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Tawhai tunnel lining recovery

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ABSTRACT: Tawhai Tunnel, located on KiwiRail's Stillwater–Ngakawau Line (SNL) on the West Coast of New Zealand's South Island, was constructed in 1891 and is 373m long. Its tunnel lining system consists of a 250 to 400 mm thick concrete sidewall extending to the tunnel spring-line and a single-layer, 250 mm thick concrete block arch forming the tunnel crown. In mid-June 2024, the 133-year-old tunnel had three sections of tunnel lining fail. Immediately following the event, KiwiRail established a multi-disciplinary tunnel recovery team, comprising the Client (Ki-wiRail), Design Consultants, and Contractors. This team worked collaboratively to restore the tunnel safely, efficiently, and to a high-quality standard within a short timeframe. The recovery design and construction work were completed within 26 weeks, and the tunnel reopened for coal train operations on 12 January 2025. This paper provides a brief overview of the tunnel's con-struction history. Based on site observations, it also discusses the back-analysis undertaken to determine geotechnical analysis parameters plus the design and construction of the recovery and strengthening works throughout the tunnel. Special attention is given to the unique planning, de-sign and execution challenges relating to this tunnel project.

1 INTRODUCTION

Tunnel 1, Tawhai Tunnel, on the SNL is located on the West Coast of New Zealand's South Island, near Reefton. Both tunnel portals are accessible from State Highway 7, Figure 1. The tunnel length is 373 m. State Highway 7, which connects Greymouth and Reefton, passes closely over the southeastern side of the tunnel at a location known as the 'Reefton Saddle'.

Figure 1. Location of SNL tunnel 1 and south portal.

Constructed in 1891, the existing tunnel lining system comprises lower concrete sidewall extending to the tunnel springline and a single-layer concrete block arch forming the crown. The block arch is approximately 250 mm thick, while the concrete sidewalls range from 250 to 400 mm in thickness.

In June 2024 during planned track works inside the tunnel, some issues were identified with the 133 year old tunnel lining. The tunnel was safely evacuated and drone video surveys were undertaken which identified three sections of tunnel where the lining had partially collapsed.

This paper focuses on the tunnel recovery works design and construction.

2 GEOLOGY

The regional geology is based on the GNS Science 1:250,000 geological map of the Greymouth area. The tunnel is situated within the Pliocene-aged Old Man Group, comprising weathered gravel with predominantly greywacke and schist clasts. Approximately 1 km southeast of the site, Ordovician Greenland Group basement rocks outcrop, with a thin strip of fluvial sandstone, estuarine mudstone, and minor conglomerate forming the basal unit of the Old Man Group along the unconformity. Site walkovers, test pits, drilling, and historical photos confirm the presence of Old Man Group gravels at the tunnel ends, and it is inferred the tunnel remains within these gravels along its entire length. All modelling and analysis assumes that the tunnel is entirely within the Old Man Group gravels. Figure 2 presents an interpretative ground model of the middle tunnel section.

Ground cover to tunnel crown is 20 to 56 m and at collapse locations are about 30 m. Limited piezometer monitoring data showed groundwater head is approximately 4 to 5 m above tunnel crown. Measurement of the tunnel outflow over tunnel length of approximate 200m from the northern portal has been reported as 0.2 to 0.3 L/s in dry weather conditions and 0.5 to 0.6 L/s after 100 mm of rainfall over a week, in early to mid August 2024.

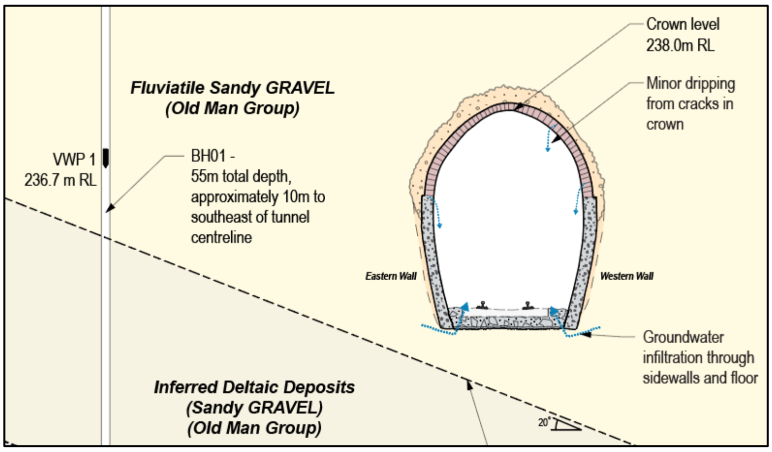

Figure 2. Interpretive geology of SNL tunnel 1.

3 TUNNEL BACKGROUND

3.1 *Tunnel construction history*

With reference to the tunnel records provided by KiwiRail, excavation and lining works for the tunnel were carried out between the late 1880s and 1891. There are no indications that suggests that temporary support was required during tunnel excavation prior to the installation of the permanent lining.

Track lowering works were undertaken in 1984 to improve train clearance. Approximately 14m from the north portal, a section of the original concrete block arch was removed and replaced with a steel rib arch. Additionally, the concrete sidewalls were strengthened by applying an approximately 100 mm thick layer of reinforced concrete.

3.2 *Fall of grounds*

The lining failure occurred on the morning of 15 June 2024. Three separate Falls of Ground (FOGs) developed, Figure 3. After the initial failures, there were no additional ground falls observed (based on repeat drone video surveys conducted while tunnel access remained restricted). A 3D point cloud survey was undertaken to record and assess tunnel deformation and to capture detailed information related to the FOGs.

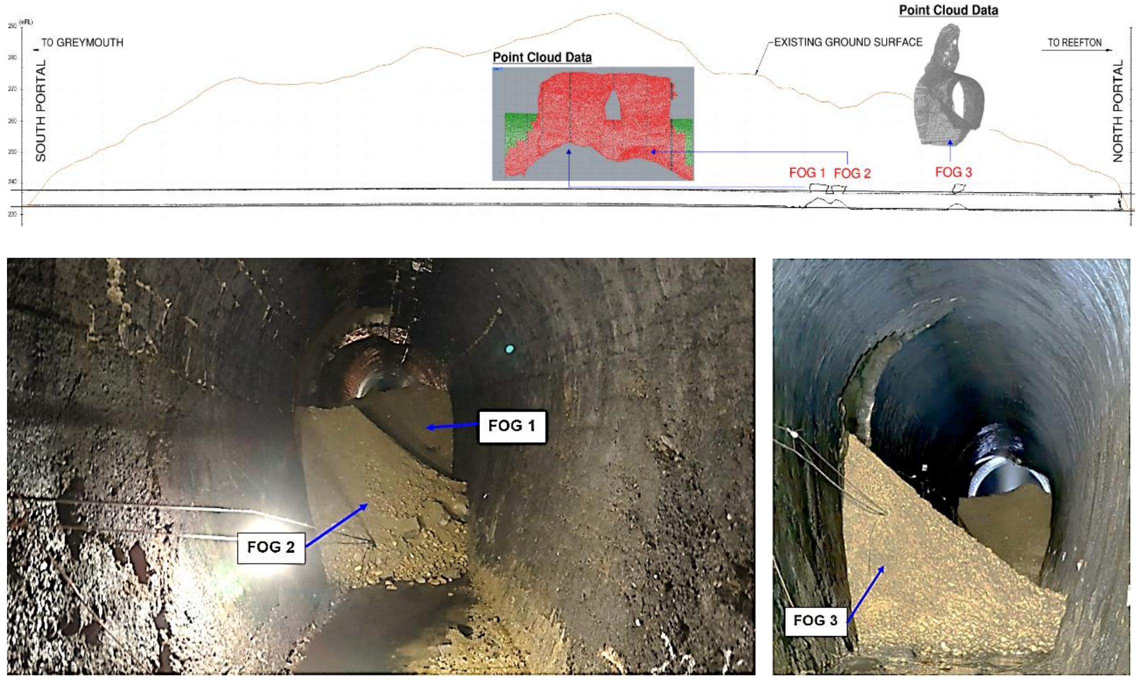

Figure 3. Tunnel long section and fogs of SNL tunnel 1

3.3 *General tunnel condition*

After the FOG event, the tunnel lining near the FOGs deformed with inward movement of 100 to 200mm at walls and shoulders. Other areas of the tunnel were observed with negligible movement by scan profile comparison before (Dec 2023) and after the event (June 2024).

The materials and construction details were consistent with a tunnel structure over 130 years old. The cored concrete test showed the concrete strength ranging 6 to 16 MPa.

To ensure a long-term resilient future for the tunnel, it was decided that the lining should be treated for the whole length of the tunnel.

4 THE TUNNEL SUPPORT SYSTEM

4.1 *General concept*

The primary focus was developing a solution which effectively treated the tunnel lining and could be executed very rapidly in order to re-open the railway line as soon as possible.

The project team considered plant and resources that were immediately available for use under emergency conditions. There were different recovery options developed considering the use of shotcrete and/or cast-in-place concrete, ground anchoring, different types of track formation plus tunnel invert and footing treatments to achieve the required tunnel clearances, safe tunnel restoration and long-term structural resilience.

A detailed assessment was carried out to evaluate the different recovery options by comparing their advantages and disadvantages. The selected recovery solution included ground anchors, a ballast trackform over a sub-ballast concrete slab, and a new shotcrete lining as presented in Figure 4.

A clearance assessment was also conducted, which considered the independent kinematic envelopes of three different wagon and locomotive types. These represented the worst-case clearance scenarios for all rolling stock with operational access rights through the tunnel.

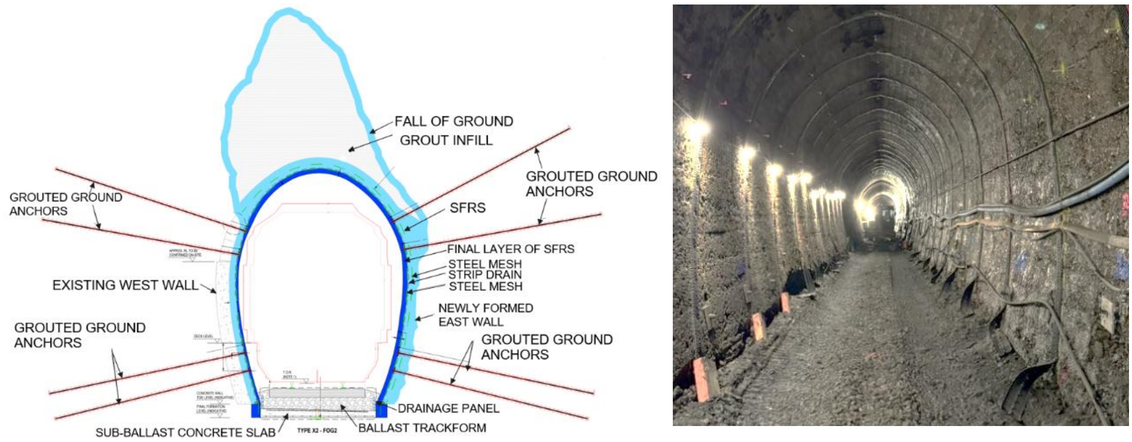

Figure 4. Typical tunnel recovery system.

4.2 *Geotechnical back analysis*

A back-analysis was conducted to determine appropriate geotechnical parameters (effective cohesion *c'*, friction angle ϕ', and Young's modulus *E*) for modelling tunnel stability and observed site conditions. Using PLAXIS 2D, key parameters—particularly *c'* and ϕ'—were iteratively adjusted and validated against slope stability analysis results (e.g. steep and stable slopes were observed along the nearby rail corridor and State Highway 7) and 3D Point Cloud data. The modelling aligned well with the observed geometry of the FOGs.

Ground arching height was estimated using the back-calculated parameters and Terzaghi's theory. The agreement between analytical results and site observations supported the reliability of the selected parameters and confirmed the inferred ground loads.

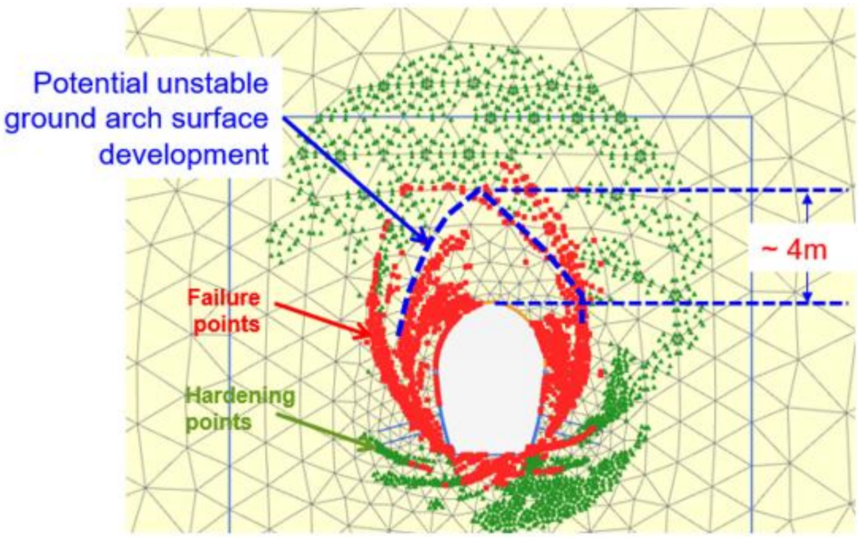

Figure 5. Ground failure development and ground arch formation, PLAXIS 2D.

4.3 *Tunnel collapse recovery and improvement works*

4.3.1 *Typical tunnel support system*

The typical tunnel support system was formed by (1) ground anchors, (2) shotcrete lining, and (3) ballast track form, and (4) sub-ballast concrete slab. This system extends to the whole tunnel with varying quantities depending on the specifics of the different tunnel sections.

1. Passive ground anchors (e.g. no pre-tensioning) were installed on the lower walls as pre-support measures to maintain lining stability for further floor lowering for track formation work and at other locations where required.
2. Steel Fibre Reinforced Shotcrete (SFRS) of 40 MPa was adopted to reinforce the existing tunnel lining. The fibres used have a maximum length of 35 mm, with a length-to-diameter ratio of 65. The minimum dosage applied was 35 kg/m³ in mixed shotcrete to achieve the required structural performance.
3. The existing tunnel is a drained tunnel, and the recovered tunnel lining remains consistent with this approach. Strip drain channels were installed at regular intervals to collect seepage and direct it to the longitudinal subsoil drain integrated within the ballast track form.
4. The reinforced sub-ballast concrete slab is designed to withstand train loading, the self-weight of overlying materials, axial loads transferred from the tunnel lining, and groundwater pressure in the event of drainage blockage. The slab is maintained in a drained condition through the installation of riser pipes with Megaflo panels, which effectively manage water beneath the slab and prevent the build-up of hydrostatic pressure.

4.3.2 *Fall of ground support*

In addition to the typical support system, reinforcement mesh was incorporated into the shotcrete lining to provide additional structural capacity at the locations of the Falls of Ground (FOGs). Furthermore, shotcrete and anchor supports were installed immediately adjacent to the FOG areas before any work commenced within these zones. The cavity was backfilled in stages using grout and lightweight expansive concrete. Any debris and damaged concrete block or wall sections were removed prior to backfilling. A 3D numerical analysis, Figure 6, was conducted in FLAC 3D to assess the effectiveness of the tunnel collapse treatment measures, specifically to evaluate the safety and feasibility of people entering and working beneath the affected areas.

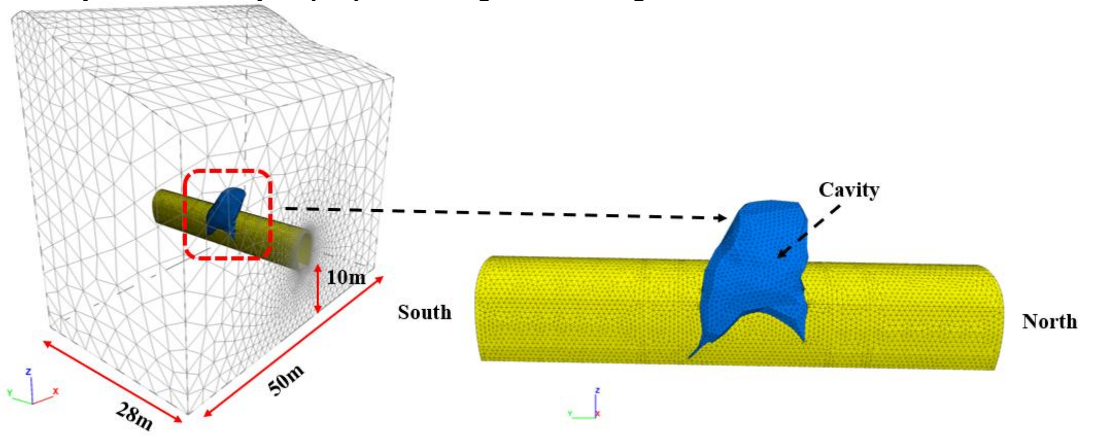

Figure 6. 3D Analysis of temporary support works, FLAC3D.

Detailed step by step support and construction sequences for FOGs crossing was developed in agreement with the client and the construction team which was then detailed in the construction drawings. The key aspects are:

- No personnel were allowed to enter the unsupported ground areas.
- Shotcrete and anchors support were completed right next to the FOGs prior to commencement of works within FOG area.

- Removal of debris and damaged concrete block/wall took place from the top in 0.5m increments.
- Sealing the exposed ground cavity with total 150mm thick SFRS in layers was undertaken.
- The damaged lining was sealed or plugged to re-form the tunnel arch using steel mesh (and prefabricated metal for FOG1 and FOG2) to receive SFRS.
- At FOG3, a full 100mm thick SFRS was applied to the entire tunnel section covering at least 2m before and after the collapse area to provide initial support.
- At FOG1 and FOG2, a construction sequence was developed for the top heading (to form a temporary working platform, seal natural the ground and re-form lining arch) and bench (to remove the remaining debris and damaged wall).
- Final structural support was constructed prior to final backfilling of the cavities.

4.3.3 *Fall of ground crossing works*

Excavation and support works were managed using a Required Excavation and Support Sheet (RESS) for each defined section, based on the design drawings. Regular Tunnel Review Meetings (TRMs) were held to assess working conditions and review the excavation and support measures outlined in the RESS. These meetings evaluated whether the current RESS remained suitable or required amendments, based on worker observations, convergence and crack monitoring, lining quality (existing and new), installed support systems, geological and hydrogeological conditions, and construction sequencing.

For the recovery of the FOG, an initial thickness of shotcrete was applied to the roof cavern to stabilise the exposed ground and restore the ground support conditions for safe entry. To rebuild the tunnel structure and re-establish ground arching, Tek mesh was installed around the new arch for the initial shotcrete application. Reinforcing bars, spaced at 1 m intervals, were bent to improve the mesh stiffness. Reinforced mesh was then bent and installed onto the bars. Tek mesh was clipped to the reinforcement mesh to ensure good adhesion of the shotcrete. The mesh was positioned above the existing tunnel profile to allow sufficient thickness for the development of a new arch, approximately 400 to 500 mm thick. The remaining void above the newly formed lining was filled with grout and low-density expansive concrete.

Figure 7. Fall of Ground (FOG) crossing works.

4.3.4 *Fall of ground crossing challenges*

The fall of ground crossings were particularly challenging (compared with the wider tunnel works) due to having to work above the spoil pile with limited visibility overhead to install roof support. The shotcrete robot had to work at the limits of its geometric range. Multiple scans were required to capture and review applied thickness and ensure adequate temporary support was installed.

Because of the fall of ground, sequential removal of spoil with immediate support installation was required to re-establish tunnel stability. The spoil pile had to be removed in small vertical increments with lower wall support installed with each cycle. Mucking out was able to be done with the use of an underground loader with long reach able to keep operators out from underneath the fall area until temporary support had been installed down to floor level.

Ensuring tunnel support at the collars of the falls of ground were also challenging to work through. To address this, where required additional anchoring was undertaken.

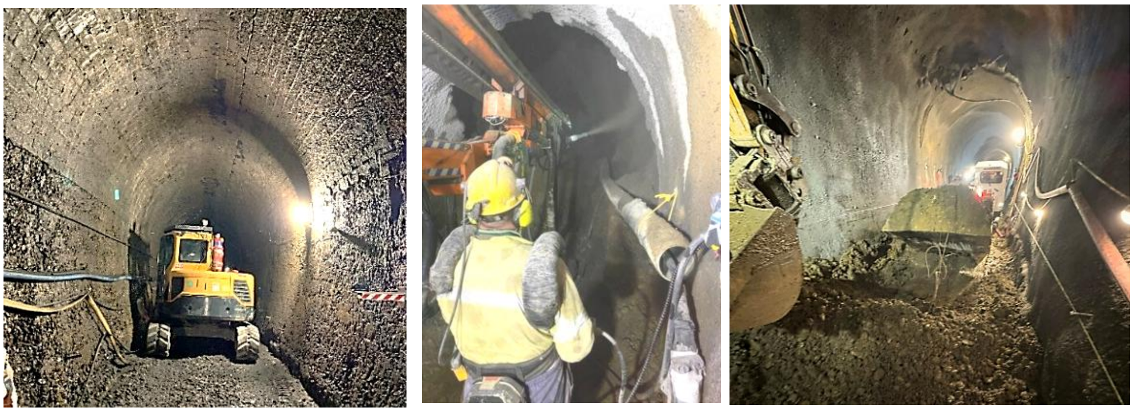

Figure 8. Machines operating in constrained work site.

5 CONSTRUCTION LOGISTIC AND CHALLENGES

The recovery works presented a range of logistical, geotechnical, and operational challenges due to Reefton's remote location in the South Island and the constrained working areas at the tunnel.

Limited local availability of materials (particularly shotcrete, steel anchors, and grout) combined with the absence of nearby suppliers and ready-mix plants, created some logistics challenges and the need for careful planning to ensure effective delivery of the recovery works. Given the remote location, turnaround times for material and quality assurance testing were longer than industry norms. These issues required special procedures to be put in place in order maintain the recovery programme.

The clearance between the finished support surface and the required design train structural gauge profile was tight, often within 10 mm. Daily scanning and depth pin control were used to manage shotcrete thickness. Depth pins could not be installed in "unsupported" sections, requiring operators to work carefully and precisely. A temporary shotcrete layer was often applied first to provide safe access for installing depth pins before the final shotcrete coat was placed with high accuracy. Ground anchor hardware had to be carefully selected to minimise anchor head protrusion and the position of every anchor had to be set out to avoid pinch points around the train structural gauge profile. Several sections of the newly sprayed shotcrete lining still fouled the train profile and required milling to achieve the required train clearances.

Site access was limited to a single-entry point with tight clearances, often preventing personnel access during machine operations. Using multiple machines introduced delays, as equipment had to be swapped in and out of the tunnel. The narrow access and profile also created safety challenges, especially for ventilation, emergency egress, and personnel movement during early recovery stages. Spatial constraints limited machine size and power, affecting excavation and support rates. The site's remoteness and tight programme further complicated the selection and transport of compliant underground machinery.

Worker safety under sections of the existing lining with varying stability was a key challenge during the recovery work. A domain map was used to communicate which areas of the tunnel were safe to work in and access. The map was kept up to date and used as a key tool communicating with the construction crews.

Given these logistical and physical challenges and programme constraints, the project team had to adopt an adaptive construction approach, with continuous re-evaluation of support designs based on observed ground behavior. Close collaboration between the Contractor, Designer, and Client representatives was essential to manage safety risks while maintaining progress. Frequent shift review and toolbox talks, revised sequencing, and temporary support modifications were employed to address emerging issues in real-time.

6 CONCLUSION

The recovery design and construction work were completed within 26 weeks, with the tunnel reopening for coal train operations on 12 January 2025. Robotic machines applied approximately 950 m^3 of concrete to reinforce the tunnel lining. A total of 886 rock bolts were installed to anchor the lining to the surrounding ground. Additionally, about 373 m of modern concrete tunnel lining and a new track bed drainage system were installed.

The project was successfully delivered through a fully integrated, multidisciplinary team approach, with all parties working as one to achieve safe, efficient, and high-quality outcomes. Strong collaboration, tunnel support design re-evaluation, and shared commitment enabled the team to overcome challenges and complete the works within a short timeframe.

Figure 9. Repaired SNL tunnel 1.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Terzaghi, K and Peck, R. 1948. *Soil Mechanics in Engineering Practice*. John Wiley & Sons, London.