Waterview Connection Project Cross Passage Tunnels:
Safety in Design and Construction

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ABSTRACT

The Waterview Connection is the final 5km link to complete the NZ Transport Agency’s Western Ring Route motorway around Auckland. The Waterview Connection is the largest and most complex road infrastructure project ever undertaken in New Zealand. A 14.4m outside diameter Earth Pressure Balanced (EPB) Tunnel Boring Machine (TBM) was used to complete the twin 2.4km long tunnels, located at the heart of the scheme.

The Well-Connected Alliance delivering the project recognized the importance of identifying and mitigating hazards throughout all phases of the project. As a result, a rigorous safety-in-design procedure was mandated for all design packages so that safety risks were designed out wherever possible. The risk mitigation measures were implemented in construction works, with multiple verification mechanisms in place.

This paper describes key design and construction safety-in-design features that were developed for the 16 cross passages linking the two mainline tunnels. Such measures included a clear and robust safe man entry procedure for working under green shotcrete; excavation and lining geometry optimized for risk mitigation; extensive shotcrete trials designed for requisite early strength gain and all anticipated conditions; canopy tube ground support; and targeted grouting in high permeability zones. Safe benched excavation sequencing was adopted to address the confined nature of the relatively small, short cross passage tunnels. Critical construction activities were monitored with instrumentation to ensure safety of personnel at all times. This case study provides learnings from the project’s safety-in-design and construction initiatives, which set a benchmark for the industry practice. The Waterview Connection cross passage tunnels were all successfully completed on time without any accidents or lost time injury.

1. INTRODUCTION

Recent advancement in tunnel construction technique has dramatically reduced the rate of accidents in tunnel construction. This safety improvement is also further driven by increasing safety awareness around the globe. However, the general consensus seems to be that the rate of serious harm and incidents is still relatively higher in sequential excavation methods (SEM) tunnel construction compared to the construction industry in general as suggested by, for example, Kikkawa et al (2015). Therefore, it is absolutely critical that the industry continues to raise safety awareness and improve tunnel safety-in-design and construction practices. One way of achieving such objectives is to proactively share knowledge and lessons learned from projects and case histories in industry forums. This paper presents a number of safety measures implemented in the design and construction of mined cross passage tunnels on the Waterview Connection Project. While it is acknowledged that
some of these safety measures and features may already be a standard practice in some regions and countries, they may be relatively uncommon or even unheard of in some other parts of the world. It is the authors’ wish that the successful outcome of the safety-in-design and construction initiatives implemented on the Waterview Connection Project will help advance these safety practices in the broader tunnel industry.

2. PROJECT OUTLINE

The Waterview Connection completes Auckland’s Western Ring Route by linking the city’s Northwestern and Southwestern Motorways (State Highways 16 & 20). The Western Ring Route will ease pressure on heavily congested State Highway 1 through central Auckland, and is also recognized as a project that will help underpin economic growth for New Zealand; add resilience to the motorway network in the country’s largest city; provide more reliable and safer journey times; and remove traffic off some local roads. The Waterview Connection comprises a new 5km motorway scheme with 2.5km long, 13.1m diameter twin bored tunnels. The project was delivered by the Well-Connected Alliance for the NZ Transport Agency on behalf of the New Zealand Government. The project location is shown in Figure 1.

The twin bored mainline tunnels are supported by a precast concrete segmental lining, reinforced using a combination of steel fibres and conventional steel reinforcement. The tunnels are interconnected by 16 mined cross passages (XP02–XP17) positioned at intervals of around 150m. The ground cover ranges from 18m to 43m. The cross passages have two primary purposes: to provide emergency egress between tunnels and to house mechanical and electrical equipment that support tunnel operations.

Figure 1. Waterview Connection Route
3. GEOLOGY AND HYDROGEOLOGY

The vertical tunnel alignment was designed so that the majority of the tunnel is within a sequence of inter-bedded extremely weak to weak siltstone and sandstone, as well as volcaniclastic sandstones (Parnell Grit) comprising the East Coast Bays Formation (ECBF). The unconfined compressive strength (UCS) of the siltstones and sandstones is typically in the range of 1 to 5 MPa, while the Parnell Grit often exhibits UCS values that are in excess of 10 MPa. The tunnel geological section is shown in Figure 2.

![Figure 2. Tunnel geological section](image)

There are three main areas of significant geological risk that could impact the design and construction of the cross passages. These are:

1. Residual soil and uncemented weak sandstone that occur in the northern end of the tunnel where tunnel cover is shallow (XP16 and XP17). A major road is located at relatively shallow depth above the tunnel.
2. High permeability in the Parnell Grit and surrounding area characterized by faults (XP10-13)
3. Deep weathering profile in the middle section, which imposes additional ground load (XP9).

Based on available geotechnical information, the following ground classes were developed to design the Waterview Connection mainline and cross passage tunnels.

<table>
<thead>
<tr>
<th>Ground class</th>
<th>XP* prop group</th>
<th>Predominant material**</th>
<th>Typ. UCS (MPa)</th>
<th>Typ. RMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>B</td>
<td>Weak sandstone</td>
<td>5-20</td>
<td>&gt;70</td>
</tr>
<tr>
<td>1B</td>
<td>B</td>
<td>Very weak sandstone /siltstone</td>
<td>1-5</td>
<td>50-70</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>Uncemented sandstone</td>
<td>0.6-1</td>
<td>30-50</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>Uncemented sandstone</td>
<td>&lt;0.6</td>
<td>&lt;30</td>
</tr>
</tbody>
</table>

* XP prop group 1A is applicable to several locations with slightly more critical conditions than ground class 1B.
** Rock strength description as per New Zealand Geotechnical Society Field Description of Soil and Rock (2005).
4. **KEY RISKS**

The Well-Connected Alliance identified safety as the most important measure of successful project delivery. Safety initiatives were implemented in all phases of the project, including mandatory risk workshops and safety-in-design workshops for all design work packages. These workshops were attended by all key design and construction personnel. Some of the key risks for the design and construction of the cross passages are summarized in Table 2, along with mitigation measures discussed in detail in the following sections.

**Table 2.** Keys risks and mitigation measures – Waterview Connection Cross Passages

<table>
<thead>
<tr>
<th>Risk</th>
<th>Cause</th>
<th>Consequence</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof falls</td>
<td>Wedges forming in the excavated profile</td>
<td>Serious injury / death</td>
<td>Canopy tube pre-support, early shotcrete strength analysis, enhanced permanent lining geometry</td>
</tr>
<tr>
<td>Face stability</td>
<td>Groundwater and poor ground, unfavourable bedding</td>
<td>Face collapse causing serious injury</td>
<td>Pre-excavation grouting, face dowels in anticipated poor ground in the North.</td>
</tr>
<tr>
<td>Poor adhesion of shotcrete to substrate</td>
<td>Design mix issue, application, water ingress</td>
<td>Shotcrete falls on personnel causing serious injury</td>
<td>Performance specification, shotcrete trial</td>
</tr>
<tr>
<td>Excessive water ingress or loads loosening ground behind lining</td>
<td>Loose material, higher than anticipated groundwater inflow</td>
<td>Serious injury or death</td>
<td>Probing, plugging void, grouting, probing</td>
</tr>
<tr>
<td>Overbreak</td>
<td>Poorer ground conditions, poor excavation control, slabbing</td>
<td>Possible increased loads on lining.</td>
<td>Probe holes, ground improvement or grouting, instrumentation of excavation</td>
</tr>
<tr>
<td>Ground squeezing</td>
<td>Poorer ground conditions, insufficient support, wrong support type, misinterpreted ground data</td>
<td>Lining instability, excessive ground movement, remedial works causing delay</td>
<td>Design allowance for convergence, face mapping, daily review meeting, monitoring</td>
</tr>
</tbody>
</table>
5. SAFETY IN DESIGN

5.1 Cross passage design overview

The cross passages connecting the mainline tunnels serve two primary purposes: to provide egress routes in emergencies and to house tunnel operation equipment. The cross passage tunnels were mined using SEM and supported using a steel fibre reinforced shotcrete (SFRS) temporary lining and a cast-in-place concrete permanent lining. The excavation profiles were a nominal 6.5m in height with a span of 6m and typically 11.6m long.

Figure 3. Completed cross passage permanent lining (left) and opening steel segments (right)

Openings in the mainline tunnels are created within the mainline tunnel precast concrete segmental lining for cross passages using a support system that comprised of steel segments. A total of six purpose-built steel segments 2m in width were built into the concrete segmental lining at each of cross passage location, as shown in Figure 3.

5.2 Shotcrete early strength analyses

Falling ground and/or freshly sprayed shotcrete presents a safety hazard to personnel performing excavation and support activities in a sequentially excavated tunnel or cross passage. The main competing and conflicting factor in this regard is safe re-entry time for personnel versus productivity goals to excavate the next round quicker. Safety assurance is made more difficult in the confined work space of a cross passage between twin tunnels.

To address risks of falling of shotcrete under self weight, due to lack of adhesion to substrate and/or failure caused by weight imposed by a loosened wedge of ground, the design specified that the first layer of the shotcrete shall be placed by a robotic shotcrete sprayer. The first layer shall also be a minimum thickness of 100mm and shall achieve at least 3 MPa unconfined compressive strength before personnel entry was allowed. These requirements were noted in the construction sequence drawings.

Mechanical properties of shotcrete greatly vary from the time of its spray, due to progressive aging and hardening. The wet-mix shotcrete needs to have sufficient fluidity for effective pumping and spraying, while gaining the specified minimum strength to allow early personnel entry. The design basis for the early age strength characteristics for the shotcrete was based on J2-Curve of the O-Norm- Austrian Standards for shotcrete application for tunnel works, shown in Figure 4. The J-2 curve was also compared with quality assurance testing for early age strength from some of the recent major infrastructure projects in Australia and the UK.
The project specifications of the shotcrete works included the necessary requirements for shotcrete mix design, inspection and testing to implement the design in respect of safe re-entry of personnel in the working area of the cross passage.

![Figure 4](image-url)  
**Figure 4.** Early age shotcrete strength gain curve (O-Norm Austrian Standards)

**5.3 Excavation sequence and canopy tube support**

The ground support design initially consisted of an SFRS primary lining of variable thickness with rock bolts or canopy tubes—the latter assigned to poorer ground conditions.

During the construction stage, canopy tubes were installed in advance of excavation for all ground classes, as shown in Figure 5. The canopy tube option allowed longer excavation rounds and eliminated the need for rock bolts, thus allowing faster construction. Most notably, the canopy provided pre-support and enhanced personnel safety significantly.

![Figure 5](image-url)  
**Figure 5.** Cross passage excavation sequence (canopy tube option)
The excavation sequence was also changed from full face to benched excavation as shown in Figure 6.

![Figure 6. Cross passage benched excavation](image)

The main advantage of the benched excavation is that the bulk of excavation can be completed while maintaining the bench at the segmental lining opening level so that excavators and personnel can safely enter and exit without any platform. The invert was completed after the cross passage excavation broke through.

### 5.4 Permanent lining geometry

The permanent lining was designed as a largely unreinforced concrete lining with reinforcing bars only in the collar and invert. This reduces the risk of harm associated with handling steelwork in the confined space of the tunnel.

The introduction of the canopy tubes throughout resulted in an enlargement of the tunnel crown excavation to accommodate the canopy tubes, the position of which was dictated by the location of pre-fabricated penetrations in the steel segments. This would result in around 600 mm of shotcrete in the crown, in order to achieve the temporary lining profile (Figure 7a). This 600mm thick shotcrete in the crown was considered a falling object hazard, so the permanent lining geometry was raised to bring it closer to the canopy tube array to reduce the potentially hazardous thick shotcrete in the crown area, as shown in Figure 7b.

![Figure 7. Cross passage permanent lining geometry enhancement](image)
6. SAFETY IN CONSTRUCTION

6.1 Probing and pre-excision grouting

In addition to observations recorded during routine TBM cutterhead interventions, subsequent observations from three probe drill holes and canopy tube drilling were used to characterize the ground and identify areas of high rock mass permeability, as shown in Figure 8.

In general, the ECBF rock matrix has a very low permeability of around $1 \times 10^{-9}$ m/s while the rock defects have a comparatively high permeability of around $1 \times 10^{-4}$ m/s. Storativity and rock mass permeability is dependent on the defect characteristics (e.g. persistence and aperture) and the level of connectivity between defects.

![Figure 8. Groundwater monitoring probe hole locations (cross passage long section)](image)

Probe hole logging indicated that the most fractured rock mass was encountered around XP8, XP10, XP11 and XP12, shown in Table 3. This was consistent with the high groundwater flow measurements in the probe holes at these cross passages. These four cross passages were selected for pre-excision grouting (e.g. fractures and fissure grouting) prior to excavation to reduce the groundwater inflow and mitigate the risks identified as follows:

- Non-engineered landfill areas were located above the tunnel alignment and persistent fractures could have allowed contaminant migration into the cross passages during excavation.
- Drawdown of the regional or perched groundwater tables could have induced settlement and damaged existing infrastructure and buildings.
- High groundwater inflows would have made cross passage excavation and construction more difficult, particularly with respect to adhesion of the temporary shotcrete support and managing the removal of water from the excavation.
Table 3. Summary of probe hole potential groundwater inflows

<table>
<thead>
<tr>
<th>Test location</th>
<th>Test results</th>
<th>Expected groundwater conditions and considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak inflow(^1)</td>
<td>24 hr inflow(^1)</td>
</tr>
<tr>
<td></td>
<td>(L/min)</td>
<td>(L/min)</td>
</tr>
<tr>
<td>XP 08</td>
<td>76</td>
<td>24</td>
</tr>
<tr>
<td>XP 10</td>
<td>40</td>
<td>26</td>
</tr>
<tr>
<td>XP 11</td>
<td>109</td>
<td>90</td>
</tr>
<tr>
<td>XP 12</td>
<td>66</td>
<td>66</td>
</tr>
</tbody>
</table>

The aim of the grouting was to fill fractures in the rock mass outside the cross passage excavation profile with grout to form a grout curtain and cut-off water from entering the excavation profile. To achieve this, grouting was carried out through “primary,” “secondary” and “tertiary” holes, as shown in Figure 9.

Figure 9. Grout hole layout (cross passage long section)

All holes were grouted regardless of the groundwater inflow rates measured following drilling and grouting was stopped when one or both of the following criteria were met:

a. Volume (Vmax) = 100 litre per metre of borehole. For connected holes Vmax was the sum of Vmax for each connected hole (i.e. for two connected holes Vmax connect = 2 x Vmax)
b. Grout take was < 2 L/min for a period of 5 minutes with pressure at Pmax (7.5 bar)
Table 4 shows the flow recorded out of the tertiary holes to confirm that groundwater inflows had been reduced below the target criteria.

**Table 4: Tertiary reader hole flow rates after grouting**

<table>
<thead>
<tr>
<th>Tertiary reader hole</th>
<th>Target criteria to terminate grouting (L/min)*</th>
<th>Groundwater inflow (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XP8</td>
<td>27</td>
<td>Nil</td>
</tr>
<tr>
<td>XP10</td>
<td>27</td>
<td>12</td>
</tr>
<tr>
<td>XP11</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>XP12</td>
<td>27</td>
<td>2</td>
</tr>
</tbody>
</table>

* The reader holes had a slightly smaller diameter than the original probe holes resulting in a slightly reduced calculated target groundwater inflow for the reader holes of 27 L/min sustained over 24 hours.

The risks were significantly reduced by actively managing the groundwater inflow through pre-excavation grouting.

### 6.2 Shotcrete trial

Adequate strength gain and adhesion of shotcrete are critical issues for safe man entry in the underground environment. Hence it is imperative that the contractor demonstrates that the plant, shotcrete and accelerator are working in unity to achieve a reliable temporary support prior to commencing any underground excavation. Shotcrete trials were undertaken to ensure that the final concrete mix design could achieve the J-2 curve (Figure 4) when sprayed onto the substrate surface.

The critical risks that are associated with spraying underground are:

- Spraying shotcrete overhead
- Spraying shotcrete onto a wet substrate and permeable ground
- Duration of transport to final application

To minimize these inherent risks, a number of trials were conducted to ensure that shotcrete used for temporary support during excavation of the cross passages would meet specifications. The mix design chosen to achieve the criteria had a cementitious content of 450 kg to ensure that the reaction of the cement and accelerator would achieve the required rapid strength gain and achieve the 28-day strength requirements of 30 MPa, as seen in Figures 10 and 11.
Figure 10. Proposed shotcrete mix design – early strength

Figure 11. Proposed shotcrete mix design – long-term strength
The shotcrete early strength was tested using the following:

**Table 3. Shotcrete early strength tests**

<table>
<thead>
<tr>
<th>Testing Method</th>
<th>Testing Duration</th>
<th>Strength Range</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Penetrometer Testing</strong></td>
<td>0.5hr – 3hrs</td>
<td>0.1 – 1.5MPa</td>
<td>Initial testing should be carried out using a penetrometer, Mecmesin BFG 1000m</td>
</tr>
<tr>
<td><strong>Hilti Gun and Pull Testing</strong></td>
<td>3hr–12hrs, every 3 hours</td>
<td>1.0 – 5.0MPa</td>
<td>Nail gun should only be used by those trained by Hilti</td>
</tr>
<tr>
<td><strong>Core Compression Testing</strong></td>
<td>12hrs – 56days, every 7 days</td>
<td>5.0 – 80Mpa</td>
<td>Test should be conducted by an ISO-accredited Lab and Technician</td>
</tr>
</tbody>
</table>

The trials demonstrated that the mix could be applied and would adequately adhere to the various overhead surfaces. Methods were established for testing to provide reliable data to monitor strength gain for direct comparison to the J2 Curve.

To address the risk of delamination from wet substrates, a simple trial was devised to demonstrate application could be achieved in these conditions. Shotcrete was sprayed on to a hose wetted surface to simulate ground with excessive water flows. Water was released from above the area to be shotcreted at approximately 60 L/min, and shotcrete was then applied to determine if the material was able to adhere to the substrate. Initial results showed sloughing of the surface after the application was completed. The shotcrete mix design was slightly adjusted by the addition of Silica Fume and an increase in accelerator to 8%. The testing was repeated yielding the following observations:

- No bonding failure between the substrate surface and shotcrete layer
- No physical signs of the shotcrete sloughing off the wet surface
- No significant rebound of shotcrete from the surface during spraying
- Shotcrete finish was normal and no cracks were observed
The performance of shotcrete and spraying system against a surface with excessive water inflow was satisfactory.

To mitigate any risks of the shotcrete mix losing slump during transport to final application, slump retention trials were conducted at the concrete plant to mirror slump loss over a 3-hour period. This was to ensure that the shotcrete would retain its workability for the application process.

### 6.3 Drainage

Groundwater ingress results in inadequate adhesion of shotcrete, and often exerts additional load and undermines the ground support. For this project, external drainage, comprising hoses and dimple sheets, were installed and maintained throughout the excavation and lining construction where significant seepage was encountered. The substrate drainage was connected to a temporary sump in the invert, which was kept operational until the completion of the permanent lining.

### 6.4 Monitoring and instrumentation

The cross passage opening steel segments were monitored with an array of strain gauges and displacement monitoring points, while excavations were monitoring with an array of monitoring prisms, as shown in Figure 12. The monitoring data were continually checked by a dedicated instrumentation and monitoring manager who reported results to the project team for daily review. Trigger levels and response actions were set for both the cross passage entry opening and excavation. The trigger actions were:

- Alert - review monitoring results
- Alarm - increase monitoring frequency, construction review and contingency plan
- Action - stop work, inspect site and convene emergency engineering review

The monitored displacements and strains were generally well below the alert trigger level, with the exception of the northern most XP17 opening, which is located in the weaker residual soils. This cross passage was eventually completed safety, with additional surveillance.

![Cross passage opening monitoring](image)

![Cross passage excavation monitoring](image)

**Figure 12.** Cross passage opening and excavation monitoring arrangement
7. CONCLUSION

All 16 cross passages were completed without any serious harm or lost time injury. Safety-in-design and construction measures—implemented from the beginning of the project in conjunction with the development of a proactive safety culture in the workforce—are largely attributable to this remarkable safety achievement. These safety initiatives provide a very useful case study for tunnel design and construction practice around the world. It is the authors’ wish that this paper will contribute to the advancement of safety practice and awareness in the industry.

8. ACKNOWLEDGEMENTS

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9. CITATIONS AND REFERENCES


