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Geotechnical investigations to address Earthquake Hazards for the Petone to Grenada Link Road, Wellington, New Zealand

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ABSTRACT

The New Zealand Transport Agency is developing a new Petone to Grenada (P2G) link between Hutt Valley and Porirua, to improve road access and reliability in the region. Resilience is a key objective for the project and for the transportation network in the Wellington region. The P2G project crosses land that has complex geotechnical issues and is exposed to significant natural hazards, and consequently a comprehensive programme of site investigation was carried out to characterise the ground conditions and inform the development of robust and resilient options for the road alignment. Particular geotechnical issues investigated for this project were the location of the active Wellington Fault, the liquefaction hazards in Petone, the slope failure hazards in the steep hilly terrain, the properties of the highly fractured and faulted greywacke bedrock and the depth and distribution of deeply weathered material. A comprehensive ground model is presented that incorporates the geomorphology and geology of the site with the geotechnical issues and hazards, and implications for the geotechnical design of the project are discussed. It is noted that the development of this project is in progress, and additional geotechnical investigations are currently being carried out to inform further development of the design.

Keywords: earthquake, hazards, site investigations, resilience, road development

1 INTRODUCTION

The New Zealand Transport Agency is developing a new link road between the Hutt Valley and the northern Wellington districts. The project area lies between State Highway 2 at Petone and State Highway 1 at Tawa/Grenada North and is called the Petone to Grenada route (P2G). The proposed link is approximately 6 km in length and proposes tying SH1 and SH2 together through new interchanges at both Petone and Tawa, as well as an interchange in the middle of the route to connect to the proposed development at the Lincolnshire Farms area and Grenada Village via Mark Avenue, see Figure 1. This project includes widening the section of SH1 between Tawa and the southern extent of the Transmission Gully expressway at Linden.

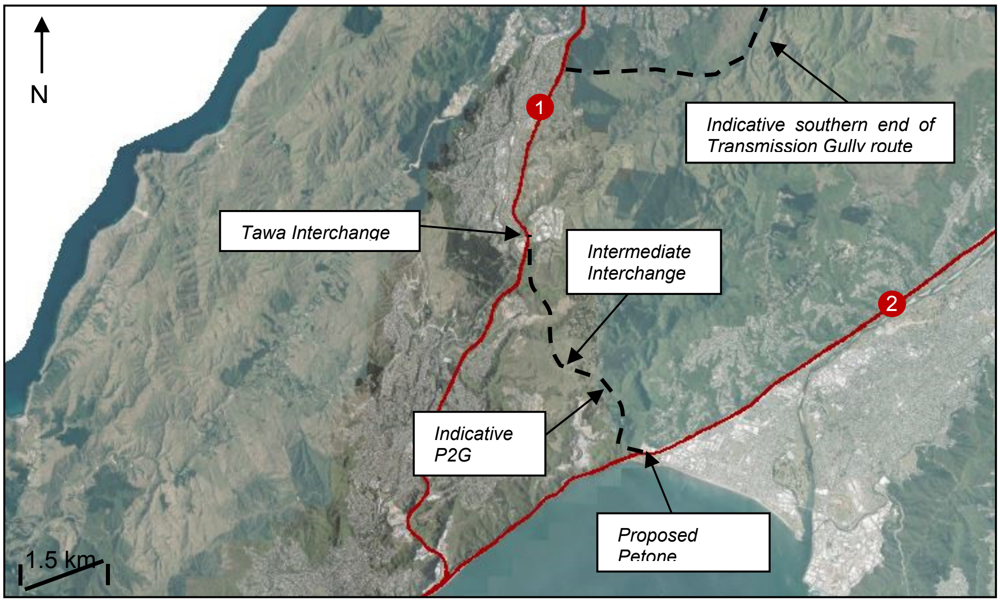

Figure 1. Location of Petone to Grenada Route (image: Greater Wellington Regional Council, n.d.)

To achieve robust and resilient alignment options for the link, a comprehensive ground model has been developed to address the complex geotechnical issues and earthquake hazards that could adversely impact the performance of the road.

2 RESILIENCE

One of the key objectives for the new road is to enhance the resilience of the Wellington state highway network. Previous assessments of the existing state highway network indicate that the region has poor resilience in the event of a large earthquake and the need to enhance resilience is of critical importance for the road controlling authorities such as the New Zealand Transport Agency and local authorities. These authorities have a responsibility to proactively manage the risks to their road networks from natural hazards and enhance resilience. A new route between SH1 and SH2 would achieve enhanced resilience of the network, as well as improve connectivity between the lower Hutt Valley and Wellington's northern suburbs and Porirua, reduce journey times across the region as well as enhance safety.

Resilience studies of the road networks in the region indicate poor resilience of access into the region in the aftermath of hazard events such as a large earthquake or storms (Brabhaharan and Mason, 2012). The loss of access will severely impact the supply of essential goods and services for emergency response and recovery. Not only will the region be cut off, the individual districts will be cut off from each other, making it difficult for the districts to help each other. In addition to this, the Wellington Region has very limited redundancy and connectivity in its network outside the city centres. The Greater Wellington area comprises only two state highways and parallel rail links providing road or rail access from outside the region, one along the western corridor (SH 1) and one from the east (SH 2) and there are very few viable alternative arterial local roads. In terms of connectivity, there are no viable connections between the cities of Wellington and Hutt Valley, and between Porirua and Hutt Valley other than SH2 and SH 58 respectively; both of which are assessed to have poor route resilience (Brabhaharan and Mason, 2012). Both these networks are expected to be cut off following a large magnitude 7.5 earthquake in the Wellington region due to their vulnerability to large landslides and liquefaction. Critical points such as Haywards Hill (SH58), Rimutaka Hill (SH2) and SH2 between Ngauranga and Petone are expected to be closed for many weeks to months due to large landslides, see Figure 2.

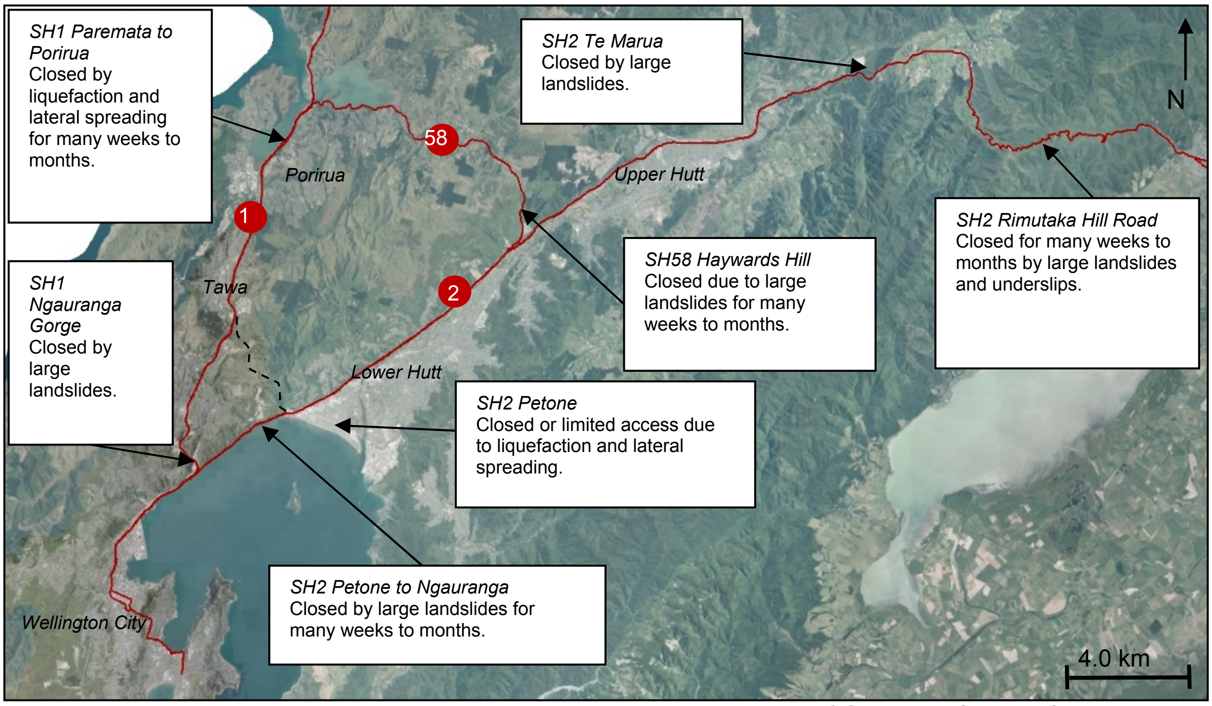

Figure 2. Wellington Region Vulnerabilities between the intersection of SH1 and SH2 to SH58 and the Rimutaka Hill (image source: Greater Wellington Regional Council, n.d.)

The Petone to Grenada route would provide an opportunity to enhance the regional resilience by providing a viable connection between Porirua and the Hutt Valley by bypassing the critical points located along SH2 and SH58. This would enhance access resilience into the Hutt Valley in the aftermath of hazard events such as earthquakes and improve redundancy of access.

The overall resilience of the P2G route will be dependent on the specific alignment selected. Understanding the vulnerabilities of each alignment to earthquake induced ground damage is critical to the overall resilience of the project and as the project area is subject is complex geotechnical issues and exposed to significant natural hazards, a comprehensive programme of site investigations has been carried out to assess these issues and inform the development of robust and resilient options for the road.

3 EARTHQUAKE HAZARDS AND GEOTECHNICAL INVESTIGATION

The Wellington Region is exposed to a high level of seismicity which is associated with a number of major active faults and the main subduction zone marking the active plate boundary between the Pacific and Australian plates. There are four major active faults within 20 km of the P2G route which represent significant earthquake sources and are capable of generating earthquakes of Mw 7.5 to 8+. These faults and their characteristic magnitudes and recurrence intervals are the Wellington Fault (M7.5, 840 years), Wairarapa Fault (M8.2, 1,200 years), Ohariu Fault (M7.4, 2,460 years) and Moonshine Fault (M7.1,12,540 years) (Stirling, et al, 2010). Earthquakes of this scale would cause strong ground shaking and induce significant ground damage in the form of fault rupture, landslides and liquefaction and associated ground subsidence and lateral spreading in the region.

To assess the vulnerability of the overall P2G route and various alignments to damage from these hazards, an extensive programme of investigations was undertaken to characterise the ground conditions and provide site specific information to inform geotechnical assessment. This assessment is critical to ensuring a resilient design. For ease of this assessment, the route is considered in two sections based on the characterisation of the geomorphology, geology and geotechnical issues; the Petone section and the hilltop section. The investigations undertaken were targeted to address the potential ground damage effects of earthquake hazards, specific to each section, as described below.

3.1 The Petone Section

The P2G route begins in Petone at the south-western end of the Hutt Valley. An interchange is proposed at Petone to tie into the existing SH2 and the local roads near the Korokoro Valley and stream, see Figure 1.

The wider area of the lower Hutt Valley is characterised by low lying, flat coastal and alluvial terraces with a naturally high water table. The geology consists of an extensive sequence of Quaternary marine and alluvial deposits which have aggraded within the Hutt Basin in excess of 300 m at the western end of the Esplanade in Petone. These deposits are described to be bound to the west by the Wellington Fault which is mapped to pass through the Petone area in the vicinity of the proposed P2G interchange. Figure 3 depicts this situation; showing the relationship of the Wellington Fault and the basin sediments (Begg et al., 2008). Fault rupture, ground shaking and liquefaction are considered to be the critical hazards in the Petone section and are described in more detail below.

3.1.1 The Wellington Fault

The influence of the Wellington Fault is considered a principal hazard to the P2G route. It represents a significant earthquake source within the Wellington Region and has been mapped in close proximity to the proposed interchange in Petone. The fault has a recurrence interval of 610 to 1,100 years and ruptures in large earthquakes of magnitude 7.5 with typical coseismic displacements of the ground surface of 5 m horizontally and 1 m vertically (Little et al., 2010). Confirming the location of the fault is imperative for the siting and resilient design of interchange structures and ensuring the fault rupture zone is avoided.

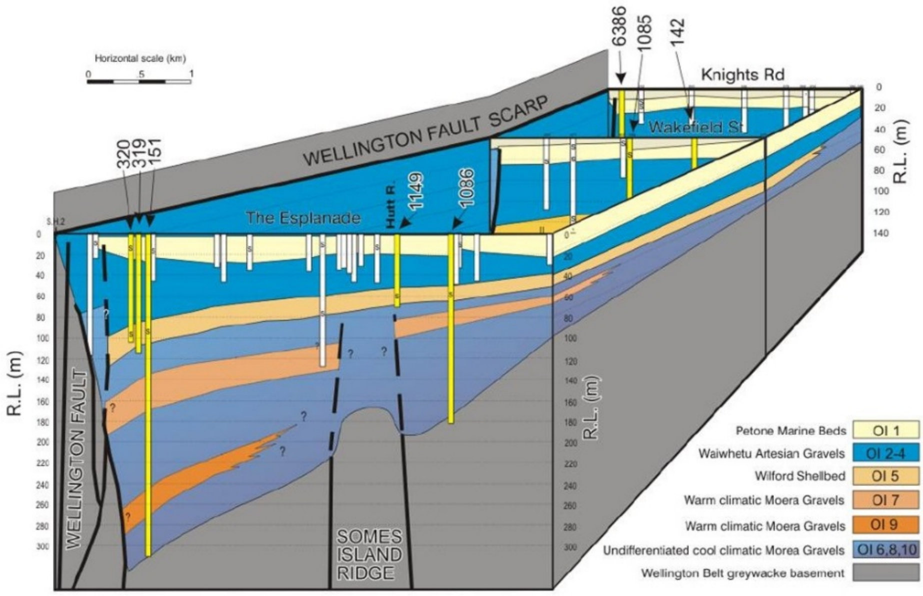

Figure 3. 3D block model of the Wellington Fault scarp and Lower Hutt Basin (Begg et al. 2008)

The location of the Wellington Fault in Petone and the Wellington Harbour is poorly constrained due to the lack of surface expression. This is apparent from differing published geological maps of the area. Prior to this study, the location of the active trace of the Wellington Fault was inferred to lie approximately 200 m from the proposed P2G interchange at Petone. This was based on geological mapping of the active fault trace north of the SH2 Dowse Interchange and on geophysical imaging of the fault zone in the harbour to the south of Kaiwharawhara (IGNS, 1996, 2000). The 1:20,000 Wellington Fault Hazard Map (Wellington Regional Council, 1991) shows the fault to have two strands and suggests a wider fault zone. The northern strand runs closer to the section of State Highway 2 between Horokiwi and Petone off-ramp. The southern strand runs parallel to the northern strand but about 550 m to the south, refer Figure 4.

Given the uncertainty in the fault's location, the width of the fault zone and the possible fault splay/s, geotechnical and geophysical investigations were carried out; targeted to refine the fault's location as well as determine the ground conditions and stratigraphy in the vicinity of the fault zone. Initially, stereo aerial photo analysis and field mapping were conducted before a series of boreholes were undertaken. The boreholes indicated a sharp change in depth across a relatively short horizontal distance indicating a steep step. To gain an understanding of the fault location, a series of seismic refraction lines were then undertaken. These were accompanied by a microgravity survey. Both these geophysical techniques are influenced by the depth to bedrock and were able to be correlated with the borehole data. These surveys indicated the presence of several steps in the bedrock between the main fault structure and the interchange area. The data from these geophysical surveys allowed for a location of these steps to be more accurately known at the ground surface and using this information, an additional, inclined borehole was undertaken in an attempt to physically observe fault disturbed material.

Figure 4. Map depicting Wellington Fault Splays (WRC, 1991) and Wellington Fault (IGNS, 2000)

3.1.2 Liquefaction

The close proximity of the Wellington Fault increases the risk of a higher level of ground shaking in a seismic event leading to a higher level of ground damage in both the Petone section and across the remainder of the P2G route. In the Petone section, this is particularly relevant for the assessment of potential ground damage caused by liquefaction.

It has been well documented that there is a liquefaction hazard in the Petone area due to the high water table and extensive loose alluvial and marine soils (Wellington Regional Council, 1993). Liquefaction ground damage can lead to foundation failure, subsidence and lateral spreading, which could affect any surface development and more specifically, the interchange structures. The proposed location of the Petone interchange is located in a zone mapped with a high liquefaction potential and as such, it is critical to determine the extent of liquefiable material present and to assess the potential for ground damage in a large earthquake. This information will be valuable for the design of the interchange.

Boreholes and static cone penetration tests (CPTs) were targeted across the wider interchange area to determine the depths and lateral extent of potentially liquefiable material. They were placed to cover various geological deposits such as alluvial material around the Korokoro Stream, colluvial deposits from the adjacent hillslopes and the fill, beach and marine sediments closer to the foreshore. The CPTs provided detailed information about the soil characteristics which were correlated with physical samples retrieved from the boreholes. The borehole samples were also used for laboratory testing (particle size distribution, Atterberg limits and plasticity index) to provide further site specific detail for liquefaction analysis.

The soil characteristics determined from these methods enabled an assessment of liquefaction in the Petone and Tawa Interchange areas. The assessment indicated that there would be liquefaction expected in the Petone interchange area which will be taken into consideration in the design, but not expected to be a significant issue in the Tawa interchange area.

3.2 The Hilltop Section

The hilltop section comprises the remainder of the P2G route through to Grenada/Tawa. Immediately following the Petone interchange, the link road climbs the adjacent southwestern slopes that bound the Hutt Valley. These slopes are the result of uplift associated with the Wellington Fault and represent the heavily eroded fault scarp. They are steep and are bisected by steeply incised gullies. The slopes rise from sea level at the SH2 Petone interchange, to 290 m elevation on the hilltops in Horokiwi at the summit of the route. The summit and the adjacent Lincolnshire Farms area has more gently rolling topography and is characterised by the remnants of an ancient erosion surface called a K-Surface. This surface has been subsequently uplifted and dissected so that only remnants of it are preserved; as rounded ridge crests and undulating tableland surfaces. This area is the location of a proposed intermediate interchange. From the Lincolnshire Farms area, the route continues north across a steeply sloping gully and past Grenada Village before sidling down to the existing SH1 to connect at the Tawa / Grenada North Interchange.

The hilltop section of the route is dominated by Wellington belt greywacke which comprises interbedded sandstone, siltstone and mudstone/argillite of varying proportions. These rocks have been complexly folded and faulted through numerous deformation events which have caused significant fracturing of the rock including joint sets generated due to the change in stress direction over time.
The earthquake hazards considered to be most significant in this section are earthquake induced slope instability and to a lesser extent, the presence of the Moonshine Fault.

3.2.1 Earthquake Induced Slope Instability

Moderate to large earthquakes can lead to slope failures in steep to very steep slopes, including cuttings which are generally steeper than the natural hillslopes. The P2G route crosses steep, hilly terrain, particularly at its southern end between Petone and the hilltops at Horokiwi. This area, along the western side of SH2 is characterised by steep hillslopes and deeply incised gullies of the uplifted block of the Wellington Fault. Here, the hills rise from sea level at the SH2 Petone interchange up to 290 m elevation on the hillslopes near Horokiwi. These slopes have been mapped as having high susceptibility to earthquake induced landslides, particularly along the eroded Wellington Fault scarp along the Wellington Harbour and along the flanks of deeply incised valleys such as the Korokoro Stream valley, see Figure 5 (Brabhaharan *et al*, 1994). This is influenced by evidence of historical earthquake induced landslides, most notably 'Gold's Slide' along SH2 in close proximity to the proposed route, which was triggered during the 1855 earthquake (Brabhaharan et al, 1994). To overcome the sharp change in elevation in this area and to still achieve a design gradient for the road, significant cuts up to 70 m high are being considered. A further large cut slope north of Lincolnshire Farms in the vicinity of Grenada Village is also being considered.

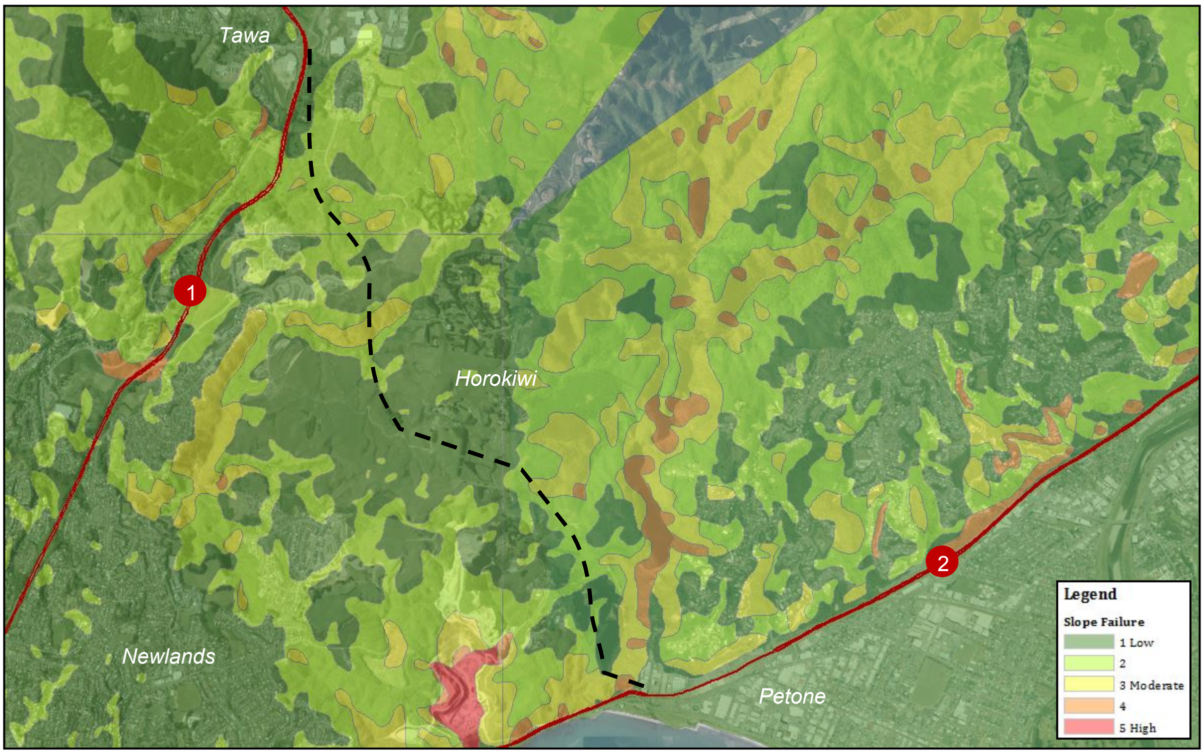

Figure 5. Earthquake induced slope failure susceptibility map (Brabhaharan et al, 1994)

The hazard of earthquake induced slope instability is strongly controlled by the level of ground shaking during an earthquake event, but also by the geology and orientation and form of the cut slope design. The areas where large cut slopes are being considered are both predominantly greywacke, however have undergone differing weathering and tectonic deformation processes resulting in highly variable rock quality. The hillslopes rising from the Petone area have undergone tectonic deformation associated with the Wellington Fault. The greywacke is generally less weathered but there are prominent zones of breccia, sheared and crushed zones and clay seams. These zones can be extremely weak and are likely to more readily fail during a seismic event, particularly if they daylight in the cut slope at an unfavourable orientation; as for any significant joint set or bedding plane which can act as a failure surface. At the summit and north of Lincolnshire Farms, processes associated with the K-Surface have had more influence over the rock mass quality. Here the weathering profile is significantly deeper (>30 m) (IGNS, 1996) below ground level, indicating a greater depth of more highly weathered and generally weaker rock exposed in the proposed cut slopes.

Initially stereo aerial photo analysis and field mapping of rock exposures and landforms were conducted. This allowed historical slope failures to be identified and enabled the expected modes of failures in individual material types and angles at which failures could be expected at along the route to be assessed. This work identified the potential for landslides in weathered bedrock along the Moonshine Fault, shallow landslides and rill-gully erosion in colluvium and residual soil on the K-surface, possible shallow landslides in colluvium and larger rock block slides on the flanks of the Korokoro Stream. The Wellington Fault scarp above SH2 was also identified as a zone of historical slope failure, as mentioned earlier. This area is important to the resilience of the P2G project as it is currently a critical point of weakness in the existing regional State Highway network. Field mapping also allowed for the identification of weathering and strength characteristics of exposed rock, as well as measurement of shear zone orientations and other surficial features.

To gather information on the subsurface ground conditions, a series of deep, cored boreholes were drilled and accompanied by down hole televiewer surveys. The boreholes were positioned along the route in the expected locations of cut slopes so that the weathering profile and changes in strength and rock mass quality over the depth of the cut could be physically examined. These also provided information on the properties and thickness of soil overburden which was identified as particularly important along the K-Surface where a significant thickness of loess had been mapped. A number of representative samples were used for triaxial and unconfined compressive strength testing to determine accurate rock properties for use in cut slope analysis. This information is critical to design to ensure the form of the cut slope (angle, height, bench width etc.) is appropriate to achieve a resilient design. The identification of critical defect orientations is also imperative to a resilient design, which were obtained both through field mapping and downhole acoustic and optical televiewer surveys. These surveys were able to be correlated to the borehole data to assess the defect orientation and differentiate defect types such as sheared zones, joint sets and bedding which could impact the slope performance. This defect data was invaluable for the subsequent assessment of the stability of the proposed 30 m to 80 m high greywacke rock cut slopes. Three mechanisms of failure; (a) failure along dominant defects (b) rock mass failure through intensely jointed rock and (c) combined failure through dominant defects and break out through rock mass, were identified, and analyses for static as well as earthquake conditions enabled the design of preliminary cut slope angle and slope configuration. This will be presented in a subsequent paper in the future.

3.2.2 Moonshine Fault

Similar to the Wellington Fault in the Petone area; the P2G route crosses the Moonshine Fault trace near the proposed interchange with State Highway 1 at Tawa/Grenada North. However, unlike the Wellington Fault, this fault has a very long recurrence interval (>11,000 years) and accordingly a very low probability of rupture. The location, width, characteristics and form of the fault zone are poorly defined. As a result, the Moonshine fault is considered of low risk to the P2G route and conceptual designs and no site investigations have been targeted to address the fault hazards.

However, notwithstanding the low level of assessed risk, the potential ground damage effects associated to a seismic event on the Moonshine Fault have been broadly considered to ensure a resilient design is maintained. The siting of the interchange structures should avoid the mapped fault rupture zone.

4 CONCLUSIONS

The existing State Highway network in the Wellington region has poor resilience in the event of a large earthquake event and the need to enhance this resilience is of critical importance to the region. The proposed Petone to Grenada link road provides an opportunity to offer a viable connection between Porirua, Northern Wellington and the Hutt Valley. This alternative route will compensate for one of the significant deficiencies in the current network; the likelihood that access into the Hutt Valley will be cut off for months, whereas the new route is likely to be able to be opened in days to 2 weeks after a large earthquake. To achieve this level of resilience for the route, it must be designed to reduce the impact of hazards associated with a large earthquake event so that it can be quickly recovered to an accessible state.

The earthquake hazards that are likely to most severely impact the route are fault rupture associated with the Wellington Fault, liquefaction in the Petone area and earthquake induced slope instability along the Wellington Fault scarp and the cut slopes. The influence of the Wellington Fault is of critical importance to the resilience of the link road. The fault represents a significant earthquake hazard and given the close proximity of the route, particularly to the Petone interchange and the adjacent cut slopes, the likely high level of ground shaking induced from such an event will intensify the amount of ground damage sustained.

The geotechnical investigations described in this paper were invaluable in selecting a suitable alignment for the project avoiding areas of major hazard such as historical slope failure sites, the Wellington Fault scarp along the Wellington harbour foreshore and the Wellington Fault strand in Petone. The investigations enabled preliminary design of the proposed major cut slopes and embankments and provide input for consideration of interchange structures. It is noted that given the nature of the project and the uncertainties a staged investigation programme was adopted and further detailed investigations are ongoing to inform scheme assessment and assessment of environmental effects at the time of presentation of this paper.

A key lesson of this project is the importance of identifying hazards at an early stage, and to plan and implement a staged programme of geotechnical investigations that can provide an appropriate level of information at each stage as the project progresses.

5 ACKNOWLEDGEMENTS

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