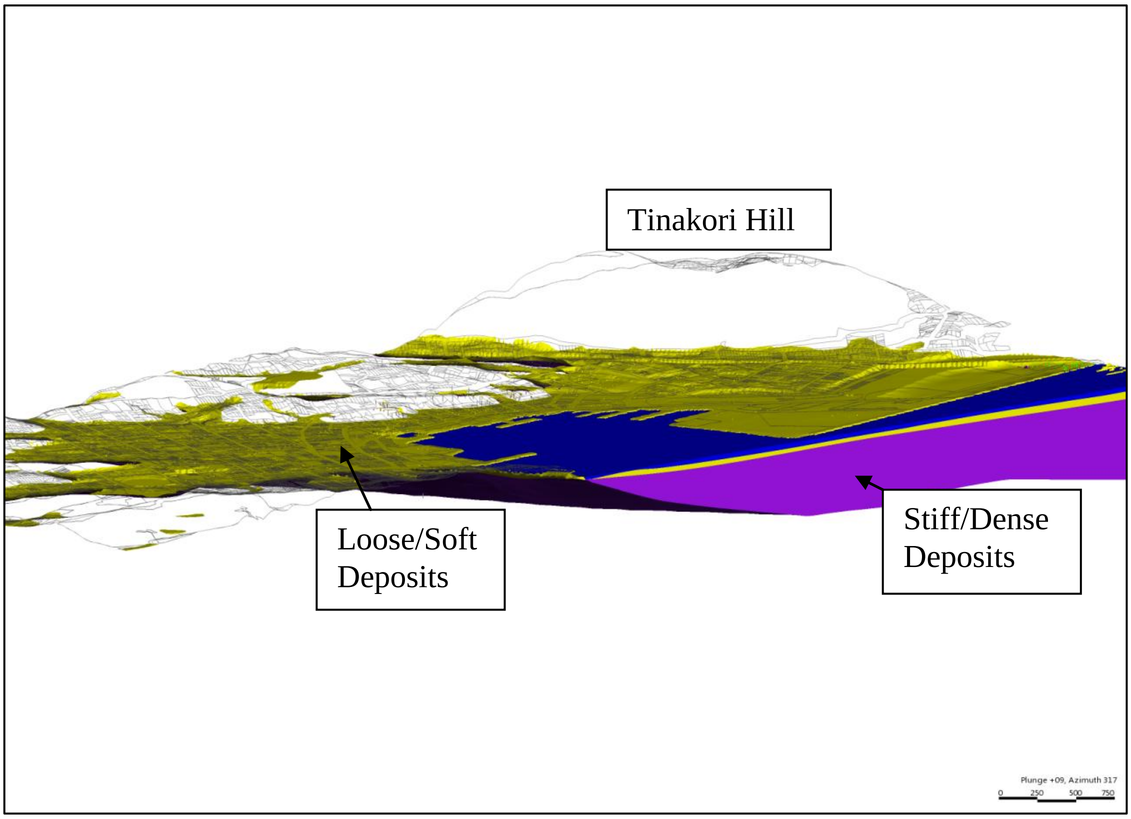


Figure 5.6: Model greywacke bedrock surface and depth to bedrock contours.

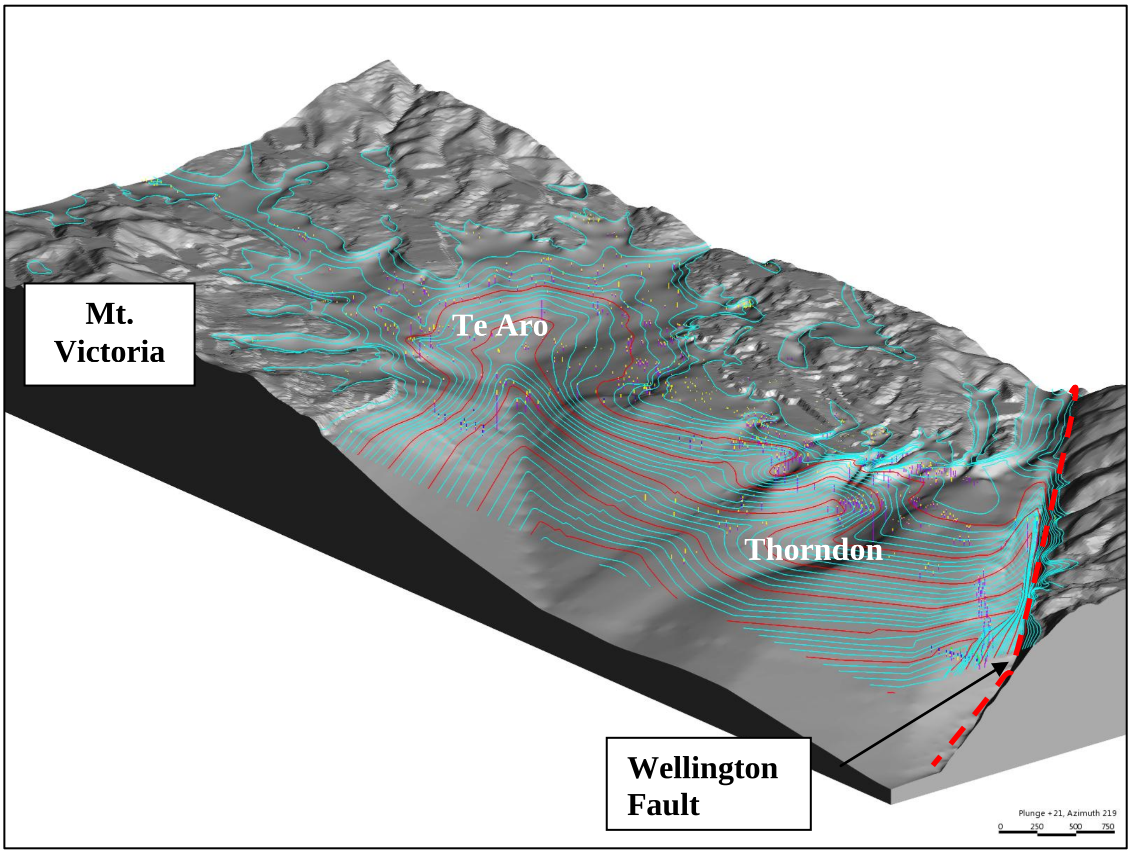
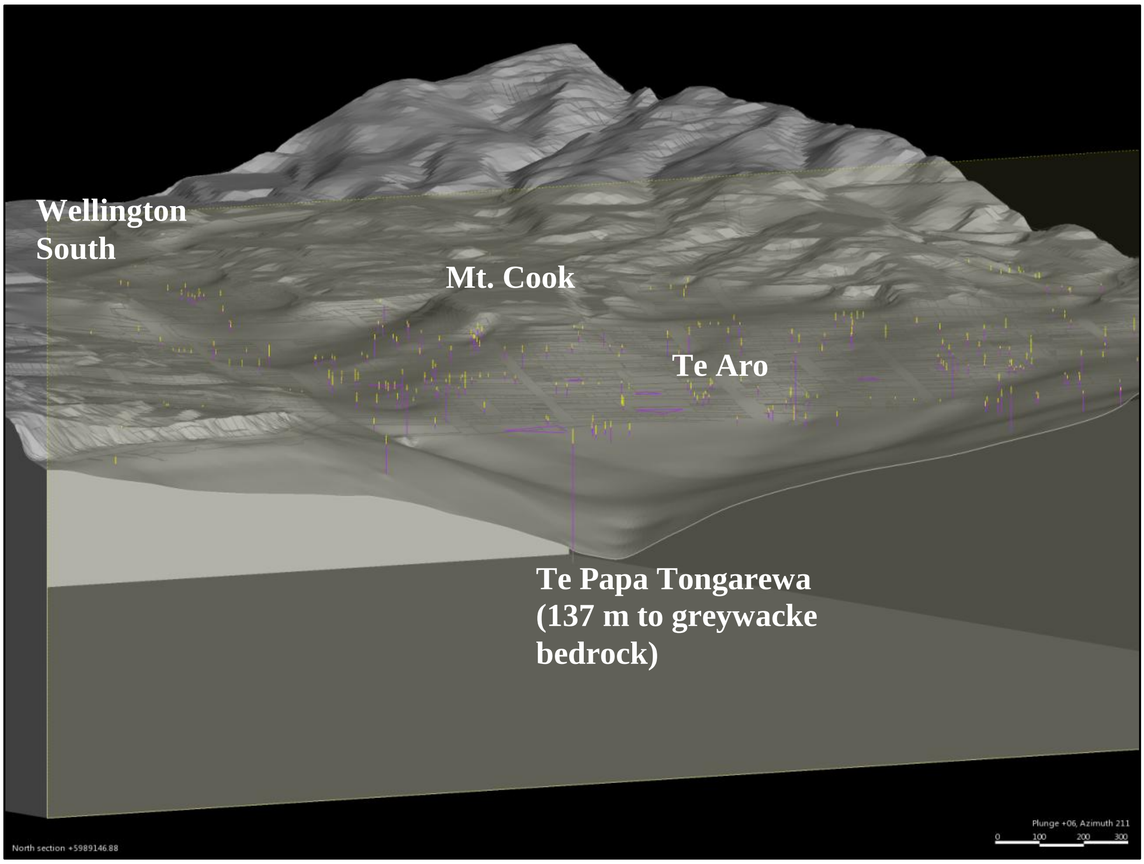


Figure 5.7: Model cross section example.



5.4 MODEL ASSUMPTIONS AND SOFTWARE LIMITATIONS

A number of assumptions were made in order to complete the 3D geological model. These assumptions were:

- The data used from the boreholes was true and correct.
- Deposits with similar lithological and geotechnical properties could be grouped together. The grouping was required to model the complex geology.
- Coordinate and elevation errors were small. The model is only as accurate as the data it represents. Given that the boreholes generally have minimum horizontal location errors of 5 m, combined with the vertical location errors of the deposits logged in the boreholes, any one subsurface point is likely to have an error of ± 7 m or more. Thus the model can only be used to visualise the subsurface geology and make constrained estimates of unit depth and properties.
- 3D interpolation of the borehole data produced geological volumes that are credible. The four groups were individually checked to make sure that they were located correctly relative to each of the boreholes containing them.

- The hills surrounding Wellington city were assumed to consist entirely of greywacke bedrock at or near the surface (topsoil was ignored in the model).
- The Wellington Fault was assumed to be vertical.

A number of limitations have been encountered during the construction of the 3D geological model with Earth Research. It was found to be difficult to model complex (real) geological relationships (especially interbedded deposits) as the software is designed to make simplified geological models based different units being assigned a stratigraphic order. This is difficult given that the drill hole data used in this thesis does not contain deposit age information.

Faults must be “drawn in” and are represented by a plane (that has a dip and orientation characteristic of the fault). This process was easy for the Wellington Fault as it was represented by a vertical plane (which based upon available data is a good approximation). For more complicated faults (i.e. in which the dip angle changes with depth) this process would not work. Whilst not necessarily a limitation Earth Research is a product that is still in the development phase and as such no tutorials, software guide or help files exist.

Earth Research can be used to construct simplified geological models from scattered drill hole data. A simplified 3D geological model of the Wellington commercial area was successfully created from borehole and microtremor (estimated depth to rock) data. The model allows the user to visualise the subsurface geology in three dimensions. The viewer software also allows the user to manipulate the model, create sections (refer to Figure 5.7) and print images.

5.5 MAPPING OUTPUTS

A suitable mapping software package was required to complete the mapping outputs for this thesis. The software needed to be user friendly, compatible with Microsoft Excel and available for the duration of this thesis. ESRI’s ArcMap 9.2 best fitted these requirements. ArcMap is an easy to learn mapping programme and is also compatible with other ArcGIS software programmes including ArcInfo (GIS software used to create Q-Map). Additionally, ArcGIS software is used by the Wellington City Council, GNS Science and consulting engineers thus increasing the number of potential users.

5.6 DATA LOCATION MAP

The data location map (refer to Appendix 8A) was created using the unique borehole identification values and coordinates to project the borehole positions on to a map at a suitable scale (1:5,000). The inputs used to create this map include:

- Microsoft Excel .cvs (comma delimited) file containing the borehole identification values, their corresponding coordinates and presence of SPT data per row (refer to Figure 5.8).
- Microsoft Excel .cvs file containing coordinates for the centres of the arrays used in the analysis of the 12 SPAC microtremor sites.
- Microsoft Excel .cvs file containing coordinates for additional microtremor measurements from other studies.

5.6.1 METHODOLOGY AND RESULTS

The data location map was created using ArcMap. The Excel .cvs files were imported into ArcMap and represented with a point and labelled. ArcMap Shapefiles containing the position and orientation of the SPAC arrays (SPAC Sites.shp) scaled to the size of the array used for analysis and the cadastral boundaries (Parcels.shp) within the Wellington City study area were then created. The parcel shapefile was created from cadastral data obtained from Wellington City Council FTP site (accessed June 6th 2009). A shapefile containing 5 m bathometric contours for Wellington Harbour was obtained from the National Institute of Water and Atmospheric Research (which the author is grateful for). These contours were then trimmed to fit the study area and saved as a shapefile (5 m Bathometry Contours.shp). The location point and shapefile data was then used to create a map document in ArcMap.

Figure 5.8: Screen capture image of the Microsoft Excel .cvs file containing borehole information.

	A	B	C	D	E
1	**Borehole_ID**	**NZMG_E**	**NZMG_N**	**Z**	**SPT**
2	GD-1	2659199	5988079	7.2	y
3	GD-2	2659162	5988134	5.69	y
4	GD-3	2659131	5988203	5.49	y
5	GD-4	2659015	5988242	14.79	y
6	GD-5	2658653	5988415	18.13	y
7	GD-6	2658490	5988489	18.99	y
8	GD-7	2658435	5988516	20.01	y
9	GD-8	2658308	5988667	23.5	y
10	GD-9	2658308	5988806	26.66	y
11	GD-10	2658318	5988867	25.2	y
12	GD-11	2659256	5988022	12.42	y
13	GD-101	2658934	5988182	17.06	y
14	GD-102	2658950	5988236	15.7	y
15	GD-103	2659004	5988389	14.5	y
16	GD-104	2658792	5988327	20.18	y
17	GD-105	2658819	5988362	18.41	y
18	GD-106	2658588	5988321	20.72	y

The data location map shows the locations of all 1025 boreholes in the Wellington City study area. Additionally the positions of the 12 SPAC testing sites and the arrays used for analysis are shown. The locations of microtremor measurements from other studies are also shown. All data point locations are given a location error of ± 5 m with the exception of the 12 boreholes listed in Table 5.2. (refer to Chapter 4, Section 4.3.4 for errors determination). The error of ± 5 m is a maximum value and many (658) of the boreholes have been assigned a location error of ± 2 m with the three boreholes logged as part of this thesis (refer to Chapter Four, Section 4.4.2) assigned location errors of ± 1 m as their positions were accurately measured.

Table 5.2 Boreholes assigned location errors of 10 m or more.

Borehole ID	Location Error	Reason Error Assigned
GM22-1	± 400 m	No site plan. Only "Aotea Quay grain silo" recorded on the log (most likely occurs at the northern end of Aotea Quay).
GM12-1	± 50 m	No site plan. May occur anywhere along Cottleville Terrace (100 m long).
GM12-4	± 50 m	No site plan. May occur anywhere along Cottleville Terrace (100 m long).
T5173-4	± 25 m	Poor quality site plan sketch. Bore hole occurs in the vicinity of the southern corner of Willeston Street and Jervois Quay.
GW107-4	± 20 m	No site plan. Location description given (Biological Sciences Block, VUW).
GW107-6	± 20 m	No site plan. Location description given (Biological Sciences Block, VUW).
GW43-1	± 15 m	No site plan. Located on the corner of Wakefield and Farish Streets (Racing Conference).
GW43-2	± 15 m	No site plan. Located on the corner of Wakefield and Farish Streets (Racing Conference).
T4334-Office1	± 10 m	No site plan. Description of bore hole locations given in accompanying report (site width 20 m).
T4334-Office2	± 10 m	No site plan. Description of bore hole locations given in accompanying report (site width 20 m).
T4334-Office3	± 10 m	No site plan. Description of bore hole locations given in accompanying report (site width 20 m).
T4334-Office4	± 10 m	No site plan. Description of bore hole locations given in accompanying report (site width 20 m).

It should be noted that borehole GM22-1 was included for completeness in the model and mapping outputs, but was not used to influence the outputs in any way. The remaining boreholes in this table are either not deep enough, or are located in close proximity to other better constrained boreholes, so they do not influenced the output results.

5.7 WATERFRONT RECLAMATION MAP

The Wellington waterfront reclamation map (refer to Appendix 8B or the reduced version in Figure 2.12) was constructed using information from the:

- Wellington Harbour Board 1936 map “Historical plan of reclamations in the port of Wellington (Port Nicholson)” to map areas of reclamation before 1936.
- Bastings 1936 “A subsoil survey of Wellington City” map to obtain stream positions.
- Wellington Waterfront Limited 2009 “Reclamations map” to map reclamations after 1936.
- 5 m Bathometry Contours shapefile (5m Bathometry Contours.shp).

5.7.1 METHODOLOGY AND RESULTS

Heads-up digitizing (features traced from an image on a computer screen) was used to accurately trace the fill zones from the 1936 Wellington Harbour Board map, the stream positions from Bastings 1936 map and the post 1936 reclamations from the Wellington Waterfront Ltd map. Three shape files (WHB Map.shp, Streams.shp and Fill Zones.shp) were then created from this digitised information. The WHB Map.shp, Streams.shp, Fill Zones.shp along with the previously created Parcels.shp and 5 m Bathometry Contours.shp files were then used to create a map document in ArcMap.

The waterfront reclamation map shows the locations of historic reclamation around Wellington City's waterfront. From this map it can be seen that a significant portion of the central city is built on reclaimed land (refer to Chapter Two, Section 2.8). The 1936 positions of streams are also shown, many of which are now directed through culverts to the sea.

5.8 SURFICIAL DEPOSIT MAP

The Wellington City surficial deposit map (refer to Appendix 8C) is not a geological map in the purest sense. The map was constructed to show different Quaternary sediment zones and greywacke bedrock at a scale useful to site investigations (1:5,000). The Wellington City surficial deposit map was constructed using information from bore hole investigations, test pits, site observations, aerial photographs, limited field mapping and existing maps. The inputs used to create this map include:

- Microsoft Excel .cvs (comma delimited) file containing points representing measured bedding and jointing within the greywacke bedrock in the Wellington City study area.
- The previously created WHB Map.shp, Streams.shp, Fill Zones.shp, Parcels.shp and 5 m Bathometry Contours.shp files.
- "Defining the Wellington Fault within the urban area of Wellington City" report and maps (Perrin & Wood 2003). These maps were used to map the location of the Wellington Fault within the study area.
- A shapefile containing the geology polygons and fault positions in Wellington City from the 1996 Geology of the Wellington area, scale 1:50 000 Map (Begg & Mazengarb).

- Bastings 1936 “A subsoil survey of Wellington City” map to obtain the former Te Aro swamp location.

5.8.1 METHODOLOGY AND RESULTS

The location of greywacke bedrock outcrop was obtained from limited field mapping (there is very little greywacke outcrop in the heavily urbanised field area), existing map data, aerial photographs and specialist opinion (from a GNS Science Engineering Geologist). Once determined, the polygons representing greywacke outcrops were drawn in ArcMap and saved into the WCBD_Geology shapefile. It should be noted that whilst these areas indicate greywacke bedrock at the surface, it may be found at depths up to ~5 m. Numerous small in-filled gullies within the study area have not been included as they are too small to be shown at this scale.

The position of the Wellington Fault was digitized from the “Defining the Wellington Fault within the urban area of Wellington City report” and saved into the Wellington_Fault.shp file. The remaining secondary fault locations are poorly known. These fault positions within Wellington City were obtained from the 1:50,000 “Geology of the Wellington area” map (Begg & Mazengarb 1996). The locations of these faults were then modified based on specialist opinion and information from existing reports.

The swamp location given in Bastings’ 1936 map was digitized and saved as swamp sediments in the WCBD_Geology shapefile. The shapefile containing the geology polygons from the 1996 Geology of the Wellington area, scale 1:50 000 Map was then imported into ArcMap. These polygons were then modified to fit the new Te Aro Swamp position, stream positions and the location of reclamation (including possible hydraulic fill) along the waterfront (using the previously created WHB Map and Fill Zones shapefiles). The WHB Map, Streams, Fill Zones, Parcels, 5 m Bathometry Contours, WCBD Geology, Wellington Fault and Wellington Central Faults.shp files were then used to create a map document in ArcMap.

The surficial deposit map shows the nature of sediments at or near the surface in Wellington City. This map was created as these deposits have very different geotechnical properties and as such are like to behave very differently under earthquake loading. The map can be used to assist in site investigations by illustrating the most likely sediments found at or just below the surface of a site.

5.9 DEPTH TO BEDROCK CONTOUR MAP

The depth to bedrock contour map (refer to Appendix 8D) shows contours at 10 m intervals to the greywacke bedrock basement. The 1025 boreholes used in the study are shown with symbols indicating whether bedrock was struck or not and are labelled with either rock depth or hole depth if no rock was struck. The following inputs were used in the construction of the depth to bedrock contour map:

- Microsoft Excel .cvs file containing the location coordinates for the 1025 boreholes used in this study, their depth, whether rock was struck and at what depth.
- Existing maps and limited field mapping.
- Greywacke bedrock polygon from the WCBD_Geology.shp file.
- The Streams.shp, Parcels.shp, 5 m Bathometry Contours.shp, Wellington Fault.shp and Wellington Central Faults.shp files (from the surficial deposit map).
- Estimated depth to bedrock from 10 SPAC microtremor tests.
- Estimated depth to bedrock from additional microtremor tests (including ReMi, Nakamura and SPAC).
- Specialist opinion (from a GNS Engineering Geologist).

5.9.1 METHODOLOGY AND RESULTS

The Excel .cvs file was imported into ArcMap and the boreholes which struck rock were labelled indicating the depth to bedrock. The boreholes that did not strike bedrock were labelled with their hole depth (representing a minimum depth to bedrock value). A shapefile of the greywacke bedrock outcrop (Greywacke_Outcrop.shp) was created from the WCBD_Geology.shp file by removing all except the greywacke polygons.

A map document containing the borehole and microtremor depth to rock data along with the Greywacke_Outcrop.shp was created. The ArcMap 3D analyst extension was then used to automatically contour the data at 10 m intervals. The automatic contouring was not successful due to the spread of data and in particular the lack of points striking bedrock, especially in the Thorndon area. After discussion with a GNS Mapping Specialist it was decided that drawing and then digitizing depth to bedrock contours was the best way forward.

The automatic contours were removed from the map and it was printed off at a scale of 1:5,000 (the intended scale for the final map). Depth to bedrock contours were then drawn by hand on the printed map. Heads-up digitizing was then used to transfer the contours into ArcMap and store them as a shape file (10 m Depth to Bedrock Contours.shp). The contour map was then printed off to scale and checked. After final corrections were made the map was printed at 1:5,000 scale with the depth to bedrock and hole depth labels rounded to the nearest metre to avoid overcrowding.

The depth to bedrock contour map shows a basin in Te Aro (up to 160 m deep) which deepens in a north-easterly direction. The maximum confirmed depth to bedrock in this area is given by a borehole located at the Museum of New Zealand. At least seven deep (> 45 m to bedrock) boreholes help constrain the bedrock basin edges in this area. However, no boreholes have been drilled to rock in the centre of the basin so the error in the depth to bedrock contours in this area remains high.

Between Victoria Street and Queens Wharf bedrock occurs at less than 50 m below the surface, although more commonly less than 20 m. Further north between Waring Taylor Street and Bowen Street a shallow dipping ridge of bedrock is shown to extend in an easterly direction toward the waterfront.

As a result of contouring, a deep valley (150 m^+) is shown in the area north of Wellington Railway Station. One borehole (GM20-W5) at the head of this valley is the only borehole in the Thorndon area to strike bedrock (at 114 m below the surface). Generally, the greywacke bedrock surface is shown to dip in an easterly direction in the Thorndon area.

A valley is shown along the Wellington Fault which rapidly increases in depth in a north-easterly direction from 0 m (greywacke bedrock at the surface) in the southwest to more than 300 m to greywacke bedrock in the northeast. Four boreholes help to constrain this valley in the George Street area, but further to the northeast contours are based on the offset K-surface (refer to Section 2.7.1).

It should be noted that where no subsurface information exists (e.g. in the area of Premier House, southern Tinakori Road), depth to bedrock contours have been drawn based on topography, distance to greywacke outcrop and expert opinion. The depth to bedrock map provides a "best fit" model of the data collated for this study. This map can be used to estimate the depth to greywacke basement but errors particularly where borehole distribution density is low must be considered.

The deep valley and basin features shown on the depth to bedrock contour map are likely to experience greater levels of ground shaking amplification during a damaging earthquake event.

5.10 CROSS SECTION LOCATION MAP

This map (Appendix 8E) shows the positions of the 48 cross sections used to refine the site period and V_s30 maps. In addition the 282 pseudo boreholes for which site period and V_s30 values were calculated are also shown. Refer to Sections 5.10.1 and 5.10.2 for map relevance and cross section calculations.

5.10.1 SITE PERIOD, V_S30 MAP REFINEMENT

It was immediately obvious that the measured site period and V_s30 values in Wellington City were too sparse to map and contour with any level of certainty. It was decided that the calculation of additional site period and V_s30 values from pseudo boreholes would be used to add points to the map. The additional pseudo points could then be used to refine contour lines between the real measured points.

5.10.2 PSEUDO BOREHOLE CALCULATIONS

48 cross sections were constructed around the basin edges of the central city. From these cross sections V_s30 and site periods were calculated for 282 pseudo boreholes positioned on these sections. Cross section positions (refer to Appendix 8E, cross section location map) were chosen so that a least one real data point (measured site period/V_s30 or borehole that struck rock) was intercepted. Pseudo boreholes were then positioned along these sections starting from the basin edge (greywacke bedrock out crop) at even intervals. The depth to bedrock for these pseudo boreholes was then measured directly off the depth to bedrock contour map. Then using geological information from nearby real boreholes a layer model (lithological layers with differing shear wave velocities) was developed for each pseudo borehole. This involved assigning two or more layers to each borehole. These layers were then assigned a shear

wave velocity based on Table 5.3 Wellington City layer properties. The shear wave velocity ranges in table 5.3 have been determined from real measured velocities obtained from seismic cone penetrometer and microtremor testing.

Once all pseudo boreholes had been assigned a layer model, site period and V_s30 values were calculated in the site class cross section calculation spreadsheet. Figure 5.9 shows an example of these calculations from cross section 11 (refer to Appendix 8E & cross section calculation spreadsheet).

Site period and V_s30 values calculated from the pseudo boreholes were then compared with real measured values. If significant differences were found the pseudo borehole layer models were adjusted to better fit the measured values. The calculated site period and V_s30 values were then used to refine the site period and V_s30 maps. Figures 5.10A-C shows this process for the refinement of site period contours. It should be noted that the process is the same for the refinement of V_s30 contours (V_s30 values are used instead of site periods).

Table 5.3: Shear wave velocities of typical Wellington City deposits.

Description	Minimium Vs (m/s)	Maximium Vs (m/s)	Location
Hydraulic Fill	50	150	Aotea Quay
Rock Fill	125	250	Railway yards/Te Papa
Other Fill	200	300	Subdivisions
Holocene lake silt, swamp, peat	50	200	Thorndon (rare), Te Aroa
Holocene sand/gravel loose	150	300	
" med dense	250	350	
" dense	350	450	
" very dense	400	500	
Beach sand/gravel	150	250	Under waterfront reclamations
Holocene silt/clay, soft-firm	100	200	
Holocene silt/clay, firm-stiff	200	350	
Older silt/clay very stiff	400	700	Paleosols v. Thin (Pleistocene)
Pleistocene gravel/sand/silt, dense	250	400	Thorndon/Te Aro
" deeper, v. dense	400	700	(effective bedrock 100m+ @ Te Papa Tongarewa)
" deepest, v. dense	700	1000	
CW Bedrock	200	700	Terrace Tunnel
Crushed Bedrock	500	900	
HW Bedrock	600	1000	
MW Bedrock	700	1100	
SW Bedrock	900	1300	
UW Bedrock	1200	1750	
Deep UW Bedrock	1500	2000	

Figure 5.9: Cross section 11 site period and Vs30 calculations.

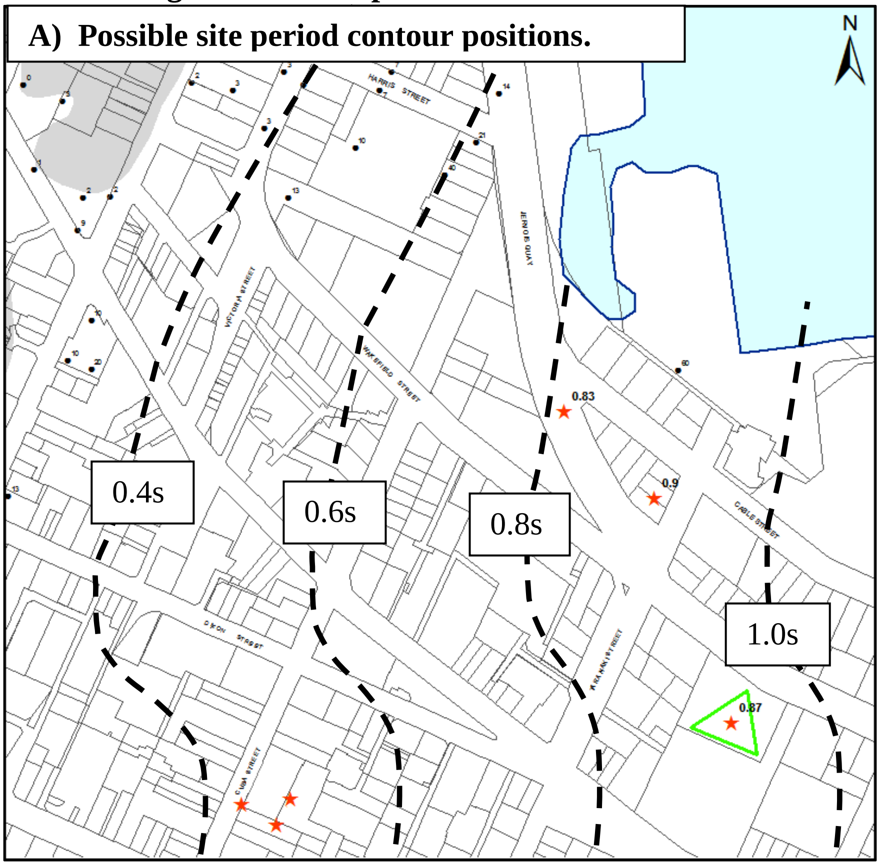
C	D	E	F	G
		Formula		
Hole LL:				
Minimum Vs Values:				
Depth from	Depth to	Description	$V_{s\ (m/sec)}$	Travel time
0	6	Fill - sand/silt/gravel	125	=(D6-C6)/F6
=D6	27	M. Dense gravel/sand/silt	250	=(D7-C7)/F7
=D7		Rock		
		TOTAL	=SUM(G6:G7)	Seconds
		4 times	=4*F12	Natural Period
Average Vs Values:				
Depth from	Depth to	Description	$V_{s\ (m/sec)}$	Travel time
0	5	Fill - sand/silt/gravel	190	=(D19-C19)/F19
=D19	27	M. Dense gravel/sand/silt	270	=(D20-C20)/F20
=D20		Rock		
		TOTAL	=SUM(G19:G20)	Seconds
		4 times	=4*F25	Natural Period
Max Vs Values:				
Depth from	Depth to	Description	$V_{s\ (m/sec)}$	Travel time
0	6	Fill - sand/silt/gravel	250	=(D32-C32)/F32
=D32	27	M. Dense gravel/sand/silt	300	=(D33-C33)/F33
=D33		Rock		
		TOTAL	=SUM(G32:G33)	Seconds
		4 times	=4*F38	Natural Period
Vs 30 (Ave. Values)				
Depth from	Depth to	Description	$V_{s\ (m/sec)}$	Travel time
0	6	Fill - sand/silt/gravel	190	=(D45-C45)/F45
=D45	27	M. Dense gravel/sand/silt	270	=(D46-C46)/F46
=D46	30	CW-HW Rock	800	=(D47-C47)/F47
		Total	=SUM(G45:G47)	Seconds
		Vs 30=	=30/F53	m/sec

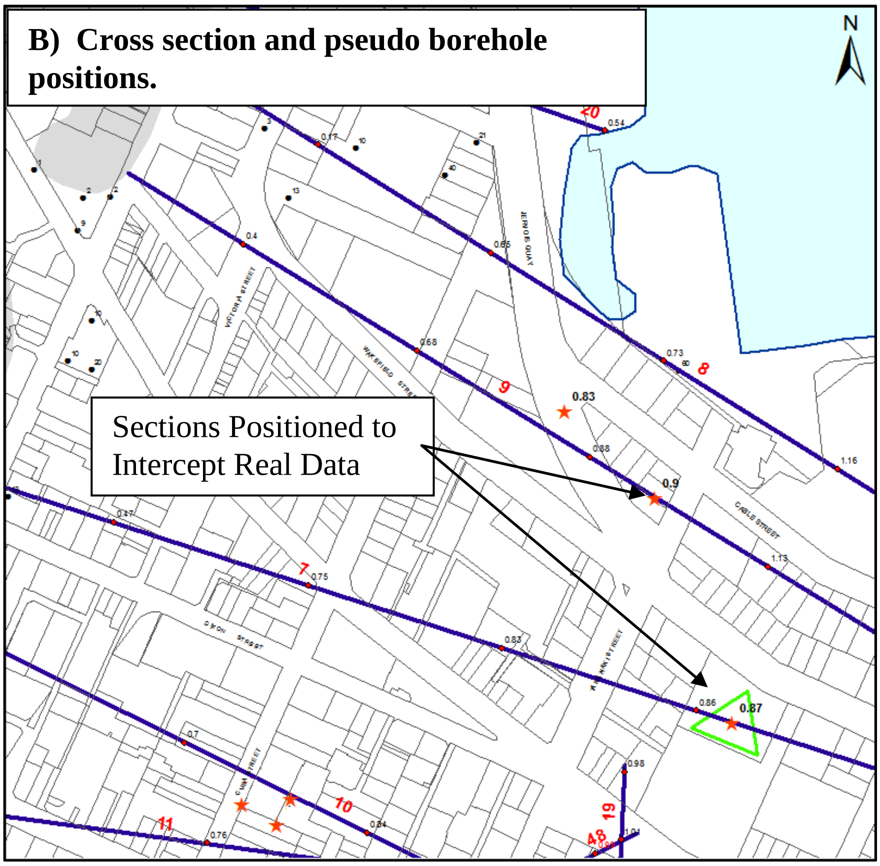
Site Period Calculation

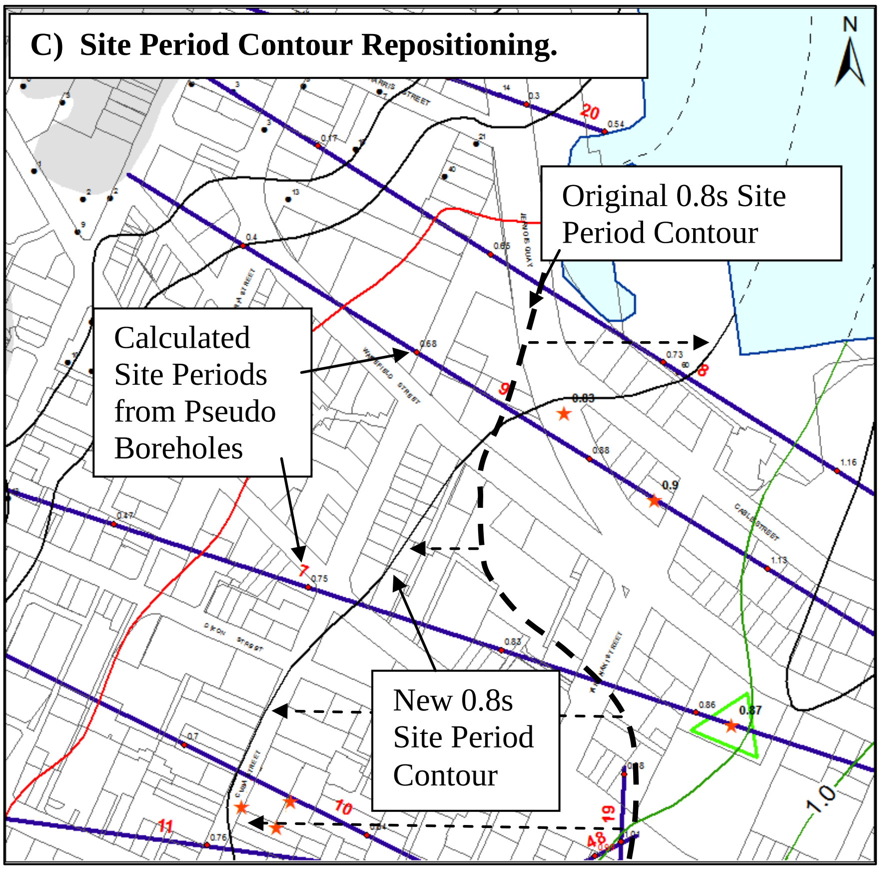
V_s30 Calculation

I	J	K	L	M
		Calculated Values		
Hole LL:				
Minimum Vs Values:				
Depth from	Depth to	Description	Vs (m/sec)	Travel time
0	6	Fill - sand/silt/gravel	125	0.048
6	27	M. Dense gravel/sand/silt	250	0.084
27		Rock		
		TOTAL	0.132	Seconds
		4 times	0.528	Natural Period
Average Vs Values:				
Depth from	Depth to	Description	Vs (m/sec)	Travel time
0	5	Fill - sand/silt/gravel	190	0.026
5	27	M. Dense gravel/sand/silt	270	0.081
27		Rock		
		TOTAL	0.107	Seconds
		4 times	0.431	Natural Period
Max Vs Values:				
Depth from	Depth to	Description	Vs (m/sec)	Travel time
0	6	Fill - sand/silt/gravel	250	0.024
6	27	M. Dense gravel/sand/silt	300	0.07
27		Rock		
		TOTAL	0.094	Seconds
		4 times	0.376	Natural Period
Vs 30 (Ave. Values)				
Depth from	Depth to	Description	Vs (m/sec)	Travel time
0	6	Fill - sand/silt/gravel	190	0.032
6	27	M. Dense gravel/sand/silt	270	0.077
27	30	CW-HW Rock	800	0.004
		Total	0.113	Seconds
		Vs 30=	265.23	m/sec

Figure 5.10: Site period contour refinement.







5.11 LOW AMPLITUDE NATURAL PERIOD (SITE PERIOD) MAP

The low amplitude natural period (site period) map (Appendix 8F) shows contour lines representing site period at two second intervals. The inputs used to create this map include:

- Microsoft Excel .cvs file containing measured site periods.
- Microsoft Excel .cvs file containing site periods that were calculated from the cross sections shown on the cross section location map (refer to Section 5.10).
- Greywacke_Outcrop.shp, 10m_Depth_to_Bedrock_Contours.shp, Streams.shp, Parcels.shp, 5 m Bathometry Contours.shp, Wellington Fault.shp and Wellington Central Faults.shp files (from the surficial deposit and depth to bedrock contour maps).

5.11.1 METHODOLOGY AND RESULTS

Site period contours were created in ArcMap following the same method described for the creation of the depth to bedrock contours (using site period values instead of depth to rock). The site periods (Site_Period_Contours.shp) along with

Greywacke_Outcrop.shp, Streams.shp, Parcels.shp, Wellington Fault.shp and Wellington Central Faults.shp files were then added to a map document to create the map.

The site period map reflects the depth to bedrock contours (as depth to bedrock is used in its calculation). Site period contours in Te Aro range from 0.2s (generally bedrock less than 20 m from the surface) to > 1.4s (along the waterfront at the Museum of New Zealand). In the Queens Wharf area site period contours reach a maximum value of 0.6s, but generally 0.4s or less. In Thorndon the site period contours range from 0.4s to > 1.8s, but are generally greater than 0.6s. The 0.6s site period contour can be used to differentiate between NZS 1170.5:2004 subsoil class C and D sites (as was done when constructing the subsoil site class map).

Sites with a greater site period (e.g. central Te Aro and eastern Thorndon areas) are likely experience greater amplification levels than sites with low site periods (e.g. greywacke bedrock sites). Thus, it can be seen from the site period map that greater levels of ground shaking amplification would be expected in these areas.

5.12 V_S30 MAP

V_s30 is the shear wave velocity of the top 30 m of ground calculated from shear wave propagation time to that depth. V_s30 is used in ground classification in the United States of America and the creation of this map (Appendix 8H) allows comparison to that system. The inputs used to create this map include:

- Microsoft Excel .cvs file containing V_s30 values from measured data.
- Microsoft Excel .cvs file containing V_s30 values that were calculated from the cross sections shown on the cross section location map (refer to Section 5.10).
- Greywacke_Outcrop.shp, Parcels.shp, 10m_Depth_to_Bedrock_Contours.shp, 5m Bathometry Contours.shp, Wellington Fault.shp and Wellington Central Faults.shp files (from the surficial deposit and depth to bedrock contour maps).

5.12.1 METHODOLOGY AND RESULTS

V_s30 contours were created in ArcMap following the same method described for the creation of the site period and depth to bedrock contours (using V_s30 values instead of depth to rock or site period). The site periods (Site_Period_Contours.shp) along with Greywacke_Outcrop.shp, Streams.shp, Parcels.shp, Wellington Fault.shp and Wellington Central Faults.shp files were then added to a map document to create the map. V_s30 values calculated from measured data were represented with a star on the V_s30 map. Calculated V_s30 values (from the cross sections described in section 5.10) were represented with a large coloured circle. This was done to assist in the construction of the V_s30 zones and to make the V_s30 values clearer. V_s30 zones were created from the V_s30 contours and show the minimum most likely V_s30 value range expected.

The V_s30 map has been created to illustrate the range of likely V_s30 values for the Wellington City area. Average V_s30 values in Te Aro and Thorndon range from 251-349 m/s. The variation in calculated V_s30 values in these areas may be the result of the calculation process itself or may show areas of materials of slightly differing densities. As expected, V_s30 values in Wellington City range from 300 m/s to more than 700 m/s near the basin edges and rapidly decrease with increasing sediment depth (the greater the sediment depth the lower the shear wave velocity).

It has long been understood that structural damage arising from strong ground motion is dependent upon the shear wave velocity of the soil. Soils with lower shear wave velocities are generally associated with stronger ground motion resulting in higher levers of amplification and hence more damage. Thus from the V_s30 map it can be seen that the Thorndon and Te Aro areas are likely to experience greater amplification during a damaging earthquake event

There are significant errors associated with the construction of this map (i.e. only data from approximately 40 measured sites was used) and as such must be used with caution. The use of V_s30 can lead to non-conservative site condition assessment as obviously sediment at depths greater than 30m are unaccounted for in the assessment. Thus, if a thick, very soft/loose layer was to occur at 31 m below the surface it would be unaccounted for even though it would have significant implications on a site’s dynamic response.

5.13 NZS 1170.5:2004 SITE SUBSOIL CLASS MAP

The creation of the NZS 1170.5:2004 site subsoil class map (Appendix 8G) was the second part of the primary objective of this thesis (with the first being the construction of the database, refer to Chapter Four). The inputs used to create this map include:

- Table 3.2 (site class definitions).
- Microsoft Excel .cvs file containing the 1025 boreholes with assigned site classes.
- Microsoft Excel .cvs file containing measured site periods.
- Greywacke_Outcrop.shp, 10m_Depth_to_Bedrock_Contours.shp, Streams.shp, Parcels.shp, 5 m Bathometry Contours.shp, Site_Period_Contours.shp, Wellington Fault.shp and Wellington Central Faults.shp files (from the surficial deposit and depth to bedrock contour maps).

5.13.1 METHODOLOGY AND RESULTS

A site subsoil class was assigned (according to NZS 1170.5:2004 specifications, refer to Chapter Three, Section 3.4) to each of the 1025 boreholes from the geotechnical borehole database. Where it was difficult to assign a site class to a given borehole the more conservative class was used (i.e. if it was difficult to decide between class C and class D, class D was used).

The shapefiles previously listed in inputs were then added to ArcMap to create a map. Measured site period points were added to the map document and labelled with their respective site periods. Theses points were then colour coded based on the site subsoil class they fell into (i.e. site class D if period > 0.6s was coloured light red). Points representing site subsoil class from the 1025 boreholes were then added. Again theses were colour coded based on the site class they represent.

The site subsoil class B polygons were created by applying a buffer to the Greywacke_Outcrop shapefile. This was done as site subsoil class B sites must not have a surface layer of more than 3 m of highly to completely weathered rock and or soil. Probable site subsoil class E was assigned to the area containing hydraulic fill in the vicinity of Aotea Quay and a polygon representing this was created. No evidence exists to support this classification. However, two boreholes in this area fall just outside the necessary 10 m of very soft soil (SPT N < 6) needed for classification as site subsoil class E sites, so to be conservative class E was assigned. The area containing possible hydraulic fill was assigned a possible E site subsoil class and is represented on the map as such. It should be noted that the probable class E polygon is much smaller than that of the hydraulic fill polygon shown on the surficial deposit map. This is because 10 m of very soft soil is required for class E designation and this is not present around the landward perimeter of the hydraulic fill reclamation (reclamation Z, refer to Appendix 8B waterfront reclamation map). The possible class E polygon is the same size as that of the possible hydraulic fill polygon because the extent of the hydraulic fill in this area is unknown due to a lack of subsurface information. The two site class D polygons were created using the 0.6s site period contour and the probable/possible E class boundaries. Site subsoil class C was then assigned to the remaining areas of the map (i.e. between class B and class D).

The NZS 1170.5:2004 site subsoil class map shows the areas assigned the four different site subsoil classes which occur in Wellington City. This map is designed to assist engineering professionals with site classification in Wellington City, but in no way should it replace site specific investigations.

Site subsoil class B is shown to occur in areas where greywacke bedrock is at or just below the ground surface (< 3 m highly to completely weathered rock and or soil). The areas assigned site subsoil class B classification have a high error associated with them. This is because soil and rock weathering depth in these areas has not been mapped and so it can only be assumed that the < 3 m of highly to completely weathered rock and or soil criterion is met. Site subsoil class C areas are shown to occur around the basin edge in Te Aro, Wellington South, the Aro Valley and western Thorndon areas. Site subsoil class D is shown to occur in the Thorndon and central Te Aro areas. Site subsoil class E has been conservatively assigned to areas underlain by hydraulic fill in the vicinity of Aotea Quay.

Areas that have been assigned a lower site subsoil class (class D and E) on the map are more likely to experience higher levels of ground shaking amplification (for weak motions which are in the elastic range of the soil) than those areas that have been assigned a higher site subsoil class (class B). Areas assigned a C site subsoil class are likely to experience moderate levels of ground shaking amplification in a damaging earthquake event. Structural damage in an earthquake will be greatest where ground shaking amplification is greatest. Thus, to mitigate against this effect structures with increased strength need to be designed in these areas and as a result design and construction costs will be greater. From the NZS 1170.5:2004 site subsoil class map it can be seen that structures in the central Te Aro and Thorndon areas (site class D) would require greater design strength to meet the seismic loading requirements than those situated in class C areas (around the basin edges).

It is recommended that site specific investigations are used in areas where limited subsurface information exists (or where the data is insufficient to allow site classification) to prove/disprove the assigned site subsoil class.

5.14 GROUND SHAKING AMPLIFICATION HAZARD MAP

A ground shaking amplification map of the Wellington City study area was created from the NZS1170.5:2004 site subsoil class map (refer to Section 5.13) which contains four classes of subsoil with respect to ground shaking amplification.

5.14.1 METHODOLOGY AND RESULTS

The four site subsoil class areas from the NZS 1170.5:2004 site subsoil class map were assigned a colour based on expected levels of amplification for ground motions which are in the elastic range of the soil. Non-essential elements were then removed to make the map clearer. These elements included depth to bed rock contours, the 0.6s site period contour, SPAC sites, additional microtremor data points and the borehole data points.

The ground shaking amplification hazard map is analogous to the NZS 1170.5:2004 site subsoil class map and has been used to clearly show areas of differing amplification for the benefit of the layman. It should be noted that the map is only indicative for motions which are in the elastic range of the soil (PGA < 0.4g). Soft or loose soils will attenuate strong motions when the soil yields and behaves non-linear. The point at which this cross-over occurs is considered to be at a PGA (peak ground acceleration) of about 0.4g. Thus for near-field strong motions greater than this PGA, soft/loose soils may effectively act as a base isolation system for stiff buildings with a natural period much less than the site period of the ground itself. Structures are most likely to be damaged when resonance occurs (when the natural period of the ground shaking approaches the natural period of the structure) and thus when the natural period of a structure and the ground differ significantly amplification is unlikely to occur. Ground shaking amplification is also governed by the characteristics of the earthquake motion itself. Some earthquakes with a high stress drop may generate predominantly short period motions which are likely to be most damaging to low, stiff buildings built on rock or shallow soil. Other low stress earthquakes may generate predominantly long period motions which are likely to be most damaging to taller, more flexible structures built on deeper softer soils.

For motions which are in the elastic range of the soil, very high levels of amplification can be expected in the area underlain by hydraulic fill in the vicinity of Aotea Quay. Moderate to high levels of amplification can be expected in the Thorndon and central Te Aro areas. Low levels of amplification can be expected around Te Aro basin, along the waterfront by Queens Wharf and in the area west of Parliament Buildings.

5.15 LIQUEFACTION POTENTIAL MAP

A generalised map showing the liquefaction potential in Wellington City from a large earthquake (M_w 7.5) centred on the Wellington Fault was created based on borehole lithology, mapped lithology and SPT N count data. It should be noted that this generalised map was not one of the major outputs to this thesis and has been included for completeness only. The inputs used to create this map include:

- The Streams.shp, Parcels.shp, 5 m Bathometry Contours.shp, Wellington_Fault.shp and WCBD_Geology.shp files (from the surficial deposit map).
- Surficial deposit map shapefile.
- Microsoft Excel .cvs borehole location file.
- Kingsbury & Hastie liquefaction potential map.

5.15.1 METHODOLOGY AND RESULTS

Each of the geological polygons created for the surficial deposit map was assigned a liquefaction potential value from extreme to no potential based on their lithology and average approximate stiffness (SPT N data). Refer to Table 5.4 for liquefaction potential classification. Once all the geologic polygons had been assigned a liquefaction potential value they were colour coded with hot colours representing high potentials and cool colours low potentials.

The liquefaction potential map shows extreme potential for liquefaction to occur in the vicinity of Aotea Quay. High potential for liquefaction is shown in the Waterfront, Thorndon and Te Aro for the given earthquake scenario. It should be noted that although areas of greywacke bedrock are assigned no liquefaction potential, small isolated pockets of fill too small to be mapped occur within these areas and may undergo liquefaction for the given earthquake scenario.

Table 5.4: Liquefaction potential classification.

Deposit Type	Assigned Liquefaction Potential
Loose Hydraulic Fill	Extreme
Reclamation Fill	High
Shallow Marine	High
Swamp	High
Alluvium/Colluvium	Low to High
Colluvium	Low
Greywacke bedrock	No Potential for Liquefaction

5.14 CHAPTER SUMMARY

A 3D simplified geological model of the Wellington City study area was successfully created. The model shows four different lithological groups which are based on a unit's geological and geotechnical properties.

The Wellington data location map shows the accurate positions of all borehole, test pit and microtremor data sources used in this thesis. Each data point is labelled with a unique identification value which is consistent with those used in the geotechnical borehole database, SPAC testing, 3D geological model and additional mapping outputs.

Waterfront reclamation and surficial deposit maps have been successfully created. These maps show areas of reclamation, swamp, marginal marine and alluvial/colluvial sediments and provide a useful initial reference for site investigations in the Wellington City study area.

A depth to bedrock map was created for the study area using all the available information collated for this study. The map shows two deep sedimentary (150 m^+) basins in the Thorndon and Te Aro areas with the Wellington Fault occupying a deep valley north of the central city. The thicker sediments in these areas are likely to experience greater levels of ground shaking amplification during a damaging earthquake event.

V_s30 and site period maps were successfully created from both measured and pseudo data points. The lack of site period and V_s30 measurement results in Wellington city made it necessary to refine these maps using the values calculated from the pseudo boreholes. The V_s30 values in Wellington City were shown to rapidly decrease around the basin edges (up to a depth of 30 m to greywacke bedrock). In the Thorndon and Te Aro areas V_s30 values were relatively constant (range of 250-349 m/s), except for some low velocity areas along the waterfront and near the Basin Reserve in an area formerly occupied by the Te Aro swamp. As a result of the low velocities in these areas ground shaking amplification levels are likely to be highest in a damaging earthquake event. A slow velocity area may also exist in the area of hydraulic fill in the vicinity of Aotea Quay but no data exists to prove/disprove this. The site period contour map shows contours of site period increasing in an easterly direction away from the basin edges in Thorndon and Te Aro reaching a maximum along the northern half of Aotea Quay. Thus, ground shaking amplification (for motions ~ < 0.4g) is likely to be greatest in these areas with amplification levels decreasing with decreasing (shorter) site period consistent with reducing depth to bedrock. The 0.6 second site period contour was used to define the site class C/D boundary in the site subsoil class map.

A site subsoil class map made to the specifications outlined in NZS 1170.5:2004 was successfully created for the Wellington City study area completing the primary objective of the thesis. The map shows the four different site classes that occur in the central city and their distribution. This map is designed to assist engineering professionals with site classification in Wellington City however, because of incomplete data, it is recommended that site specific investigations are used to prove/disprove the assigned site class in this map for a particular site. Areas that have been assigned site subsoil class D and E on the map are more likely to experience higher levels of ground shaking amplification (for motions ~ < 0.4g) than those areas that have been assigned class B. Areas assigned class C are likely to experience moderate levels of ground shaking amplification, in a damaging earthquake event.

Ground shaking amplification and liquefaction potential maps were also created. These maps were not major outputs from this thesis and have been included only for completeness. The ground shaking amplification map is the same as the site subsoil class map and has been redesigned to emphasise the potential of ground shaking amplification (for motions ~ < 0.4g) in Wellington City for non engineering professionals. The liquefaction potential map shows areas of differing liquefaction potential for a large earthquake centred on the Wellington Fault. Both these maps show the potential for liquefaction and ground shaking amplification to be highest in the area along Aotea Quay which was reclaimed in the early twentieth century using hydraulic fills.

CHAPTER SIX

PROJECT APPLICATIONS AND SYNTHESIS

6.1 INTRODUCTION

This chapter sets out to synthesise the information presented in Chapters One to Five and discusses the practical application of the outputs from this thesis with comparison to previous research. The aims of this chapter are:

- To synthesise the geotechnical and geological information presented in Chapter Four and Five.
- To discuss the practical application of the outputs from this thesis. Namely:
    - Site subsoil class determination
    - Foundation assessment
    - Liquefaction and hazard assessment
- To compare and discuss the results from this thesis with previous research.
- To assess the three geotechnical tests (borehole investigations, SCPT and SPAC) undertaken to help characterise the subsurface within the study area, in terms of their effectiveness in Wellington City deposits.

6.2 PROJECT APPLICATIONS

A readily accessible geotechnical borehole database was created and contains lithological and geotechnical information from 1025 bore logs, test pits and site observations. This information stored in this database can be used to assist engineers with foundation design, hazard planning and site subsoil class assessment.

6.2.1 SITE SUBSOIL CLASS AND FOUNDATION ASSESSMENT

The second part of the primary objective of this thesis was the creation of a site subsoil class map based on the New Zealand structural design specifications (NZS 1170.5:2004) at a commercially useful scale (1:5,000). The map shows the location of the four different site subsoil classes that occur in the central city. This map has been designed to assist engineering and planning professionals with site classification determination in Wellington City as it allows the user to visualise the assigned site subsoil class and its proximity to existing data points which may be used to prove/or disprove its classification.

A simplified 3D geological model of the Wellington commercial area was successfully created from scattered borehole and microtremor (estimated depth to rock) data. The model allows the user to visualise the subsurface geology in three dimensions. Sediment location and thickness can be used in combination with assumed or preferably real shear wave velocity data to estimate a sites natural period. This is achieved by measuring the depth to basement at a point, and calculating a site period using four times the shear wave travel time through material from the surface to greywacke bedrock. The natural period in combination with subsurface geological information (i.e. greater than three metres to bedrock) can then be used to assign a site subsoil class in accordance with NZS 1170.5:2004.

The V_s30 and site period maps created for this thesis can be used to determine areas that are most susceptible to ground shaking amplification (for motions ~ < 0.4g). These areas are likely to have a long site period and low Vs30 values (as is the case with the area underlain by hydraulic fill in the vicinity of Aotea Quay).

The Waterfront reclamation and surficial deposit maps show areas of reclamation, swamp, marginal marine and alluvial/colluvial sediments and provide a useful initial reference for site investigations in Wellington City. A depth to bedrock map was created for the study area using all the available information collated for this study. It is envisaged that this map is used as a modern update to the Grant-Taylor et al. (1974) depth to bedrock map.

6.2.2 LIQUEFACTION AND HAZARD ASSESSMENT

A generalised map showing the liquefaction potential in Wellington City was created from data compiled and stored in an accessible database. Liquefaction was not dealt with specifically in this thesis and the liquefaction potential map has been included for completeness only.

The evaluation of liquefaction potential under earthquake loading can be done using standard penetration testing data. Put simply the process has three main steps:

1. Estimation of the cyclic shear stress induced at various depths within the soil by the earthquake, and the number of significant stress cycles.
2. Estimation of the cyclic shear strength of the soil.
3. Comparison between the induced cyclic shear stress and the cyclic shear strength. Where the induced shear stress exceeds the shear stress required to cause initial liquefaction, a potential for liquefaction exists (the greater the difference the higher the potential).

The SPT spreadsheet within the geotechnical borehole database compiled for this thesis contains over 5000 individual SPT N count measurements at 536 different locations in the Wellington City study area (refer Appendix 8A, Data location map for SPT site distribution). This information is readily available and could be used to create a more refined liquefaction potential map by calculating potentials for all the boreholes within database as per the 3 main steps outlined above.

The ground shaking amplification map is a derivative of the site subsoil class map and has been redesigned to emphasise the potential of ground shaking amplification in Wellington City for non engineering professionals at PGA ~ < 0.4g. Both the liquefaction potential and the ground shaking amplification maps can be used to assist with hazard assessment.

6.3 GEOTECHNICAL TESTING EFFECTIVENESS IN WELLINGTON CITY

6.3.1 SPAC MICROTREMOR TECHNIQUE

The non-invasive SPAC technique was successfully used at 10 out of 12 sites in the Wellington City study area (refer to Chapter 4, Section 4.4.4). At the remaining two sites (1_VTNZ and 2_WGC) no HVSR peak was observed when the microtremor tremor records were analysed and therefore no depth to rock estimate could be determined. It was likely that the subsurface geology of these two sites was more complicated than expected with the soft and firm layers lacking a clear impedance contrast. Based on the results from the 12 test sites in Wellington it is concluded that provided the subsurface geology is relatively simple and flat lying, SPAC testing is a convenient economical tool to estimate the effect of subsurface geology on seismic motion. However, caution needs to be taken when choosing sites to avoid poor or unexpected results and sites that are known to have a complicated subsurface geology should be screened out and if possible another technique such as borehole investigations should be used.

6.3.2 SEISMIC CONE PENETRATION TESTING (SCPT)

SCPT is an inexpensive geotechnical tool that can be used to determine material type, thickness and shear wave velocity of the total thickness penetrated. The technique is however limited to penetrating soft-stiff materials and can be problematic where there are alternating layers of soft and dense materials. Conducting an SCPT in Wellington subsurface conditions is very limited due to the presence of alternating dense silty and clayey gravels.

6.3.3 GEOTECHNICAL BOREHOLE INVESTIGATIONS

Geotechnical borehole investigations are a reliable way of obtaining additional subsurface information in typical Wellington City deposits. An advantage of using boreholes for the characterisation of the subsurface is that samples can be taken of representative samples in-situ and used for further analysis.

6.4 OUTPUT COMPARISON WITH PREVIOUS WORK

This section discusses the output results of this thesis in comparison with those studies mentioned in Section 3.6 in chronological order.

The depth to bedrock map (Grant-Taylor et al. 1974) was constructed using information from more than 30 boreholes along with the residual gravity results in Wellington City. This map has been very useful in providing an indication of bedrock depth in the central city, which is vital for foundation investigations, and is still in use today. A comparison between the depth to bedrock map created for this thesis and the map produced by Grant-Taylor et al. (1974) can be seen in Figure 6.1.

Figure 6.1: Depth to bedrock map comparison.

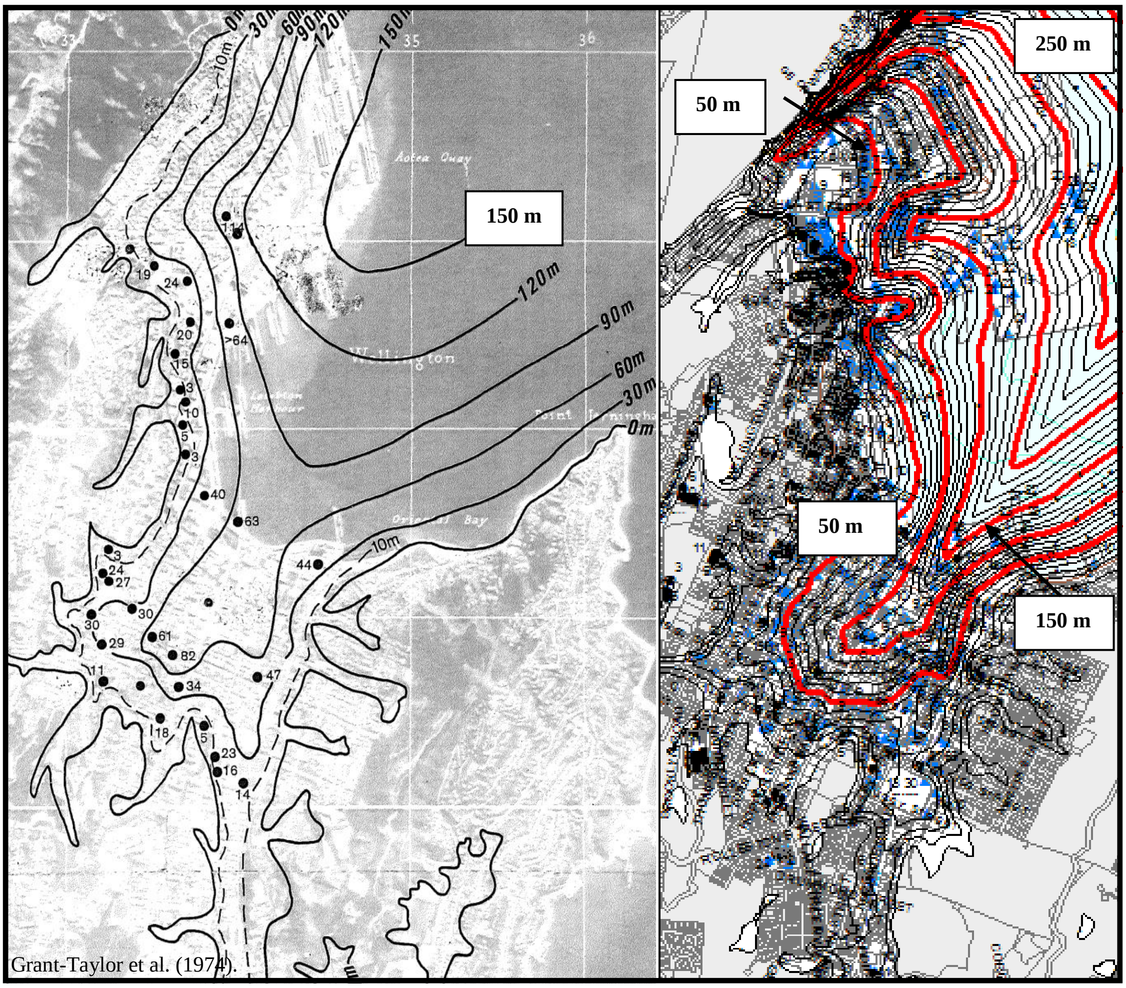


Image on the left has been modified from Grant-Taylor et al. (1974). Image on right is from this thesis (see section 5.9) with red lines representing 50 m contour intervals. Select depth to bedrock contours are labelled.

The comparison between the 1974 depth to bedrock map and the one produced from this project show that similar contour trends exist in both maps. The depth to bedrock map produced as part of this thesis has a number of advantages over the 1974 map. Firstly, it was produced using a far greater number of data points including those used to construct the 1974 map. Therefore, based on the greater distribution of data, it can be concluded that the depth to bedrock contours on the Wellington City depth to bedrock contour map are more reliable than those from the 1974 study.

Two significant geological maps on the geology of the Wellington region have been published (Begg & Mazengarb 1996; Begg & Johnston 2000). However, as these maps focus on the region wide geology they are only useful to engineering professionals as an initial indication on a site's geology. Quaternary and Recent deposits in Wellington City have very different geotechnical properties depending on the deposit type.

Destegul et al. (2009) produced a ground shaking amplification map (refer to Figure 6.2 for comparison image with the site subsoil class map created for this thesis) for New Zealand using the site classes described in the New Zealand loadings standard NZS 1170.5:2004 (refer to Section 3.4). Their map was constructed by assigning a site subsoil class to every geological polygon within the national geological map.

The NZS 1170.5:2004 site subsoil class map produced as part of this thesis has two significant advantages over the map produced by Destegul el al (2009). The NZS 1170.5:2004 site subsoil class map created for this thesis used both geological and geotechnical information. Firstly, the site subsoil class C/D boundary was determined using the 0.6s site period contour line. The contour line's position was based on real and pseudo information that was calculated by the preferred method of site classification outlined in Clause 3.1.3.1 of the New Zealand loadings standard (NZS 1170.5:2004).

Secondly, the ground shaking amplification map for New Zealand (Destegul et al. 2009) was designed to be used as a guide to the nationwide site subsoil class distribution (and therefore ground shaking amplification hazard potential), and as such is produced at a large scale which is not applicable to site specific investigations. (other than as an initial starting point). Whilst the Destegul et al. (2009) map is generally over conservative (as is the nature of trying to map site specific parameters at a national scale), it provides the user with a good starting point for site specific investigations and a technique that is successful at larger scales.

Figure 6.2: Site class map comparison.

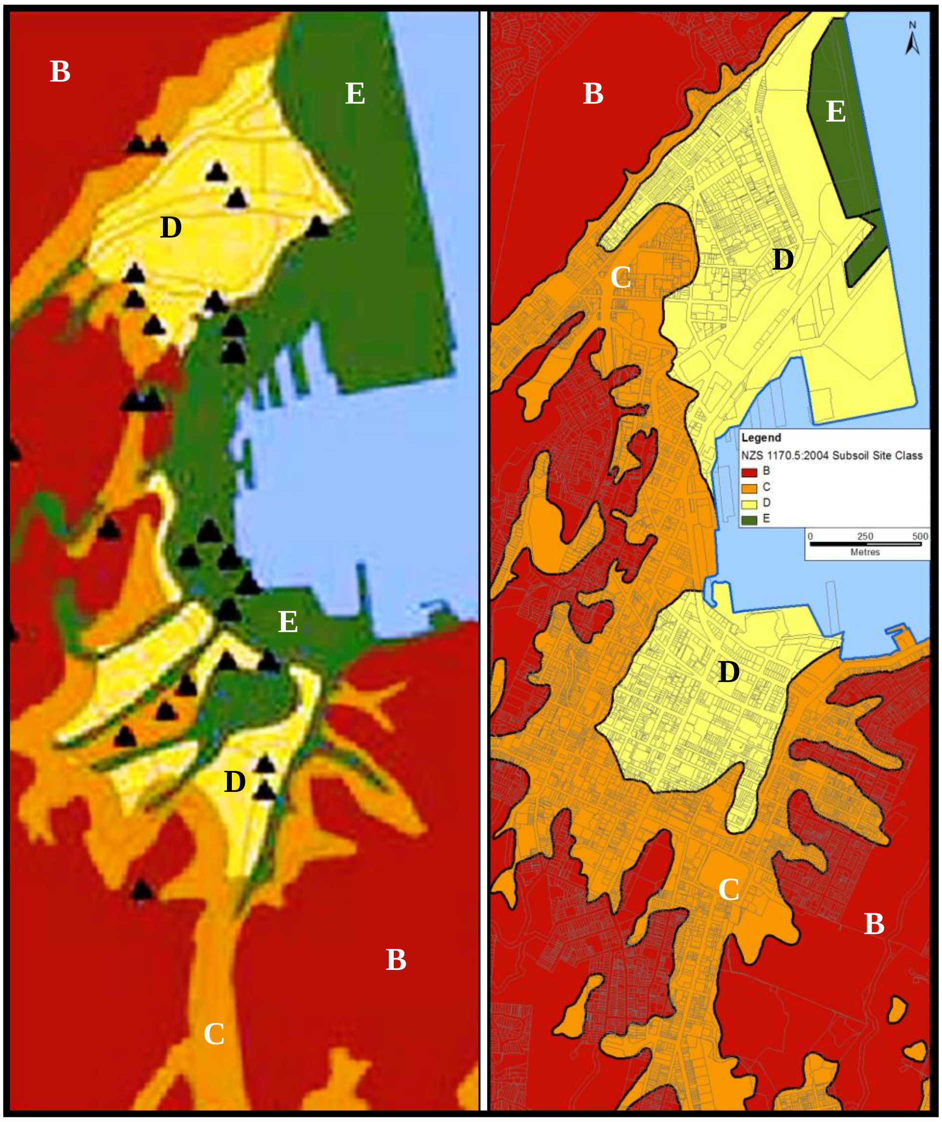


Image on the left has been modified from Destegul et al. (2009). Image on right is from this thesis (see section 5.13) with colours matched to those used by Destegul et al (2009). Site subsoil class B, C, D and E are labelled.

6.5 SYNTHESIS

Greywacke sandstone mudstone sequences and Quaternary deposits consisting of alluvium, colluvium, terrestrial and shallow marine sediments are the two main geological units in the Wellington area. In addition, waterfront reclamations in the city have added more than 155 hectares to the city, using both end dumped and hydraulically pumped fill materials. Amplification, subsidence and liquefaction potential are greatest in the younger Quaternary sediments. Increasing density of the progressively older Quaternary sediments will result in reduced levels of amplification from these deposits. The Wellington region sits astride the active Australian and Pacific Plate boundary zone with around 50 active faults capable of producing damaging earthquakes. The Wellington Fault accounts for more than 50 percent of the earthquake risk in the region, which is the greatest in New Zealand. Wellington City is at high risk from a number of earthquake induced phenomena most significantly ground shaking amplification (reflecting the scope of this thesis).

The geological setting of Wellington City is the cause of such high risk, as a large portion of the central city is founded on sediments expected to amplify strong ground motion (particularly those motions with a low stress drop and PGA < 0.4g). Damage patterns from historic earthquakes support this.

A readily accessible Excel database containing lithological and geotechnical information from 1025 bore logs, test pits and site observations has been constructed, with increased accessibility to the information held within this database being achieved by uploading the information into GNS Science’s PETLAB Database.

A simplified 3D geological model and ten mapping outputs were successfully created for this study. These outputs show that the areas underlain by hydraulic fill along Wellington’s Aotea Quay have the highest ground shaking amplification risk followed by the Te Aro and Thorndon areas. The outputs from this thesis are directly relatable to engineering professionals and as such can be used to assist preliminary geotechnical analysis.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

7.1 THESIS AIMS

The objectives of this study were:

- To create a readily accessible database containing all the available borehole information within the study area.
- To create a 3D geological model for the central Wellington commercial area.
- To create surficial deposits, depth to bedrock, site period, Vs30 and NZS 1170.5:2004 site subsoil class maps (1:5,000 scale).

The Wellington City study area runs from the Thorndon overbridge in the north to Wellington Hospital in the south, and from Kelburn in the west to Oriental Bay in the east. It includes many of the major buildings and infrastructural elements located within the central commercial area.

7.2 WELLINGTON CITY GEOLOGY

Late Triassic to early Jurassic sandstone mudstone sequences of the Rakaia Terrane form the basement rock within the Wellington City study area. Pleistocene deposits lie unconformably on top of greywacke bedrock and consist of weathered alluvium, colluvium and shallow marine deposits. These deposits typically consist of dense silty sandy gravels with interbedded stiff silts and organic clays. Holocene sediments overlie the Pleistocene deposits and generally consist of weathered alluvium and colluvium with minor beach, estuarine and swamp deposits. Reclamation landfill has added more than 155 hectares to the Wellington City waterfront with two main types, hydraulic and locally sourced end tipped fill, used.

Previous research, including damage patterns from historic earthquakes, concludes that Wellington City will experience ground shaking amplification during a large damaging earthquake. Areas most susceptible to ground shaking amplification are those underlain by reclaimed landfill (especially hydraulic fill) in areas surrounding Wellington's waterfront. Significant levels of amplification are also likely to occur in Thorndon and Te Aro, especially in the area once occupied by the Te Aro Swamp (refer to Appendix 8C).

As well as the likelihood of experiencing ground shaking amplification during both large distant and Wellington-Hutt Valley Fault rupture events, Wellington City is at high risk from a number of other earthquake induced phenomena. A large portion of Wellington City is founded on sediments that are expected to amplify strong ground motion. This, combined with the city's close proximity to 7 major seismogenic sources, results in Wellington City having the highest seismic risk in New Zealand.

7.3 SITE EFFECTS

Ground shaking amplification depends on a number of factors including amplitude, frequency and duration of motion, distance from the epicentre, site topography and local site conditions (geological and geotechnical properties of the soil and rock).

Structural design in New Zealand takes into consideration site effects which are incorporated in the New Zealand loadings standard (NZS 1170.5:2004). New Zealand's loading code is current and well respected, but is so far untested by a large damaging earthquake. The standard sets out five site subsoil class categories, based on geological and geotechnical properties, which must be used in the calculation of horizontal and vertical loading. Lower site subsoil classes (D and E) are assigned to deep/soft and very soft soils and require greater structural design strength, resulting in increased design and construction costs (the opposite holds true for higher site subsoil classes A and B).

7.4 GEOTECHNICAL BOREHOLE DATABASE

An accessible Excel database containing lithological and geotechnical information from 1025 bore logs, test pits and site observation was constructed, fulfilling the first objective of this thesis. Increased accessibility to the information was achieved by developing new parameters and uploading the information into GNS Science's PETLAB Database.

The non-invasive SPAC technique, SCPT and geotechnical borehole investigations were used to better characterise and refine the subsurface geology in the Wellington City study area. The SPAC technique was found to be a useful cost-effective method for obtaining shear wave velocity and estimated depth to bedrock information provided the site geology was simple and there was a strong impedance contrast between the bedrock and overlying sediments. SCPT was found to have limited potential in the Wellington City subsurface sediments because the test was unable to penetrate dense/hard materials (as the probe is pushed rather than drilled into the ground). Geotechnical borehole investigations were found to be the best method for determining subsurface conditions in the study area and had the additional benefit of obtaining samples that can be used for further analysis.

7.5 WELLINGTON CITY 3D GEOLOGICAL MODEL

A 3D simplified geological model of the Wellington City study area was successfully created from the borehole microtremor (estimated depth to rock) data compiled for this thesis using Earth Research, thereby achieving the second objective of this thesis. The model allows the user to visualise the subsurface geology in three dimensions and shows four different lithological groups which are based on a unit's geological and geotechnical properties. These are:

- Hydraulic Fill
- Loose/Soft Deposits
- Stiff Dense Deposits
- Greywacke Bedrock

7.6 MAPPING OUTPUTS

ArcGIS software (ArcMap) was used to create the mapping outputs for this project, thereby completing the third objective of this thesis. The mapping outputs include:

- Surficial deposit map.
- Depth to bedrock contour map.
- Low amplitude natural period (Site period) map.
- NZS 1170.5:2004 site subsoil class map.
- V_s30 map.

A surficial deposit map was created showing deposit type and likely distribution within Wellington City. The depth to bedrock map shows two deep sedimentary (150 m^+) basins in the Thorndon and Te Aro areas with the Wellington Fault occupying a deep valley north of the central city. The V_s30 map shows that V_s30 values are relatively constant (range of 250-349 m/s) in the Thorndon and Te Aro areas, except for some low velocity areas along the waterfront and near the Basin Reserve (a known area of former swamp).

The 0.6 second site period contour from the site period contour map was used to define the site class C/D boundary in the NZS 1170.5:2004 site subsoil class map. The NZS 1170.5:2004 site subsoil class map was successfully made to the specifications outlined in the standard. The map shows four different site classes in the central city and is designed to assist engineering professionals with site classification. One major advantage the site subsoil class map from this thesis has over previous research is that it is presented in a form that is readily usable by engineering professionals. Previous maps such as the ground shaking amplification map for New Zealand created by Destegul et al. (2009) are not at a scale that is commercially useful to site specific investigations. The output maps from this thesis can be used to assist planners and engineers with foundation, liquefaction and ground shaking amplification hazard assessment in Wellington City.

Five additional maps were also created as part of this thesis and include the liquefaction potential, waterfront reclamation and ground shaking amplification potential maps. The waterfront reclamation map provides a useful guide to the location of fill zones around the Wellington City waterfront. The liquefaction potential map provides a generalised guide to areas that are most susceptible to liquefaction from a large earthquake centred on the Wellington-Hutt Valley segment of the Wellington Fault. The ground shaking amplification potential map is analogous to the NZS 1170.5:2004 site subsoil class map and is aimed at the layman who may not have an understanding of site subsoil classification. The coloured map makes it easy to see which areas in Wellington City are at high risk from ground shaking amplification from motions which are in the elastic range of the soil (~ < 0.4g).

7.7 FUTURE WORK

The comprehensive investigation of liquefaction potential in Wellington City from the compiled geotechnical borehole database is one area of potential further research highlighted by this study. More than 5000 SPT N count measurements at 536 different locations in the Wellington City study area have been compiled into the SPT spreadsheet of the geotechnical borehole database (refer to Appendix 8A for SPT site distribution). This information is electronically accessible and could be used to create a more refined liquefaction potential map, by using the SPT data to evaluate the cyclic shear strength of the soil. Other potential areas of research include:

- Developing a relationship between SPT N count and shear wave velocity in Wellington City using information from the geotechnical borehole database.
- Investigating topographic effects in more detail, including basin edge effects and their impact on ground shaking amplification.
- Investigating the possibility of creating a continuum function to assign site subsoil class or the addition of another intermediate subsoil class between class C and D. This would help to reduce the large difference in base shear between these classes that needs to be designed for currently. Correctly classified sites with an intermediate class would still meet the design requirements but would be cheaper to design and build.

The geotechnical borehole database that has been compiled for this thesis is a very useful and accessible resource, but is by no means comprehensive. Additional potential data holders should be approached, in particular the consulting engineering and drilling companies that did not provide information for this study (due to the time constraints of a master’s thesis). The database will become more comprehensive with time if additional information is added. The geotechnical borehole database could be electronically linked to an ArcReader (free, user friendly mapping application that allows users to view and print maps) map containing all of the available data within the study area. The user would then be able to view the locations of the boreholes on screen and bring up the corresponding database entry when a specific borehole is selected. The bore logs contained in the appendix (4B) could also be linked to the database so that they could be instantly referred to if needed. The compilation of available data in other areas of New Zealand into a single electronic database could also be of significant benefit especially in cities such as Christchurch where a number of site subsoil categories are present. It should be noted that the database and accompanying maps are in no way designed to save money on geotechnical investigations (it is the author's personal and perhaps biased opinion that not enough money is currently spent on geotechnical investigations). Rather, if properly used, they are designed to assist engineering and planning professionals by allowing them to visualise the available data, plan new investigations based on this data and remove the need (and cost) of searching through archived material. They could also be used as a secondary check on geotechnical classifications. If the model and actual investigations differ, further subsurface investigations may be needed.

It is envisaged that one day all available geotechnical data within New Zealand will be compiled and made readily available through PETLAB or similar applications. Inspiration can be drawn from overseas projects such as the EC-funded project Access to the Earth Through Boreholes (eEarth) system, which includes testing undertaken for private sector purposes in the database once sufficient time has passed to reduce the commercial value of the information.

7.7.1 PROPOSED FUTURE SUBSURFACE INVESTIGATIONS IN WELLINGTON CITY

Figure 7.1 shows three areas (outlined with purple) in the Wellington City study area that require additional subsurface investigation to better characterise the subsurface geology and to prove or disprove some of the findings of this thesis. Based on the findings of SPAC, SCPT and borehole investigations in this thesis, it is recommended that borehole investigations are used to characterise the subsurface in these areas (SPAC could not be used to estimate a rock depth in Thorndon as no HSVR peak was observed and SCPT is limited to penetrating soft-stiff materials and will not penetrate the dense materials at depth in these areas).

It is proposed that 10 geotechnical boreholes (cyan coloured star on Figure 7.1) are to be drilled to bedrock in the three highlighted areas within the Wellington City study area (actual position will depend upon access, buried services etc). If the depth to bedrock contours in these areas are correct, it is expected that a total depth of approximately 1000 m (refer to Table 7.1) of drilling will be required for all ten boreholes at an approximate cost of $300,000 including GST (based on a market value of $300 per m including GST). The results of drilling these ten boreholes would help considerably in constraining the depth to bedrock contours in these areas. If the rock depth is found to be outside the limits of uncertainty in these areas the geology model can be updated to provide a more comprehensive planning and investigation tool. The boreholes can also be used to prove or disprove estimated depth to rock obtained from microtremor measurements in these areas.

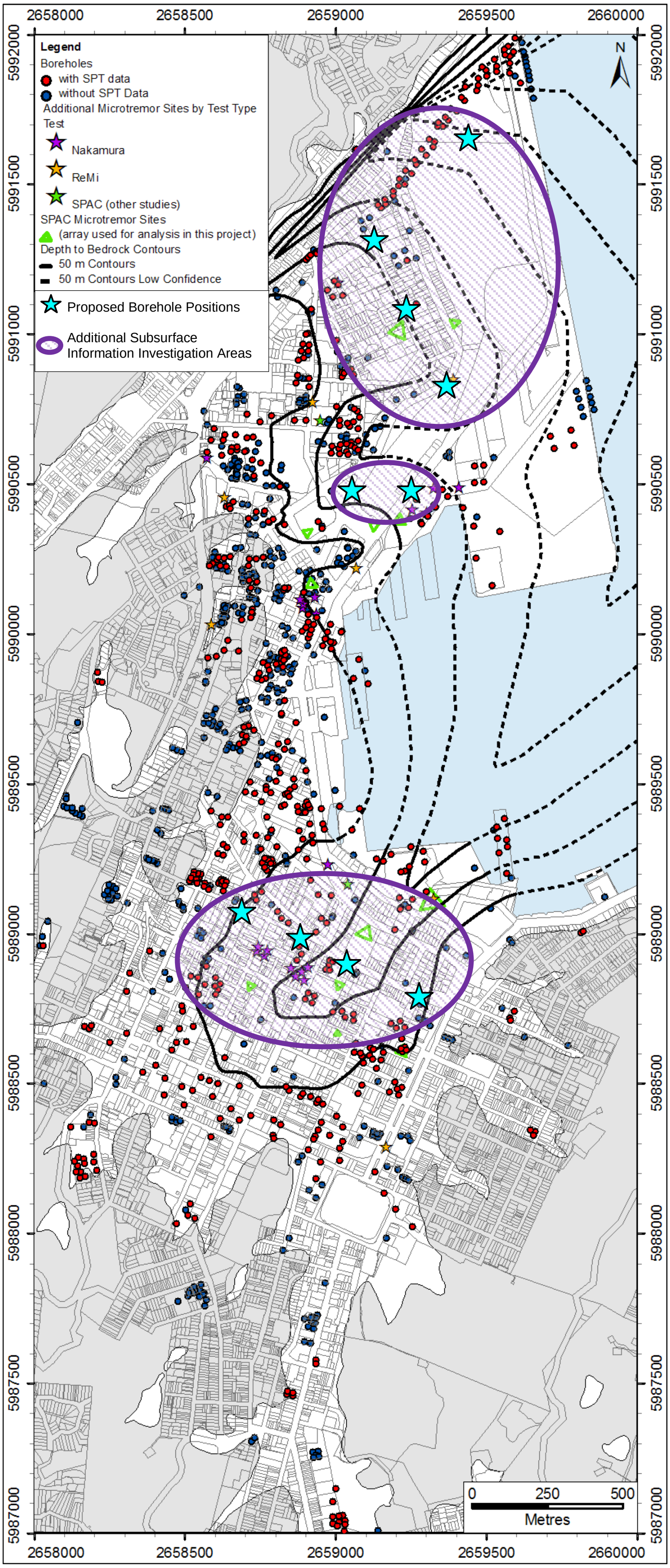
Table 7.1: Proposed geotechnical boreholes.

Investigation Area	No. of Boreholes proposed boreholes	Total Depth of Boreholes (m)	Total Cost (based on $300/m)
Thorndon	4	550	$165,000
Rail Station	2	150	$45,000
Te Aro	4	300	$90,000

7.8 RECOMMENDATIONS

- In addition to the points outlined in the future work section, further public education on earthquake hazard preparation should be made to increase the country's resilience to such events.
- An ongoing programme to assemble all remaining borehole and geotechnical testing data from consultants and private companies, within Wellington City, possibly fronted by the city council or territorial authority.
- A forward programme focussing on constraining the variability in subsoil data.

Figure 7.1: Proposes future investigation sites in Wellington City.



- Should significant redevelopment take place in the vicinity of Aotea Quay (currently occupied by port and rail companies), a comprehensive subsurface investigation should be undertake to characterise the hydraulic fills in this area. This is necessary as the outputs from this thesis show that these sediments are the most prone to liquefaction and ground shaking amplification in Wellington City.
- The development of an incentive program whereby the city council or territorial authority pay the additional drilling costs to bore down to bedrock on boreholes which are already being drilled, but not to the depth required. This would allow the necessary "data gaps" in the city to be filled in overtime and would reduce the cost to the council by not having to meet full cost on their own.
- Additional SPAC microtremor testing in Wellington at sites not targeted in this study.

7.8.1 NZS 1170.5:2004 REVISION

Currently it is not a requirement to prove or disprove a specific site subsoil class in the New Zealand loadings standard (NZS 1170.5:2004) by geotechnical testing, as classification can be done using the least preferred method given in the standard which is based on surface geology and estimates of the depth to bedrock. In order to make all site classifications equal for engineering and planning purposes, a statement requiring that: "All sites must be assigned the lowest subsoil site class unless proven otherwise" could be added to clause 3.1.3 of the New Zealand loadings standard (NZS 1170.5:23004). Obviously, this new clause would shift the balance of risk between clients, local authorities, designers and insurers and would require a significant review of the loadings standard. Such a review could also address the issues associated with the site class C and D boundary, with the possibility of adding an additional intermediate class between C and D.

SEE VOLUME 2 FOR APPENDICES.

GLOSSARY OF TERMS

This glossary provides a reference to the terms used throughout the thesis. In addition, other useful terms which may be encountered when carrying out further research related to earthquake engineering and geology have been included.

Accelerograph:
An accelerometer equipped to measure and record ground motion during an earthquake.

Alluvial Soils:
Soils formed by fluvial processes, may contain varying amounts of clays silts sands and rounded gravels.

Atterberg limits:
The water contents of a soil mass corresponding to the transition between a solid, semi-solid, plastic solid or liquid (Laboratory tests used to distinguish the plasticity of clay and silt particles).

Bearing Capacity:
The ability of the underlying soil to support the foundation loads without shear failure.

Bearing Pressure:
The total stress transferred from the structure to the foundation, then to the soil below the foundation.

Bedrock:
Strong rock underlying subsurface deposits of soil and weathered rock (in the case of Wellington the term refers to Torlesse greywacke sandstone/mudstone rock).

Before Present (BP):
A time scale used in geology to specify when events in the past occurred. Because the "present" time changes, standard practice is to use 1 January 1950 as the arbitrary origin of the age scale. For example, 1500 BP means 1500 years before 1950, that is, in the year 450. Such calibrated dates are expressed as cal BP, where "cal" indicates "calendar years" or "calibrated years".

Bulk Density:
The total mass of water and soil particles contained in a unit volume of soil.

Clay:
Soil particles which are finer (smaller) than 0.002 mm in size.

Coarse-Grained Soils:
Soils with more than 50% by weight of grains retained on the #200 sieve (0.075mm).

Cobbles:
Soil particles between 60 mm and 200 mm in size.

Cohesionless Soils:
Granular soils (sand and gravel type) with values of cohesion close to zero.

Cohesive Soils:
Clay and silts with angles of internal friction close to zero (cohesion holds together molecules within a substance).

Colluvial Soils:
Soils deposited at the base of hills by gravity and/or erosion (angular gravels).

Compaction:
Volume change in soils in which air is expelled from the voids, but with the water content remaining constant (achieved by; vibration, self-weight, rolling and tamping.

Cone Resistance:
The resistance force divided by the end area of the cone tip, measured during the cone penetration test (CPT).

Cone Penetration Test (CPT):
A penetration test in which a standardised cone that has a 60º point is pushed into the ground at a continuous rate. Resistance is measured by correlating the depth penetrated with the force applied.

Consolidation (see settlement):
The settlement or volume change due to dissipation of excess pore pressure from static loads.

Cyclic Stress Ratio:
A numerical rating for the potential of liquefaction in sands.

Density:
The ratio of the total mass to the total volume of a unit of soil (Imperial = lb/ft^3, Metric = kg/m^3).

Depth to Basement:
Depth (metres) to greywacke sandstone/mudstone bedrock.

Disaster:
A disaster is the tragedy of a natural or man-made hazard that exhibits a negative effect on society or environment and may occur as the consequence of inappropriately managed risk (can include events such as earthquakes, landslides, floods, and tsunami).

Dredging:
The removal of sediment from a sea, river or lake bed in order to deepen the waterway for water travel and/or provide hydraulic fill material.

Dry Density:
The ratio of the mass of solids (soil grains) to the total unit volume of soil (Imperial = lb/ft^3, Metric = kg/m^3).

Dynamic Compaction:
The compaction of (generally) granular soils using high energy impact.

Effective Stress:
The portion of the total stress that is supported by grain-to-grain contact within the soil. Effective stress = Total stress - Pore water pressure.

Engineered Fill:
Fill that is placed in accordance with engineered specifications. These specifications may delineate soil grain-size, plasticity, moisture, compaction, angularity, and many other index properties depending on the application (include retaining wall backfill, foundation support, dams, slopes reclamation etc.).

Epicentre:
The point on the Earth's surface that is directly above the hypocenter or focus of an earthquake.

Erosion:
The mobilization of rock particles by an agent such as streams, glaciers or wind.

Factor of Safety:
The ratio of a limiting value of a quantity to the design value of that quantity.

Fault:
A shear fracture in a rock mass along which movement has taken place.

Field Density (In-place density) Test:
Field testing that determines the density of compacted fill to verify that it meets the required specifications.

Fine Grained Soil:
Silt and clay soils (containing particles smaller than No. 200 sieve or 0.075 mm in size according to the Unified Soil Classification System).

Fines Content (fraction):
Soil grains smaller than the No. 200 sieve (0.075 mm), namely Clay and Silt particles.

Fluvial:
System or deposits associated with rivers and streams.

Footing:
An enlargement at the base of a foundation that is designed to transmit forces to the soil.

Foundation:
A structural element that transfers building loads to the ground (includes; pad footings, strip footings, raft foundations, piles and piers).

Founding Depth:
The depth below the ground surface at which the base of a foundation is located.

<u>Friction Pile:</u>
A pile that derives the majority of its load bearing ability from the skin friction between the soil and the pile.

<u>Hazard:</u>
A hazard is a situation that poses a level of threat to life, health property or the environment. A hazard does not exist when it is happening and once active can create an emergency situation.

<u>Hydraulic Gradient:</u>
Total head loss per unit length, along the flow path.

<u>In Situ:</u>
In the Field

<u>Lacustrine:</u>
Sediments relating to a lake environment.

<u>Liquid Limit (wL, LL):</u>
If the water content of a fine grained soil is greater than this, the soil will flow like liquid.

<u>Liquefaction:</u>
The sudden, large decrease of shear strength in cohesionless soil caused by the collapse of the soil structure, produced by small shear strains associated with sudden but temporary increase of pore water pressure (saturated poorly graded sands most at risk).

<u>Microtremor/Microseism:</u>
A low amplitude (in the order of microns) ambient vibration of the ground caused by man-made (traffic etc) or atmospheric disturbances (such as coastal wave action and wind) and is unrelated to earthquake activity. Microtremors are recorded by a seismometer and their observation can give useful information on a site's dynamic properties.

<u>N-Value (standard penetration resistance):</u>
The number of blows required to drive a split-spoon sampler during a standard penetration test a distance of 300mm (12 inches) after the initial "seating" penetration of 150mm (6 inches). Refer to standard penetration test (SPT).

<u>Organic Soil:</u>
Earth comprised of organic material, peat, etc.

<u>Peneplain:</u>
Gently undulating, almost featureless plain.

<u>Permeability:</u>
A measure of how easy water can flow through a soil (unit of velocity), also known as hydraulic conductivity.

Pier:
A large diameter (>7m) pile (caisson). Used under bridge abutments. Usually cast-in-place, instead of driven, drilled or jetted as a pile.

Piezometer:
A device used to measure in-situ pore water pressures (within a borehole).

Piezometric Surface:
An imaginary surface corresponding to the hydrostatic water level (in a confined body).

Pile:
A long generally cylindrical structural element, used as a foundation. Piles are usually driven (hammered), drilled or jetted into the ground and constructed of timber, steel or pre-stressed reinforced concrete.

Plastic Limit:
The moisture content in which a soil will have a plastic consistency.

Plastic Strain:
Deformation of soil that is not recovered upon unloading.

Plasticity:
The property of a soil which allows it to deform continuously, usually a mass of clay sized particles.

Plasticity Index (PI):
The difference between the liquid limit and plastic limit of a soil mass (the range of water content over which the fine grained soil remains plastic).

Plastic Limit (wP, PL):
A fine grained soil remains plastic, only above this water content.

Pore Pressure (Hydrostatic Pressure):
The pressure exerted by the fluid within the pores or voids of a porous material. In saturated soil the pore pressure = pore water pressure.

Pore Water Pressure:
Pressure of the water held within the voids.

Porosity (n):
Void volume as a percentage of the total volume (% or unitless).

Residual Soils:
Soils that have been formed in place (i.e. weathered parent bedrock).

Risk:
Risk = Likelihood of occurrence of a hazardous event multiplied by the seriousness if the incident occurred (i.e. severity of injury, ill health building damage etc.).

Sand:
Particles that are between 0.06 (fine) - 2mm (coarse).

Saturated Density:
Density of a field capacity soil (voids filled with water).

Seismic Cone Penetration Test (SCPT):
A penetration test in which a standardised cone that has a 60º point is pushed into the ground at a continuous rate. Resistance is measured by correlating the depth penetrated with the force applied.

Seismic Microzonation:
Involves the mapping of seismic hazard incorporating the effects of local site conditions within an area.

Seismogenic:
Capable of generating earthquakes.

Settlement:
The downward movement of soils or foundations.

Shear Strength:
The maximum shear stress which a soil can sustain under a given set of conditions. For clay, shear strength = cohesion. For sand, shear strength = the product of effective stress and the tangent of the angle of internal friction.

Site Investigation:
Methodical process involving the observation of site conditions (surface geology etc), soil sampling and field testing in such a manner as to development and enhance existing site knowledge.

Standard Penetration Test (SPT):
The standard penetration test (SPT) is an in-situ dynamic penetration test and the test procedure is described in NZS 4402.6.5.1:1988 (Standards New Zealand 1988). The test uses a thick-walled sample tube, with an outside diameter of 50 mm and an inside diameter of 35 mm, and a length of 650 mm. The sampler is driven into the ground at the bottom of a borehole by blows from a slide hammer (usually using an automatic trip) with a weight of 63.5 kg (140 lb) falling through a distance of 760 mm (30 in). The sample tube is driven 150 mm into the ground (initial "seating") and then the number of blows (N) needed for the tube to penetrate each 150 mm (6 in) increment up to a depth of 450 mm (18 in) is recorded (may be recorded per 75mm i.e. 4 counts per 75mm rather than two per 150mm). The sum of the number of blows required for the 300mm of penetration is termed the "standard penetration resistance" or the "N-value". In cases where 50 blows are insufficient to advance it through a 150 mm (6 in) interval the penetration after 50 blows is recorded. The blow count provides an indication of soil density and is used in a number of geotechnical engineering formulae. A field test that measures resistance of the soil to the penetration of a standard split-spoon sampler that is driven 12 inches (0.3 m) with a 140-pound (63.5 kg) hammer dropped from a height of 30 inches (0.76 m). The N-value is derived from this test.

S-Wave:
S-waves, secondary waves, or shear waves is one of the two main types of elastic body waves (they move through the body of an object). The S-wave moves as a shear (transverse wave) so motion is perpendicular to the direction of wave propagation.

Tip Resistance (Point-Bearing Capacity):
The bearing capacity at the bottom tip of one member of a deep foundation system

Triaxial Shear Strain:
A strain parameter used in the interpretation of triaxial stress test results.

Triaxial Stress Test:
Laboratory tests including; consolidated-drained (CD), consolidated-undrained (CU) and unconsolidated-undrained (UU). These tests are used to determine the soils' strength characteristics such as cohesion and angle of internal friction.

Ultimate Bearing Capacity:
The bearing stress which would cause shear failure in the soil below a foundation. Dependent upon the shear strength of the soil, applied loads and on the shape and depth of the foundation.

Unconfined Compressive Strength Test:
Laboratory test similar to the unconsolidated-undrained test performed on plastic soils, usually clay. From this test, the undrained shear strength is calculated as 1/2 of the unconfined compressive strength. Cohesion is considered to be equal to the undrained shear strength.

Unconsolidated:
Non-compact sediments.

Undrained Shear Strength:
The shear strength of a saturated soil for a given water content under loading conditions where no drainage of pore water can take place. The undrained shear strength of soil is independent of applied stresses and therefore can be measured at any level of stress, provided the void ratio remains constant. The undrained Mohr-Coulomb envelope will be horizontal.

Unified Soil Classification System (USCS):
A system of soil classification based on grain size, liquid limit and plasticity of soils.

Shear Vane Test:
A field test used to measure the shear strength of a low-strength, homogeneous, cohesive soil.

Void Ratio:
The ratio of the volume of voids to the volume of solids (unitless).

Water Content (Moisture Content, w%):
The ratio between the mass of water and the mass of soil solids (determined in a laboratory).
w = (wet weight - dry weight) / dry weight.

Water Table:
The level in the earth at which the hydrostatic water pressure is zero.

Weathering:
The process whereby destructive forces (physical, chemical or biological) act to alter a rock or soil near the surface of the earth.

REFERENCES

Adams RD, Orr RH 1970. Microseismic noise survey in central Wellington. Geophysics Division Report No. 60. Department of Scientific and Industrial Research. 1 sheet+12 p.

Aki K 1957. Space and time spectra of stationary stochastic waves, with special reference to microtremors. Bulletin of the Earthquake Research Institute 35: 415-456.

Anderson G 1984. Seawalls and Reclamations. In: Fresh about Cook Strait - An appreciation of Wellington Harbour. Auckland, Methuen Publications New Zealand Ltd. Pp. 110-130.

Baillie H 1924. The Early Reclamations and Harbour-works of Wellington. Transactions and Proceedings of the Royal Society of New Zealand 55: 701-720.

Barnes P 1998. Fault kinematic adjustments during the last 2 Myr in the transition area between continental collision and Hikurangi Margin subduction. Geological Society of New Zealand Miscellaneous Publication 101A: 35.

Barnes PM, Audru J-C 1999. Quaternary faulting in the offshore Flaxboume and Wairarapa Basins, southern Cook Strait, New Zealand. New Zealand Journal of Geology & Geophysics 42: 349-367.

Barnes PM, Pondard N, Lamarche G, Mountjoy J, Van Dissen R, Litchfield N 2008. It's Our Fault: Active faults and earthquake sources in Cook Strait National Institute of Water & Atmosphere Research Ltd Report WLG2008-56.

Bastings L 1936. A subsoil survey of Wellington City. NZ Inst Archit 15(5): 75-78.

Beanland S 1995. The North Island dextral fault belt, Hikurangi subduction margin, New Zealand. Unpublished Ph. D. thesis, School of Earth Sciences, Victoria University of Wellington, New Zealand. 341 p.

Beavan J, Tregoning P, Bevis M, Kato T, Meertens C 2002. Motion and rigidity of the Pacific Plate and implications for plate boundary deformation. Journal of Geophysical Research 107: no.B10, 15.

Beetham RD, Stephenson WR, Perrin ND, Barker PR 2010. A non-invasive site investigation method for determining site class from microtremor records. in proceedings, 11th IAEG Congress, Auckland, New Zealand, 5-10 September, 2010.

Begg JG 1999. Quaternary geology of the Hutt Valley. In: Speden IG, Skinner DNB ed. 8th International Symposium on Antarctic Earth Sciences: field trip guides. Pp. 33-57.

Begg JG, Mazengarb C 1996. Geology of the Wellington area, scale 1:50 000. Institute of Geological & Nuclear Sciences geological map 22, Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited. 1 Sheet+128 p.

Begg JG, Van Dissen RJ 2000. Documentation of multiple post-glacial ruptures on the Akatarawa Fault, Wellington region, New Zealand Institute of Geological & Nuclear Sciences Client Report 2000/81.

Begg JG, Johnston MR 2000. Geology of the Wellington Area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 10. Graphic Press & Packaging Ltd, Levin: 64+1 Sheet.

Begg JG, Van Dissen RJ, Rhoades DA 2004. Subsidence in the Lower Hutt Valley and the interplay between Wellington and Wairarapa Fault earthquakes. 2004 NZSEE Conference, paper 43. Pp. 1-9.

Begg JG, Langridge RM, Van Dissen RJ, Little T, Little TA 2008. Wellington Fault : neotectonics and earthquake geology of the Wellington - Hutt Valley segment. Geological Society of New Zealand Miscellaneous Publication 125B: 5-67.

Benites R, Olsen KB 2005. Modeling Strong Ground Motion in the Wellington Metropolitan Area, New Zealand. Bulletin of the Seismological Society of America 95(6): 2180-2196.

Berryman KR 1990. Late Quaternary movement on the Wellington Fault in the Upper Hutt area, New Zealand. New Zealand Journal of Geology and Geophysics 33(2): 257-270.

Berryman KR, Van Dissen RJ, Mouslopoulou V 2002. Recent Rupture of the Tararua section of the Wellington Fault and relationships to other fault sections and rupture segments. New Zealand Earthquake Commission Research Report 97/248. Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. Pp. 22 pp.

Borcherdt RD 1994. Estimates of site-dependent response spectra for design (methodology and justification). Earthquake Spectra 10(4): 617-653.

Borja-Navarrete G, Diaz-Canales M, Vazquez-Vera A, Valle-Calderon E 1986. Damage Statistics of the September 19, 1985 Earthquake in Mexico City. In: Cassaro MA, Romero EM ed. Proceedings of the International Conference: The Mexico Earthquakes - 1985, Factors involved and lessons learned, Camino Real Hotel, Mexico City, Mexico, American Society of Civil Engineers, New York. 70-77.

British Standards Institution 2005. BS EN 1998-5:2004 Eurocode 8: design of structures for earthquake resistance, Part 5, Foundations, retaining structures and geotechnical. London, United Kingdom, British Standards Institution. Pp. 48.

Cassaro MA, Romero EM 1986. Prolog. In: Cassaro MA, Romero EM ed. Proceedings of the International Conference: The Mexico Earthquakes - 1985, Factors involved and lessons learned, Camino Real Hotel, Mexico City, Mexico, American Society of Civil Engineers, New York. Pp. v-vii.

Chavez-Garcia FJ, Cuenca J 1996. Site effects in Mexico City urban zone. A complementary study. Soil Dynamics and Earthquake Engineering 15: 141-146.

Chavez-Garcia FJ, Rodrigue M, Stephenson WR 2004. Site effects and SPAC. Results for three sites in Wainuiomata. Bulletin of the New Zealand Society for Earthquake Engineering 37(3): 101-110.

Chavez-Garcia FJ, Rodriguez M, Stephenson WR 2005. An alternative approach to the SPAC analysis of microtremors: exploiting stationarity of noise. Bulletin of the Seismological Society of America 95(1): 277-293.

Chavez-Garcia FJ, Rodriguez M, Stephenson WR 2006. Subsoil structure using SPAC measurements along a line. Bulletin of the Seismological Society of America 96(2): 729-736.

Clitheroe GM, Taber JJ 1995. Assessing earthquake site response using microtremors: a case study in Wellington City. In Proceedings, 1995 Pacific Conference on Earthquake Engineering. Melbourne, Australia. Pp. 247-256.

Cochran U 2002. Detection of large Holocene earthquakes in the sedimentary record of Wellington, New Zealand, using diatom analysis. Unpublished Ph. D. thesis, Victoria University of Wellington, Wellington. 303 p.

Cochran U, Hannah M, Harper M, Van Dissen R, Berryman K, Begg J 2007. Detection of large, Holocene earthquakes using diatom analysis of coastal sedimentary sequences, Wellington, New Zealand. Quaternary Science Reviews 26: 1129-1147.

Cooper RA (Compiler) 2004. New Zealand Geological Timescale 2004/2 wallchart. Institute of Geological & Nuclear Sciences information series 64.

Cotton CA 1912. Recent and sub-recent movements of uplift and subsidence near Wellington, New Zealand. Scottish Geographical Magazine 28: 306-312.

Cotton CA 1921. The Warped Land-surface on the South-eastern Side of the Port Nicholson Depression, Wellington, N.Z. Transactions of the Royal Society of New Zealand 53: 131-143.

Cotton CA 1956. Tectonic features in a coastal setting at Wellington. Transactions of the Royal Society of New Zealand 84(4): 761-790.

Cotton CA 1957. Dissection and redissection of the Wellington landscape. Transactions of the Royal Society of New Zealand 85: 409-425.

Cotton CA, Te Punga MT 1955. Solifluxion and Periglacially Modified Landforms at Wellington, New Zealand. Transactions of the Royal Society of New Zealand 82(Part 5): 1001-1031.

Cousins J 2008. Underwriting the future. In: Graham IJ ed. A continent on the move: New Zealand geoscience into the 21st century. GSNZ Miscellaneous Publication 124, Geological Society of New Zealand. Pp. 388.

Cousins WJ, Perrin ND, McVerry GH, Hefford RT, Porritt TE 1996. Ground conditions at strong-motion recording sites in New Zealand Institute of Geological and Nuclear Sciences (GNS) Science Report 96/33.

Cyclopedia Company Limited 1863. The Cyclopedia of New Zealand, Wellington Provincial District. View Of Lambton Quay And Terrace 1863. Retrieved 10/01/2010 http://www.nzetc.org/tm/scholarly/Cyc01Cycl-fig-Cyc01Cycl0244a.html

Davenport PN 2004. Review of seismic provisions of historic New Zealand loading codes. 2004 Annual New Zealand Society for Earthquake Engineering (NZSEE) Technical Conference. Rototua, New Zealand, Paper 17. Pp. 1-10.

Davenport PN, Stephenson WR 2005. Use of microtremors to assess local site effects. 2005 NZSEE Conference. Pp. Paper Number 9.

Destegul U, Dellow G, Heron D 2009. A Ground Shaking Amplification Map for New Zealand. New Zealand Society for Earthquake Engineering Bulletin 42(2): 122-128.

Evening Post ca. 1925. Land reclamation, Thorndon, Wellington, circa 1925. Taken by an unidentified photographer. Series: Evening Post: Photographic negatives and prints of the Evening Post newspaper Series: PA-Group-00287. ID: EP-0114-1/2-F Retrieved 10/01/2010 http://find.natlib.govt.nz/primo_library/libweb/action/search.do?vid=TF

Fry B, Stephenson W, Benites R 2010. It’s Our Fault - Seismic instrumentation and inversion for velocity structure of the Wellington region. GNS Science Consultancy Report 2010/18.

Gabites I 1993. Wellington's Living Cloak, a guide to the natural plant communities. Wellington, Victoria University Press. 120 p.

GeoMil Equipment B.V. 2009. Seismic CPT (SCPT). Retrieved 21/12/2009 http://www.geomil.com/CPT/SCPT.htm

GNS Science 2000. News Release 17 March - Geologists discover another active fault in Wellington. Retrieved 12/12/2009 2009, from http://www.gns.cri.nz/news/release/otaki_fault.html

GNS Science 2009. Media Release 18 September - New research shows lower threat from Wellington Fault. Retrieved 12/12/2009 2009, from http://www.gns.cri.nz/news/release/20090918ourfault.html

Grant-Taylor TL, Adams RD, Hatherton T, Milne JDG, Northby RD, Stephenson WR 1974. Microzoning for earthquake effects in Wellington, NZ. New Zealand Department of Scientific and Industrial Research Bulletin 213. Ruscoe QW ed. Wellington, New Zealand Department of Scientific and Industrial Research. 7 Sheets+62 p.

Grapes R, Downes G 1997. The 1855 Wairarapa, New Zealand, earthquake-Analysis of historical data. Bulletin of the New Zealand National Society for Earthquake Engineering 30: 271-368.

Grapes RH, Wellman HW 1986. The north-east end of the Wairau Fault, Marlborough, New Zealand. Journal of the Royal Society of New Zealand 16(3): 245-250.

Greater Wellington Regional Council 1996. Combined Earthquake Hazard Map 1:30000, Sheet 1 Wellington (1st ed.). Pub . No. WRC/RP-T-96/13 Greater Wellington Regional Council, Wellington, New Zealand.

Heron D, Van Dissen RJ, Sawa M 1998. Late Quaternary movement on the Ohariu Fault, Tongue Point to MacKays Crossing, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 41(4): 419-439.

Holt WE, Haines AJ 1995. The kinematics of northern South Island, New Zealand, determined from geologic strain rates. Journal of Geophysical Research B100(9): 17991-18010.

Imai T, Tonouchi K 1982 Correlation of N value with S-wave velocity and shear modulus. - Proceedings of the 2nd European Symposium on Penetration testing, Amsterdam, 24-27 May, 1982. Pp. 67-72.

Ingham CE 1971. Elastic properties of rock, Wellington urban motorway tunnel. Department of Scientific and Industrial Research, Wellington, Geophysics Division report 71.

Kelly M 2005. Heritage trail : old shoreline, Wellington City, Wellington City Council. 69 p.

Kelsey HM, Cashman SM, Beanland S, Berryman KR 1995. Structural evolution along the inner forearc of the obliquely convergent Hikurangi margin, New Zealand. Tectonics 14(1): 1-18.

Kerr J, Nathan S, Van Dissen R, Webb P, Brunsdon D, King A 2003. Planning for Development of Land on or Close to Active Faults: A guideline to assist resource management planners in New Zealand. Institute of Geological & Nuclear Sciences client report 2002/124. 71 p.

Kingsbury PA, Hastie WJ 1993. Liquefaction hazard map 1:50000. With notes. Wellington Regional Council, Wellington, New Zealand: 1 sheet+9 p.

Kramer SL 1996. Geotechnical Earthquake Engineering, Prentice Hall. 653 p.

Landcare Research 2009. Soil Orders from the New Zealand Soil Classification (NZSC).

Langridge RM, Berryman KR, Van Dissen RJ 2007. Late Holocene paleoseismicity of the Pahiatua section of the Wellington Fault, New Zealand. New Zealand Journal of Geology & Geophysics 50: 205-226.

Leaming EM 2009. Bibliography of New Zealand Earth Science Theses, 3rd edition. Geological Society of New Zealand Miscellaneous Publication No. 127.

Lensen GJ 1958. The Wellington Fault from Cook Strait to Manawatu Gorge. New Zealand Journal of Geology & Geophysics 1: 178-196.

Lensen GJ 1968. Analysis of progressive fault displacement during downcutting at the Branch River terraces, South Island, New Zealand. Geological Society Of America Bulletin 79: 545-556.

Lensen GJ 1976. Sheets N28D, O28C and N29B, Hillersden (1st edition); Sheets O28D, P28A and P28C, Renwick (1st edition). Late Quaternary Tectonic Map of New Zealand 1:50 000. Department of Scientific and Industrial Research, Wellington, New Zealand.

Lewis KB 1989. A reversal of throw and change of trend on the Wellington Fault in Wellington Harbour. New Zealand Journal of Geology & Geophysics 32: 293-298.

Lewis KB, Carter L, Davey FJ 1994. The opening of Cook Strait: Interglacial tidal scour and aligning basins at a subduction to transform plate edge. Marine Geology 116: 293-312.

Litchfield N, Van Dissen R, Heron D, Rhoades D 2006. Constraints on the timing of the three most recent surface rupture events and recurrence interval for the Ohariu Fault: trenching results from MacKays Crossing, Wellington, New Zealand. New Zealand Journal of Geology & Geophysics 49: 57-61.

Litchfield N, Van Dissen R, Langridge R, Heron D, Prentice C 2004. Timing of the most recent surface rupture event on the Ohariu Fault near Paraparaumu, New Zealand. New Zealand Journal of Geology & Geophysics 47(1): 123-127.

Little TA, Van Dissen R, Schermer E, Carne R 2009. Late Holocene surface ruptures on the southern Wairarapa fault, New Zealand: Link between earthquakes and the uplifting of beach ridges on a rocky coast. Lithosphere 1(1): 4-28.

Little TA, Schermer L, Van Dissen R, Begg J, Carne R 2008. Southern Wairarapa Fault and Wharekauhau Thrust (Palliser Bay). Geological Society of New Zealand Miscellaneous Publication 124B: 75-120.

Little TA, Van Dissen R, Rieser U, Smith EGC, Langridge RM 2010. Co-seismic strike-slip at a point during the last four earthquakes on the Wellington fault near Wellington, New Zealand. Journal of Geophysical Research Solid Earth.

Louie JN 2001. Faster, better: Shear-wave velocity to 100 meters depth from refraction microtremor arrays. Bulletin of the Seismological Society of America 91(2): 347-364.

Mackintosh L 2001. Overview of New Zealand Climate. Wellington, National Institute of Water and Atmospheric Research Ltd.

McKay A 1892. On the geology of Marlborough and south-east Nelson. New Zealand Geological Survey, Report of geological explorations 21. 1-28 p.

Mcsaveney MJ, Graham IJ, Begg JG, Beu AG, Hull AG, Kim K, Zondervan A 2006. Late Holocene uplift of beach ridges at Turakirae Head, south Wellington coast, New Zealand. New Zealand Journal of Geology & Geophysics 49: 337-358.

Mildenhall DC 1993. Holocene and late Last Glaciation pollen record from drillholes at Miramar and Lambton Harbour, Wellington, New Zealand. New Zealand Journal of Geology and Geophysics 36: 349-356.

Mildenhall DC 1994. Palynostratigraphy and paleoenvironments of Wellington, New Zealand, during the last 80 ka, based on palynology of drillholes. New Zealand Journal of Geology and Geophysics 37: 421-436.

Molloy L 1988. Soils in the New Zealand Landscape: the living mantle. first ed. Wellington, Mallinson Rendel Publishers Ltd. 239 p.

Murashev A, Palmer S 1998. Geotechnical issues associated with development on Wellington's waterfront. IPENZ Transactions 25(1/CE): 38-46.

Nakamura Y 1989. Method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Quarterly Report of RTRI (Railway Technical Research Institute) (Japan) 30(1): 25-33.

NZ Geotechnical Society Inc 2005. Field Description of soils and rock - Guideline for the field classification and description of soil and rock for engineering purposes. 38p.

NZ Geotechnical Society Inc 2005. Field Guide Sheet. In NZ Geotechnical Society Inc 2005. Field Description of soils and rock - Guideline for the field classification and description of soil and rock for engineering purposes. 2p. www.nzgeotechsoc.org.nz

New Zealand Government 2009a. Building Act 2004 No 72 (as at 01 August 2009), Public Act. Pp. 302.

New Zealand Government 2009b. Resource Management Act 1991 No 69 (as at 08 December 2009), Public Act. Pp. 795.

New Zealand Standards Institute 1935. NZSS No. 95-1935. New Zealand Standard Model Building By-Law. Sections I to X. Wellington, New Zealand.

New Zealand Standards Institute 1965. NZSS 1900:1965. New Zealand Standard Model Building Bylaw, Chapter 8, Basic Design Loads. Wellington, New Zealand.

NIWA 2009. Climate Data and Activities. National Institute of Water and Atmospheric Research Ltd

Okada H 2006. Theory of efficient array observations of microtremors with special reference to the SPAC method. Exploration Geophysics 37: 73-85.

Ota Y, Williams DN, Berryman KR 1981. Late Quaternary tectonic map of New Zealand, Part sheets Q27, R27 and R28, Wellington, Scale 1:50,000 with notes. New Zealand Department of Scientific and Industrial Research, Lower Hutt, Wellington.

Perrin ND 1971. Geology of test drives for Terrace tunnels. Lower Hutt: New Zealand Geological Survey. New Zealand Geological Survey Report EG 108/A.

Perrin ND 1993. Location of Wellington Fault in relation to Thorndon Overbridge, Wellington Urban Motorway. Institute of Geological and Nuclear Sciences Ltd client report 352952.11.

Perrin ND, Campbell HJ 1992. Compilation of geological data, Wellington area. DSIR Geology & Geophysics Contract Report No. 1992/24.

Perrin ND, Wood PR 2003. Defining the Wellington Fault within the urban area of Wellington City 2002/151. 33 p.

Perrin ND, Stephenson WR, Semmens S 2010. Site class determinations (NZS1170.5) in Wellington using borehole and microtremor techniques. in proceedings, New Zealand Society for Earthquake Engineering Technical Conference, Wellington, New Zealand, 26-28 March 2010.

Pitilakis K 2004. Site Effects, Chapter 5. In: Ansal A ed. Recent advances in earthquake geotechnical engineering and microzonation. Dordrecht, The Netherlands, Kluwer Academic Publishers. Pp. 139-197.

Raul J, Marsal F 1986. Geotechnical notes on the effects of Mexico's 1985 earthquakes. In: Cassaro MA, Romero EM ed. Proceedings of the International Conference: The Mexico Earthquakes - 1985, Factors involved and lessons learned, Camino Real Hotel, Mexico City, Mexico, American Society of Civil Engineers, New York. 78-95.

Reyners M 1998. Plate coupling and the hazard of large subduction thrust earthquakes at the Hikurangi subduction zone, New Zealand. New Zealand Journal of Geology and Geophysics 41: 343-354.

Rodgers DW, Little TA 2006. World's largest coseismic strike-slip offset: The 1855 rupture of the Wairarapa Fault, New Zealand, and implications for displacement/length scaling of continental earthquakes. Journal of Geophysical Research 111: B12408 (1-19).

Rowe GH 1980. Applied geology of Wellington rocks for aggregate and concrete. Unpublished thesis, Victoria University, Wellington. 429 p.

Singh SK, Mena E, Castro R 1998. Some aspects of source characteristics of the 19 September 1985 Michoacan Earthquake and ground motion amplification in and near Mexico City from strong motion data. Bulletin of the Seismological Society of America 78(2): 451-477.

Skyscraper Source Media 2009. Wellington. Skyscraper Source Media, SkyscraperPage.com, Victoria BC, Canada.

Standards Association of New Zealand 1976. NZS 4203:1976. Code of practice for General Structural Design and Design Loadings for Buildings. Wellington, New Zealand.

Standards Association of New Zealand 1984. NZS 4203:1984. Code of practice for General Structural Design and Design Loadings for Buildings. Wellington, New Zealand.

Standards New Zealand 1988. NZS 4402.6.5.1:1988, Part 6 Soil strength tests - 6.5 Determination of the penetration resistance of a soil - Test 6.5.1 Standard penetration test (SPT). Wellington New Zealand.

Standards New Zealand 1992. NZS 4203:1992. Code of practice for General Structural Design and Design Loadings for Buildings, (Loadings Standard) Wellington New Zealand.

Standards New Zealand 2004. NZS 1170.5:2004 Structural Design Actions - Earthquake Actions. Section 3 - Site Hazard Spectra, Standards New Zealand. Pp. 81.

Semmens S, Perrin N, Barker P 2010. What lies beneath: Geological and geotechnical characterisation of the Wellington central commercial area. in proceedings, 11th IAEG Congress, Auckland, New Zealand, 5-10 September, 2010.

Stephenson WR 2007. HVSR, SSR, and VS30 values at three New Zealand basin arrays. Journal of Earthquake Engineering 11(6): 987-1009.

Stephenson WR, Barker PR 1992. Report on cone penetrometer and seismic cone penetrometer probing in Wellington City, Kapiti Coast and Upper Hutt Valley. DSIR Land Resources Contract Report No. 92/14 (prepared for Wellington Regional Council). 45 p.

Stevens GR 1975. Rugged Landscape: The geology of central New Zealand. Wellington, A.H. & A.W. Reed Ltd. 286 p.

Stirling MW, Wesnousky SG, Berryman KR 1998. Probabilistic seismic hazard analysis of New Zealand. New Zealand Journal of Geology & Geophysics 41: 355-375.

Stirling MW, McVerry GH, Berryman KR 2002. A new seismic hazard model for New Zealand. Bulletin of the Seismological Society of America 92(5): 1878-1903.

Suggate RP 1979. The Alpine Fault bends and the Marlborough faults. In: Walcott RI, Cresswell MM ed. The origin of the Southern Alps. Royal Society of New Zealand Bulletin 18. Pp. 67-72.

Taber JJ 1993. Instrumental recording of microzonation effects. In Proceedings, New Zealand Society for Earthquake Engineering technical conference. Taupo, New Zealand. Pp. 119-124.

Taber JJ, Richardson W 1992. Frequency dependent amplification of weak ground motions in Wellington City and the Kapiti Coast. Institute of Geophysics, Victoria University of Wellington (Report prepared for Wellington Regional Council).

Taber JJ, Kozuch M, McVerry GH 1998. How much will it shake where you live? Tephra June 1998, Ministry of Civil Defence & Emergency Management: 12-14.

Tait A, Bell R, Burgess S, Gorman R, Gray W, Larsen H, Mullan B, Reid S, Sansom J, Thompson C and others 2002. Meteorological Hazards and the Potential Impacts of Climate Change in the Wellington Region NIWA Client Report WLG2002/19, WRC Pub. No. WRC/RP-T-02/16. 155 p.

Teves-Costa P, Matias L, Bard PY 1996. Seismic behaviour estimation of thin alluvium layers using microtremor recordings. Soil Dynamics and Earthquake Engineering 15(3): 201-209.

United States Geological Survey 1990. The Modified Mercalli Intensity Scale. Retrieved 10/01 2010, from http://earthquake.usgs.gov/learn/topics/mercalli.php

US National Geophysical Data Center (NGDC) 1964. Leaning Apartment Houses in Niigata, Japan. Retrieved 10/10 2009, from http://www.ngdc.noaa.gov/nndc/

US National Geophysical Data Center (NGDC) 1967. Tipped Residence Due to Differential Settling, Caracas, Venezuela. Retrieved 26/01 2010, from http://www.ngdc.noaa.gov/nndc

Van Dissen RJ, Berryman KR, 1991. Timing, size, and recurrence interval of prehistoric earthquakes in the Wellington region, New Zealand. Geological Society of New Zealand Miscellaneous Publication 56: 53-54.

Van Dissen RJ, Berryman KR 1996. Surface rupture earthquakes over the last ~1000 years in the Wellington region, New Zealand, and implications for ground shaking hazard. Journal of Geophysical Research 1(B3): 5999-6019.

Van Dissen RJ, Heron D, Palmer AS 1999. Ohariu and Northern Ohariu Faults: Field guide to late Quaternary faulting. Geological Society of New Zealand Miscellaneous Publication 107A. Massey University, Palmerston North, New Zealand. Pp. 29-69.

Van Dissen RJ, Begg JG, Robinson R 2001. The Akatarawa Fault: a newly discovered active fault in the Wellington region, and implications for increased hazard on the Wellington fault. New Zealand Society for Earthquake Engineering Inc Technical Conference and AGM, Wairakei Resort Hotel, Friday/Sunday 23-25 March 2001: Conference Technical Papers: Paper no. 4.06.01 (8p).

Van Dissen RJ, Berryman KR, Pettinga JR, Hill NL 1992a. Paleoseismicity of the Wellington - Hutt Valley Segment of the Wellington Fault, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 35: 165-176.

Van Dissen RJ, Taber JJ, Stephenson WR, Sritharan S, Perrin ND, McVerry GH, Campbell HJ, Barker PR 1992b. Earthquake ground shaking hazard assessment of the Wellington area, New Zealand. DSIR Geology & Geophysics Contract Report 1992/23.

Van Dissen RJ, Taber JJ, Stephenson WR, Sritharan S, Perrin ND, McVerry GH, Campbell HJ, Barker PR 1993. Ground shaking hazard zonation for Wellington city and suburbs, New Zealand. In Proceedings, New Zealand Society for Earthquake Engineering technical conference. Taupo, New Zealand. Pp. 134-141.

Van Dissen RJ, Berryman KR, King AB, Webb TH, Brackley HL, Barnes P, Beavan RJ, Benites RA, Barker PR, Carne R, Cochran UA, Dellow GD, Fry B, Hemphill-Haley M, Holden C, Lamarche G, Langridge RM, Litchfield NJ, Little T, McVerry GH, Ninis D, Palmer NG, Perrin ND, Pondard N, Semmens S, Stephenson WR, Robinson R, Villamor P, Wallace LM, Wilson KJ 2009. “It's Our Fault” Better defining the Earthquake Risk in Wellington: results to date and a look to the future. New Zealand Society for Earthquake Engineering conference, Christchurch, New Zealand, Apr. 3-5, 2009.

Van Dissen R, Barnes P, Beavan J, Cousins J, Dellow G, Francois-Holden C, Fry B, Langridge R, Litchfield N, Little T, McVerry G, Ninis D, Rhoades D, Robinson R, Saunders W, Villamor P, Wilson K, Barker P, Berryman K, Benites R, Brackley H, Bradley B, Carne R, Cochran U, Hemphill-Haley M, King A, Lamarche G, Palmer N, Perrin N, Pondard N, Rattenbury M, Read S, Semmens S, Smith E, Stephenson W, Wallace L, Webb T, Zhao J 2010. It’s Our Fault: better defining earthquake risk in Wellington. in proceedings, 11th IAEG Congress, Auckland, New Zealand, 5-10 September, 2010. Paper No. in press, 8p.

Walcott RI 1998. Modes of oblique compression; late Cenozoic tectonics of the South Island of New Zealand. Reviews of Geophysics 36(1): 1-26.

Walcott RI, Christoffel DA, Mumme TC 1981. Bending within the axial tectonic belt of New Zealand in the last 9 Myr from paleomagnetic data. Earth and Planetary Science Letters 52(2): 427-434.

Wallace LM, Beavan RJ, McCaffrey R, Darby DJ 2004. Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. Journal of Geophysical Research, Solid Earth 109(B12): B12406.

Wellington Harbour Board 1936. Historical plan of reclamations in the port of Wellington (Port Nicholson)

Wellington Waterfront Limited 2009. Reclamations. Retrieved 8/10 2009, from http://www.wellingtonwaterfront.co.nz/docs/reclamations.pdf

Williams DN 1975. Ohariu Fault zone at Porirua, Wellington, New Zealand. New Zealand Journal of Geology & Geophysics 18: 659-666.

Wood HO 1908. Distribution of Apparent Intensity in San Francisco. In The California earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission, Volume 1, part 1, Carnegie Institution of Washington publication. no. 87, Washington, D.C. 220-245 p.

Zachariasen J, Berryman KR, Prentice C, Langridge RM, Stirling MW, Villamor P, Rymer M 2001. Size and timing of large prehistoric earthquakes on the Wairau Fault, South Island. New Zealand Earthquake Commission Research Report No 99/389. Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. Pp. 41 pp.

Zachariasen J, Berryman K, Langridge R, Prentice C, Rymer M, Stirling M, Villamor P 2006. Timing of late Holocene surface rupture of the Wairau Fault, Marlborough, New Zealand. New Zealand Journal of Geology & Geophysics 49: 159-174.

AN ENGINEERING GEOLOGICAL INVESTIGATION OF THE SEISMIC SUBSOIL CLASSES IN THE CENTRAL WELLINGTON COMMERCIAL AREA

VOLUME TWO: APPENDICIES

A thesis submitted in partial fulfilment of the requirements for the

Degree of

Master of Science in Engineering Geology

in the University of Canterbury

by

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February 2010

Frontispiece: You can't beat Wellington on a good day!

VOLUME TWO: APPENDICES
TABLE OF CONTENTS:

APPENDIX SEVEN

APPENDIX 1A

NZ Geological Timescale

(see attached DVD)

Cooper RA (Compiler) 2004. New Zealand Geological Timescale 2004/2 wallchart. Institute of Geological & Nuclear Sciences information series 64.

APPENDIX 2A

New Zealand Geotechnical Society Field Guide Sheet

(see attached DVD)

APPENDIX 2B

New Zealand Geotechnical Society Field Description of Rock & Soil

(see attached DVD)

APPENDIX 3A

Site Effects - Basic Theory

SITE EFFECTS - BASIC THEORY

Seismic waves travel faster through harder denser rocks and compact sediments than through soft rocks and loose sediments. Generally, the density of sediments, impedance and therefore shear wave velocity within those sediments (velocities are faster through denser materials), increases with depth. As the wave travels from harder to softer rock it slows down, and therefore must increase in amplitude as the conservation of elastic wave energy requires energy flux to remain constant.

For a very simple horizontal 1D site (ignoring wave scattering and material damping), E, the energy per unit volume, is constant (i.e. independent of depth).

E is given by:

$E = \rho V_s \mathring{u}$ .... (Kramer 1996)

Where

ρ = the density of the soil/rock

V_s = the shear wave velocity

$\mathring{u}$ = the particle velocity

As a wave travels up to the surface the sediment density decreases (as does the impedance), therefore the shear wave velocity also decreases. If E is to remain constant as a wave approaches the surface, the particle velocity $\mathring{u}$ must increase to compensate the decrease in density and shear wave velocity. Thus as a result it can be seen that velocity will increase. Both sediment impedance (resistance to particle motion) and damping (attenuation) affect the amplitude of earthquake ground motion. Damping or inelastic attenuation is greatest in soft/loose sediments and partially counters the increase in seismic amplitude from resonance.

It is clear that when two layers with differing densities overly one another, an impedance contrast exists. The trapping of seismic waves due to the impedance contrast between bedrock and the overlying sediments is the primary cause of amplification in those sediments. Maximum resonance arises when interference of these trapped reverberating waves are in phase with one another. Resonance is frequency dependent and related to the density, damping and wave velocities of a soil. Resonance patterns become very complex for real 3D sites. “The fundamental resonant frequency may vary between 0.2Hz (for very thick deposits or for extremely soft materials) and 10Hz or more (for very thin deposit layers or weathered rock)” Pitilakis (2004).

Analysis using elastic (seismic) wave theory can demonstrate 1D site amplification. For the simple homogeneous one dimensional layer example given in Figure 3A.1, the natural frequencies (ω_n), (ignoring damping and free surface effects), are given by:

$$\omega_n = \frac{(2n-1)\pi V_s}{2H}$$ ....(Kramer 1996)

Where

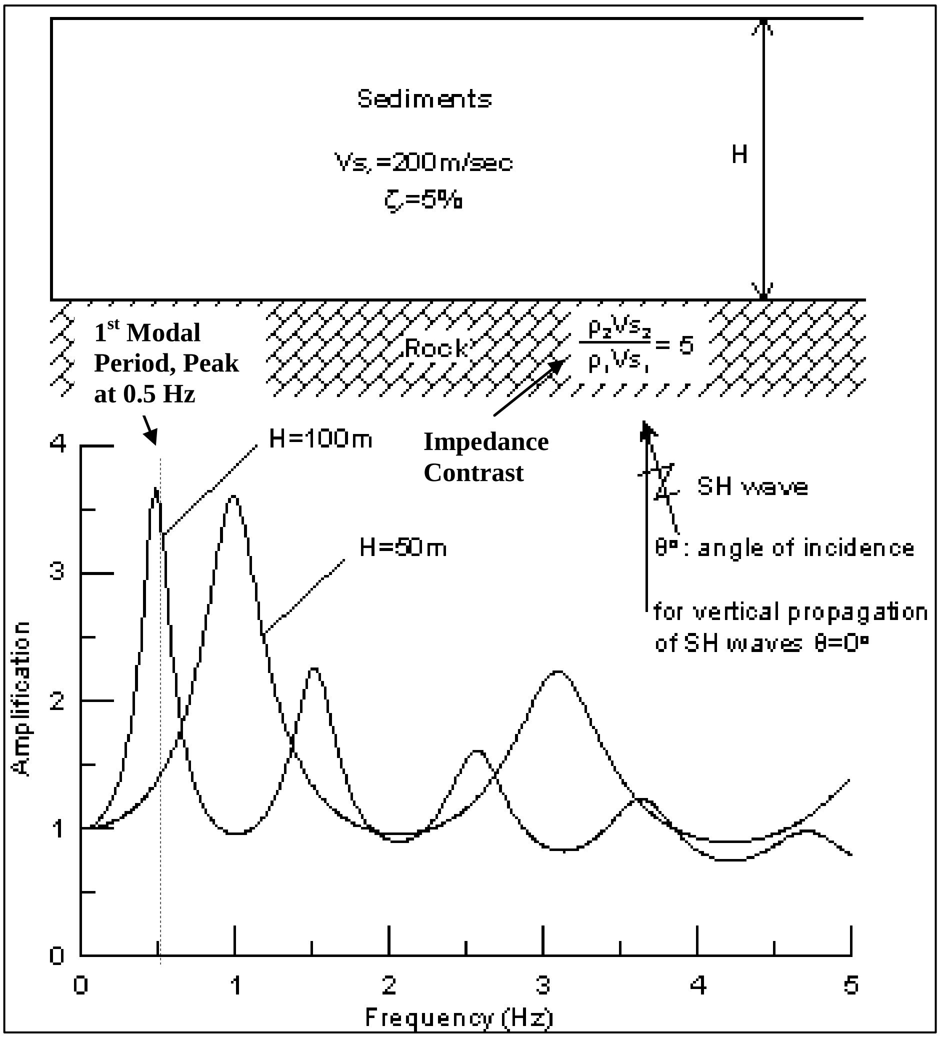
n = mode number

H = soil thickness (surface to bedrock)

Vs = shear wave velocity of the soil

π = 3.14159265

Figure 3A.1: Simple 1D site amplification example (Pitilakis 2004).



Illustrates the effects of resonance in the frequency domain with low resistance sediments overlying rock (Pitilakis 2004).

Earthquakes contain waves with a range of frequencies, some of which will be amplified more than others. Amplification values as high as 20 may occur in situations where the stiffness contrast between rock and the overlying soil is high. For the simplest case (in the example above) with a soil overlying a stiffer denser layer (rock) the impedance contrast (ζ) is given by:

$$\zeta = \frac{\rho_2 V_{s2}}{\rho_1 V_{s1}} \text{ ....(Pitilakis 2004)}$$

Where

ζ	=	impedance contrast – the contrast in stiffness and density between bedrock and the overlying soil
ρ_1	=	soil layer density
V_{s1}	=	soil shear wave velocity
ρ_2	=	density of stiffer layer (bedrock)
V_{s2}	=	shear wave velocity of stiffer layer (bedrock)

The fundamental period (T) for a soil layer overlying bedrock is given by:

$$T = \frac{2\pi}{\omega_1} = \frac{4H}{V_s} \text{ ....(Kramer 1996)}$$

Where

V_s	=	soil shear wave velocity
H	=	soil thickness (surface to bedrock)
ω_1	=	natural frequency
π	=	3.14159265

It should be noted that period is inversely proportional to frequency.

For the example in Figure 3A.1 it can be seen that the first modal period in the deeper sediment layer (100 m in the example) occurs at a lower frequency than the first modal period of the shallower layer (50 m in the example). Peaks occur at the natural frequencies and diminish as frequency increases. Amplification levels in soft soils are reduced by the increased nonlinearity behaviour at higher velocities. The 100 m layer (in Figure 3A.1) has peaks of amplification at approximately 0.5, 1.5, 2.5 Hz and higher and the 50 m layer has amplification peaks at approximately 1.0, 3.0 Hz and higher.

For complicated (real) sites the natural (fundamental) period estimates can be made using the approximation that period is equal to the sum of 4 times the travel time of shear waves through each individual layer (this is used in the New Zealand loadings code NZS 1170.5:2004). Shown by:

$$T \cong \sum_{1}^{n} \left[\frac{4H}{V_s}\right]_i$$

This approach provides a useful means of estimating site period especially since accurate measurement of shear velocity is seldom undertaken in New Zealand. However, it should be noted that this can lead to inaccurate non-conservative estimates.

Site topography also has a profound effect on ground motion. Complicated amplification and deamplification patterns can be produced from topographic irregularities. Ridge crests generally amplify ground motions. Sedimentary basins filled with soft deposits can trap body waves, generating surface waves within the sediments (Kramer 1996; Pitilakis 2004). As a result ground motion within alluvial basins may be significantly different than predicted with considerable variation observed near the basin edge (edge effects). Most loading codes (including New Zealand's) do not directly consider topographic effects with the notable exception of the European Seismic Code BS EN 1998-5:2004 (British Standards Institution 2005).

Clearly seismic design needs to incorporate the effects of local site conditions, which must be accounted for on a case by case basis. In New Zealand site conditions are dealt with in part 5 of the structural design actions (NZS 1170.5:2004).

APPENDIX 3B

Mexico City Case Study
(1985 Michoacán Earthquake)

1985 MICHOACÁN (MEXICO CITY) EARTHQUAKE CASE STUDY

There have been no large damaging earthquakes in Wellington City since the adoption of the 2004 seismic loading code (NZS 1170.5:2004), thus the current code remains untested. Additionally, there are no well documented examples of site conditions influencing ground shaking amplification in Wellington since the adoption of modern seismology, it is therefore necessary to look overseas for appropriate examples. The 1985 Michoacán Earthquake clearly demonstrated the effects that local site conditions have on amplification of ground motion and subsequent damage. Observed structural effects in one of the world's most populous cities in combination with good strong ground motion records provides one of the best natural laboratory environments for study. A significant portion of Wellington City is founded on basin sediments as opposed to greywacke bedrock, not unlike Mexico City which is founded on old lake bed sediments. Although geologically very different (colluvium/alluvium in Wellington City as opposed to soft lake sediments in Mexico City), the sediments underlying Wellington City would be expected to amplify strong ground motion under similar circumstances as the 1985 Michoacán Earthquake.

THE SEISMIC EVENT

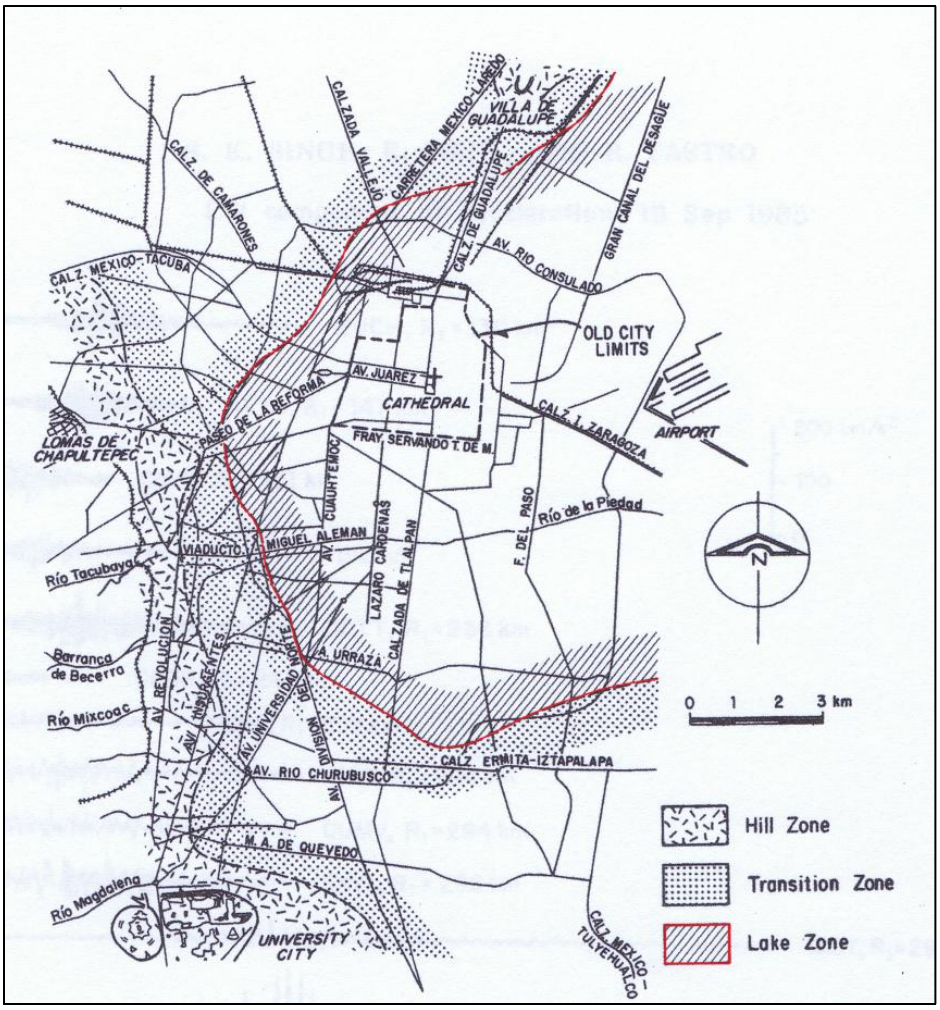
On Thursday 19th September, 1985, at 7:19 A.M., a magnitude 8.1 earthquake struck off the Pacific coast of Mexico as the Cocos Plate was thrust beneath the North American Plate. The main shock was followed by several aftershocks including the largest (magnitude 7.5) which occurred on September 20th 1985. The earthquake resulted in strong ground shaking lasting three to four minutes in Mexico City (MMIX), 400 km east of the epicentre. Eighteen strong motion instruments recorded the earthquake and its aftershocks between the coast and Mexico City. At least 20 sustained cycles of vibration were recorded with a dominant period of approximately 2 seconds. "Ground accelerations ranged from 5 to 20 percent of gravity in a period range between 1.5 and 3 seconds" (Cassaro & Romero 1986).

SITE EFFECTS & DAMAGE

Mexico City is located on the old Lake Texcoco basin, which was formed by the faulting of an uplifted plateau and closed off by volcanic activity in the Late Pliocene. The near surface geology of Mexico City is classified into three zones (refer to Figure 3B.1), namely the old lake bed, transition and hill (firm ground). Hill zone soils consist of weathered volcanic rocks and tuffs and are generally uncompressible with relatively low water content. Transition zone soils consist of thin lake sediments interbedded with alluvial sands, clays and gravels.

Transition zone deposits have high water content, but lower than that of lake zone sediments. The old lake bed zone contains thick lacustrine deposits interbedded with clay, sands and silts (primarily clays) with high water contents. The central city is largely built on these soft unconsolidated lake deposits. These deposits have S-wave velocities of about 80 m/sec and average thicknesses of about 30-45 m (Raul & Marsal 1986; Chavez-Garcia & Cuenca 1996).

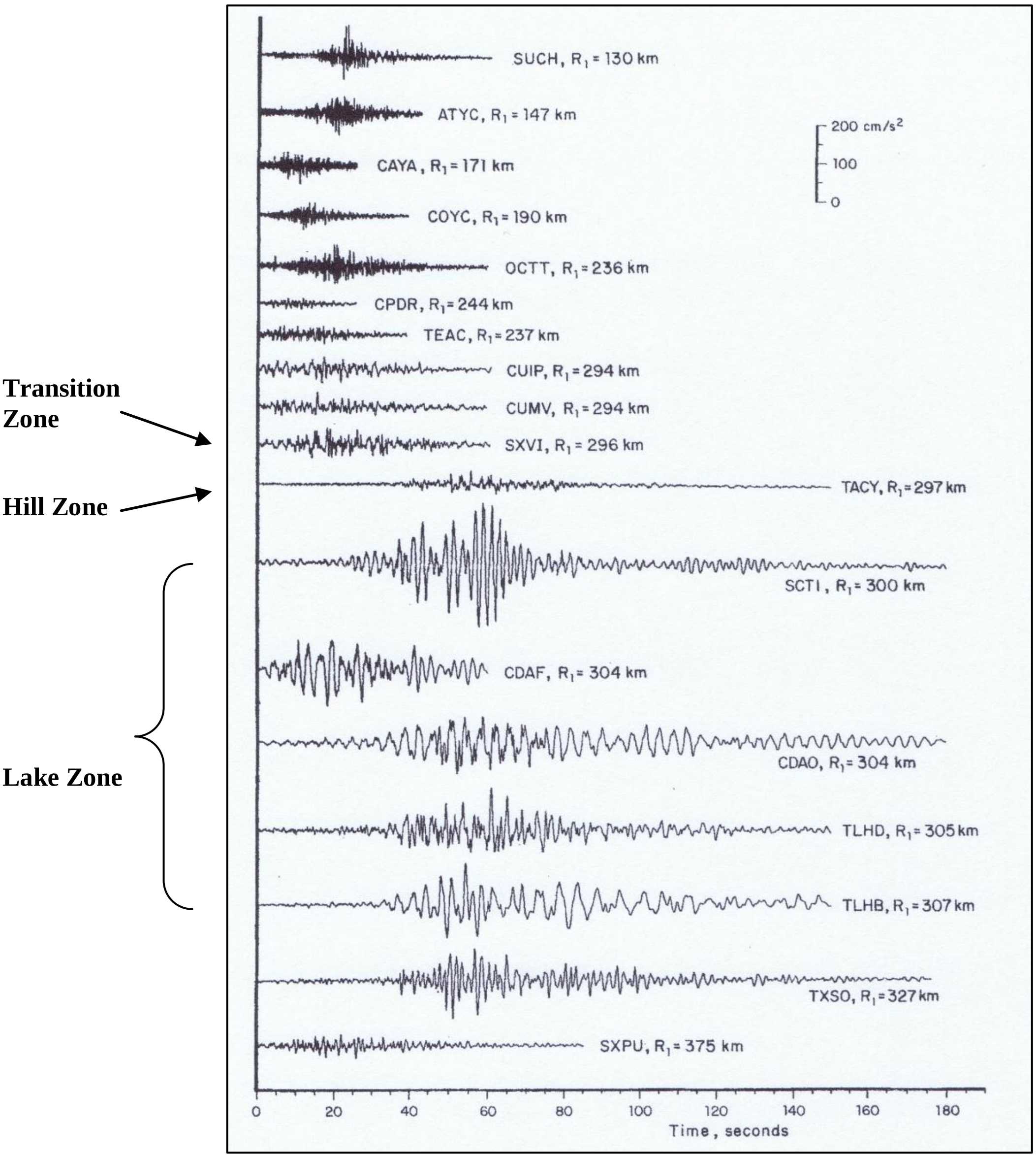
Figure 3B.1: Soil zoning in Mexico City (Raul & Marsal 1986).



The old lakebed zone deposits have a natural period of approximately 2 seconds (Raul & Marsal 1986). This coincided with the incoming earthquake waves resulting in amplification (refer to Figure 3B.2). Amplification levels between 8-50 times that measured on a nearby hill zone at Ciudad Universitaria, (CUIP) were recorded within this zone (Singh et al. 1998). Structures that had a natural frequency of vibration similar to that of the underlying soil experienced co-resonance with amplified shaking resulting in extensive damage and collapse.

These soft deposits also subsided as a result of strong ground shaking resulting in liquefaction and the dramatic settlement of numerous buildings (Borja-Navarrete et al. 1986).

Figure 3B.2: E-W component of acceleration in the 1985 Michoacán Earthquake (Singh et al. 1998).



Accelerograph sites CUIP, CUMV, SXVI, TACY, SCTI, CDAF, CDAO, TLHB and TLHD are all in Mexico City. Accelerograph stations CDAF, CDAO, SCTI, TLHB and TLHD are located within the lake zone, SXVI within the transition zone and TACY within the hill zone.

In Mexico City damage was severe and largely concentrated within the lake zone, where nearly all of the collapsed buildings were located (Borja-Navarrete et al. 1986). Damage in Acapulco, located 100 km closer to the epicentre, was relatively minor. It is estimated that from a population of 18 million people, 10,000 were killed, and a further 50,000 were injured (although controversy over the actual number of people killed remains today). A further 250,000 were left homeless with property damage amounting to $3-4 billion (USD). More than 400 buildings were destroyed with an additional 3200 damaged, including hotels, three of the city's largest hospitals, schools and businesses. Life lines including water, sewage, electricity and communications were seriously damaged. Structures between 6-15 stories high (Borja-Navarrete et al. 1986) were most severely affected with many collapsing as a result of co-resonance. Structures outside this height range with different natural frequencies were less damaged even though in places they were located adjacent to severely damaged structures. Differential movements of adjacent buildings also lead to significant damage with taller, more flexible structures often failing when located against shorter, more rigid structures because of lateral impact. Many buildings also had their more flexible upper floors severely damaged as a result of the long duration of shaking, leaving their lower floors relatively intact (Borja-Navarrete et al. 1986).

ADVANCES IN KNOWLEDGE AND LESSONS LEARNED

At the time of the 1985 earthquakes, a respected modern building code had been adopted in Mexico City with provisions derived from the lessons learned in the 1957 and 1976 earthquakes. The peak acceleration in Mexico City was more than double that of any previous severe earthquake and far greater than anticipated by engineers and the building code (Cassaro & Romero 1986). It is also argued that a lack of enforcement of this code may have led to increased damage. Numerous studies have been carried out on the well constrained data from the 1985 earthquake, with findings extending the understanding of earthquake engineering including:

- Amplification of seismic waves in soil deposits (particularly clays), including the effects of long duration ground motion.
- Foundation, lifeline and structural performance (highlighting the need to avoid co-resonance, and design suitable symmetric structures).
- Emergency management and disaster mitigation; the earthquake served as a catalyst for improving urban search and rescue methods.

After the earthquake Mexican officials significantly modified and upgraded the seismic loading provisions in the Mexican building code.

APPENDIX 4A

Geotechnical Borehole Database

(see attached DVD)

APPENDIX 4B

Electronic (.PDF) Bore Log Appendix

(see attached DVD)

APPENDIX 4C

Wellington Central Park Flats - Bore Logs

(see attached DVD)

APPENDIX 5A

Waterfront SCPT Results Spreadsheet

(see attached DVD)

APPENDIX 6A

SPAC Coherency Plots

(see attached DVD)

APPENDIX 6B

SPAC HVSR Plots

(see attached DVD)

APPENDIX 6C

SPAC Field Sheets

(see attached DVD)

APPENDIX 6D

SPAC Results Spreadsheet

(see attached DVD)

APPENDIX 7A

Wellington 3D Geological Model Scene Files

(see attached DVD)

APPENDIX 7B

Earth Research Viewer Software

(see attached DVD)

APPENDIX 7C

3D Geological Model Data

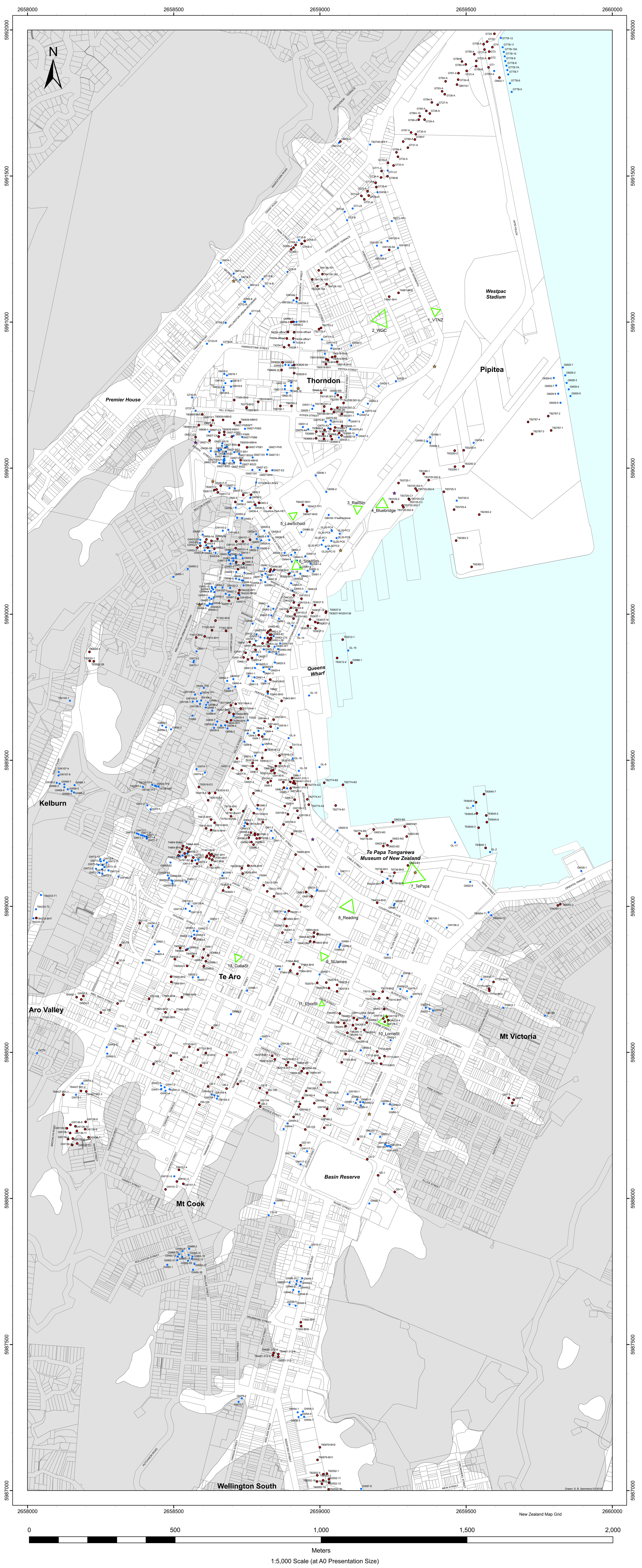
(see attached DVD)

APPENDIX 8 - MAPS

8A	Data Location Map (A0 Size)
8B	Waterfront Reclamation Map (A3 Size)
8C	Surficial Deposits Map (A0 Size)
8D	Depth to Bedrock Contour Map (A0 Size)
8E	Cross Section Location Map (A3 Size)
8F	Low Amplitude Natural Period (Site Period) Map (A0 Size)
8G	NZS 1170.5:2004 Site Subsoil Class Map (A0 Size)
8H	Vs30 Map (A3 Size)
8I	Ground Shaking Amplification Hazard Map (A3 Size)
8J	Liquefaction Potential Map (A3 Size)

(see back pocket)

Map 8A
Wellington City Data Locations



Map shows location of 1025 boreholes including where SPT data were obtained. Also shown are 12 SPAC microtremor sites used to acquire data specifically for this study and microtremor sites from other investigations.

Refer to Chapter 5 of thesis for more information.

Legend

Boreholes (with identification labels)

- with SPT Data
- without SPT Data

SPAC Microtremor Sites (with identification labels)

- (array used for analysis in this project)

Additional Microtremor Data by Test Type

Test

- Nakamura
- ReMi
- SPAC (other studies)

Definition of Terms

SPT:

The standard penetration test (SPT) is an in-situ dynamic penetration test that provides an indication of soil density and is used in a number of geotechnical engineering formulae.

SPAC:

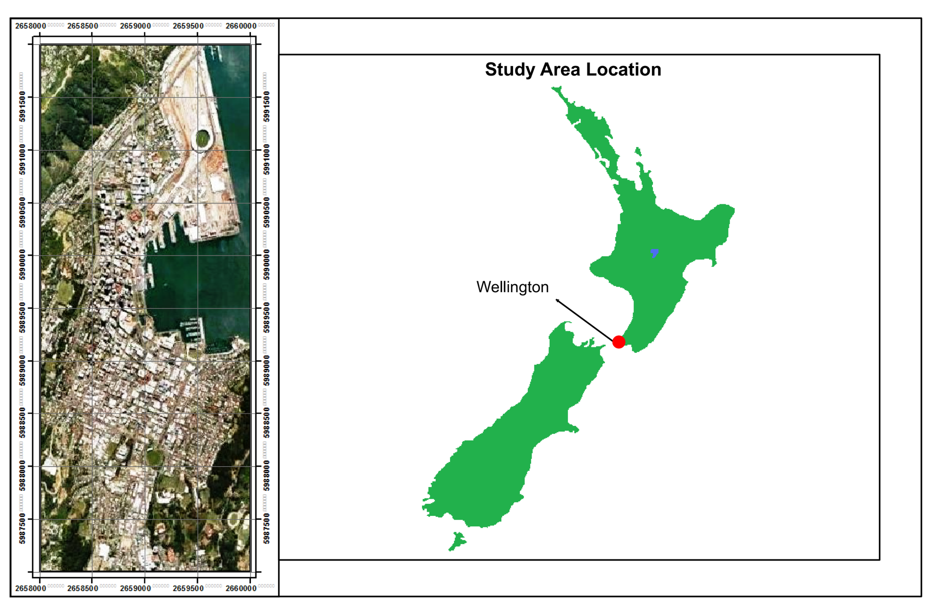
SPatial AutoCorrelation (SPAC) is a non-invasive technique that uses an array of geophones to make simultaneous records of the vertical component (Rayleigh waves) of microtremor motion.

Nakamura:

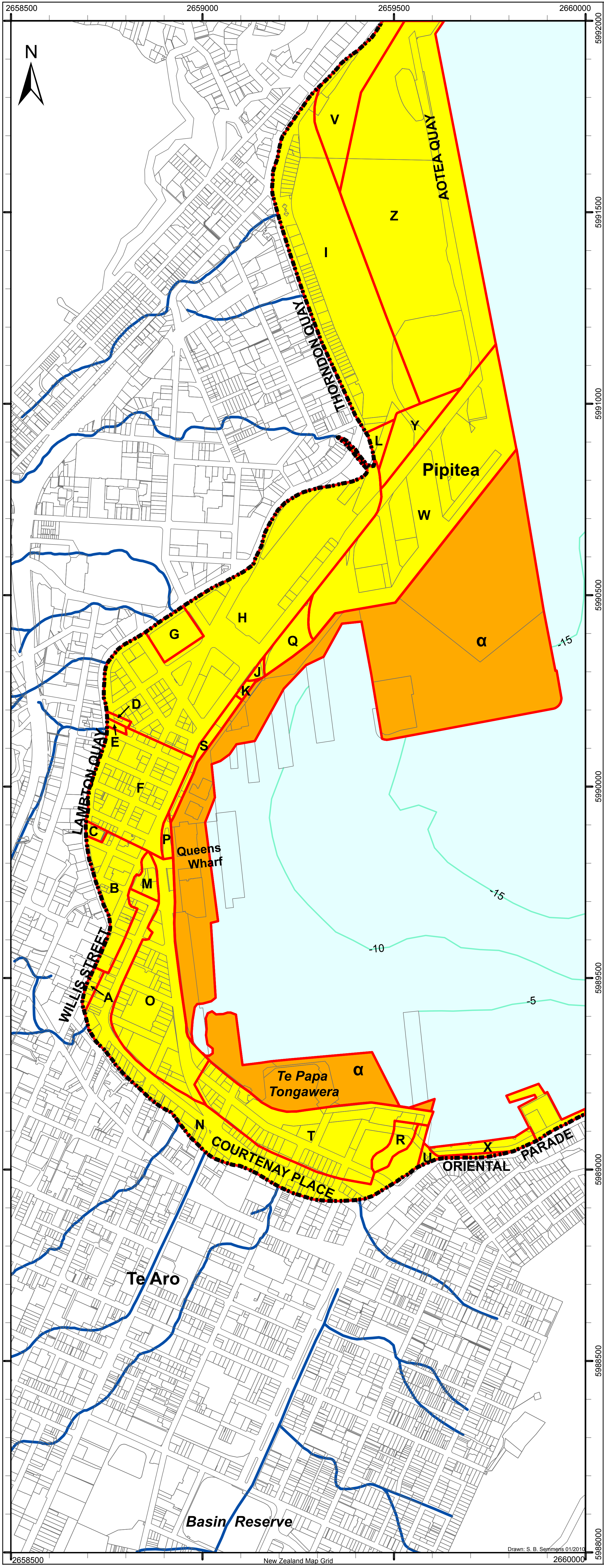
This microtremor technique also known as the Horizontal to Vertical Spectral Ratio (HVSR) method can be used to give a direct measurement of site period.

ReMi:

The Refraction Microtremor (ReMi) technique uses a linear array of vertical geophones spaced at intervals of a few metres, to synchronously record microtremors.



Semmens S 2010. An engineering geological investigation of the seismic sub soil classes in the central Wellington commercial area. Unpublished thesis, University of Canterbury, Christchurch, New Zealand.



Map 8B
Wellington City Waterfront Reclamations

Map shows the location and construction dates of waterfront reclamations in Wellington City based on:
Wellington Harbour Board (WHB) 1936. Historical plan of reclamations in the port of Wellington (Port Nicholson) - Fill zones A to Z.
Wellington Waterfront Limited (WWL) 2009 - Fill zone α.
Bastings L. 1936. A subsoil survey of Wellington City - Former stream and shoreline locations.

Refer to Chapter 5 for map construction methodology.

Legend

- 1852-1932 WHB Fill Zones
- 1965-1972 Reclamation
- Bathymetric Contours (5m)
- Former Streams (Bastings)
- Shoreline (pre European settlement)

Reclamation Zones by Construction Date

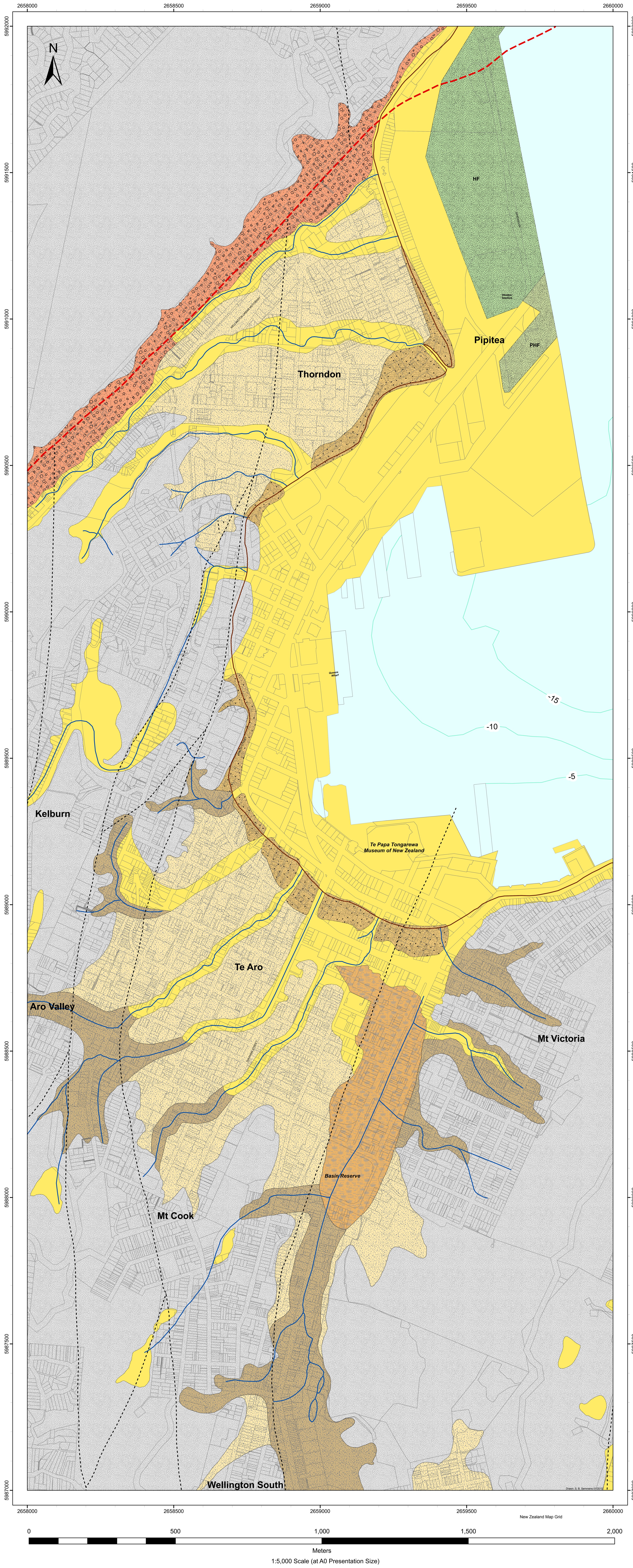
Reclamation No.	Date	Source
A	1852	WHB
B	1857-1863	WHB
C	1859	WHB
D	1864	WHB
E	1865	WHB
F	1866-1867	WHB
G	1875	WHB
H	1876	WHB
I	1882	WHB
J	1882	WHB
K	1882	WHB
L	1884	WHB
M	1886	WHB
N	1886	WHB
O	1889	WHB
P	1893	WHB
Q	1893-1901	WHB
R	1895	WHB
S	1901-1903	WHB
T	1901-1914	WHB
U	1902-1925	WHB
V	1904	WHB
W	1904-1916	WHB
X	1906	WHB
Y	1910-1913	WHB
Z	1924-1932	WHB
α	1965-1972	WWL

This map provides a guide to the reclamations around the waterfront in Wellington City, but does not replace the need for professional consultation and site specific investigations.

0 125 250 500 750 1,000
Metres

1:10,000 Scale (at A3 presentation size)

Semmens S 2010. An engineering geological investigation of the seismic subsoil classes in the central Wellington commercial area. Unpublished thesis, University of Canterbury, Christchurch, New Zealand.



Map 8C
Wellington City Surficial Deposits

Map shows surficial (typically < 5m depth) deposits in the Wellington CBD study area. This map was compiled using information from borehole investigations, test pits, site observations, aerial photographs, limited field mapping and existing maps (Bastings 1936; Wellington Harbour Board 1936; Begg & Mazengarb 1996). The position of the Wellington Fault was digitized from Perrin & Wood (2003). Other Fault locations were obtained and modified from Begg & Mazengarb (1996).

Refer to Chapter 5 of thesis for more detailed information.

Legend

Wellington Fault

Other Faults

Shoreline (pre European Settlement)

Former Streams (from Bastings 1936)

Bathymetric Contours (5m)

Geological Legend

Reclamation Fill: Locally quarried, end dumped, weathered greywacke sandstone, mudstone and spoil, domestic waste (bricks, glass, wood etc), sand, boulders and engineered fill poorly compacted to compact (V_s ~125-300 m/s).

HF / PHF — **Hydraulic Fill (HF) including Possible Hydraulic Fill (PHF)**: Dredged mud, sand and silt from the seabed, soft to loose (V_s ~50-150 m/s).

Swamp Sediments: silt (organic), silty sands and gravelly silt, mud, peat, clay, sand, organic matter and wood. Soft/loose to firm/medium dense (V_s ~100-200 m/s).

Young Alluvium: Holocene alluvial weathered gravels, sands and silts. Sub-angular to sub-rounded, loose/soft to very dense (V_s ~150-500 m/s).

Old Alluvium/Colluvium: Pleistocene alluvial and colluvial deposits consisting of sands, silts, weathered gravels and clays. Poorly sorted to well sorted, medium dense to very dense/effective bedrock (V_s ~250-700+ m/s).

Colluvium: Holocene/Pleistocene weathered angular to sub angular gravels, sands, clays and silts. Poorly sorted (fan gravel deposits), loose to dense (V_s ~150-400 m/s).

Marginal Marine: Sand (dominant), silt and gravels with shells. Loose/soft to medium dense (V_s ~150-250 m/s).

Greywacke Sandstone/Mudstone: Grey brown (becoming yellow brown with increased weathering) quartzo-feldspathic sandstone mudstone sequences. Faulted, jointed, completely weathered (Vs ~200 m/s at surface) to unweathered (V_s ~2000 m/s at depth).

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

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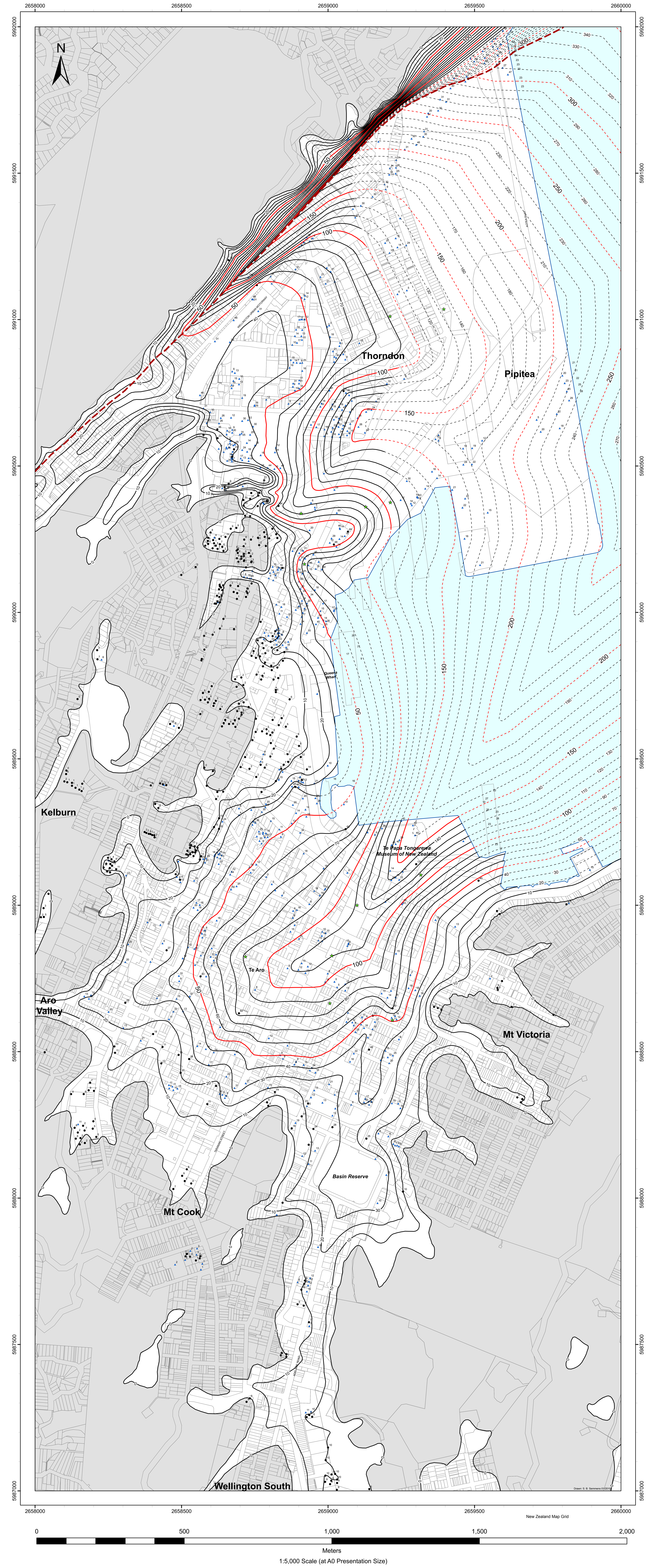

Map 8D
Wellington City Depth to Bedrock

Map shows depth to bedrock contours over 10m elevation intervals for the Wellington CBD study area. Contour elevation represents rock-head depth from the ground surface or mean sea level for offshore areas. Map was compiled using data from 1025 boreholes, test pits, site observations and 12 SPAC microtremor tests. No offshore subsurface information was obtained in this study and where limited subsurface data exists the contours have been dashed (indicating low confidence).

Refer to Chapter 5 of thesis for more information.

Legend

Boreholes
- Rock (depth indicated m)
- No Rock (hole depth indicated m)

SPAC Microtremor Sites
- (depth to bedrock calculated)

Depth to Bedrock Contours
- 10m
- 50m
- 10m Low Confidence
- 50m Low Confidence

Wellington Fault

Greywacke Bedrock Outcrop

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

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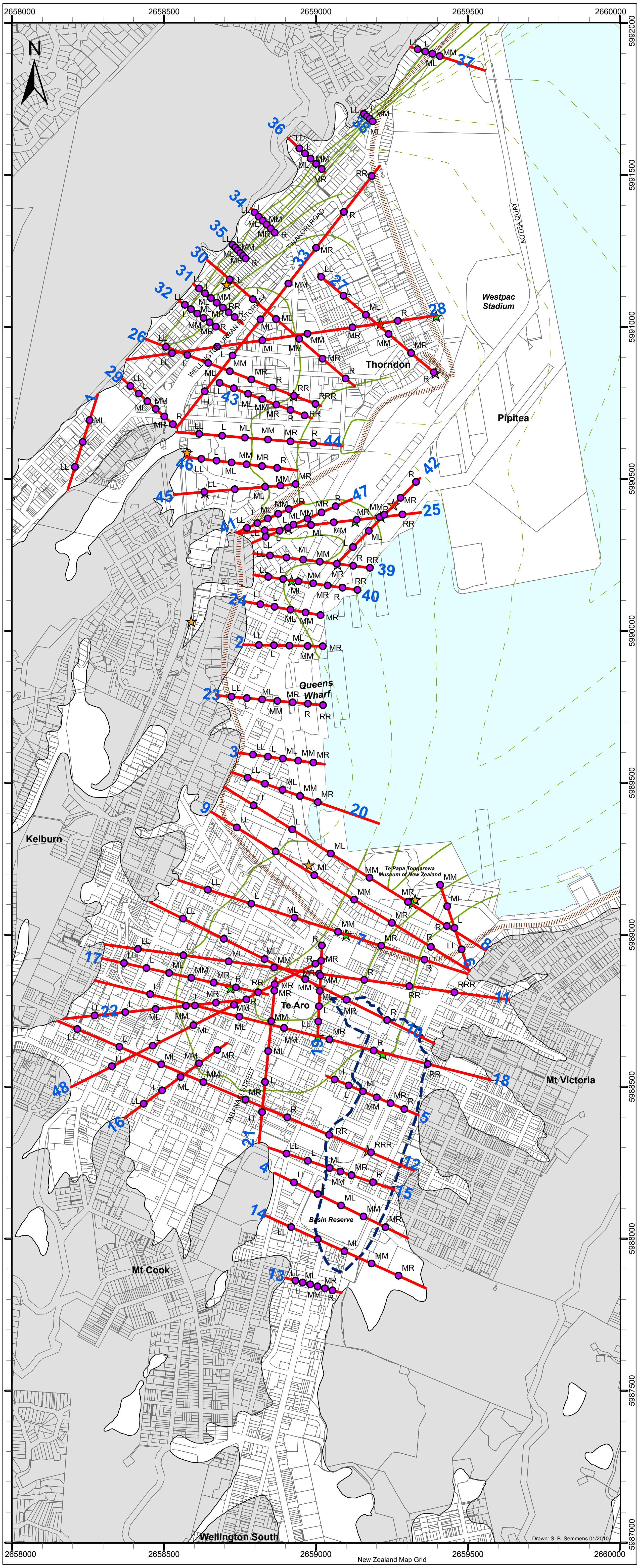


Map 8E
Wellington City
Cross Section Locations

Map shows the location of the 48 cross sections used to refine the site period and Vs30 maps (refer to Chapter 5 of thesis). Also shown are the shoreline (pre European settlement) and former Te Aro swamp (Bastings 1936). Cross sections are labelled with their section number (blue number). Pseudo-boreholes are labelled with an identification code (LL, L, ML, MM, MR, R, RR and RRR) as given in the cross section calculation spreadsheet. The combination of cross-section number and pseudo-borehole code provides a unique identifier for each pseudo-borehole.

Legend

- Pseudo Borehole with Lettering ID
- 20 Cross Section with Number ID

Measured Vs30 & Site Periods

- 12 SPAC Microtremor Sites
- Determinations from other studies

Shoreline (pre European Settlement)

Former Te Aro Swamp (from Bastings 1936)

Depth to Bedrock Contours

- 50m Contours
- 50m Contours (low confidence)

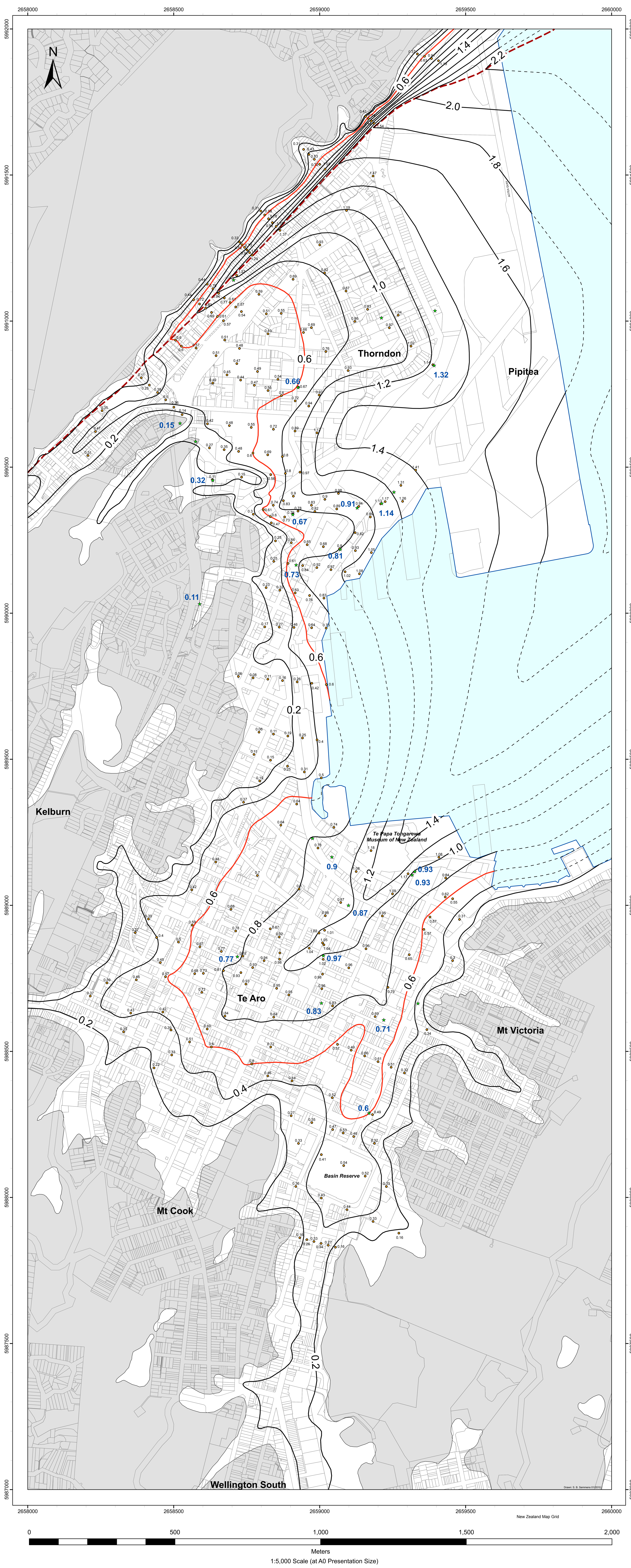
Greywacke Bedrock

0 250 500 750 1,000

Metres

1:12,500 Scale (at A3 presentation size)

Semmens S 2010. An engineering geological investigation of the seismic subsoil classes in the central Wellington commercial area. Unpublished thesis, University of Canterbury, Christchurch, New Zealand.



Map 8F
Wellington City
Low Amplitude Natural Period

Map shows low amplitude natural period contours over 0.2 second intervals for the Wellington CBD study area. This map has been constructed using measured and pseudo site period information (refer to chapter 5 of thesis for more information). It should be noted that no subsurface information was available for the harbour area and the contours (dashed lines on map) used to connect the Thorndon and Te Aro areas have a low confidence.

Legend

Measured Site Periods (seconds)

- (from various microtremor methods)
- (number indicates calculated period in seconds)

Site Period Contours

- 0.2 Second Contour Intervals
- 0.6 Second Contour (site subsoil class D >0.6s)

Wellington Fault

Greywacke Bedrock

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

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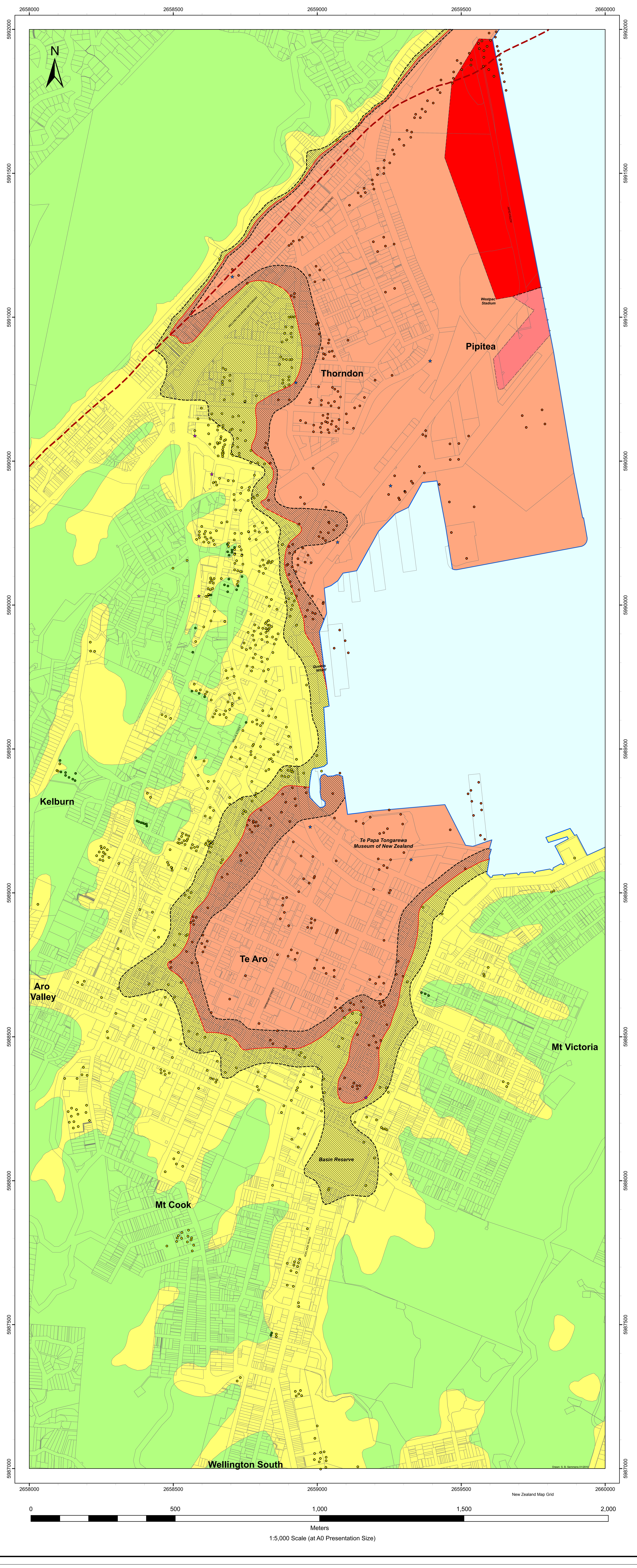

Map 8G
Wellington City NZS1170.5:2004 Site Subsoil Class

Map shows site subsoil classes as prescribed by NZS1170.5:2004 for central Wellington. Map has been constructed using geological and geotechnical data from 1025 boreholes along with measured and pseudo low amplitude natural periods (site periods). The site class C/D boundary is shown with its uncertainty illustrated by hatching. "Possible" and "Probable" Site subsoil Class E has been conservatively assigned to the area containing hydraulic fill in the vicinity of Aotea Quay (refer to Chapter 5 of thesis for more detailed information).

Legend

Measured Site Periods

- C Site Subsoil Class
- D Site Subsoil Class

Borehole Data

- B Site Subsoil Class
- C Site Subsoil Class
- D Site Subsoil Class

Site Period

- 0.6s Contour

C/D Site Subsoil Class

- Boundary Uncertainty

Wellington Fault

Table 1: NZS1170.5:2004 Site Class Definitions (Standards New Zealand 2004)

Class	Description	Definition
A Not in Study Area	Strong Rock	UCS > 50MPa ....& V_s 30m > 1500m/s ....& Not underlain by < 18MPa or V_s 600m/s materials.
B	Rock	1< UCS < 50MPa ....& V_s 30m > 360 m/s ....& Not underlain by < 0.8MPa or V_s 300m/s materials, A surface layer no more than 3m depth (HW -CW rock/soil).
C	Shallow Soil	Not class A, B or E, Low Amplitude Natural Period ≤0.6s, or Have depths of soils not exceeding those in Table 2 (see below).
D	Deep or Soft Soil	Not class A, B or E, Low Amplitude Natural Period > 0.6s, or Have depths of soils exceeding those in Table 2, or Underlain by < 10m soils with undrained shear strength < 12.5 KPa, or < 10m soils SPT N < 6.
E Probable Possible	Very Soft Soil	> 10m soils with undrained shear strength < 12.5 KPa, or > 10m soils with SPT N < 6, or **> 10m soils with Vs 150 m/s, or** >10m combined depth of above properties.

Table 2: NZS1170.5:2004 Maximum depth limits for site class C (Standards New Zealand 2004)

Soil Type & Description		Max. Depth (m)
Cohesive Soil	**Representative Undrained Shear Strength (KPa):**	
Very Soft	< 12.5	0
Soft	12.5-25	20
Firm	25-50	25
Stiff	50-100	40
Very Stiff/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

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

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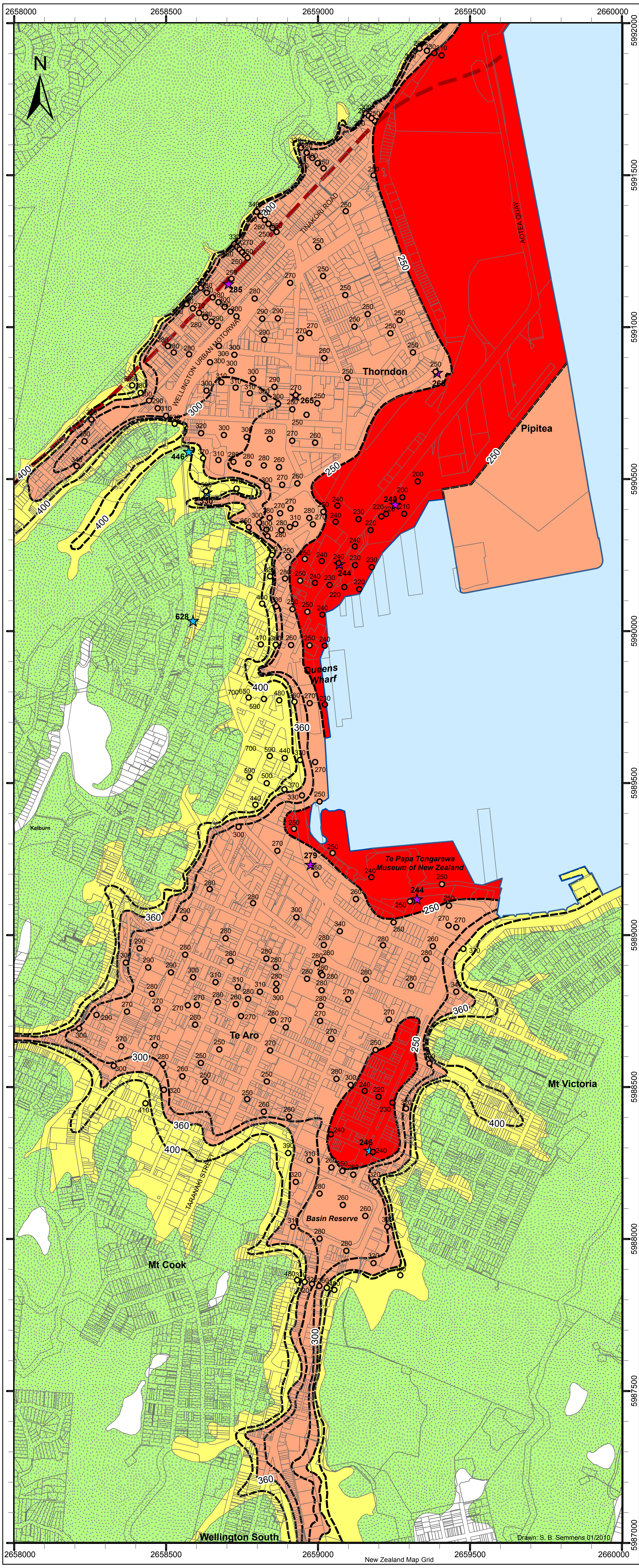

Map 8H
Wellington City Vs30

Map shows distribution of Vs30 values for the Wellington CBD study area. Vs30 is the shear wave velocity over the top 30m of material beneath the surface and forms the basis of site hazard classification under the US National Earthquake Hazards Reduction Program (NEHRP) provisions and the US Uniform Building Code (UBC). This map was constructed using measured and pseudo Vs30 information (refer to chapter 5 of thesis).

Legend

Measured Vs30 (m/s)
- 1170.5:2004 Site Class C
- 1170.5:2004 Site Class D

Pseudo Borehole Vs30 Values (m/s)
- ≤ 250
- 250-360
- 361-700

Vs30 Contours (m/s)
- (intervals labelled)

Vs30 Range (m/s)
- No Subsurface Information
- < 250
- 250-360
- 361-700
- > 700

Wellington Fault

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

0 250 500 750 1,000

Metres

1:12,500 Scale (at A3 presentation size)

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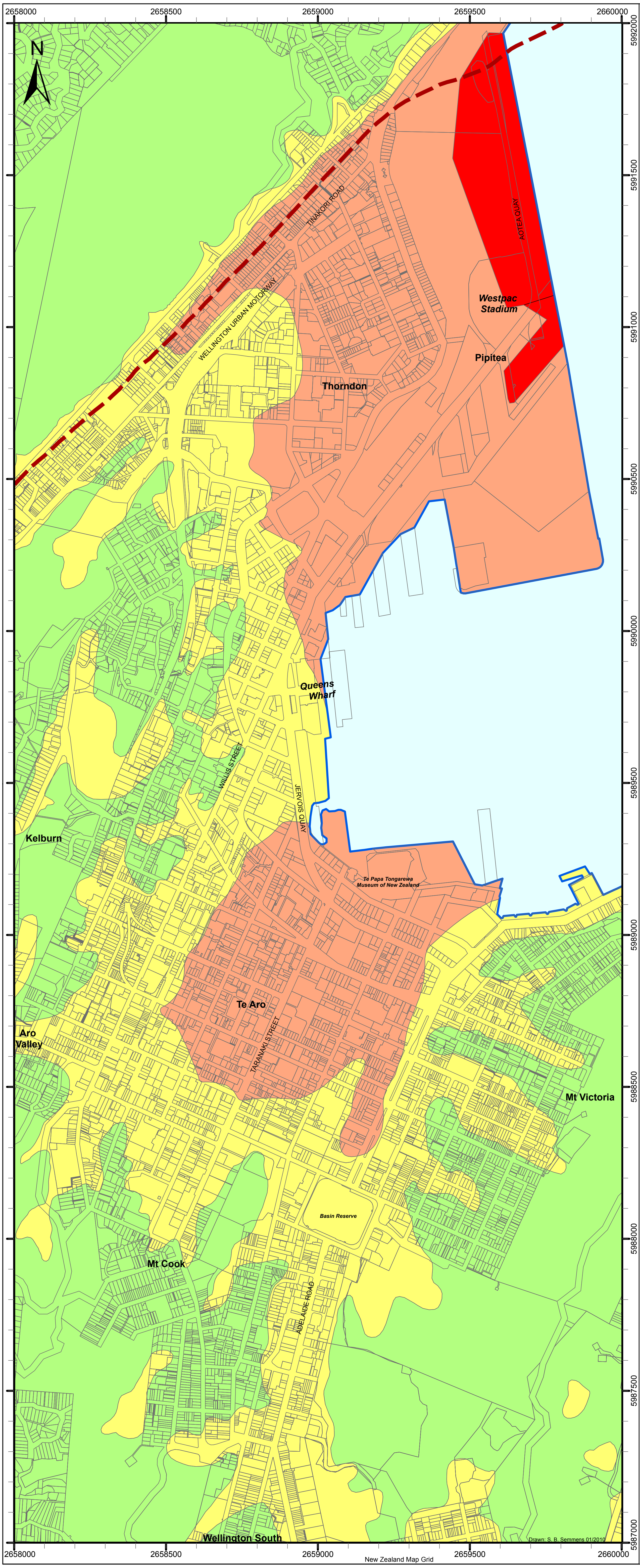

Map 8I
Wellington City
Ground Shaking Amplification Hazard

Map shows ground shaking amplification potential in the Wellington CBD study area for motions which are in the elastic range of the soil (PGA ~ < 0.4g). This map was created from the NZS1170.5:2004 site subsoil class map (refer to Chapter 5 in thesis).

Legend

Ground Shaking Amplification Potential

- High
- Moderate
- Low
- Bedrock

Wellington Fault

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

0 250 500 750 1,000

Metres

1:12,500 Scale (at A3 presentation size)

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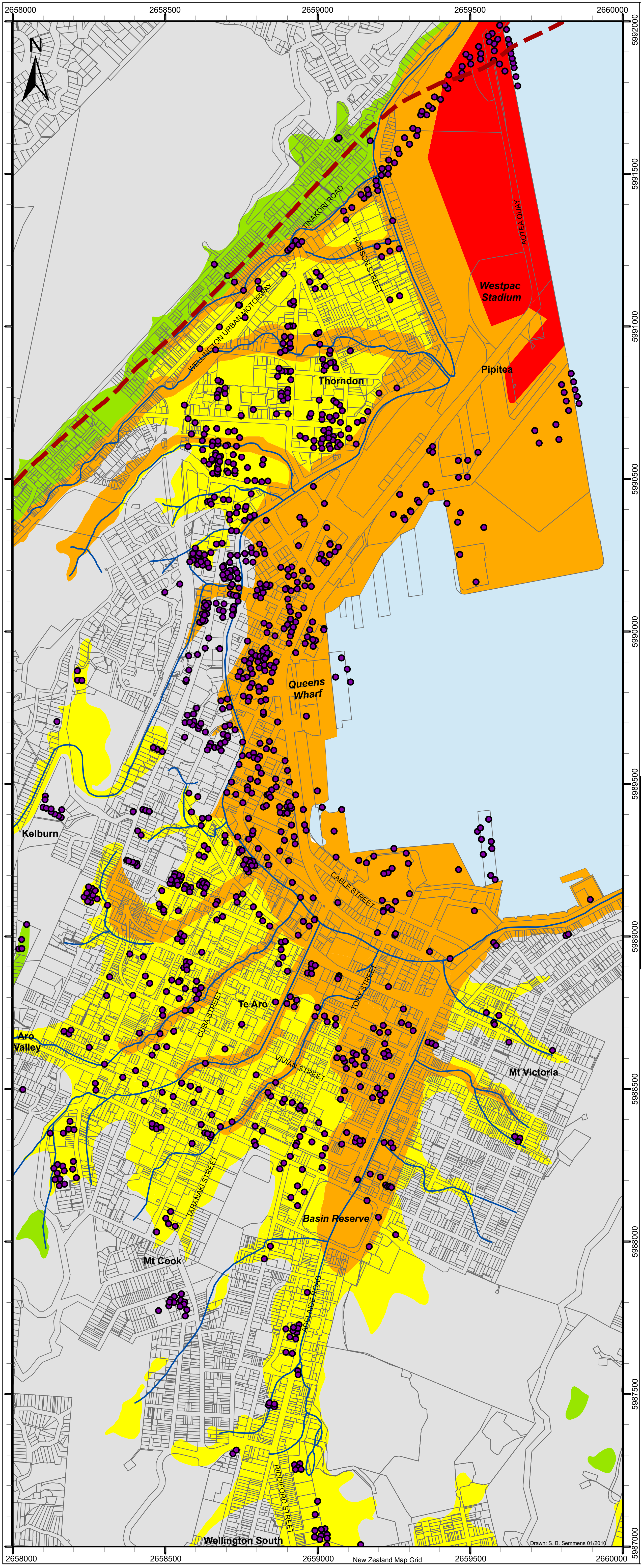

Map 8J
Wellington City Liquefaction Potential

This generalised map shows liquefaction potential in the Wellington CBD study area from a large earthquake (M_w 7.5) centred on the Wellington Fault. This map was created using geological and SPT N count data from approximately 500 boreholes within the Wellington CBD study area. Hot colours represent high liquefaction potential and cool colours low liquefaction potential. Although areas of greywacke bedrock are assigned no liquefaction potential on this map, small isolated pockets of fill occur within these areas and may undergo liquefaction for the given earthquake scenario.

Refer to Chapter 5 for map construction methodology.

Legend

- Wellington Fault
- Boreholes
- Streams

Typical Deposit Type	Assigned Liquefaction Potential
Hydraulic Fill	Extreme
Reclamation Fill	High
Marginal Marine	High
Swamp	High
Young Alluvium	Low to High
Old Colluvium/Alluvium	Low to High
Colluvium	Low
Greywacke bedrock	No Potential for Liquefaction

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

0 250 500 750 1,000

Metres

1:12,500 Scale (at A3 presentation size)

Semmens S 2010. An engineering geological investigation of the seismic subsoil classes in the central Wellington commercial area. Unpublished thesis, University of Canterbury, Christchurch, New Zealand.