ABSTRACT: Road networks are key lifelines for the community, and improving their performance is critical to the availability of road access after earthquakes. The performance of the Wellington Road network in moderate to large earthquakes as well as storms and the consequential risks were identified through a systematic study with the aid of a geographical information system. The performance assessment and mitigation of two retaining walls along Ngaio Gorge Road is presented.

A performance based approach was used to decide on the mitigation solutions and an appropriate level of risk mitigation. This enabled the selection of strengthening solutions that meet the performance requirements for the Ngaio Gorge Road, but also at optimum cost. One breastwork retaining wall was strengthened using soldier piles, and tied back using rock anchors. The other breastwork wall site was improved using soil nailing of the retaining wall backfill and the slope below. The soil nail design solution allows for significant deformation of the road during a large earthquake, but would maintain access along this section of the road.

An economic analysis was used to justify the strengthening work for funding.

1 INTRODUCTION

Wellington is New Zealand’s capital city and is located in steep hilly terrain in an area of high seismicity. The road network has a significant vulnerability to natural hazards, particularly earthquakes and storms. Lifeline studies highlighted the vulnerability of the road network, and this led to mitigation of key bridge structures such as the Thorndon Overbridge and the Aotea Quay ramp.

Wellington City Council recognised the vulnerability of its road network through damage suffered particularly after large storm events and the potential for damage in earthquakes. This was confirmed by its in-house study of road reopening scenarios in 1995. Wellington City Council engaged Opus International Consultants, who assessed the risks to the road network and developed a long term strategy to manage the risks, based on the performance of the road network in earthquake and storm events. The strategy is being refined to take into consideration other risks to the road network.

On the basis of this strategy, Ngaio Gorge Road was prioritised for risk mitigation, and initially two vulnerable retaining wall sites were investigated and their performance in earthquakes and storms was assessed. Opus used a performance based approach to develop mitigation solutions to provide an adequate level of performance, and designed and managed the implementation of strengthening works.

This paper briefly presents the performance based approach used to assess the risks to the road network, and to select mitigation solutions. It also outlines the economic analyses used to consider the improvement in performance that would be achieved by the mitigation measures, to help justify funding for the strengthening work. The strengthening work was implemented over 2003-2004.
2 THE PHYSICAL SETTING

Wellington is located in the steep hilly terrain, at the south-western tip of the North Island of New Zealand. The Central Business District (CBD) is largely built on reclaimed land, with much of the residential areas located on the hillsides and narrow and elevated valleys.

Given the terrain, much of the road network, except in the flat CBD area, is through hilly areas, and has commonly been built by cutting into the hillsides and often with steeply sloping sidling fills or supported by retaining walls. The sidling fills have often been formed by end tipping and with minimum compaction. The retaining walls are commonly in poor condition and have not been designed for earthquake motions.

The geology is predominantly Triassic Age sandstone and argillite, commonly known as Wellington Greywacke, which is well indurated, but is generally highly fractured and disturbed by the tectonic activity in the area. The weathering is variable with fresh to completely weathered rocks exposed in road cuttings. The bedrock is commonly overlain by colluvium on hillside slopes, and alluvium in valleys. Fill is common along road corridors, and is generally derived from the parent rock or colluvium, and originates from local cutting, past slip debris or quarry overburden or waste rock.

Wellington is located in an area of high seismicity in New Zealand. The active Wellington Fault transects the district. A characteristic rupture of the Wellington to Hutt Valley section of the strike-slip Wellington Fault could give a 4 m horizontal and 1 m vertical surface displacement and an earthquake of about Richter magnitude 7.5 at a return period of about 600 years. A number of other regional faults could also lead to large earthquakes, such as the Wairarapa and Ohariu Faults. The Wairarapa Fault can give a magnitude 8 earthquake.

3 NETWORK RISK ASSESSMENT

A comprehensive review of the hazards to the road network by Opus led to storm and earthquake hazards being prioritised as posing the most significant risks to the road network. This was followed by a study of the likely performance of the road network in storm (slope failures) and earthquake events (slope failures, liquefaction and fault rupture) and the consequential risk to the serviceability of the road network.

The comprehensive network risk study covered all principal, arterial and collector roads, and was carried out using a spatial Geographical Information System (GIS) database. The spatial risk management approach was developed by Brabhaharan et al (2001).

Road links were prioritised based on the importance to the road network, considering a variety of factors such as traffic volumes, commercial and public transport use, importance for emergency services and the availability of alternative routes (Brabhaharan, 2004). The prioritisation for the road network is presented in Figure 1.

The vulnerability of the Wellington Road Network was characterised based on the impact of storm and earthquake hazards on the performance of the road network, and is illustrated in Figure 2.
The risk map indicates that many key routes of high importance for the road network also have a significant vulnerability to natural hazards. Risk-economic analyses were carried out to assess relative benefit-cost ratios for mitigation of the risks (Brabhaharan, 2004).

A risk management strategy was developed to put in place a long term approach to manage the risks to its road network. On the basis of prioritisation, considering Ngaio Gorge Road was chosen by the Council for implementation of risk mitigation from 2003.

4 PERFORMANCE OF NGAIO GORGE ROAD WALLS 1 AND 2

4.1 Location and Description

The two walls chosen for risk mitigation are located along the Ngaio Gorge Road, which connects the Hutt Road north of Wellington to the northern suburbs of Chartwell, Ngaio and Khnadallah. It also provides part of the alternative road out of Wellington to the north, to the State Highway 1 through the Ngauranga Gorge, see Figure 2. The location of the Ngaio Gorge Road and the two walls, Wall 1 and Wall 2 are shown on Figure 3.

The walls are located on the downhill southern side of the road and support the road platform. Wall 1 is about 26 m long and 4.5 m high, whereas Wall 2 is about 20 m long and 2.3 m in height. The walls are of breastwork construction and were built in the 1970s. The breastwork walls have vertical reinforced concrete pillars at 1.8 m centres supported on shallow footings founded on colluvium or fill. The pillars are anchored using tie bars to a deadman block within the road fill behind the wall. The backfill is retained by 130 mm by 100 mm infill rafters spanning between the pillars, and spaced with a single course of brick over the upper 2 m height. No brick spacers are used over the lower section of higher walls. The construction of Wall 1 is shown on Figure 4.
The anchors are 28 mm steel bars of unknown type and corrosion protection, installed at approximately 2 m vertical height intervals. The walls are generally in good condition, except for the anchors which were badly corroded at the anchor head. The anchor head had been repaired and coated with epoxy in about 2000, but the anchor itself and particularly the section immediately behind the wall, is likely to be in a worse state.

4.2 Ground and Groundwater Conditions

The walls are underlain by steep sidling fill / colluvium gullies that slope at about 40°. Site investigations comprised engineering geological mapping of exposures, hand excavated trial pits and the drilling of six boreholes at Wall 1 and three at Wall 2.

The geotechnical investigations showed that the walls are underlain by:

Wall 1  Fill, colluvium and alluvium that are loose to medium dense with gravel and cobble in a sandy silt matrix and occasional boulders, underlain by unweathered to slightly weathered, strong to very strong sandstone and siltstone.

Bedrock at about 10 m to 12 m below the road surface where the colluvium and fill is thickest. The thickness of colluvium and fill reduces down slope, and bedrock is exposed at the surface in the lower part of the slope about 25 m below the wall, see Figure 5.

Wall 2  Firm gravelly silt and loose silty sandy gravel and stiff plastic clayey silt, underlain by moderately to highly weathered, weak, closely jointed sandstone.

Bedrock is about 6 m below the top of the wall or about 3 m below the existing ground surface at the base of the wall.

Groundwater was not present in the fill and colluvium during drilling in the spring time, but strong seepages observed in the lower part of the slope particularly at Wall 1 indicated that groundwater may be flowing down the bedrock / overburden interface, and could be higher during storm events or in the event of blockage of the culvert in the gully.

4.3 Performance in Earthquake and Storm Events

The failure of the anchors supporting the pillars could lead to failure of the walls themselves in moderate earthquake events. Given the presence of steep slopes below, the performance of the road will be controlled by the stability of the overall slope given that the walls are founded within the loose fill and medium dense silty sandy gravel (Wall 1) or firm to stiff clayey silt (Wall 2) colluvium.
Stability analyses were carried out using the Slope/W limit equilibrium analyses software. Different extents of slope failure were considered in the stability analyses for Wall, see Figure 5:

- A small slope failure surface removing the wall and part of the road (FS1);
- An intermediate slope failure removing the whole road (FS2); and
- A larger failure removing the complete road bench (FS3).

At Wall 2, given the narrow road platform, failure is likely to remove at least half the road width.

The stability analyses indicated that at Wall 1, the slope may become marginally unstable in a storm event, leading to slope deformation, but complete collapse of the whole road is unlikely. The wall itself may fail depending on the condition of the anchors, but this is unlikely to remove the complete road as there is a wider road bench at this location, and access would be possible at least on a single lane basis.

![Figure 5 Section showing failure surfaces considered at Wall 1](image)

Under earthquake shaking, the analyses indicated that the wall and the complete road bench is likely to fail in a design earthquake shaking of 0.35g based on the Bridge Manual (Transit New Zealand, 1998) for a freestanding wall carrying a state highway (this is considered appropriate given that the Ngaio Gorge Road carries 10,000 vehicles per day). This ground acceleration equates to a recurrence interval of about 670 years. Complete road bench failure is certainly likely in a characteristic Wellington Fault event giving a ground shaking of the order of 0.45g to 0.75g at this site.

At Wall 2, the slope would also fail at a design earthquake shaking of 0.35g.

It is assessed that significant road damage and deformation could be expected in earthquakes with peak ground accelerations greater than about 0.15g at the site.

Therefore, risk mitigation measures were considered essential to improve the performance of the road, given that the Ngaio Gorge Road is a high priority road link within the Wellington Road Network.

5 DEVELOPMENT OF RISK MITIGATION BASED ON PERFORMANCE

5.1 Performance Expectations and Criteria

Risk mitigation to achieve a normally accepted factor of safety at a somewhat arbitrary design peak ground acceleration of 0.35g could be both expensive and probably inadequate given the potential for much large levels of earthquake shaking at the site and the importance of the Ngaio Gorge Road link.

Failure of the walls and slopes below would lead to loss of the road platform, and it would take a long period of time to reinstate these sections of the road with high retaining walls to support the road. Ngaio Gorge Road is an important road link, and such long period of closure would have a significant effect on the community and emergency response and recovery. It is desirable to ensure that road access can be maintained along the road in the Wellington Fault earthquake event.
It would be very costly to design the mitigation of the wall/site to a routine standard and factor of safety against failure. Therefore, the performance criteria presented in Table 1 were developed for risk mitigation of the walls at Ngaio Gorge Road.

Table 1 Performance Criteria for Walls at Ngaio Gorge Road

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Performance</th>
<th>Return Period</th>
<th>Peak Ground Acceleration for Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Level (Bridge Manual)</td>
<td>No more than minor damage with cracking of road not exceeding 150 mm.</td>
<td>670 years</td>
<td>0.35g</td>
</tr>
<tr>
<td>Wellington Fault Event (Contingency Level)</td>
<td>Some damage to structure requiring repairs and extensive deformation of the road is acceptable, but road should be able to remain open for traffic.</td>
<td>-</td>
<td>0.47g (50 percentile for rock sites)</td>
</tr>
</tbody>
</table>

5.2 Risk Mitigation Options

A variety of risk mitigation options were considered for the strengthening of the two wall sites and appropriate solutions were chosen based on the ability to achieve the performance criteria in an efficient and cost effective manner. Possible risk mitigation options are outlined in Table 2.

The solutions suitable for the Ngaio Gorge Road are the soldier piled and anchored walls or soil nails.

Table 2 Risk Mitigation Options for Ngaio Gorge Walls

<table>
<thead>
<tr>
<th>Option</th>
<th>Comments</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soldier piled wall with anchors</td>
<td>Strengthen walls with soldier piles and rock anchors. Rigid solution and wall would need to be designed for full design loads.</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>Reinforced soil wall</td>
<td>The wall would require excavation of large amount of existing soil and would require closure of existing road and relocation of services.</td>
<td>High</td>
</tr>
<tr>
<td>Soil nailing</td>
<td>Flexible solution able to be designed to allow displacement in earthquakes. Requires trials and grouting in poor ground.</td>
<td>Moderate</td>
</tr>
<tr>
<td>Reinforced concrete cantilever wall</td>
<td>Very difficult to construct for the high walls and are vulnerable to failure of slope below and hence are not suitable.</td>
<td>High</td>
</tr>
</tbody>
</table>

5.3 Risk Mitigation at Wall 1

Wall 1 is underlain by bedrock at significant depth (8.5 m below wall or 10 m to 12 m below road level), and therefore strengthening using soldier piles and anchors would be very costly due to the need for long piles and long anchors and also the need to design the relatively rigid soldier pile wall for the full design loads. Therefore, a soil nailing of the wall and slope was chosen, with load spreader beams between the nails near the top of the wall, and ground beams at the base of the wall and the bottom of the stabilised slope, see Figure 6. Wire rope and netting held to the slope by the soil nails was chosen to stabilise the slope below against shallow or progressive failures.

The soil nailed solution was designed to provide an adequate (greater than 1.5) factor of safety under static conditions, but the factor of safety was less than 1 under the earthquake load cases. However, the soil nailing spacing, lengths and load capacities were designed so that the displacement of the slope and road bench above would meet the performance criteria developed and presented in Table 1.
The slope deformations were assessed based on assessment of the critical acceleration (acceleration at which the factor of safety of the relevant failure surface in the slope is one) from the slope stability analysis, and the empirical method presented by Ambraseys and Menu (1988).

The assessed slope deformations for the soil nailed wall and slope was up to 100 mm for the 0.35g design level earthquake, and up to few hundred millimetres for the Wellington Fault event giving a peak ground acceleration of about 0.47g in the area. The soil nailed slope would ensure integrity of the slope mass, but enable it to deform and displace as a block. This meets the performance criteria as the road would still be able to be accessed, albeit with difficulty due to a uneven road surface, or after placement of some fill and surfacing to provide a more easily trafficable surface.

5.4 Risk Mitigation at Wall 2

Given the relatively shallow depth to bedrock at Wall 2, it is more difficult to achieve a more flexible deformable road mitigation solution. This is because soil nails entering bedrock will make it more rigid. Therefore, a soldier piled wall solution was adopted. The existing wall was strengthened using new reinforced concrete columns and beams supported by reinforced concrete bored piles socketed into rock, and the columns were anchored using rock anchors, see Figure 7.

The wall was designed to remain elastic under the design event (0.35g) and with allowance for the rock anchors to yield in a Wellington Fault event.

The mitigation solution meets the performance criteria for the road.

The rock anchors as well as the soil nails were double corrosion protected by pre-grouting the bars inside a sheath, before installation into drilled holes and grouting.
6 IMPLEMENTATION OF STRENGTHENING WORKS

The strengthening work at Walls 1 and 2 were implemented during Walls 1 and 2 under the construction management of Opus. Strengthening works at Walls 1 and 2 are shown in Figure 8.

Wall 1 required extensive trials for grouting the soil nails so that the Contractor could develop the use of appropriate grouts and methods for installation of the soil nails in permeable ground conditions. A block mix grout with fine aggregate was pumped into the hole with the soil nails in place to achieve the grouted soil nails and the required ground-grout bond capacities. The strengthening works were completed in mid 2004.

7 CONCLUSIONS

The risk to the Wellington Road Network from earthquake and storm hazards was developed by considering the performance of the road in such events, using a spatial risk assessment approach developed by Brabhaharan et al (2001). This provided the basis for a long term strategy to manage the risks to its road network by Wellington City Council.

Ngaio Gorge Road was prioritised for risk mitigation, and two walls were investigated, assessed, risk mitigation developed, designed and implemented. The risk mitigation was developed using a performance based approach, considering the expected performance in hazard events. The performance based approach provides a rational approach to earthquake risk mitigation to achieve the required performance, rather than a strength based approach to predetermined code design levels.

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