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Ground response for construction of 15 caverns in diverse ground conditions in Sydney – Part 2: Construction sequence and ground response

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ABSTRACT: Eleven road caverns and four ventilation caverns were recently constructed in Sydney as part of the Rozelle Interchange project. The up to 29 m wide road caverns and 24 m high ventilation caverns of the Sydney motorway were excavated in Hawkesbury Sandstone at depths between approximately 17 m and 67 m next to the harbour. The number, size, ground cover and complexity of geological conditions of these large underground excavations are unprecedented in Australia. Part 1 of this paper details the cavern geometry, ground conditions and ground support systems. This part 2 presents the construction sequence and ground response. The ground response is described in terms of in-tunnel convergence, measured using optical survey targets and steel tape extensometers, surface settlement, endoscope hole closure, rock pillar displacement monitored with inclinometers and observations of ground support performance.

1 INTRODUCTION

Eleven road caverns and four ventilation caverns were recently constructed in Sydney as part of the Rozelle Interchange project. Part 1 of the paper (Salcher, Bai, Stocker, Bentley & Trim, 2025) details the geology and ground support of the road caverns and ventilation facilities. This part 2 describes the construction sequence and ground response, with a focus on the removal of the central temporary pillar in the road caverns and deep benching in the ventilation facilities.

2 CONSTRUCTION SEQUENCE

2.1 *Permit to Tunnel*

All tunnelling on the project was carried out under the Permit to Tunnel (PTT) process. The PTT facilitates a formal review of encountered ground conditions, available monitoring data and observed ground behaviour. It sets out a plan for tunnelling activities for a defined period, location and extent. PTT meetings involving the construction team and the geotechnical construction phase services (CPS) team were held daily. Details on the PTT process adopted on Rozelle Interchange are provided by Salcher, Bai, Trim, Bertuzzi & Vidler (2023).

2.2 *Road caverns*

The construction sequence for the road caverns was primarily driven by the construction program, construction access requirements, ground conditions, ground support requirements and ventilation requirements. The typical construction sequence for a road cavern involved excavation of:

1. Heading 1
   i. On one side of the cavern
   ii. Typically 10 m to 13 m wide
2. Heading 2
   i. On the opposite side of the cavern
   ii. Similar width to heading 1
   iii. A minimum 5 m wide temporary central rock pillar (heading 3) left in place
3. Temporary central rock pillar (heading 3) towards the pillar nose
4. Bench and trench

This sequence is illustrated in Figure 1.

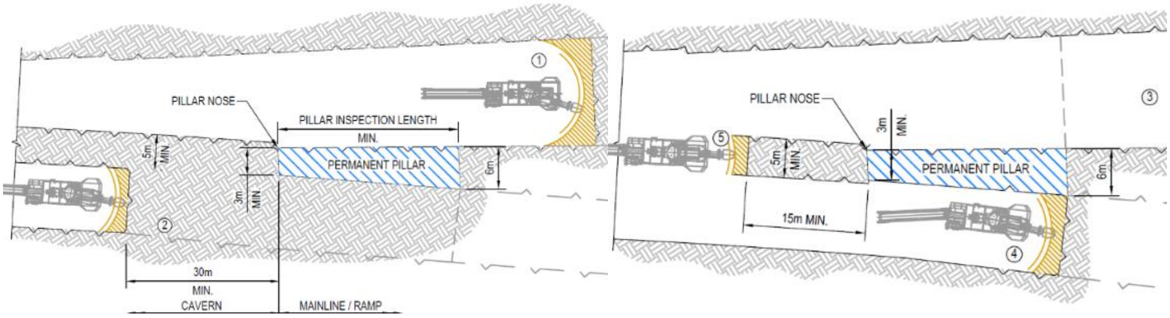

Figure 1. Three heading excavation sequence.

Some considerations associated with the typical steps listed above include:

- Roadheaders were launched into headings 1 and 2 simultaneously. The two headings were sufficiently separated by the minimum 5 m wide temporary rock pillar, allowing both roadheaders to operate at the same time.
- As mentioned in section 3, rock bolts and cable bolts were installed in two stages, referred to as initial span and full span bolts. Cavern 3 is an exception where cable bolts were installed remotely at the face (refer to Table 5 in Bai et al, 2025). The initial span bolts (typically 5.4 m long rock bolts) allowed excavation to progress through headings 1 and 2 with full span bolts (typically up to 8.5 m long cable bolts) installed behind the face off critical path before the removal of the temporary central pillar (heading 3).
- To avoid trimming and thinning of the permanent pillar, as implemented on the M4 East project and described by Salcher, Nash, De Ambrosis & Grabham (2019), strict excavation tolerances were applied to ensure that the minimum permanent pillar width was satisfied.
- At the narrow end of the caverns, headings 1 and 2 converged to transition into a split heading (two headings) at a tunnel span of less than 22 m.

A bespoke construction sequence was applied to a handful of caverns. For example, Caverns 4 and 5 were constructed in difficult ground and required additional considerations, such as replacing the permanent rock pillar with concrete (Cavern 5) or underpinning the heading shotcrete arch during benching (Cavern 4). For more information on Cavern 5, the reader is referred to Stocker, De Ambrosis & Estrada (2023). To facilitate construction access, Caverns 7 and 8 featured an intersecting tunnel cutting the temporary pillar into two portions. This involved a cross-cut through the cavern and installation of full span support before breaking out left and right to form the cavern either side of the cross-cut.

2.3 *Ventilation caverns*

Construction of the tall ventilation facilities was staged as an approximately 7 m high single or split heading followed by multiple deep benches, each 4 m to 5 m high, reaching the total cavern height of up to 24 m. Given the significant height, it was difficult for construction to reach the crown once one deep bench was removed. The excavation sequence for the ventilation facilities is illustrated in Figure 2 and Figure 3.Figure 4 presents a photograph of a completed ventilation facility. Additional discussion on the construction of the ventilation facilities can be found in Tepavac, Sun, Trim & Kumar (2022).

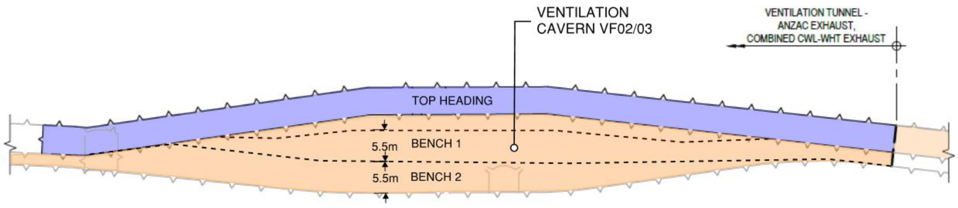

Figure 2. Long section of ventilation facility showing excavation sequence.

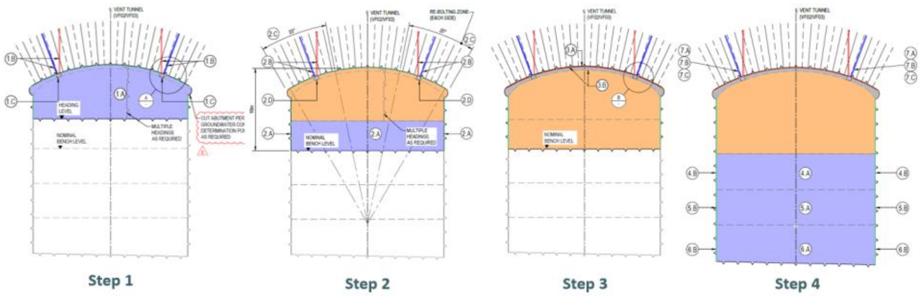

Figure 3. Ventilation facility excavation sequence cross sections.

2.4 *Plant*

Mitsui SLB300 roadheaders with axial cutterheads were employed for cavern heading excavation given their higher reach compared to other roadheaders, thus being able to cut a taller heading. This not only minimised bench excavation volumes but also provided the needed space for installation of long rock bolts and cable bolts. For significant benching activities, such as the deep benches in the high ventilation caverns, Sandvik MT720 roadheaders with a transverse milling head were used. These proved more effective in these types of excavations. Figure 5 presents a photograph of a typical benching operation in a ventilation cavern. In some instances, two roadheaders were used simultaneously side by side to cut a single bench face.

Figure 4. Inspection of endoscope hole for monitoring of rock bolts shearing in crown of completed ventilation cavern.

Figure 5. Sandvik Mt720 roadheader excavating a deep bench in ventilation cavern VF02

Two types of Caterpillar Robodrill rock bolting rigs were used for bolt installation. One was configured with a conventional drifter and was used for installing rigid rock bolts up to 6.5 m long. The other was configured to install cable bolts up to 8.5 m long. Both rigs had the capability to mix and pump grout remotely through the rig after bolt pre-tensioning.

3 GROUND RESPONSE

3.1 *Monitoring methods*

Several methods were used to monitor the response of the rock mass due to removal of heading 3 (temporary central pillar) in the road caverns and deep benching in the ventilation facilities. These methods include in-tunnel optical targets, steel tape extensometer convergence readings, optical surface settlement targets, shear endoscope holes, instrumented rock bolts and inclinometers in the permanent part of the pillar. During cavern constructions, these instruments were read daily. Selected data obtained by these methods are presented in the following sections.

3.2 *Tunnel convergence*

Optical survey targets were installed progressively, approximately every 4 m laterally across the cavern crown, as headings 1, 2 and 3 were excavated. Eye bolts for vertical tape extensometers were installed into the crown and heading floor in headings 1 and 2 on either side of the temporary central pillar (heading 3). Crown optical targets and tape extensometers were installed at a longitudinal spacing of 10 m to 20 m, with a reduced spacing near the large spans.

In-tunnel convergence results are presented in Table 1.

Table 1. Summary of cavern convergence.

Cavern no.	Max. crown sag (optical survey, mm)	Distance of max. crown sag from pillar nose or cavern centre[(1)] (m)	Max. tape extensometer vertical convergence[(2)] (mm)	Max. horizontal convergence (optical survey, mm)
Cavern 1	9	7 (0.2 D)	12	8
Cavern 2	12	12 (0.5 D)	27	15
Cavern 3	44	11 (0.4 D)	86[(3)]	16
Cavern 4	71	48 (1.7 D)	38	20

Cavern 5	11	30 (1.1 D)	52	12
Cavern 6	6	19 (0.7 D)	13	11
Cavern 7	37	33 (1.1 D)	33	11
Cavern 8	22	48 (1.9 D)	-	6
Cavern 10	11	49 (1.7 D)	22	9
Cavern 11	23	62 (2.3 D)	17	9
Cavern 12	26	18 (0.7 D)	50	22
VF01	4	2 (0.1 D)	-	11
VF02	19	3 (0.2 D)	-	26
VF03	31	8 (0.4 D)	-	33
VF04	25	9 (0.5 D)	-	26

Notes:

1. For road caverns (Caverns 1 to 12) value outside the brackets represent the distance in metres of the location of maximum crown sag from the pillar nose. The value in brackets is the same distance as a multiple of the cavern span (D) at the pillar. For ventilation facilities (VF01 to VF04) values outside the brackets represents distance of the location of maximum crown sag to the location of the widest span of the cavern (which coincides approximately with the centre of the cavern along its longitudinal axis). The value in brackets is the same distance as a multiple of the maximum cavern span (D).
2. Where no tape extensometer value is provided, no tape extensometers were installed.
3. Reported Cavern 3 measurement was deemed not reliable by the designer and site team (damage or bench heave suspected). However, tape measurements were still recorded for information only.

Table 1 shows the following:

– In some cases, the tape extensometer readings were significantly higher than crown sag measured by optical survey. This may be explained by floor heave, and in particular by bedding partings below the heading floor "popping up".
– Poorer ground conditions are associated with greater displacements (e.g. Caverns 3, 4, 5 and 12; cf. Table 2 in Bai et al, 2025)
– Maximum crown sag in the road caverns occurs some distance—and often more than one cavern span (D)—from the permanent pillar. This is consistent with observations made by Salcher et al. (2019) for the caverns of the M4 East project.
– Horizontal convergence in the tall ventilation facilities is significant compared to vertical convergence.

Figure 6 shows tape extensometer readings taken during the excavation of the temporary central pillar (top heading 3) in the road caverns. The data is presented in terms of vertical tunnel convergence against distance to the advancing face of the temporary central pillar. Figure 7 shows the same convergence data but plotted against time.

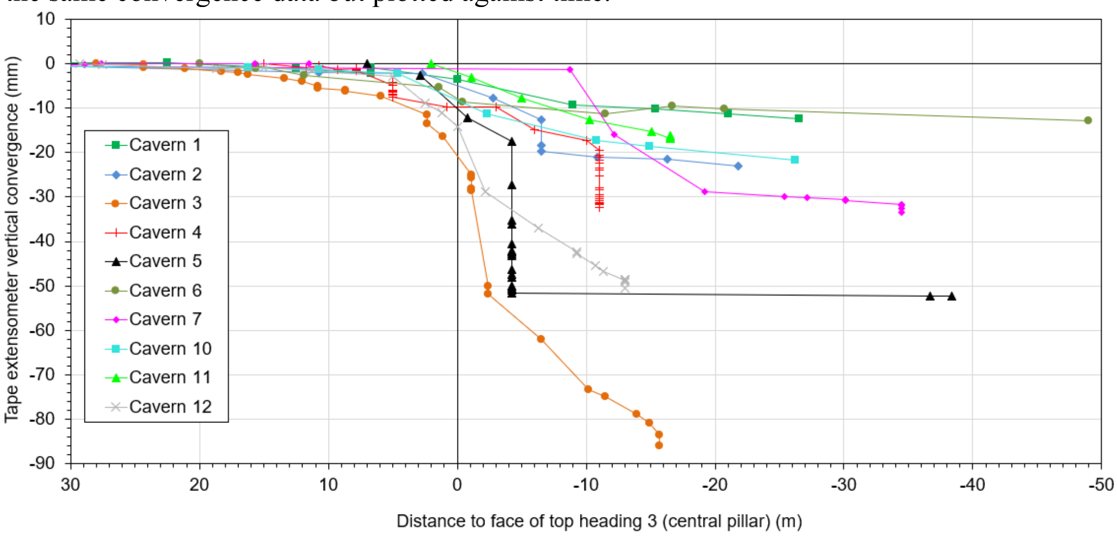

Figure 6. Tape extensometer readings in road caverns during excavation of temporary central pillar (heading 3). Negative convergence values indicate tunnel convergence (i.e. crown sag or invert heave). Negative distance to face values indicate that the tunnel face (i.e. heading 3) has passed the monitoring point.

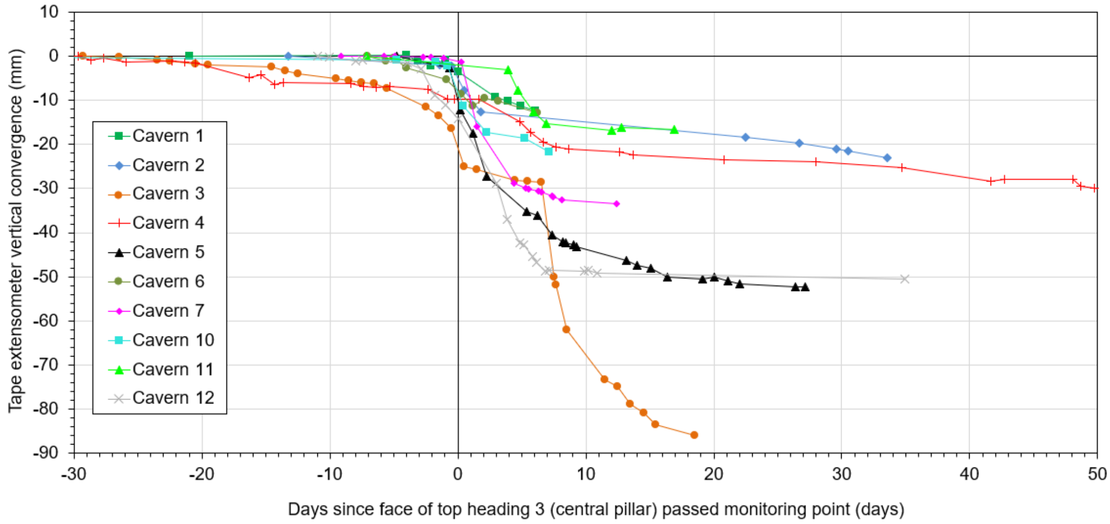

Figure 7. Tape extensometer readings in road caverns during excavation of temporary central pillar (heading 3). Negative convergence values indicate tunnel convergence (i.e. crown sag or invert heave). Positive number of days indicate that the tunnel face (i.e. heading 3) has passed the monitoring point.

Figure 6 and Figure 7 show the following:

- Onset of convergence occurs between 20 m (0.9 D[1]) and 10 m (0.45 D) ahead of the temporary central pillar face
- Convergence increased significantly once the face of the temporary central pillar passed the monitoring point
- Convergence stabilised when the temporary central pillar face had advanced between 10 m (0.45 D) to 20 m (0.9 D) beyond the monitoring point
- In two cases (Cavern 4 and Cavern 5), convergence continued to increase for several weeks even though the excavation of the temporary central pillar had been completed. Both caverns were excavated in poor ground (cf. Table 2 in Bai et al, 2025).

3.3 *Surface settlement*

Optical surface settlement points installed on roads above the caverns were surveyed daily, leading up to, during and for some time after removal of the temporary central pillar. The location of these surface monitoring points focused on publicly accessible areas (e.g., roads, footpaths, bridges, etc.) but also included sensitive privately owned buildings.

Maximum surface settlement recorded by InSAR satellite monitoring was approximately 50 mm. Optical survey of monitoring targets installed on roads and kerbs showed a maximum settlement of 35 mm. Predicted effects and impact assessment demonstrated that with the observed settlement, the risk of structural damage remained within acceptable levels. These maximum values were observed in the area where multiple caverns were excavated in poor ground. A selected settlement plot is presented in Figure 7. Negative values indicate settlement.

[1] *D* represents the 22 m cavern span, which was the limit beyond which a temporary central pillar (i.e. a third heading) was adopted.

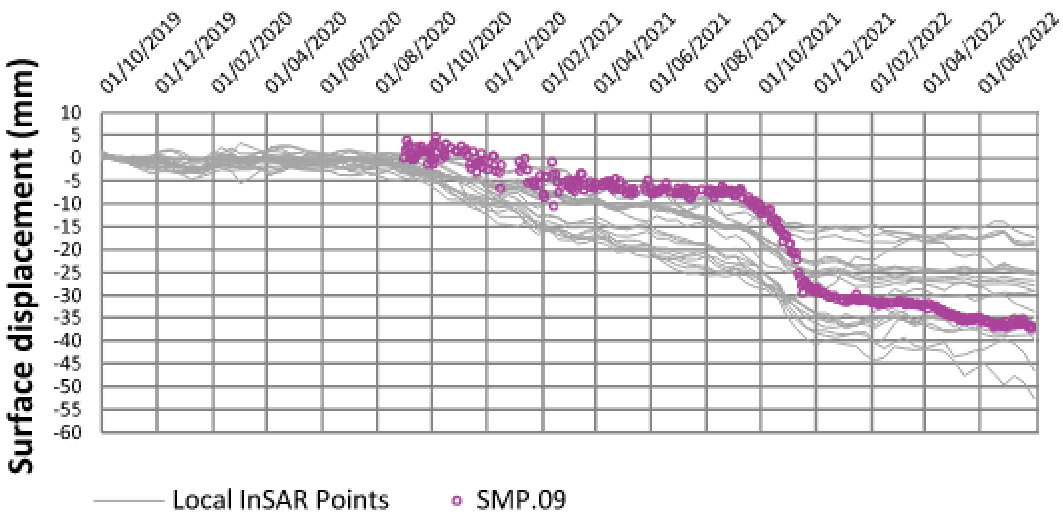

Figure 8. Example surface settlement plot showing InSAR (grey) and optical survey (purple) monitoring data.

It was noted that surface settlement took several days or longer to stabilise following the excavation. This is consistent with observations reported by Salcher et al. (2019) for the construction of the caverns of the M4 East project.

3.4 *Pillar displacement*

Where access was available, inclinometer casing was installed and grouted in boreholes that were drilled from the surface through the permanent pillars of the road caverns. Baseline readings were taken long before the headings on either side of the pillar approached the permanent pillar. During temporary central pillar removal, the inclinometers were read daily.

Figure 9 shows the uncorrected cumulative displacement of the inclinometers installed in Cavern 1. A-axis readings are shown, with the A-axis pointing towards the headings on either side of the pillar. As such, positive and negative readings denote movement towards these headings. The inclinometer response is summarised in Table 2. Photographs showing the pillar ground conditions are presented in Figure 10.

Table 2. Summary of pillar inclinometer readings.

	Cavern 1	Cavern 2	Cavern 7
Inclinometer location	10 m from nose	30 m from nose	37 m from nose
Pillar moved towards	First heading (M150)	First heading (M1D0)	First heading (M170)
Max. displacement	4.3 mm	7.2 mm	6.5 mm
Response to benching	None	None	None
Remarks	Sharp change in movement occurred at siltstone/laminite band at shoulder (see Figure)	No correlation of movement with location of siltstone rip-up clasts in crown)	Ground conditions comprised high-quality sandstone without siltstone bands.

In addition to the remarks in Table 2, the following was observed from the inclinometer readings:

- 0 to 1 mm movement when the tunnel face approached within 5 m of the inclinometer location
- 0.5 to 2.5 mm when the tunnel face was adjacent to the inclinometer location
- 2.5 to 3 mm when the tunnel face was 5 to 10 m past the inclinometer location
- 3 to 5 mm when the tunnel face was approximately 15 to 30 m past the inclinometer location
- Very little to no response to the excavation of the second tunnel
- Very little to no response to excavation of the temporary central pillar

– Very little to no response to excavation of the bench in either tunnel
– Siltstone rip-up clasts did not appear to impact pillar displacement
– Significant movement occurred along siltstone/laminite bands

The observation of the pillar not moving back towards the second tunnel following the excavation of the second tunnel is different from observations made by Salcher et al. (2019) for the caverns of the M4 East project. It is possible that correction of the inclinometer data for systematic errors, such as those described by Mikkelsen (2003), may lead to different conclusions.

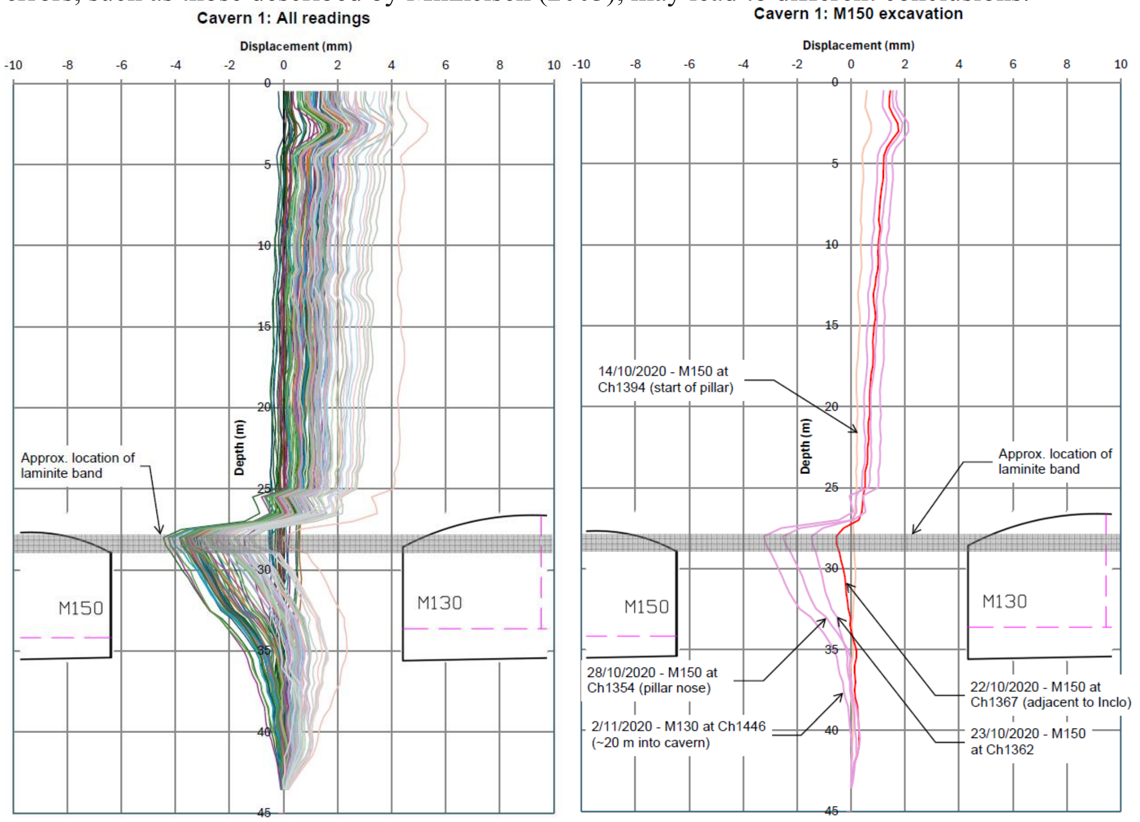

Figure 9. Cavern 1 pillar inclinometer readings. M150 was excavated first.

Figure 10. Laminite band in Cavern 1 temporary pillar (top heading 3) (left) and adjacent M150 ramp (right).

3.5 *Rock bolt shearing*

In the road caverns, endoscope holes were drilled to cable bolt length on both sides of the temporary and permanent pillar to monitor of rock bolt and cable bolt shearing due to bedding plane movements. During central pillar (top heading 3) removal, the holes were inspected daily with an endoscope camera. Wherever shearing was observed, the magnitude of shear displacement was measured and recorded. The project technical criteria deemed 10 mm of shear displacement as the limit of acceptable deformation of the protective plastic sleeve of rock bolts and cable bolts. The durability of the permanent (100-year design life) bolts was assumed to be compromised for monitoring of rock bolt and cable bolt shearing due to bedding plane movements. For structural bolt deformation, the limit of shear movement set was 20 mm.

During the excavation of top headings 1 and 2 in the road caverns, re-bolting was carried out prior to removal of the central pillar, thus requiring only replacement of the initial span rock bolts and not the full span cable bolts. There were no instances where shearing in the road caverns exceeded the 10 mm limit during or after central pillar removal. As a result, no cable bolts required replacement.

In the tall ventilation facilities, multiple instances of rock bolt shearing were observed. While some shearing occurred during top heading excavation, most instances were observed during the deep benching stages. Shearing was observed in the endoscope holes and confirmed by readings of instrumented rock bolts (i.e., strain gauges attached to rock bolts). A photograph of an endoscope inspection being carried out in the crown of one of the ventilation caverns is provided in Figure 4. A photograph of a typical shearing event, as captured by an endoscope camera looking uphole, is given in Figure 11.

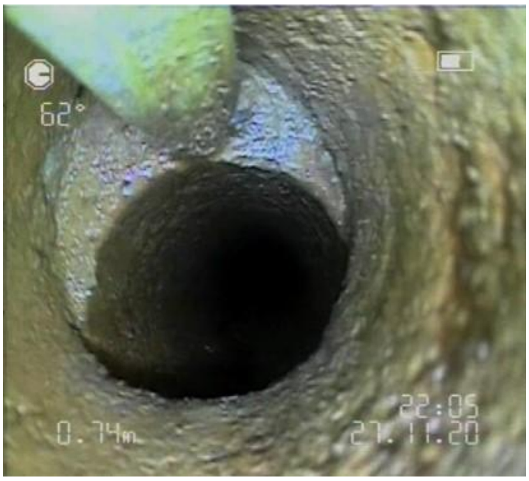

Figure 11: Uphole view of sheared bedding parting in endoscope hole. A rod of known dimension is placed against the shearing plane to assess the shearing magnitude (17 mm in this case). Source: Bai et al (2023).

Maximum rock bolt shear movements measured in the ventilation facilities remained below the 20 mm limit that the project allowed for structural rock bolt deformations (i.e., as opposed to the 10 mm allowable deformation of the plastic sheath for durability purposes). That is, re-bolting was performed before shear displacements could reach this limit.

On some occasions, a fill platform had to be constructed in the ventilation facilities to provide access to the crown for re-bolting, given the significant tunnel height and progress of benching activities at the time of the shearing events. Shearing was almost always associated with cracking of the shotcrete lining in the crown. All instances of shearing of permanent rock bolts and damage to shotcrete were rectified before handover of the tunnels.

Bai, Salcher, Fusee, Bentley, Kumar & Trim (2023) provide more details on rock bolt shearing observed on the Rozelle Interchange project and management of shear movements.

4 CONCLUSION

The scale and number of caverns constructed for the Rozelle Interchange project are unprecedented in Australia. The project involved wide and tall excavations in a variety of ground conditions. Significant dykes and faults were encountered; high quality sandstone came with adverse in situ rock stress conditions. A robust yet efficient design, along with a rigorous monitoring system, a carefully planned construction sequence, a modern fleet of construction plant and an industry-best Permit to Tunnel system were essential to delivering the project.

The successful completion of the underground works of Rozelle Interchange is an enormous achievement that is best appreciated by walking the seemingly endless kilometres of intersecting and overlapping tunnels, caverns, shafts and passages (Figure 1 in Bai et al, 2025 & Figure 11).

Figure 12. Intersection of road caverns and ventilation tunnels.

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We hope that the information presented herein will be useful for others planning to construct caverns in Sydney and elsewhere.

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