Seismic strengthening of the Seatoun Tunnel

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ABSTRACT

The Seatoun Tunnel is a 147 m long, vehicle and pedestrian tunnel built in 1906-1907 to provide a tram connection between the suburb of Seatoun and the city of Wellington. In 2011, the Seatoun Tunnel structure was assessed as part of a Wellington City Council programme to ensure the resilience of its key transport routes. The assessment concluded that the unreinforced concrete portals, wing walls and retaining walls were vulnerable to failure in moderate to large earthquakes and would require strengthening.

The portal strengthening works comprised construction of new reinforced concrete buttress overlays on both portals, new concrete ground beams hidden behind the parapet walls and a reinforced concrete beam to support the retaining wall at the south portal end. In addition, rock anchors were installed to tie back the buttresses, ground beams and retaining wall into stable rock. Strengthening work had to be completed while maintaining safe traffic passage through the tunnel at all times and minimising noise to the neighbouring residential environment.

Previous technical papers have examined the seismic performance assessment and design of strengthening measures and this paper examines how the strengthening was implemented in a live and challenging operational environment. The paper will describe the materials and construction methodology associated with the new reinforced concrete elements and rock anchoring, including the testing and performance of the rock anchors.

The work was completed in May 2020 and the result is an important and vital community infrastructure asset successfully strengthened and restored to a high standard of safety and earthquake resilience.

1 INTRODUCTION

The Seatoun Tunnel (also known previously as Crawford's Tunnel) is a 147 m long, vehicle and pedestrian tunnel located between Broadway Road in Strathmore and Ferry Street in Seatoun, Wellington. The tunnel was constructed in 1906-1907, originally to extend the tramline to the suburb of Seatoun.

The tunnel provides vital vehicle access through the hill that separates the suburbs of Strathmore and Seatoun. It carries about 6,500 vehicles a day. The alternate access routes over the hills and along the bays are much longer and more vulnerable to slope failure and underslips, hence are less resilient and not expected to be available immediately after a major earthquake. The tunnel lining comprises cast in-situ unreinforced concrete side walls, about 2.5 m in height, supporting the brick arch. The tunnel is 8.1 m wide at road level and has a 6.2 m wide carriageway, and a 1.2 m wide footpath raised about 0.6 m above the carriageway level.

2 RETROFIT DESIGN

2.1 Seismic Performance Assessment

A previous assessment of the seismic behaviour of the Seatoun Tunnel concluded that strengthening of the tunnel barrel was not necessary. The unreinforced concrete portal and wing walls at both portal ends and the retaining wall on the Strathmore end of the tunnel were found to be vulnerable to failure in moderate to large earthquake events, i.e., with recurrence periods larger than 100 years. Failure of these portal structures could lead to collapse of the tunnel barrel adjacent to the portals. This could cause access into Seatoun to be closed for several weeks or longer, as post-earthquake resources are likely to be focussed on the recovery of the city centre and regional access routes. Strengthening of the tunnel portals was recommended to enhance the resilience of this route.

2.2 Strengthening Solutions

Strengthening works that had been successfully used on other similar Wellington tunnels were utilised again on the Seatoun Tunnel. These were applied to the Seatoun portal (Northeast end) and Strathmore portal (Southwest end) (Gkeli et al, 2021). These measures comprised (see Figure 1):

- Reinforced concrete ground beams hidden behind the portal wall to provide lateral support and resist the ground loads from the slope behind.
- Reinforced concrete overlays to strengthen the existing buttresses either side of the portal arch, on both portals.
- Reinforced concrete beam to support the retaining wall on the eastern side of the Strathmore portal.
- Rock anchors to tie back and carry the loads on the ground beam, portal face, buttress overlays and the retaining wall into stable rock.

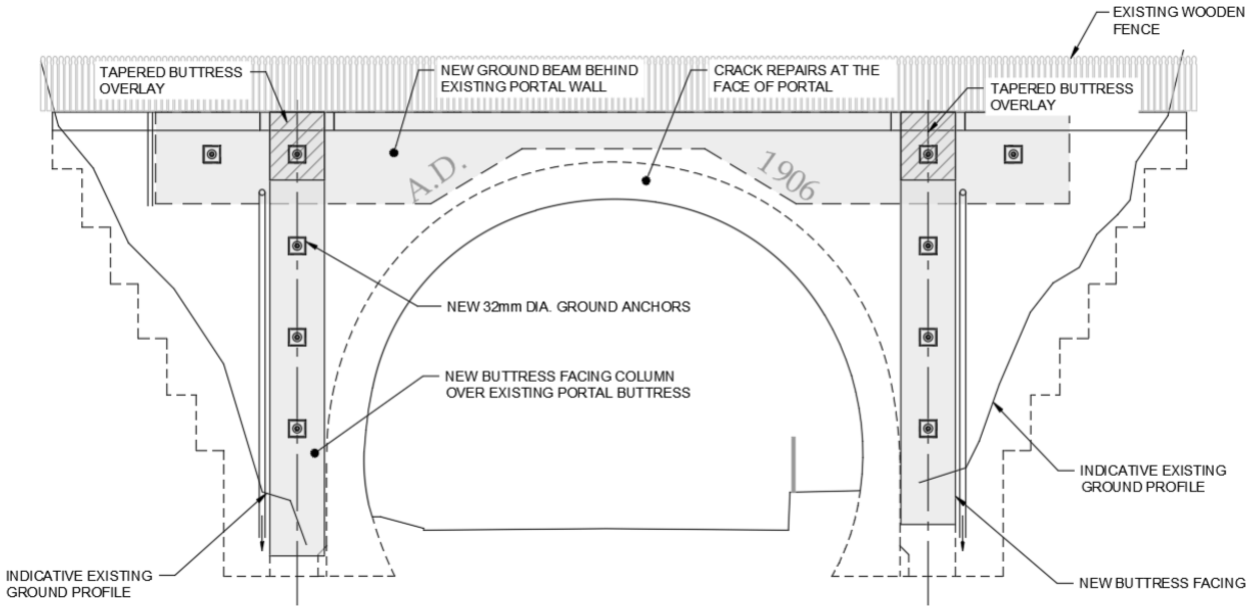

Figure 1: General layout of strengthening measures of Seatoun Tunnel portals

2.3 Heritage Design and Consenting

The Seatoun tunnel is a heritage structure, and strengthening design required careful consideration of the heritage issues to preserve the heritage status of the structure. This included locating the ground beam behind the portal and parapet, a reinforced concrete overlay to the buttresses to match the existing buttresses and locating the rock anchor heads within the reinforced concrete elements and portal wall, so that they are not visible and do not detract from the heritage of the tunnel structures. This required careful detailing of the anchor head to provide adequate capacity for transfer of the loads.

The design was carried out in consultation with heritage advisors and the Council, and resource consents were obtained to carry out the strengthening works.

The final repair and restoration of the concrete structure preserved the original appearance with little evidence of the new concrete beams and ground anchors. Figure 2 shows images of the Seatoun portal end before and after strengthening work.

Figure 2: View of the Seatoun portal end, before and after the strengthening works.

3 CONSTRUCTION FEATURES AND CHALLENGES

3.1 Rock Anchors

The rock anchors were configured using 32 mm dia. Macalloy 1030 MPa, double corrosion protected bars grouted into rock. The anchors were post-grouted using a tube-a-manchette (TAM) system to provide good capacity and minimise the need for pre-grouting and re-drilling in the variable rock conditions.

This configuration had been successfully utilised on other portal strengthening projects including Hataitai bus tunnel and Mt Victoria tunnel. The design had previously provided very good bond into the weathered rock conditions that was typical at these sites. Geoscience (2015) describes the rock at both portals as comprising highly to moderately weathered Greywacke. The nature of the rock at the portal locations can be seen in the original construction photographs as shown in Figure 3.

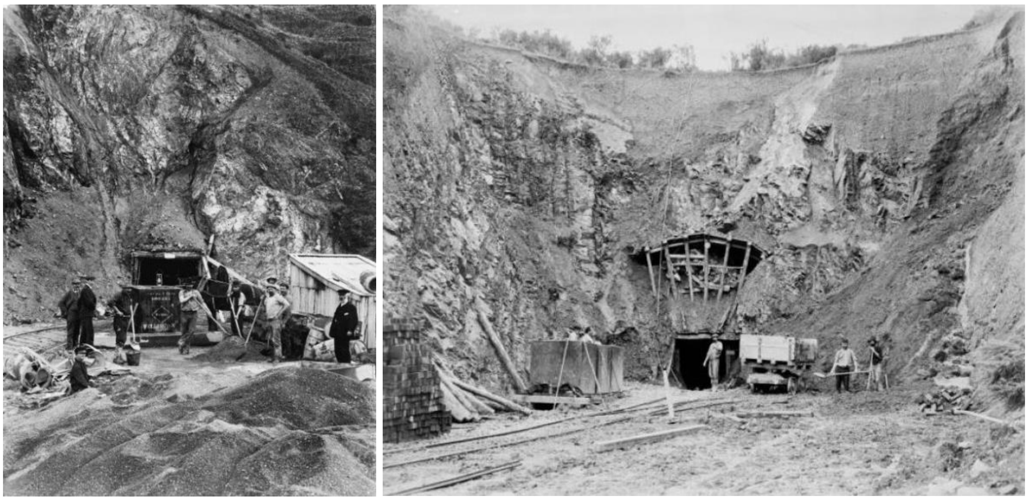

Figure 3: Photographs of the construction of the tunnel portals taken circa 1905-1906.

3.1.1 Trial Anchors

Verification of the anchor capacity is critical for each project due to the variable ground conditions. Four trial anchors were installed, and proof tested in accordance with the procedures in BS8081:1989. Trial anchors were configured using 50 mm dia. Macalloy 1030 MPa bar with an ultimate tensile capacity of 2022 kN. A bond length of 2 m was used, and the trial anchors were tested to failure to confirm the ultimate ground/grout bond strength. The proof test anchors had a hole diameter the same as required for the production anchors and the installation, grouting and post-grouting was to the same methodology as the production anchors.

Two trial anchors were installed in the Seatoun end portal and two in the Strathmore end retaining wall. The results of the trials are summarised in Table 1. The high applied forces required the use of specially designed steel plates to ensure the existing retaining wall could distribute forces without failure or excessive displacement. Load was applied using a centre hole stressing jack connected to a PROCEQ 5000 kN electronic load cell.

The trial anchors were load tested in multiple load cycles as prescribed by Table 13 of BS8081 and creep measurements were recorded. All anchors satisfied the creep criteria with maximum creep recorded as 0.2 mm. The failure mechanism was at the ground/grout interface and the ultimate bond strength was in excess of 1 MPa. The load testing operation is shown in Figure 4.

Table 1: Summary of the trial anchor results.

Ref	Tendon	Hole Dia (mm)	Bond Length (m)	Overall Length (m)	Failure Load (kN)	Bond Strength at Failure (MPa)	Post-grout Cycles
PT1 (Seatoun)	Macalloy 50	150	2.0	10.2	1140	1.20	3
PT2 (Seatoun)	Macalloy 50	150	2.0	9.0	1030	1.09	3
PT3 (Strathmore)	Macalloy 50	150	2.0	9.0	1210	1.28	3
PT4 (Strathmore)	Macalloy 50	150	2.0	7.0	980	1.04	3

Figure 4: Load testing of trial anchors with specially designed load distribution plates.

3.1.2 Production Anchors

A total of 24 rock anchors incorporating post-grouting were installed at both portals. All anchors comprised 32 mm dia. Macalloy 1030 MPa bar with an ultimate tensile capacity of 828 kN. The post-grouting was necessary to ensure the anchor was securely bonded into the highly weathered rock at the site. The typical sequence for all anchors comprised:

- Preliminary grouting of the bars into an HDPE sheath, to provide double corrosion protection.
- Drilling of the anchor hole and installation of the pre-grouted anchor assembly into the hole together with a post-grout tube (with node valves) and grout tube.
- Primary grouting of the anchor through the grout tube, using a bottom-up approach.
- Cracking the primary grout after 8-12 hours curing by applying high water pressures at each node using a tube-a-manchette (TAM). This was followed by a successive post-grouting operation through the TAM, node by node, placing a controlled amount of grout, and flushing the post-grout tube after each round of post-grouting. Each round of post-grouting was continued until sustained pressures of 400 psi to 500 psi were achieved to demonstrate a tightly grouted rock-grout interface. Usually 2 to 3 rounds of post-grouting were required.

The anchor drilling activity had to be carried out using relatively portable equipment due to the access constraints on the site. A fully-cased drilling system was used to ensure the hole remained open and stable during drilling and for anchor installation and grouting. The drilling and anchor installation required single lane closures to allow room for the drilling mast and installation of pregrouted anchor bars. The drilling equipment is shown in Figure 5.

The contractor elected to carry out the anchor drilling and installation in advance of the construction of new reinforced concrete buttress overlays and beams. Testing of the production anchors could only proceed once the new structural members were in place. This posed some additional risk in the event that the rock anchors did not pass the load test but the performance of trial anchors and full installation methodology suggested that this would not cause any issue.

Figure 5: Rock anchor drilling equipment.

A summary of all production anchors installed is included in Table 2. The overall anchor lengths varied reflecting the anchor entry point and profile of the underlying founding rock. The number of post-grouting cycles was typically 2 with an additional cycle required on a total of 3 anchors. The testing regime comprised suitability and acceptance testing as prescribed in BS8081. There was one suitability test for each set of anchors and the balance were subject to an acceptance test. The performance characteristics and creep testing for each anchor were relatively consistent and representative of the trial anchor testing.

Table 2: Summary of production anchors.

Location	**Ref**	**Tendon**	**No. of Anchors**	**Hole Dia (mm)**	**Bond Length (m)**	**Overall Length (m)**	**Test Load (kN)**	**Post-grout Cycles**	**Lock-off Load (kN)**
Strathmore Portal	SW1-9	Macalloy 32	9	150	3.0	7-10.0	485	2-3	80
Seatoun Portal	NE1-10	Macalloy 32	10	150	3-4.0	8.5-11.0	485	2-3	80
Strathmore Retaining Wall	RW1-5	Macalloy 32	5	150	3.0	8-13.0	485	2-3	80

Following construction of the reinforced concrete buttress overlays and beams, the anchor testing could be completed. Once the test results were approved by the Engineer, the anchor nut was protected against corrosion and the anchor recess was filled with mortar. There was no requirement for any future load monitoring or re-tensioning and the anchors could be covered over so they were no longer visible.

3.2 Reinforced Concrete Buttress and Beams

These structural elements were relatively conventional and only required standard construction methodologies. The main challenge experienced was planning and sequencing the work with very limited working room and the need to maintain safe traffic passage through the tunnel at all times. A full scaffold system was designed and constructed to provide full access up the buttresses and across the top of the tunnel. This allowed access to both sides of the portal regardless of lane closures. It also provided the base platform for setting up formwork and placing reinforcement and concrete.

The construction of the ground beam along the top of the portal required caution when excavating to ensure no damage was caused to the top of the existing tunnel. Temporary measures comprising rock bolting, shotcrete and rockfall netting were implemented to ensure stability of the excavation and to provide a safe work environment for personnel. Figure 6 shows photographs of the construction of beams and concreting activities with traffic management in place.

3.3 Concrete Repairs and Painting

The portals exhibited some signs of concrete deterioration and there were some isolated crack sealing and minor patch repairs required at both portals. This work was assessed once the access system was put in place and the scaffolding allowed ready access across the whole face to effect the repairs. The painting of the portals and retaining wall was carefully carried out so that the existing colours were matched, and heritage aspects maintained. An anti-graffiti surface treatment was applied to all painted areas to facilitate future graffiti removal as required.

Figure 6: Photographs of the beam construction activities at each end of the tunnel.

3.4 Traffic Management

A key success factor to the implementation of the strengthening systems was management of the traffic and ensuring that the construction activities could proceed while maintaining safe vehicle, pedestrian and cycle access through the tunnel. There were frequent requirements for single lane closures for both day and night activities. Prior to contract work starting Wellington City Council installed fixed traffic lights at each end of the tunnel to assist with traffic management during the works and for any further tunnel maintenance that may require traffic control. Routine traffic management consisted of temporary lane closure through the length of the tunnel with traffic lights controlling the single lane traffic flow. Daily operation of traffic lights was successfully coordinated between the Wellington City Council transport team and the site contracting team. Night closures and traffic diversions had to be implemented on several occasions to facilitate cleaning and painting work to the inside of the tunnel. One of the main project achievements was that, despite the interruptions and inconvenience caused by site works to regular tunnel users, no public complaints were received during the contract.

4 CONCLUSIONS

While the photographs of the finished portal strengthening work may give the appearance that the work was relatively straightforward, the project had its challenges, including a requirement to maintain safe traffic passage at all times. In addition, given the tunnel’s residential neighbours, noise had to be minimised as much as possible – especially when working at night. The rock anchoring work was a significant element of the work and it required meticulous planning and execution to ensure the performance of the in-place anchors. The experience gained by the designer, contractor and Wellington City Council on other similar projects was invaluable in ensuring a successful outcome.

The project also had its rewards, with completion ahead of schedule (in May 2020), despite the inconvenience of a four-week pause in proceedings owing to Wellington's 'Alert Level 4' status in the COVID-19 pandemic. The result is an existing structure strengthened and restored to the highest standards of safety and earthquake resilience, and a community asset that will enable residents to come and go for many years to come. Close collaboration of all parties associated with the work was instrumental in delivering this project and the key project participants stand proudly in front of the completed Strathmore portal in Figure 7.

5 ACKNOWLEDGEMENTS

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Figure 7: The proud project team at the Strathmore portal end after completion.

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