New Zealand Transport Agency (NZTA)

WELLINGTON HIGHWAY IMPROVEMENTS SCOPING

LONG TUNNEL – GEOTECHNICAL FEASIBILITY ASSESSMENT

14 JUNE 2024

CONFIDENTIAL

WELLINGTON HIGHWAY IMPROVEMENTS SCOPING
LONG TUNNEL –GEOTECHNICAL FEASIBILITY ASSESSMENT

New Zealand Transport Agency (NZTA)

WSP
Wellington
L9 Majestic Centre
100 Willis Street
Wellington 6011, New Zealand
+64 4 471 7000
wsp.com/nz

REV	DATE	DETAILS
0	14/06/2024	Issue 1

	NAME	DATE	SIGNATURE
Prepared by:	s 9(2)(a) [redacted]	June 14	s 9(2)(a) [redacted]
Reviewed by:		June 14	
Approved by:		June 14	

WSP
Wellington
L9 Majestic Centre
100 Willis Street
Wellington 6011, New Zealand
+64 4 471 7000
wsp.com/nz

TABLE OF CONTENTS

1 INTRODUCTION

1.1 BACKGROUND AND SCOPE

The New Zealand Transport Agency is undertaking a feasibility assessment for a long tunnel option for improvement of State Highway 1 (SH 1) in Wellington. The option considered in this study includes duplication of the Terrace Tunnel and two new two-lane tunnels from an interchange south of the Terrace Tunnel to Wellington Street in Kilbirnie. New interchange infrastructure north of the Terrace tunnel, at Karo Drive and Viven Street, Adelaide Road and Wellington Street connect the tunnel to the local road network.

This report gives an overview of the geology along the route and provides an initial assessment of the geohazards and geotechnical constraints for the project. If this option is pursued, a detailed desktop assessment should be undertaken followed by site investigations, assessment and design.

1.2 INFORMATION USED

This feasibility assessment is based on a limited desktop review of:

- Regional scale geological maps and hazard maps (available in ArcGIS Online).
- Previous site investigation information contained in the New Zealand Geotechnical Database (NZGD). The locations of available site investigation information are shown in *Figure 1-1*. Site investigation from the Terrace Tunnel
- Design and as-built information for the Terrace Tunnel.

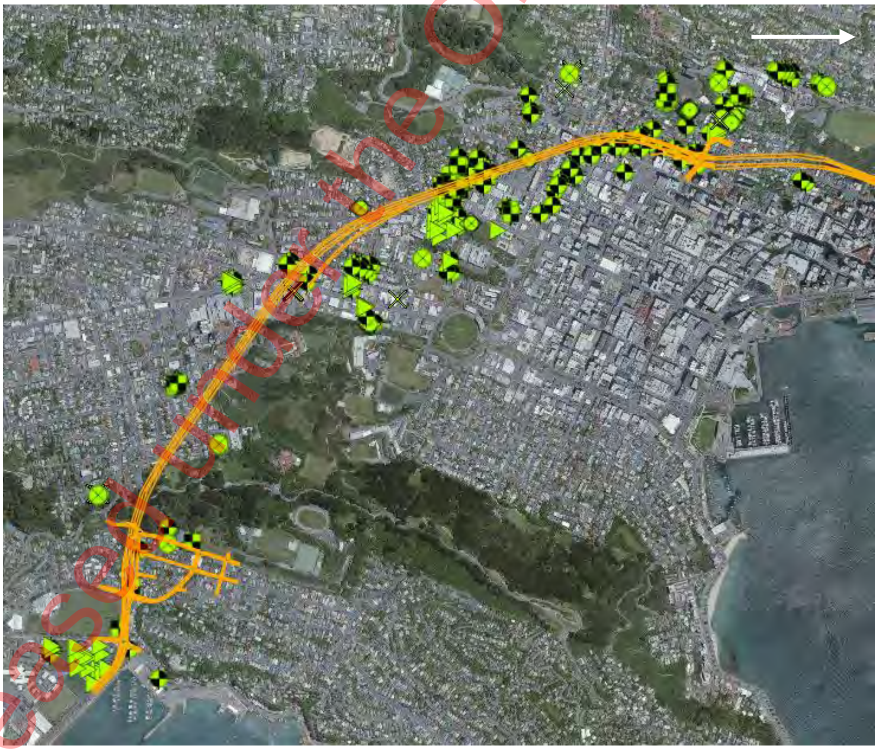


Figure 1-1: Geotechnical site investigations along approximate tunnel alignment, from NZ Geotechnical Database.

2 PROPOSED INFRASTRUCTURE

2.1 ALIGNMENT

The scheme is in the early stages of development. An overview of the current alignment is shown in *Figure 2-1* and includes:

- s 9(2)(ba)(ii) [redacted]
- Duplication of the Terrace Tunnel using the space previously allocated for this purpose. This s 9(2)(ba)(ii) [redacted]
- Construction of a new interchange at Vivien Street and Karo Drive.
- Two tunnels (two lanes of traffic in each direction) from Karo Drive, west of the CBD in the North to Wellington Street at Kilbirnie in the south. These tunnels will be constructed using a tunnel boring machine (TBM). The first tunnel will be constructed from Wellington Street, then the TBM will be turned around to construct the second tunnel.
- A south bound offramp at Adelaide Road.
- A new interchange at Wellington Street.

The tunnel construction method and construction sequence are discussed in a separate memo.

s 9(2)(ba)(ii)

[redacted]

3 GEOLOGY

3.1 GEOLOGICAL SETTING

3.1.1 GEOMORPHOLOGY

The Wellington region features a fundamental tectonic and geomorphic structure characterised by primary fault blocks. These blocks are delineated by both active and inactive faults, resulting in steeply dipping scarp-slopes typically inclined towards the north. Within the spaces between these fault blocks, there are lower-lying, relatively flat basins that have formed. These basins have accumulated and preserved thicker layers of surficial materials like colluvium, alluvium, and loess (Townsend, et al., 2020). Formation of relief across the Wellington Region, in particular the main ridges and valleys, were formed approximately 750,000 to 12,000 years ago during the middle to late Pleistocene. A combination of stream erosion, ongoing tectonic uplift, subsidence and erosion resulted in the landscape and formation of features such as the Wellington Fault scarp (Cotton, 1958 & Townsend, et al., 2020).

3.1.2 TECTONIC SETTING

The North Island of New Zealand has a historical record of large earthquake occurrence because of its location along the margin of the Hikurangi Subduction Zone (HSZ) that marks the plate boundary between the Australian Plate to the west and the subducting Pacific Plate to the east (*Figure 3-1*). New Zealand has a large number of known active earthquake sources. There are three distinct zones that generate earthquakes beneath the North Island: the continental crust of the Australian Plate, the westward subducting Pacific Plate; and at the interface between the two plates are in direct contact.

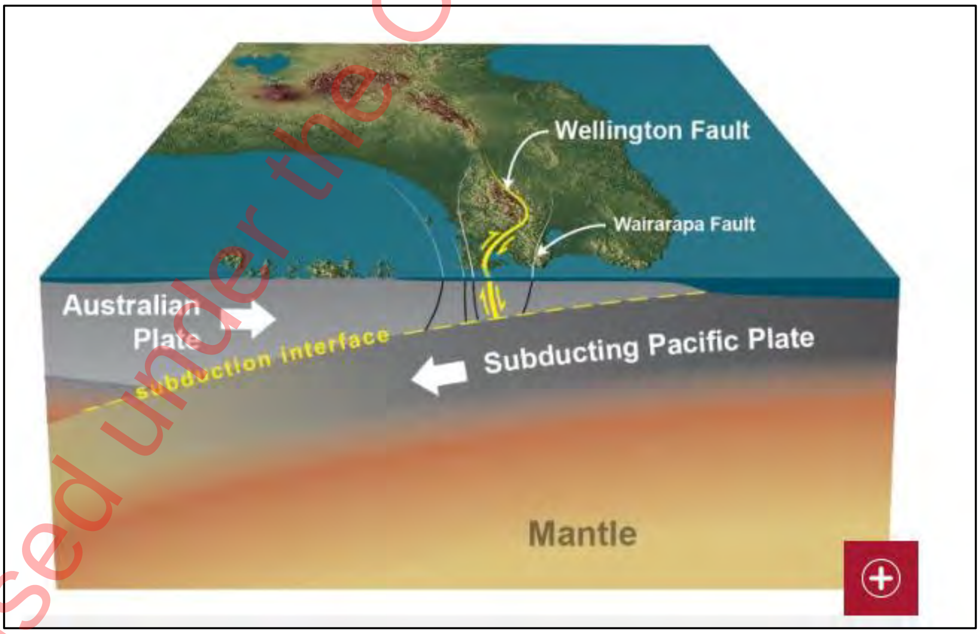


Figure 3-1: Schematic sketch of subduction of the Pacific Plate beneath the North Island. Source: https://www.gns.cri.nz/news/scientists-zero-in-on-the-causes-of-slow-slip-earthquakes/

3.1.2.1 SUBDUCTION INTERFACE

The Hikurangi Subduction Interface (HSI) marks the contact between the subducting Pacific Plate and the Overriding Australian Plate. The general geometry of the interface has been identified by Williams, et al. (2013) based on micro earthquakes and deep seismic reflection studies. Interpolation of contours of the HSI of Williams, et al. (2013) indicates the HSI Fault is located approximately 25 km beneath Wellington.

Some of the movement on the interface is released without causing an earthquake (aseismically) but the interface also gives rise to very large earthquakes that are often referred to as mega thrust earthquakes, but herein referred to as interface earthquakes. The ratio of the slip-rate across the interface to the proportion of the slip-rate that gives rise to earthquakes (seismogenic) is called the coupling effect. The coupling coefficient along the length of the HSI varies (Wallace, et al., 2009) and the section beneath the lower North Island has a high coupling coefficient of around 0.9 (i.e. 90% of the slip rate is seismogenic).

3.1.2.2 FAULTS

The Wellington Region has multiple mapped active and inactive faults (Begg & Mazengarb, 1996; Begg & Johnston, 2000; Langridge, et al., 2016; Barnes et al. 2019). Characteristics of the principal (active) and second order (inactive) faults near to the proposed tunnel alignment are presented below in *Table 3-1*, and displayed in map form in *Figure 3-2*. There may be un-mapped faults crossing the corridor.

Table 3-1: Summary of principal and second order faults in the vicinity of the proposed tunnel alignment.

FAULT	ORDER OF FAULT	FAULT SENSE	RECURRENCE INTERVAL (YEARS)	MAGNITUDE (MW)
Wellington Fault	Principal (Active)	Strike slip (dextral)	500 - 770	~7.5
Happy Valley Fault	Second Order (Inactive)	Unknown	Unknown	Unknown
Terrace Fault	Second Order (Inactive)	Unknown	Unknown	Unknown
Lambton Fault	Second Order (Inactive)	Unknown	Unknown	Unknown
Aotea Fault	Second Order (Active)	Reverse	2,200 to >6400	>7.0
Hataitai Fault	Second Order (Inactive)	Unknown	Unknown	Unknown

The preliminary tunnel alignment follows the Terrace Fault (*Figure 3-2*) before crossing over the Lambton Fault just south of Willis Street and Karo Drive Intersection. Both faults are considered inactive according to Langridge et al. (2016).

The alignment also crosses the Aotea Fault (*Figure 3-2*) just south of the John Street and Adelaide Road intersection, Newtown. The fault has been mapped offshore in the Wellington Harbour by Barnes et al. (2019) and immediately onshore, and is inferred to extend onshore further south. Site investigations for the Basin Reserve area also identified the presence of a fault. However, the onshore trace is poorly constrained, with varying inferred locations by several hundred meters to over a kilometre horizontally (Morgenstern & Van Dissen., 2020).

Analysis undertaken on bathymetric and sediment core data collected by Barnes et al. (2019) suggest the Aotea fault has a reverse slip component with a slip rate of ~ 0.6 +/- 0.3 mm/yr. At least two earthquakes have occurred within the last 10,000 years indicating surface displacements between 2 m to 4 m.

s 9(2)(ba)(ii)

3.2 WELLINGTON GEOLOGICAL MODEL

The geology of the Wellington region comprises predominantly Mesozoic-age Torlesse Supergroup greywacke rocks originating from the Rakaia, Kaweka, and Pahu terranes, forming the basement, along with Quaternary-age sediments filling the valleys and basins within the area (Begg & Johnston, 2000).

The hills and coastlines predominantly expose greywacke rock, with younger sediments derived from eroded basement and infilling basins created from erosion and faulting and folding during numerous phases of tectonic deformation. Exposed greywacke rocks are typically siliceous sandstone, siltstone and mudstone/argillite that have been subjected to low grade metamorphism (Begg and Johnston, 2000). The rocks are pervasively faulted, jointed and veined to varying degrees and contain zones of melange and broken formation (IGNS, 1996).

Human activities, such as engineering, refuse, building, and land reclamation have led to the deposition of anthropogenic fill around the region including at Kilbirnie Park. The presence of several active faults in the area displaces geological units, influencing the deposition of Quaternary sediments in fault-controlled basins.

A 3D geological ground model for the Wellington City Region was obtained from GNS Science developed by Hill, et al. (2022). The model was developed using available borehole and geophysical investigations, to model accumulations of loose to dense Quaternary sediment on weathered Rakaia Terrane greywacke (basement) rocks, see *Figure 3-3*. For a full description of the model development, refer to Hill et al. (2022).

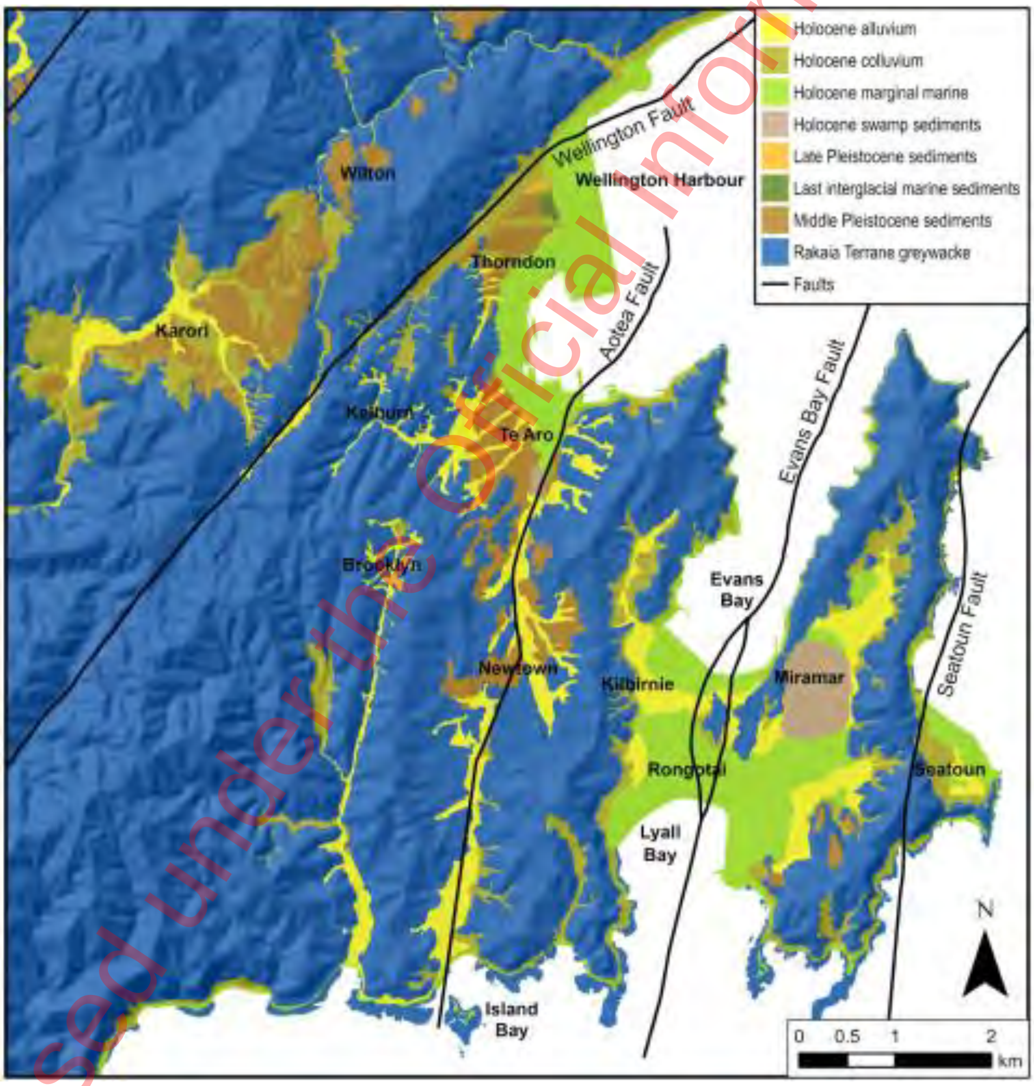


Figure 3-3: Snapshot of the 3D leapfrog model of the Wellington Region developed by Hill et al (2022). Note anthropogenic fill units are not shown on this map.

The main geological units which the proposed tunnel alignment crosses are:

- Holocene alluvium and colluvium.
- IPs Dense Sediments.
- mPs loose sediments.
- mPs loose-dense transition sediments.
- mPs dense sediments.
- Rakaia Terrane (basement).

For a full description of the model development, refer to Hill et al. (2022).

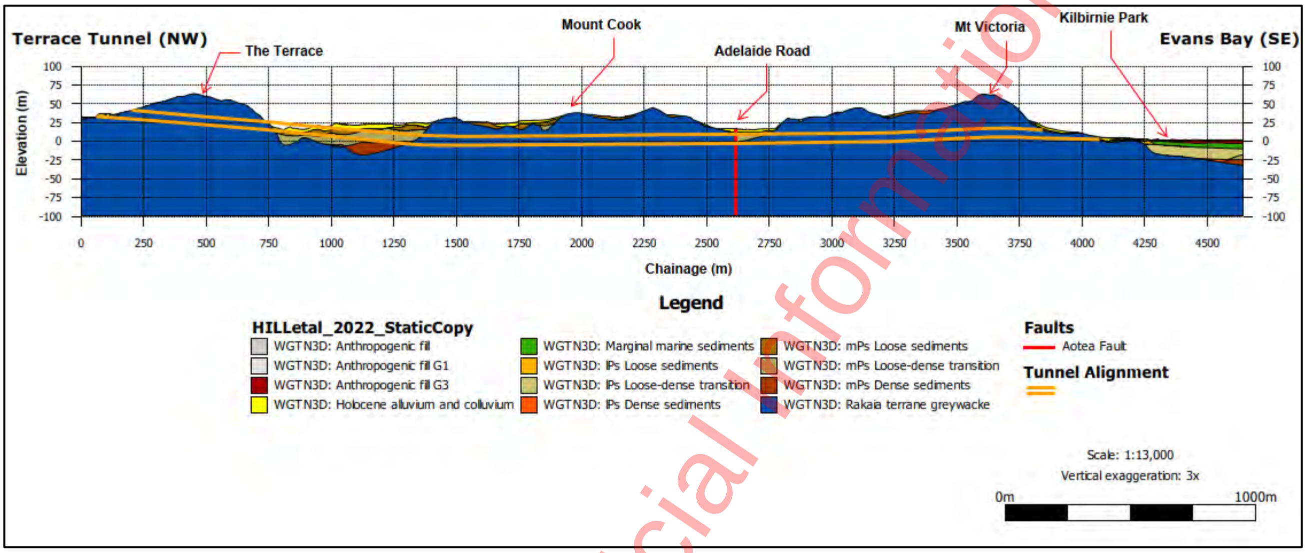


Figure 3-4: 3D Geological model section along tunnel alignment with indicative tunnel profile. This shows in some locations the tunnel passes near the base of infill sediment.

3.3 GROUNDWATER

The depth of groundwater, where noted in drilling logs in the area, ranges from 1 to >5 m below ground level. The tunnel is likely to be within saturated material over most of its length. Due to the varied topography, the higher elevation recharge may cause localised artesian pressures in lower lying areas.

4 GEOHAZARDS

4.1 SEISMIC HAZARD

4.1.1 HAZARD DESCRIPTION

Because of its proximity to the Hikurangi subduction interface and a number of active shallow crustal faults, the site is in an area of high seismicity. Earthquakes can cause two primary hazards: ground surface deformation hazards (e.g. surface fault rupture, uplift/subsidence, tilting and folding) and ground shaking (seismic) hazards. Slope instability, liquefaction, seiche and tsunami and changes to the groundwater regime may also be triggered by earthquakes.

Historically, while tunnels have performed well compared to surface structures when they have been subjected to ground deformation from fault rupture and strong ground shaking (Downding & Rozen, 1978; Wang, 1993), the seismic performance does depend on a multitude of factors such as PGA, magnitude, overburden, ground conditions, tunnel geometry and tunnel lining, all of which need to be considered in the tunnel design. Infrastructure at tunnel portals and the slopes and walls at tunnel portals are often more vulnerable to damage in earthquakes, where not designed carefully for seismic effects. The San Francisco Bay Area Rapid Transit (BART) that was specifically designed for high seismic demands, sustained no damage from the 1989 Loma Prieta earthquake (Hashash, Jeffrey, Birger, & Yao, 2001; Wang, 1993). During the 2016 Mw 7.8 Kaikoura Earthquake, the Hope Fault intersected Tunnel 18 of the MNL. The tunnel lining was sheared with 350 mm displacement. While the lining near the fault zone was locally damaged, the tunnel did not collapse (Chau, Alea, & Stocks, 2020).

4.1.2 FAULT RUPTURE DEFORMATION

Ground deformation associated with fault rupture through the rock and soil crossing or near to the tunnel could cause dislocation and offset, damage to the lining and infiltration of groundwater. The effects of rupture will depend on the characteristics of the fault, the rupture itself and the groundwater conditions.

Known shallow crustal faults crossing the alignment are mostly second order and are anticipated to have a low probability of rupture over the next 100 years. The Aotea Fault may be more active (see *Table 3-1* for recurrence interval). The location of the Aotea Fault across the corridor and its characteristic displacement are uncertain. As well as the main alignment, it may also cross the proposed off ramp at Adelaide Road. The highway corridor may cross any unknown faults.

There are various options to mitigate the Aotea fault rupture hazard should this be necessary. Depending on the nature of the hazard, these may include:

- Construction of this section in open (propped) trench or cut and cover with the trench detailed to tolerate displacement without collapse. A shallower trench or cut and cover tunnel will be easier to detail for movement and repair and groundwater infiltration will be smaller, and easier to manage. Making this section cut and cover or open trench may also have other advantages but would likely require additional property acquisition.
- Specially designed joints or caverns in the tunnel so the tunnel can tolerate the movement.
- Pumps with back-up generators to prevent flooding with groundwater infiltration.

- Egress points to the surface either side of the fault if displacements are too large to traverse.
- Permanent lowering of groundwater around the tunnels.

Subsidence, tilting and folding associated with movement of the subduction interface and other active regional faults is more likely. The associated deformation and damage may be less than rupture through the tunnel but minor changes to the alignment and minor damage to the lining together with increased leakage of groundwater into the tunnel could necessitate repairs.

4.1.3 GROUND SHAKING (SEISMIC) HAZARD

Wellington is one of the most seismically active areas in New Zealand. The National Seismic Hazard Model quantifies the seismic ground shaking hazard for New Zealand and was revised in 2022 (GNS Science, 2023). The 2022 hazard is significantly greater than the hazard referenced in current design codes that are based on earlier hazard estimates. The hazard used for the design of the existing SH1 infrastructure at the Terrace tunnel is much lower than current design standards. For earthquake geotechnical engineering, earthquakes are commonly characterised by peak ground acceleration (PGA) and magnitude (Mw). The seismic hazard from the NSHM22, the New Zealand Bridge Manual, MBIE/NZGS Earthquake Geotechnical Engineering Guidelines Module 1 and the New Zealand Loadings Code NZS1170.5 for rock are summarised in *Table* 4-1. The Hikurangi subduction interface and slab are the largest contributors to the (ground shaking) seismic hazard in Wellington (NSHM web portal, 2024).

As the tunnel is predominantly in rock, the tunnel will be exposed to generally lower accelerations in an earthquake compared to above ground infrastructure. Areas more vulnerable to damage are the slopes, walls and portals forming the approaches to the tunnel. The risk is greater at the northern interchange and approaches to the duplicate terrace tunnel where the ground is weaker and due to fault deformation of the rocks.

The seismic ground shaking hazard can be mitigated by the selection of ductile structural forms that are specifically designed for a high level of resilience and a suitably low risk to life.

Table 4-1 Seismic Hazard

AEP	Peak ground acceleration(1), PGA (g)			
	National Seismic Hazard Model (2022)	MBIE/NZGS Geotech Module 1 (2021)	NZ Bridge Manual Ed.3 (2013)	Loadings Code NZS 1170.5 (2004) (2)
1/100	0.36	0.30	0.22	0.20
1/500	0.87	0.65	0.39	0.40
1/2500	1.67	1.22	0.64	0.72

1. Weighted to a magnitude 7.5 earthquake.
2. Weighting for magnitude is assumed to have been applied in the hazard calculation.

4.2 LIQUEFACTION

The Greater Wellington Regional Council (GWRC) liquefaction hazard map (GWRC, 2018) has the tunnel alignment within areas of low to moderate liquefaction potential. Moderate hazard is indicated at the northern interchange, northern approach to Terrace tunnel and Adelaide Road.

Site specific liquefaction assessments are required to quantify the liquefaction potential in these areas. Structures can be designed to tolerate the effects of liquefaction or the ground can be improved to either prevent liquefaction or mitigate its effects.

4.3 TSUNAMI AND SEICHE

4.3.1 SOURCES AND EFFECTS

A tsunami is a natural phenomenon consisting of a series of waves generated when a large volume of water in the ocean or a lake is rapidly displaced. Seiche (a standing wave that oscillates within the harbour) can occur concurrently with and significantly influence tsunami characteristics for tsunami generated from local source earthquakes that also cause strong ground shaking at the site.

The potential sources of tsunami are (Power, 2013):

- Submarine or coastal earthquakes (uplift or subsidence of the seafloor or coast occurs);
- Underwater landslides;
- Landslides from coastal or lake-side slopes; and
- Volcanic eruptions.

Tsunami can be generated from near or far sources. There is historical evidence of Wellington being affected by both distant and local-sourced tsunamis (Power, 2013).

Tsunami can affect long stretches of coastline and extend inland for hundreds of metres to kilometres in low lying areas. The effects of tsunamis are controlled by the topography, geomorphology, bathymetry, beach slope, coastal orientation, configuration, characteristics and direction of the arising waves and the built environment within the tsunami run-up zone.

Effects of tsunami include (Power, 2013):

- Inundation and flooding of low-lying areas.
- Large hydro-static and hydro-dynamic loads on structures causing displacement and damage to buildings and other infrastructure.
- Debris impact and damming forces where debris such as logs collide with and then accumulate in front of a structure.
- Scour of soils as the tsunami comes toward land and flows seaward again, and from strong tsunami related currents in the hours and days after, undermining foundations, seawalls and eroding the shoreline.
- Sedimentation.
- Development of seiche.

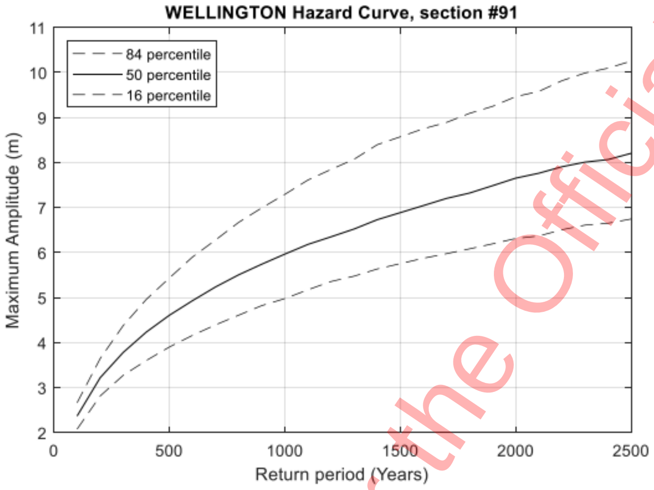
- Strong currents in the hours and days after a tsunami, making harbour navigation difficult and sometimes unviable due to elevated velocities.

Further assessment is necessary to quantify the hazard and the effects of climate change including sea-level rise and storm surge and coseismic tectonic ground movement (subsidence or uplift). Mitigation measures may include:

- Keeping the portal thresholds above an inundation level with a suitably low-level probability of exceedance for tsunami generated on regional faults where there will be limited time to respond.
- Response planning, low level tsunami walls and increasing ground levels to prevent inundation and damage in more frequent events with lower wave heights.
- Design infrastructure within potential inundation areas to tolerate the effects of tsunami and enable quick recovery.

4.3.2 NATIONAL PROBABILISTIC TSUNAMI MODEL

The National Tsunami Hazard Model (NTHM) provides estimates of wave heights at the coast (relative to tide level) for different return periods in a probabilistic tsunami hazard assessment for New Zealand (GNS, 2022). Local topographical features may focus tsunami and increase the run-up height.



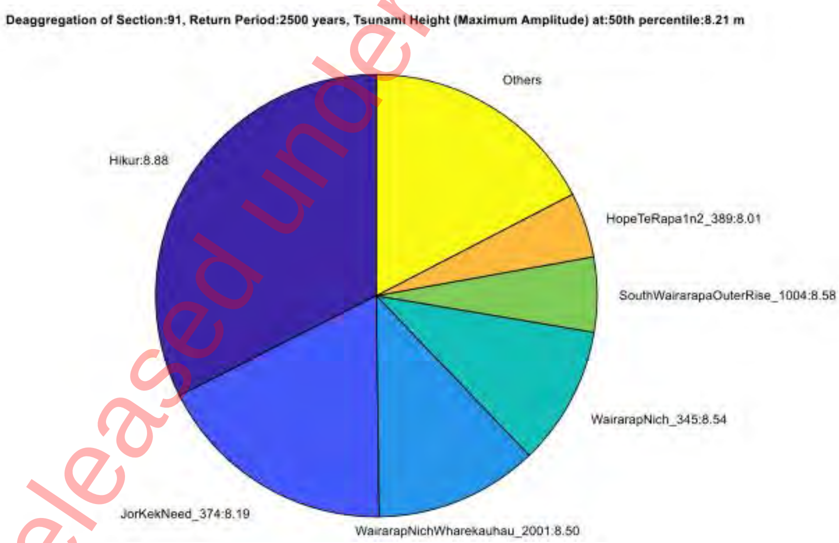


Figure 4-1: Tsunami hazard curves and deaggregation plots for 20 km coastal sections, derived from the 2021 National Tsunami Hazard Model (GNS, 2022)

The deaggregation shows the principal sources for tsunami are the Hikurangi subduction fault and regional shallow crustal fault sources. Waves generated from these sources would likely arrive within several minutes to tens of minutes of the fault rupture and would coincide with ground deformation associated with the rupture (subsidence or uplift), strong ground shaking and associated hazards including earthquake induced slope instability and liquefaction.

4.3.3 SCENARIO (DETERMINISTIC) ASSESSMENTS

4.3.3.1 INUNDATION ZONE FROM MULTIPLE SCENARIOS

Compilation of tsunami inundation hazard layers from 70 years of tsunami modelling studies were compiled to show maximum extent of modelled tsunami inundation (Scheele, et al., 2023). This modelling shows the southern interchange of the alignment (as well as the existing Cobham Drive) within a tsunami inundation zone (*Figure 4-2*). The tunnels would be outside the tsunami inundation zone from these studies. It should be noted that as this layer is a compilation of multiple tsunami modelling studies, this inundation cannot be attributed to a particular event.

s 9(2)(ba)(ii)

4.3.3.2 HIKURANGI SUBDUCTION FAULT GENERATED TSUNAMI

Rupture along the Hikurangi Margin is one of the most significant tsunami sources for Wellington. This is unsurprising given the potential large rupture areas and a fault mechanism that maximises vertical component of deformation (Mueller et al, 2014).

While the Hikurangi subduction zone is considered an important tsunami source, data available on the recurrence interval, rupture characteristics and size of earthquakes from the subduction zone is limited.

Modelling of tsunami generated from 50 Hikurangi Subduction interface rupture scenarios with an assumed magnitude, M_w of 9.0 and different slip distributions for each scenario indicates that the fault orientation and its location are not strongly conducive to directing tsunami towards Wellington unless the rupture extends into Cook Strait (Mueller et al, 2014). In the modelled scenarios, the further south the rupture propagated, the further inland inundation occurs.

The likelihood of inundation in the Wellington Region from the 50 Hikurangi subduction interface (HSI) tsunami scenarios analysed is mapped in *Figure 4-3* (Mueller et al, 2014). This high-level map shows that the southern interchange (as well as the existing Cobham Drive) is likely within a tsunami inundation zone for a Mw 9.0 rupture of the Hikurangi interface fault, but the tunnels will be outside the tsunami inundation zone.

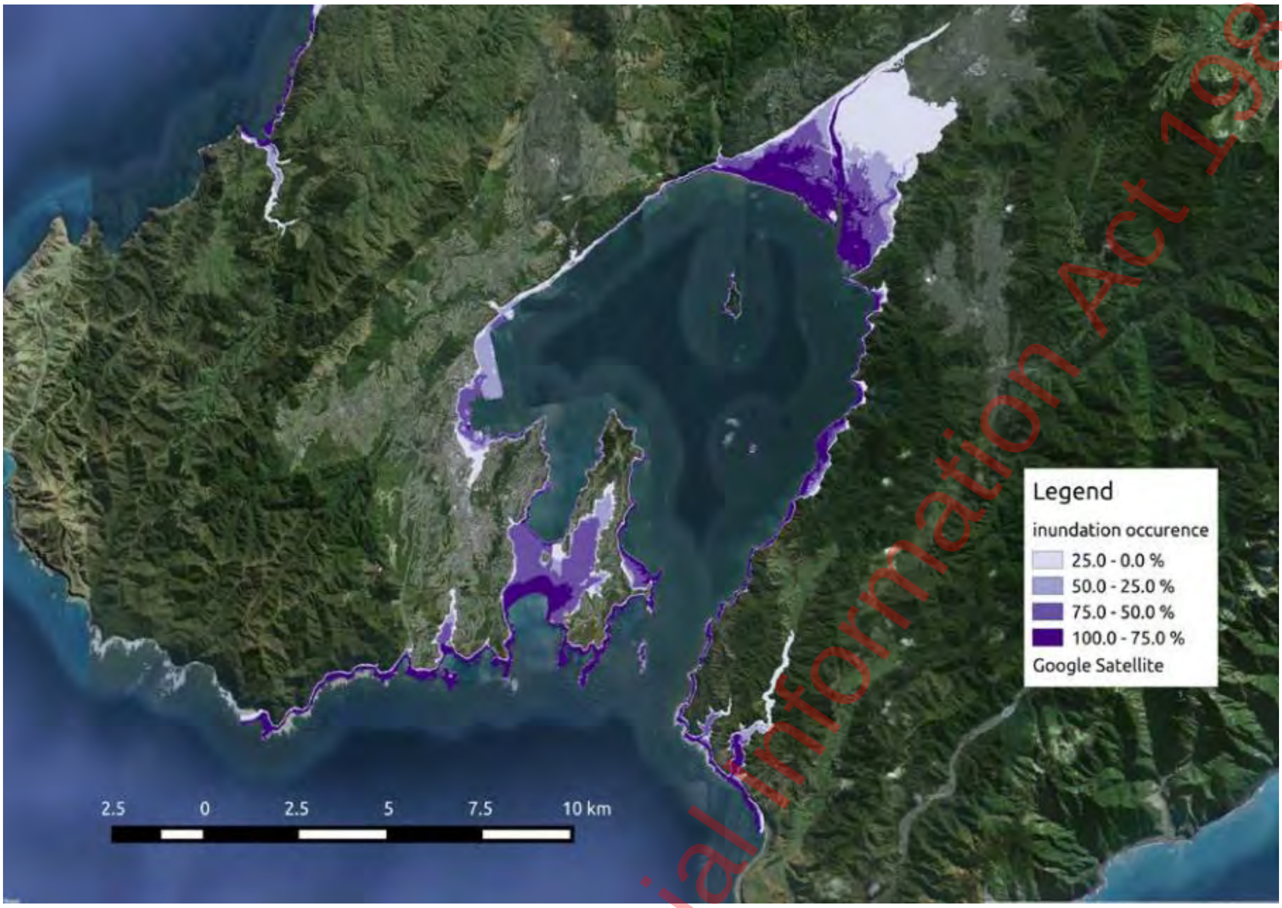


*Figure 4-3: Inundation areas for tsunami generated from the Hikurangi Subduction Zone (*Mueller et al., 2014*)*

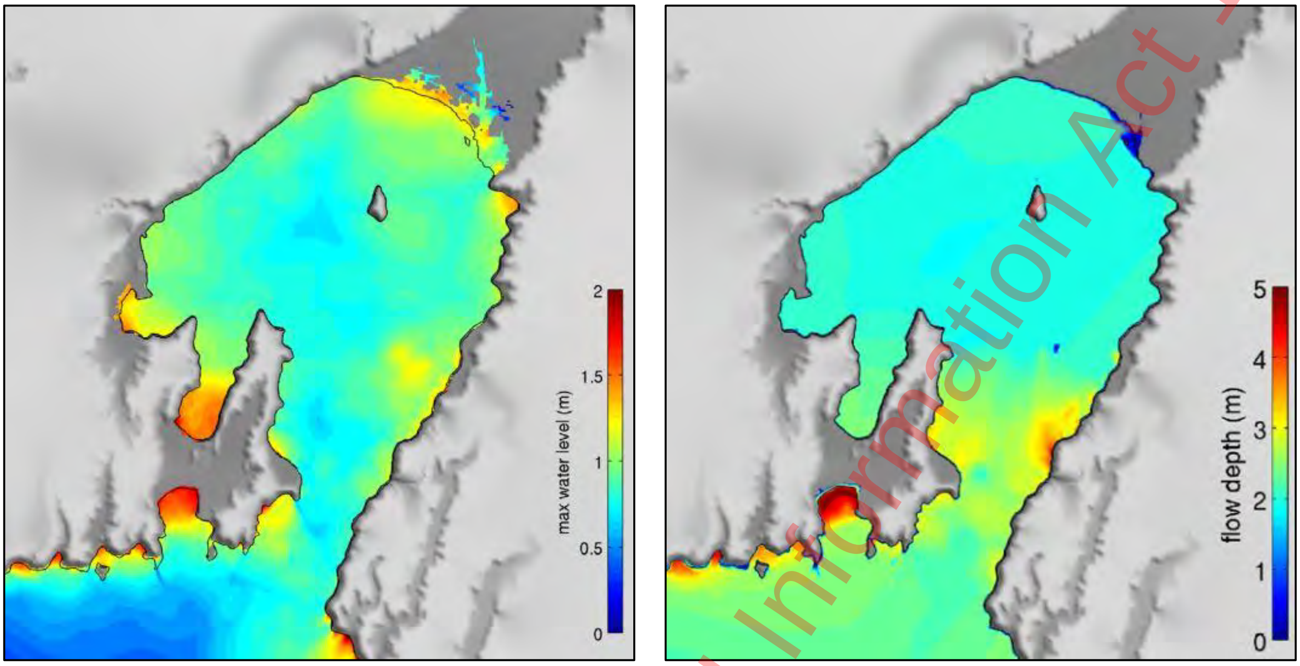
4.3.3.3 WELLINGTON AND WAIRARAPA FAULT GENERATED TSUNAMI

Approximately 30 km of the Wellington Fault (WF) is offshore, within the Wellington Harbour and Cook Strait. Modelling of the potential tsunami effects from this fault assume 10 km of rupture within Cook Strait and vertical movement of 1 – 2 m in both of these areas, and specifically a 1.5 to 2.0 m drop in elevation in Lower Hutt close to the fault through the Wellington Harbour (Mueller et al, 2014).

The modelled WF scenarios suggest that the Wellington Fault will not generate tsunami waves efficiently. The modelled inundation indicates a higher hazard to the low-lying Hutt Valley and high-water levels within the bay areas, including the area around Queens Wharf where a maximum flow depth of ~1.3 m is indicated (*Figure 4*-4).

The Wellington Region has previously been affected by tsunami caused by rupture of the Wairarapa Fault. The 1855 Wairarapa Earthquake ruptured into Cook Strait and generated a tsunami with a known run up to 4 - 5 m in several locations in Wellington (Power, 2013). The first waves only took minutes to arrive in Wellington and the waves resonated around Wellington Harbour and through Cook Strait for more than 12 hours. The tides were disturbed for the following week, possibly because of large aftershocks. In Lambton Quay, the tsunami was 2 – 2.5 m high. In addition to this, as the eastern side of the harbour was uplifted, water flowed west and caused coastal flooding. The main cause of the tsunami is considered to be the coseismic displacement of the seabed, however submarine and coastal landslides may have also contributed.

Modelling of the Wairarapa Fault zone (inclusive of the Wharekauhau Thust) indicates a maximum flow depth of ~2.5 m for much of the Wellington Harbour, including Evans Bay area (Mueller et al, 2014). Inundation of the tunnel portals in these scenarios is unlikely.



a) *Maximum water elevations computed in first five hours following Wellington Fault scenario earthquake* (Mueller et al., 2014)

b) *Maximum flow depth map for combined Wairarapa and Wharekauhau fault scenario* (Mueller et al., 2014)

Figure 4-4: Estimated flow depths from tsunami generated from rupture of the Wellington and Wairarapa faults.

4.4 SLOPE HAZARDS

Potential slope failures around the tunnel portals pose a hazard in terms of life safety and tunnel blockages.

Terrace Tunnel Northern Approach

Existing slopes immediately above and behind the existing tunnel portal are approximately 5º to 10º from horizontal and 6 m high. The portals were constructed as cut and cover, hence materials are likely to be fill. The low slope angle and height are unlikely to pose a slope stability hazard, however, require further analysis to confirm.

Existing slopes to the east of the existing portal range from approximately 30º-50º and from 8 m to 20 m in height. These slopes will likely change to allow for the northern approach construction.

Slopes to the west of the existing portal sit generally 20º-50º with localised areas up to 80-90º. Slopes extend approximately 45º to 50º m from road level to a cut platform above. Existing tied back concrete walls are present from road level to a maximum height of 16.5 m, constructed as part of the Terrace Tunnel construction (Opus, 2006). These walls may require strengthening if existing infrastructure needs to be brought up to the same standard as the new infrastructure.

Geological mapping and existing investigation data indicates reclaimed material / fill overlying rock as well as Greywacke sandstone and siltstone (N.Z. Geological Survey, 1973; Begg & Johnston, 2000). Further assessment will be required to determine how these slopes will perform in seismic conditions.

Terrace Tunnel Southern Portal

Slopes immediately above /behind from the tunnel portal are approximately 20º to 30º, standing approximately 10 m high.

Mapping indicates slopes are within fill and Pleistocene to Holocene river deposits (Begg & Johnston, 2000). The actual material and engineering properties of the fill are unknown. Further assessment will be required to determine how these slopes slope will perform in seismic conditions, but they may require strengthening if they are to be brought up to modern standards.

Southern Interchange

The proposed southern interchange/portal sits at the base of eastern margin of Mt Victoria. Existing slopes generally sit between 40º to 60º with areas above this locally steepened at approximately 80º. The slope is approximately 30 m high. Materials compromise greywacke sandstone/siltstone to different weathering, strength and quality. Further assessment will be required to determine how these slopes will perform in earthquakes and whether any stabilisation measures are required.

4.5 PLUVIAL FLOODING

The Greater Wellington Regional Council (GWRC) flood hazard map (Greater Wellington Regional Council, 2023) shows that various sections of the tunnel alignment overlap with land identified at risk of flooding. This includes the northern and southern interchanges and the northern approach to Adelaide Road.

Drainage systems will need to be designed to suitably mitigate the risk of flooding at the interchanges and potential for surface water to enter the portals and cause a hazard in the tunnels. Design of surface water treatment and drainage systems will need to be coordinated with the design of groundwater drainage, coastal overtopping and tsunami defences.

4.6 COASTAL HAZARDS

The Greater Wellington Regional Council (GWRC) Sea Level Rise and Storm Surge Modelling map shows that the southern section of the alignment towards Kilbirnie is within an area of land exposed to storm surge (Greater Wellington Regional Council, n.d). The storm surge risk is indicated at a present day sea level rise (SLR) level along Cobham Drive and is more extensive when viewing the 1.5 m SLR models.

Mitigations may include erosion and scour protection along the coastline, increasing the height of seawall or revetments or increasing road or ground levels. Design of coastal defences will need to be coordinated with the design of stormwater systems and tsunami defences.

4.7 CLIMATE CHANGE

While current risks associated with coastal hazards and pluvial flooding may or may not be suitably managed, climate change has the potential to strongly influence coastal, hydrological and hydrogeological risks. These changes could have indirect consequences such as changes to the durability of materials as well as direct consequences like increased flooding risk.

We recommend that a more in-depth study be considered to assess the effect of climate change which considers:

- The changes in frequency and severity of the climate-related hazards;
- The consequences in terms of exposure of infrastructure to those hazards; and
- The vulnerability to those hazards (i.e. the predisposition to be adversely affected).

It should be noted that the climate change hazards affect existing highway infrastructure as well as the southern interchange.

4.8 PRELIMINARY RISK ASSESSMENT

Table 4-2 presents a high-level assessment of risk from different hazards and potential mitigations. In evaluating the risk posed by each hazard and the wider implications for the resilience of route, the following considerations should be considered:

- Assessment of the frequency of each hazard, and the time-varying magnitude of impacts, is important to determine and prioritise the hazards in terms of their risk to availability.
- It is likely in the event of a large earthquake, numerous hazards will occur in unison and should be considered for their compound effects.
- Similarly, an initial hazard event may induce secondary effects to occur, either in the short or long term.

Table 4-2: Preliminary high level risk assessment from geohazards to tunnel

HAZARD	PROJECT EXPOSURE	HAZARD EFFECT	MITIGATION POTENTIAL/ RECOMMENDATIONS
Fault rupture	The moderately active Aotea Fault passes through the corridor near Adelaide Road. The exact location and characteristics of the fault are uncertain. Other low activity faults cross the corridor. Rupture of the active subduction interface and a number of nearby shallow active crustal faults could cause deformation of the tunnel route.	Partial dislocation possible with rupture of the Aotea fault, collapse of lining possible, high groundwater inflow possible. Changes to alignment, damage to the segmental lining, pavements and services, increased groundwater infiltration.	Locate and characterise the Aotea fault. Consider construction using open trench or cut and cover across the Aotea fault – more tolerant to large displacements, lower risk of collapse, easier egress either side, lower groundwater infiltration, easier to repair. Design tunnels and drainage to tolerate deformation from rupture of active faults in the area. Design drainage system to accommodate disposal of increased groundwater infiltration and to be accessible for repair.
Earthquake Ground shaking	The project is in an area of high seismicity with Hikurangi subduction zone beneath and several active crustal faults in close proximity.	High seismic demands on bridges, retaining systems and slopes at the portals and approaches affecting life safety egress. Damage to infrastructure in lower intensity but higher probability earthquakes. Damage to TBM tunnel linings.	Use of resilient structural forms for the approaches and specific seismic design to maintain life safety (safe egress) in low probability, high impact events and to maintain a level of serviceability and repair in more probable, lower impact events. Detail tunnel lining to enable quick repairs
Liquefaction	Moderate hazard at Adelaide Road and the Northern interchange due to the presence of variable alluvial soils.	Additional loads on retaining and tunnel structures within liquefiable soils, reduced anchor / nail capacity elevated groundwater pressures, subsidence.	Use of resilient structural forms. Ground improvement to mitigate liquefaction if necessary. Locate the northern interchange and tunnels within non-liquefiable greywacke to the south and west as far as practicable.
Tsunami & seiche	Rupture of the subduction interface or other regional crustal faults extending into the Cook Strait could cause tsunami and seiche to inundate low lying areas within minutes of fault rupture and strong shaking	Southern interchange is within tsunami inundation extent. Inundation of lower areas of the southern interchange is possible in relatively frequent tsunami.	Keep portal thresholds above the tsunami inundation zone. Design southern interchange infrastructure for tsunami demands in accordance with the NZTA Bridge Manual. Development of Trigger Action Response Plan (TARP).

HAZARD	PROJECT EXPOSURE	HAZARD EFFECT	MITIGATION POTENTIAL/ RECOMMENDATIONS
Pluvial (surface water) flooding	Approaches will grade into the tunnels. Low areas prone to flooding at the southern interchange and Cobham Drive.	Flooding may reduce serviceability where flood waters impede movements of vehicles or pose hazards. Significant accumulations of floodwater could damage plant and other assets.	Design stormwater system to suitably mitigate the flood risk. Consider raising areas to reduce risk.
Coastal Hazards	Low areas at Cobham Drive adjacent Evans Bay exposed to the Harbour. Coastal inundation can be exasperated by pluvial flooding and climate change effects (more frequent storms and sea level rise).	Coastal wave action can overtop the road defences, leading to flooding (with similar consequences as pluvial flooding). Wave action can cause erosion along the harbour margins, potentially causing instability of the ground above/behind.	Construct seawalls and revetments to protect the road and prevent overtopping and erosion. Consider raising ground levels to reduce risk.

5 GEOTECHNICAL ENGINEERING

5.1 GENERAL

This section outlines the key geotechnical considerations for the project and possible high level design concepts. Further work is necessary to investigate and assess these issues and design suitable mitigation measures.

General geotechnical considerations for the project include:

- High groundwater inflows at faulted and highly fractured areas of rock and along geological contacts, and the potential artesian or sub-artesian groundwater conditions affecting construction. Sudden inflow may cause partial collapse and inundation, compromising worker safety.
- Subsidence of structures and infrastructure above or near to the tunnel from stress changes and shear deformation within the ground and changes to groundwater levels (either permanent or temporary). s 9(2)(ba)(ii) [redacted] Subsidence above the tunnel will typically be greater in areas with lower cover and poorer quality rock or where the tunnel is in soil.
- s 9(2)(ba)(ii) [redacted]
- Vibration / noise causing damage or nuisance either during construction or during operation. The alignment passes under or near to the Wellington Regional Hospital, Massey University, Wellington High and historically significant structures that may be sensitive to vibration and noise.
- Precipitation/Scaling from seepage Water. Greywacke is a relatively inert rock and groundwater is unlikely to contain high concentrations of dissolved minerals. However, groundwater is often slightly acidic because of carbon dioxide uptake when infiltrating through soils. Groundwater seepage to the tunnel will pass through the concrete/shotcrete tunnel stabilisation materials (such as grouting) which may dissolve partially, and the hardness of the seepage water could increase notably. Once the seepage water is exposed to the atmosphere in the tunnel and the carbon dioxide is released, this can lead to precipitation of salts and carbonates held in solution, which leads to scaling on tunnel infrastructure. Significant precipitation and scale within the tunnel drainage system would require regular maintenance to clear and can significantly reduce the lifespan of pumps that would be used to dewater the tunnel sumps.
- Saline Intrusion and permanent changes to the groundwater regime. Long term dewatering at the tunnel could create a gradient which draws saltwater into the groundwater system towards the tunnel at locations towards Kilbirnie. Saline water within the tunnel may cause corrosion of pumping machinery. The risk of saline intrusion could be assessed in the early stages of design following confirmation of the tunnel layout. Saline intrusion is likely to be a very low risk as the current tunnel alignment indicates the tunnel only reaches depths below sea level at a distance from the coast.

5.2 NORTHERN APPROACH

s 9(2)(ba)(ii)

5.2.1 *CONCEPTUAL SLOPE GEOMETRY OPTIONS*

s 9(2)(ba)(ii)

5.3 TERRACE TUNNEL DUPLICATION

s 9(2)(ba)(ii)

5.4 NORTHERN INTERCHANGE

s 9(2)(ba)(ii)

s 9(2)(ba)(ii)

[redacted]

5.5 MAIN TUNNEL ALIGNMENT

The geotechnical related constraints include:

- Ground surface subsidence from stress changes within the rock and soil, shear deformation and consolidation from temporary or permanent lowering of groundwater pressures. See 5.1 for more discussion.
- The initial 500 m of tunnels from the northern approach is located in soil and is more vulnerable to ground deformation, and subsidence risk to properties above, than the other sections in rock.
- Noise and vibration during construction and operation.
- Changes to groundwater, either temporary or permanent

- Deformation of the tunnel from rupture of the active Aotea fault. Deformation may also occur from regional subsidence, uplift, tilting or folding along the tunnel associated with rupture of other active regional faults including the subduction interface, Wellington Hutt-Valley segment of the Wellington fault, the Wairarapa and Ohariru faults.
- Loads on tunnel lining.

Possible risk mitigations:

- Changes to the tunnel alignment or construction method to avoid structures that are vulnerable to settlement or vibration effects. Such as an alignment more to the west from the northern approach so that it can be located more in rock.
- Pre inspections, monitoring and repair of damage.
- Underpinning of buildings or infrastructure vulnerable to subsidence.
- Use of bentonite trenches, dampers or similar to reduce vibration effects.
- Property acquisition and sale upon completion of construction.

See Section 5.5 below for further consideration of the Aotea fault at Adelaide Road.

Mapping of fracture and fault zones through drilling and potentially geophysical investigations could identify areas of risk. Pre-drilling areas of greatest risk would provide the information to allow identification of zones of high groundwater pressure. Based on this the potential risks can be further assessed and mitigation measures such as depressurisation could be designed and implemented during construction, if required.

5.6 ADELAIDE ROAD AND OFF-RAMP

The geotechnical related constraints include:

- Deformation of the tunnel from fault rupture (Aotea fault).
- Subsidence of structures and infrastructure above and adjacent to the tunnel.
- Vibration / noise.
- Changes to the regional groundwater regime with leakage into the tunnel.

Possible risk mitigations:

- Significant further investigations are required here to understand the potential size, frequency, and type of fault movement. Until an improved understanding is available a range of design solutions should be considered. Options include:
    - Design TBM tunnels to mitigate fault rupture using over excavation to allow for mitigation and ease of repair following rupture (see L.A. Metro redline design approach).
    - Construction of wide section of cut and cover tunnel with a depth to pavement of about 10 m across the fault designed to shift with the ground and potentially be easier to reinstate.
    - A trenched section of tunnel at this location at a lower depth.

The shallower cut and cover or trench solutions may also reduce the length of off ramp required at Adelaide Road and reduce tunnel vertical grades. Temporary dewatering would be required.

- Subsidence caused by dewatering can be mitigated using cut off walls into rock and recharge. The permanent structure could be made watertight so that continuous dewatering is not required.
- The cut and cover section would be designed to tolerate high seismic demands and the effects of liquefaction.

5.7 SOUTHERN INTERCHANGE

Key geotechnical constraints include:

- Seismic stability (for safe egress) and seismic resilience of the approach walls, cuts, natural slopes and the tunnel portals.
- Managing damage to neighbouring structures and infrastructure from movement or vibration with excavation to construct the interchange.
- Stability of slopes to the east of the southern interchange.
- Bridge foundations.
- Tsunami inundation

Suitable infrastructure forms may include:

- Cuts formed at a safe angle, or where space is constrained, cut using top-down construction with temporary (or permanent for lower height slopes) anchored soldier pile walls / soil nail slopes to support cuts. Top-down construction with secant pile or diaphragm walls is possible in areas clear of buried obstructions.
- Locate tunnel portal further to the north, where there is greater bedrock cover, and to minimise the depth of excavation and support required for the approach trenches.
- Cut and cover at portals with concrete faced MSE slopes or walls.
- New piled bridge foundations designed for the latest seismic hazard.
- Consider avoidance or stabilisation of cut face north of new link from Kilbirnie Crescent to Evans Bay Parade.
- Allowing for the southern portal invert to be above the modelled tsunami inundation location or at a level with a sufficiently low likelihood of inundation.

6 NEXT STEPS

If this option is considered further, the next steps may include:

1. Detailed desktop assessment to better characterise the soil sand rock along the corridor and update the ground and groundwater models.
2. Geotechnical mapping, site investigations and groundwater monitoring.
3. A preliminary assessment of vibration and subsidence to identify properties vulnerable to damage.
4. Investigation and assessment of the Aotea fault rupture hazard, earthquake ground shaking hazard, surface water, coastal and tsunami hazards.

7 REFERENCES

Barnes, P., Nodder, S., Zoelz, S., & Orpin, A. (2019). The structure and seismic potential of the Aotea and Evans Bay faults,Wellington, New Zealand. *New Zealand Journal of Geology and Geophsics*, 46-71.

Begg, J., & Johnston, M. (2000). Geology of the Wellington area. Wellington: Institute of Geological & Nuclear Sciences 1:250 000 geological map 10. 1 sheet + 64p.

Begg, J., & Mazengarb, C. (1996). *Geology of the Wellington area, scale 1:50,000*. Institute of Geological Nuclear Sciences.

Chau, S. F., Alea, R., & Stocks, M. (2020). Earthquake Impacts to A Tunnel at Fault Zone and Its Repair. *ITA-AITES World Tunnel Congress, WTC2020*.

Cotton, C. (1958). Dissection and redissection of the Wellington landscape. *Transactions of the Royal Society of New Zealand*, 409-425.

Council, G. W. (2023). *Flood hazard extents*. Retrieved from GWRC Open Data.

Downding, C. H., & Rozen, A. (1978). Damage to Rock Tunnels from Earthquake Shaking. *Journal of the Geotechnical Engineering Division, 104*(GT2).

GNS. (2022). *The 2021 update to New Zealands National Tsunami Hazard Model*. GNS.

GNS Science. (2022). *New Zealand National Seismic Hazard Model*. Retrieved from https://nshm.gns.cri.nz

Greater Wellington Regional Council. (2019). *Wellington Region Liquefaction Potential*. Retrieved from GWRC Open Data: https://data-gwrc.opendata.arcgis.com/datasets/9d2074c4bc5b40e1b4352abd1f2e1ebf

Greater Wellington Regional Council. (2023). *Flood hazard extents*. Retrieved from GWRC Open Data: https://gwrc-open-data-11-1-gwrc.hub.arcgis.com/datasets/17d088f5e3e64362bb86fc9c21640b4e_2/explore

Greater Wellington Regional Council. (n.d). *Sea Level Rise and Storm Surge Modelling*. Retrieved from Climate Change Mapping: https://mapping1.gw.govt.nz/GW/SLR/

Hashash, Y. M., Jeffrey, J. H., Birger, S., & Yao, J. I. (2001). *Seismic design and analysis of underground structures.*

Hill, M., Kaiser, A., Wotherspoon, L., Manea , E., Lee, R., de la Torre, C., & Bradley, B. (2022). 3D Geological Modelling of Wellington Quaternary Sediments and Basin Geometry. GNS Science.

Langridge, R., Ries, W., Litchfield, N., Villamor, P., Van Dissen, R., Barrell, J., . . . Lee, J. (2016). The New Zealand active faults database. *New Zealand Journal of Geology and Geophysics*, 86-89.

Melhuish, A., Begg, J., Bannister, S., & Mumme, T. (1997). Quaternary stratigraphy, structure, and deformation of the Upper Hutt Basin, Wellington, New Zealand. *New Zealand Journal of Geology and Geophysics*, 19-29.

Morgenstern, R., & Van Dissen, R. (2020). *Active Fault Mapping and Fault Avoidance Zones for Wellington City*. Wellington: GNS Science.

N.Z. Geological Survey. (1973). *Engineering Geological Reports for Construction of Terrace Tunnels, Wellington Urban Motorway.* Lower Hutt: N.Z. Geological Survey.

Opus. (2006). *Terrace Tunnel Approach Walls Owner's Manual; prepared for Transit New Zealand.* Wellington, New Zealand.

Power, W. (2013). *Review of tsunami hazard in New Zealand (2013 update).* GNS Science.

Scheele, F. R., Uma, S. R., Wang, X., Syed, Y., Inglis, S., Williams, S., . . . Porter, H. (2023). *National tsunami exposure assessment for Toka Tū Ake EQC building portfolio.* Lower Hutt (NZ): GNS Science.

Townsend, D., Massey, C., Lukovic, B., Rosser, B., de Vilder, S., Ries, W., . . . Carey, J. (2020). *SLIDE (Wellington): Geomorphological characterisation of the Wellington urban area.* GNS Science.

Wallace, L., Reyners, M., Cochran, U., Bannister, S., Barnes, P., Berryman, K., . . . Power, W. (2009). Characterising the seismogenic zone of a major plate boundary subduction thrust: Hikurangi Margin, New Zealand. *Geochemistry, Geophysics, Geosystems, 10*(10).

Wang. (1993). *Seismic Design of Tunnels.*

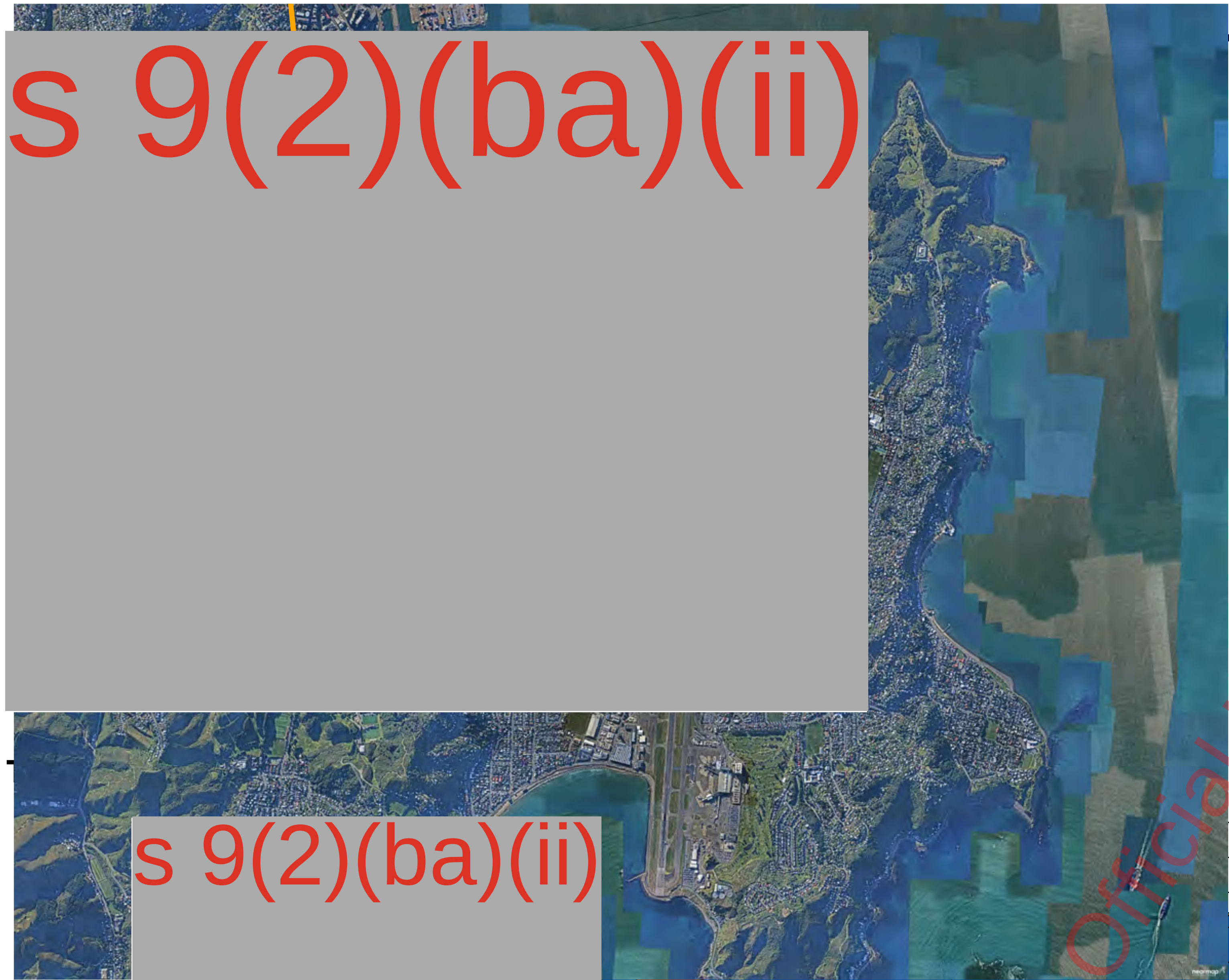
Williams, C., Eberhart-Phillips, D., Bannister, S., Barker, D., Henrys, S., Reyners, M., & Sutherland , R. (2013). Revised interface geometery for the Hikurangi subduction zone, New Zealand. *Seismological Research Letters, 84*(6).

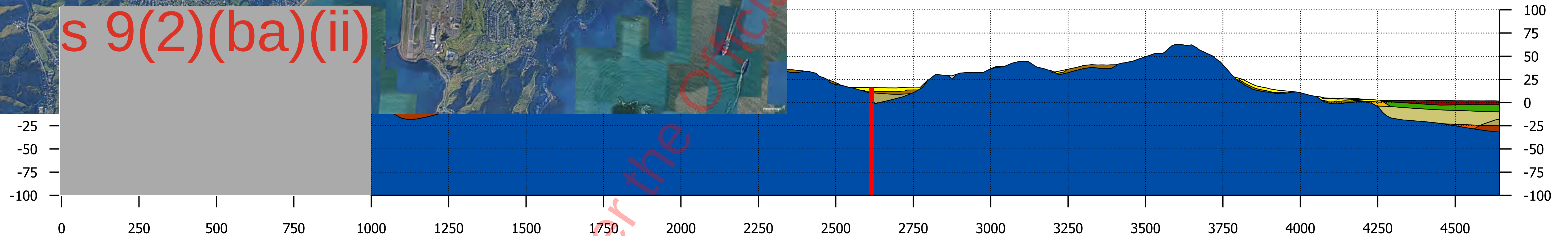
APPENDIX A

GEOLOGICAL LONG SECTION AND CROSS SECTIONS

s 9(2)(ba)(ii)

Tunnel Section





Legend

HILLetal_2022_StaticCopy

- WGTN3D: Anthropogenic fill
- WGTN3D: Anthropogenic fill G1
- WGTN3D: Anthropogenic fill G3
- WGTN3D: Holocene alluvium and colluvium
- WGTN3D: Marginal marine sediments
- WGTN3D: lPs Loose sediments
- WGTN3D: lPs Loose-dense transition
- WGTN3D: lPs Dense sediments
- WGTN3D: mPs Loose sediments
- WGTN3D: mPs Loose-dense transition
- WGTN3D: mPs Dense sediments
- WGTN3D: Rakaia terrane greywacke

Faults

- Aotea Fault

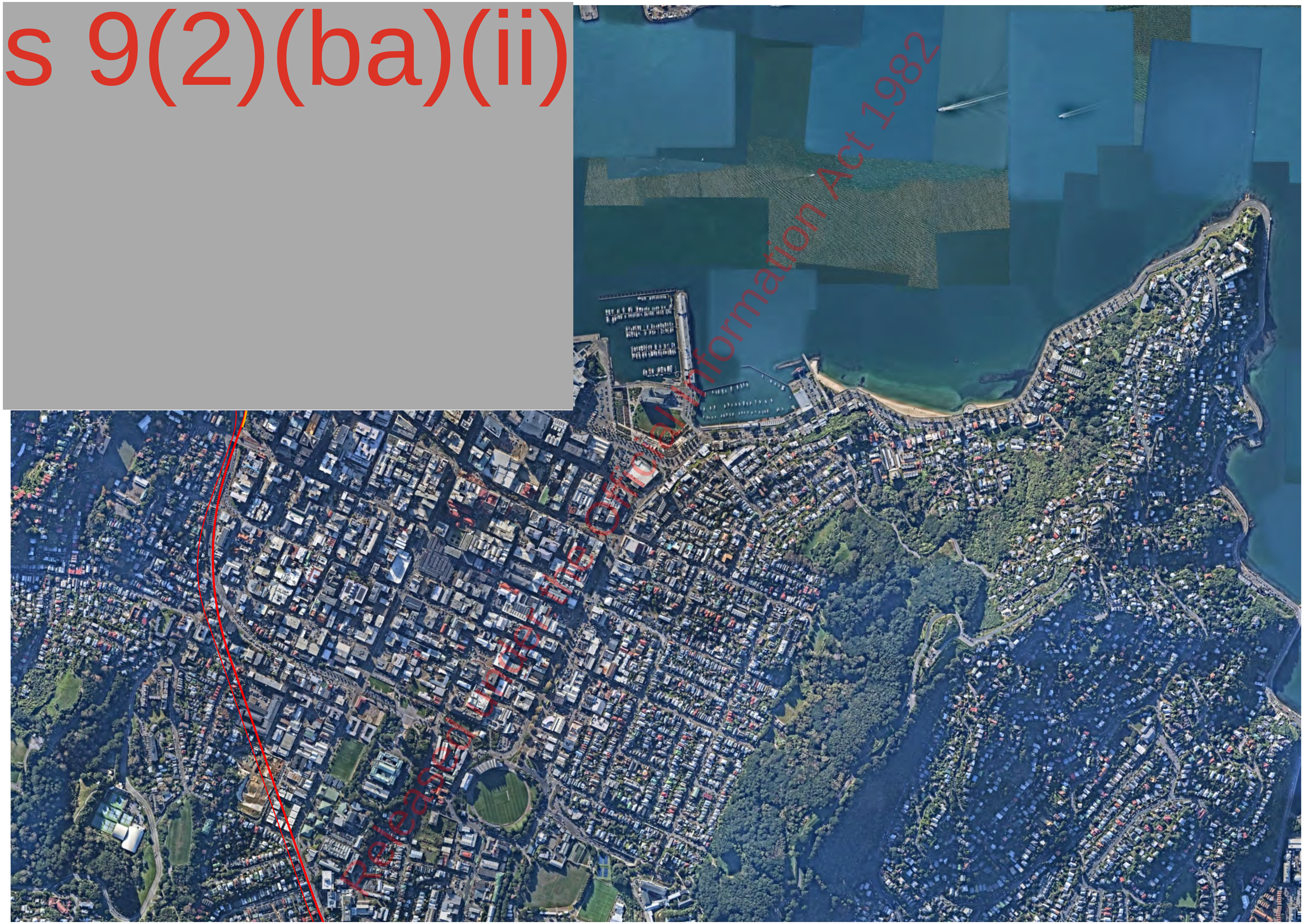
Tunnel Alignment

Scale: 1:13,000

Vertical exaggeration: 3x

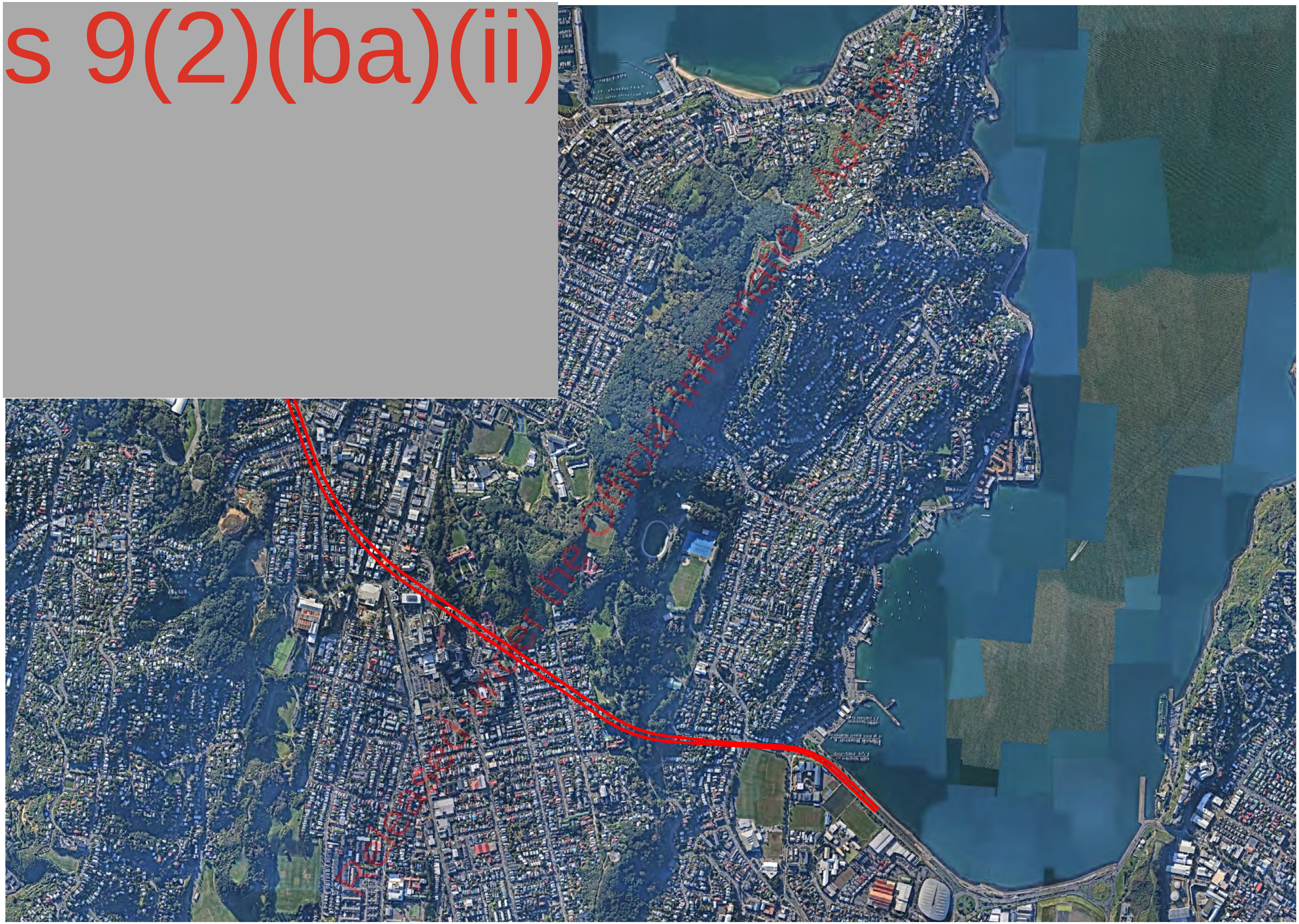
0m 1000m

s 9(2)(ba)(ii)

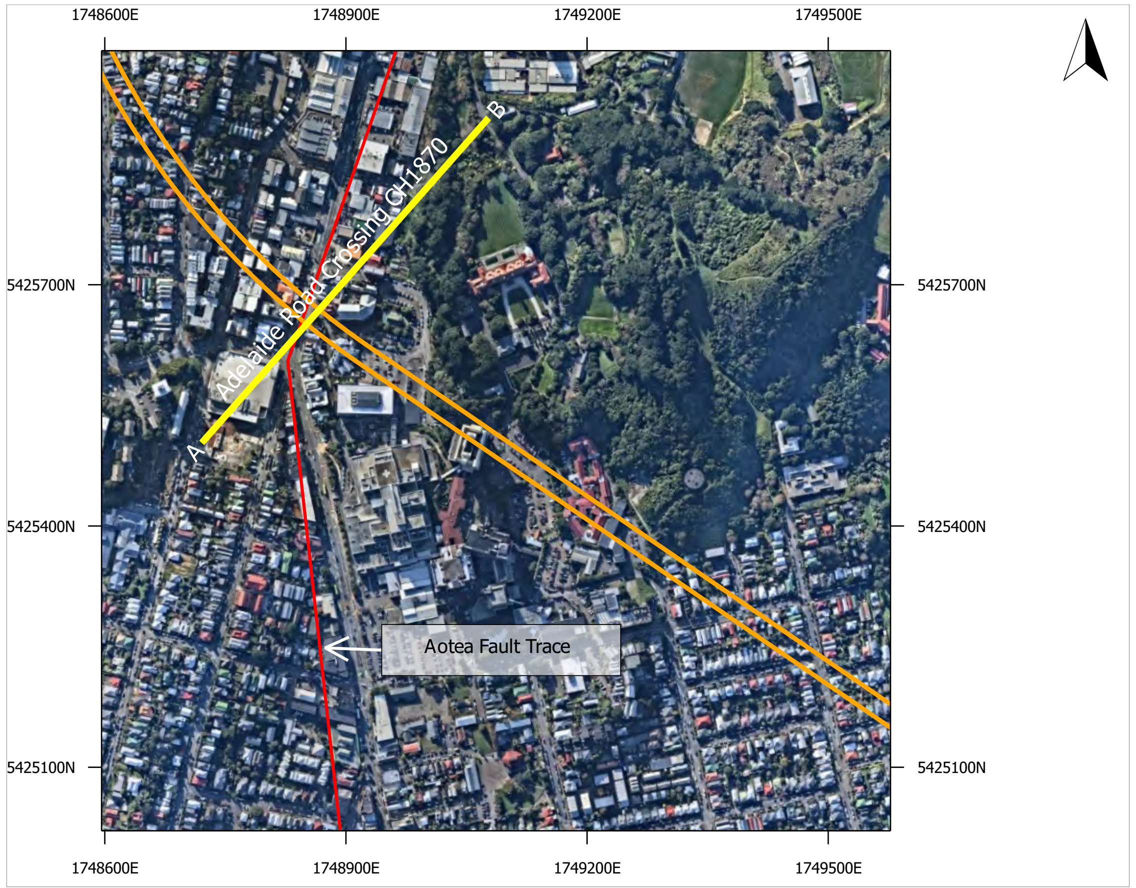


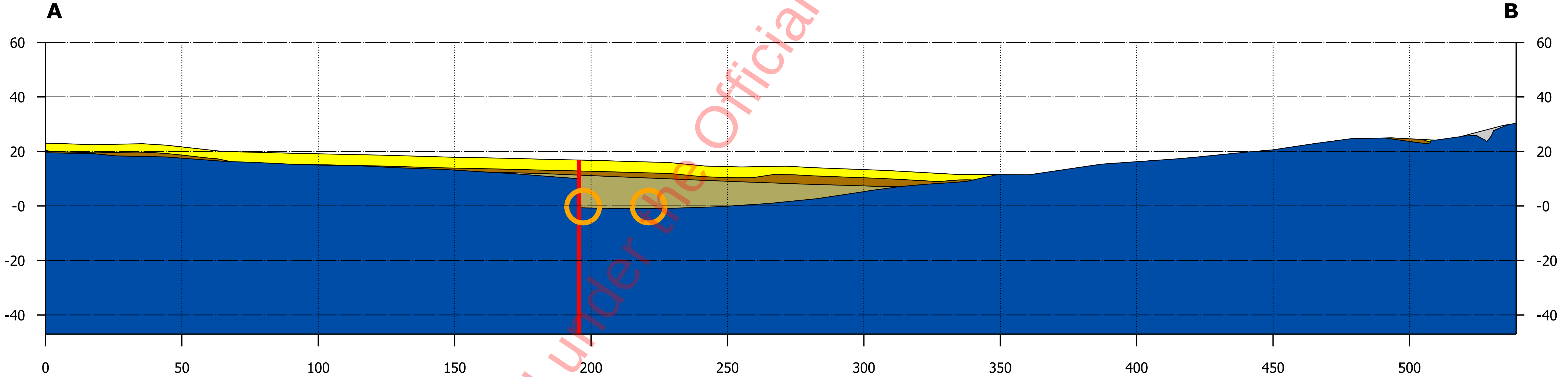
s 9(2)(ba)(ii)

s 9(2)(ba)(ii)



Adelaide Road Crossing CH1870





Legend

HILLetal_2022_StaticCopy

- WGTN3D: Anthropogenic fill
- WGTN3D: Holocene alluvium and colluvium
- WGTN3D: mPs Loose sediments
- WGTN3D: mPs Loose-dense transition
- WGTN3D: Rakaia terrane greywacke

Faults

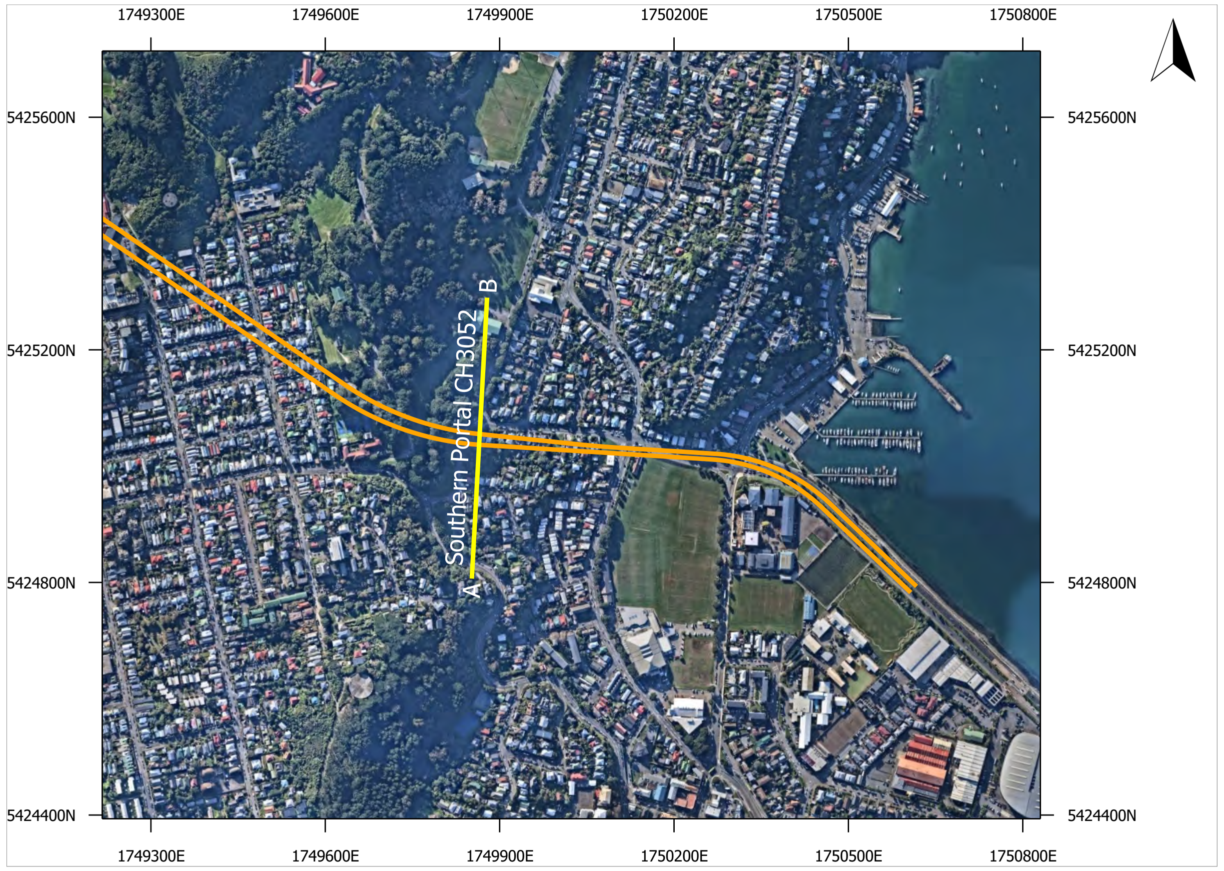
- Aotea Fault
- 5-C4800-00-DES-GEM-MDL-D013 - MCN0 TUNL TRIM

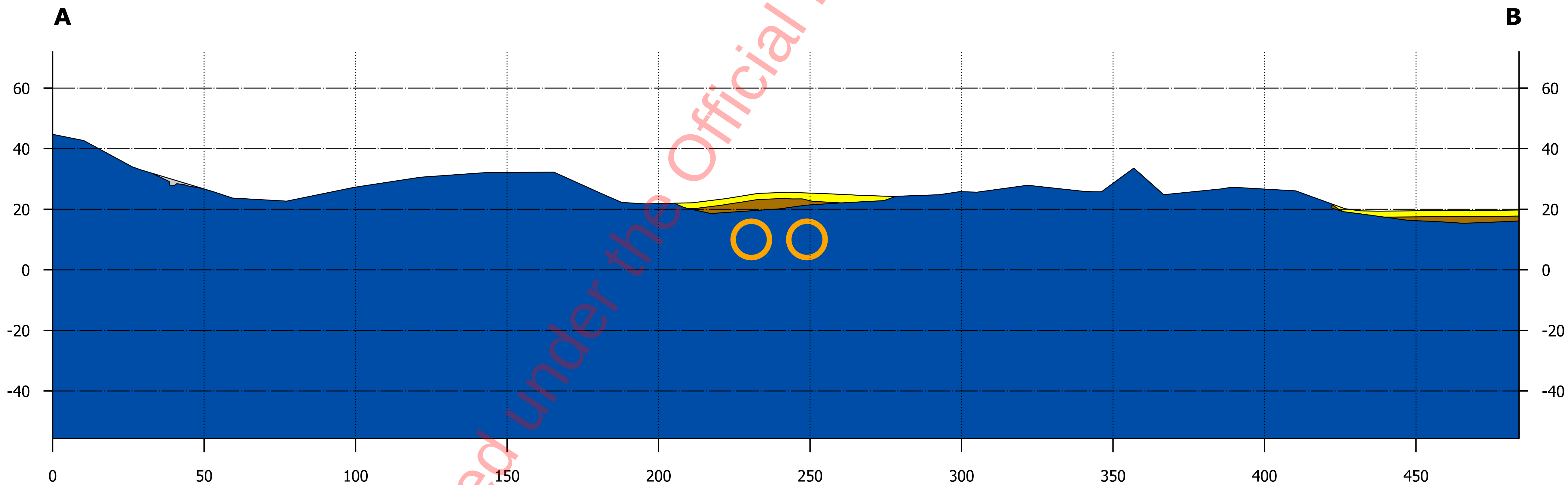
Scale: 1:1,500

Vertical exaggeration: 1x

0m 100m

Southern Interchange/Portal CH3052





Legend

HILLetal_2022_StaticCopy

- WGTN3D: Anthropogenic fill
- WGTN3D: Anthropogenic fill G3
- WGTN3D: Holocene alluvium and colluvium
- WGTN3D: mPs Loose sediments
- WGTN3D: mPs Loose-dense transition
- WGTN3D: Rakaia terrane greywacke

Faults

- Aotea Fault
- 5-C4800-00-DES-GEM-MDL-D013 - MCN0 TUNL TRIM

Scale: 1:1,500

Vertical exaggeration: 1x

0m 100m

APPENDIX B

NORTHERN APPROACH GEOLOGICAL SECTIONS AND EARTHWORKS CONCEPTS

s 9(2)(ba)(ii)

s 9(2)(ba)(ii)

s 9(2)(ba)(ii)

s 9(2)(ba)(ii)

V 1:500 0.5

s 9(2)(ba)(ii)