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Ground response for construction of 15 caverns in diverse ground conditions in Sydney – Part 1: Ground support

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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. Three of the 11 road caverns used a concrete replacement pillar. The excavation sequence for each of these caverns was a bespoke design and catered to the varying ground conditions and construction access requirements. Typically, this involved three top headings and a bench, with removal and/or thinning of a central pillar prior to benching. The excavation sequence for the ventilation caverns involved split headings and multiple deep benches to achieve the final height up to 24 m. Temporary and permanent ground support comprised rock bolts and cable bolts in the crown with shotcrete. This part 1 of the paper details the cavern geometry, ground conditions and ground support systems. 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

1.1 *Project description*

The Rozelle Interchange project in Sydney involved the construction of a 23 km long multi-level underground motorway network, including mainlines, caverns, on- and off-ramps, shafts and ventilation tunnels. It provides an underground connection from the M4 and M8 motorways to Iron Cove Bridge on Victoria Road, Anzac Bridge, City West Link and the future Western Harbour Tunnel. At peak tunnelling, 23 roadheaders were used to excavate the tunnels through Hawkesbury Sandstone with regional scale dykes and faults at depths between 5 m and 70 m.

The John Holland Group and CPB Contractors joint venture was awarded the design and construct contract. The joint venture engaged PSM and Delve Underground to design the primary and permanent ground support for the tunnels and caverns. Figure 1 shows a plan of the tunnel network with road caverns and ventilation caverns (also referred to as ventilation facilities) annotated.

This part 1 of the paper details the geology and ground support of the road caverns and ventilation facilities. Part 2 (Salcher, Bai, Stocker, Bentley & Trim, 2025) describes the construction sequence and ground response with particular focus on the rock mass response due to removal of the central temporary pillar and due to deep benching in ventilation facilities.

The paper is written from a construction and construction phase services perspective. It can be considered a companion paper to Bai, Salcher, Fusee, Bentley, Kumar & Trim (2023), which details observations of rock bolt shearing at Rozelle Interchange; and Salcher, Bai, Trim, Bertuzzi & Vidler (2023), which describes the project's Permit to Tunnel (PTT) process.

Figure 1. location plan of 11 road caverns (green) and 4 ventilation facilities (blue).Cut-and-cover structures are shown in purple.

1.2 *Cavern geometry*

Table 1 summarizes key geometric details of the road caverns and ventilation facilities.

Table 1. Cavern geometry.

Cavern no.	Type of cavern	Max. span(1) (m)	Height(1) (m)	Ground cover (m)	Length(2) (m)	Cover/span (m/m)
Cavern 1	Road	28.4	9.6	25	120	0.9
Cavern 2	Road	26.0	9.5	49	66	1.9
Cavern 3	Road	28.9	9.9	59	66	2.0
Cavern 4	Road	27.6	10.2	51	86	1.8
Cavern 5	Road	26.1	9.2	29	41	1.1
Cavern 6	Road	26.0	9.2	25	36	1.0
Cavern 7	Road	28.8	9.6	21	77	0.7
Cavern 8	Road	25.2	9.8	17	80	0.7
Cavern 10	Road	28.9	9.6	25	92	0.9
Cavern 11	Road	26.4	10.1	38	24	1.4
Cavern 12	Road	25.9	10.8	30	43	1.2
VF01	Ventilation	18.9	17.2	18	32	1.0
VF02	Ventilation	18.9	21.8	42	35	2.2
VF03	Ventilation	18.9	21.1	43	35	2.3
VF04	Ventilation	18.9	23.5	24	32	1.3

Notes:
1. Span and height represent estimated excavation line (e-line) dimensions.
2. Length is as defined on the design drawings for the cavern profile (i.e., span greater than 21 m for the road caverns).
3. Cavern 9 is not included because it is a cut-and-cover structure.

The road caverns are defined as road tunnels with a span larger than 21.0 m. The span increases from its narrowest at the mainline tunnel interface to its widest at the permanent pillar nose, where the cavern splits into mainline and on/off-ramps. The minimum permanent pillar width varied between approximately 3 m and 4 m. Six of the 15 caverns have a cover-to-span ratio of 1 or less.

A typical plan of the roads caverns is presented in Figure 2, using the example of Caverns 7 and 10. Amongst others, the plan shows the caverns (red hatching), the ramps or mainline tunnels joining or exiting the caverns and the permanent pillar at the end of the caverns between the ramps or mainlines.

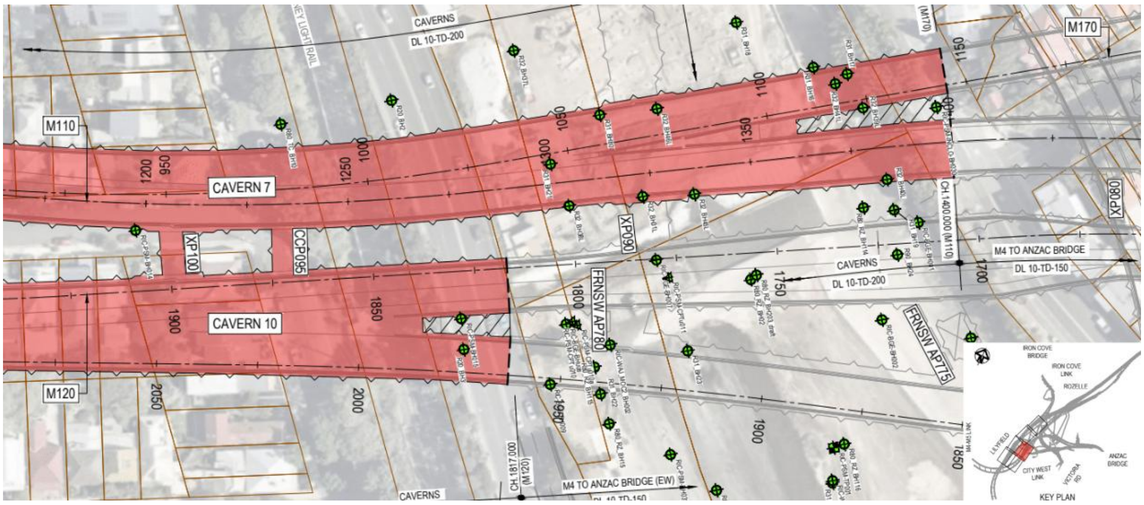

Figure 2. Plan of caverns 7 and 10.

An example of the geometry of the ventilation caverns is given in Figure 3.

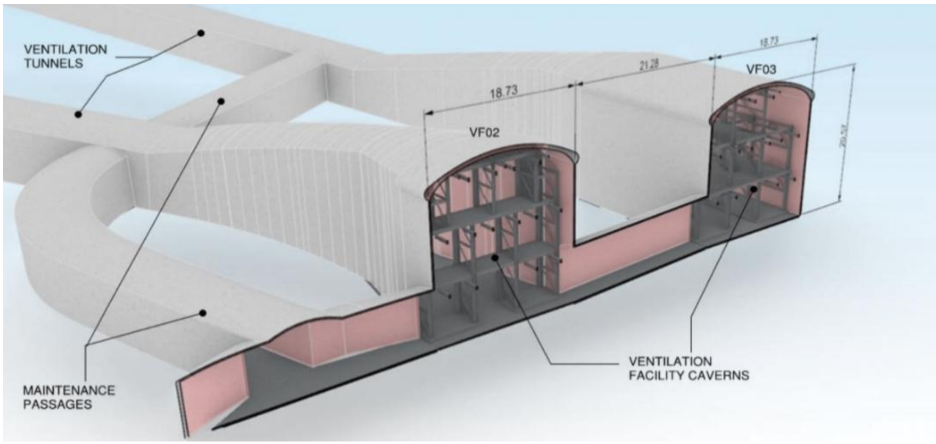

Figure 3. geometry of ventilation facilities VF02 and VF03 (18.9 m wide and 21 m to 22 m high with a 21 m wide pillar between the caverns).

2 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

The Rozelle Interchange tunnels are situated within the Sydney Basin and are located close to the harbour. The tunnels were exclusively excavated through the Lower Triassic–aged flat-lying Hawkesbury Sandstone. Within the Hawkesbury Sandstone, siltstone beds, laminites (interlaminated sandstone and siltstone), and siltstone rip-up clast layers were observed to range in thickness between 0.5 m and 3 m but typically less than 1 m, with varying persistence of less than 10 m to hundreds of meters. The project identified several areas of increased geological structure, including a paleovalley structure, persistent regional scale faults and associated structurally complex zone, and structural corridor. Details are provided by Estrada, Nash, De Ambrosis & Chan (2022).

The main surface drainage in the area is a deep, broad river valley draining from the southwest to the northeast into Rozelle Bay. Over geological time, this river-incised paleovalley was filled to current levels with marine and alluvial soils. Project geotechnical documents indicate geological structures associated with valley bulging. Relief of in situ horizontal stress in the slopes and floor of the infilled river valley and associated geological defects were expected. This included low-angle faults, bedding shears, bedding partings and increased jointing which are typical of areas of stress relief.

Notable regional scale geological structures at Rozelle Interchange include the paleovalley described above, a significant regional scale fault (Fault 1) and a dyke (Dyke B).

Fault 1 is a shallow southeast-to-east-dipping regional-scale fault. It was observed to consist of either a fault core with variable thickness of clay gouge and rock fragments or an intensely sheared and faulted zone. In either case, the fault was typically associated with a damage zone of increased bedding partings, crushed seams, joints and shears. Photographs of two different expressions of Fault 1 are shown in Figure 4 and Figure 5.

Figure 4. Fault 1 encountered in ramp adjacent to concrete replacement pillar of Cavern 5.

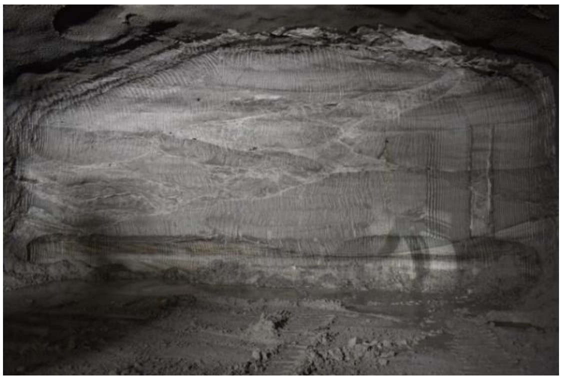

Figure 5. Fault 1 encountered in mainline tunnel.

The other major geological structure observed in the project area was a dyke (Dyke B). It extended through a northwest-southeast-trending structural corridor, characterized by an increase in faults, shears and joints. The subvertical dyke varied between 0.5 m and 3 m wide and consisted of a dolerite intrusion bounded by clayey contacts with the host rock and contact metamorphosed ("baked") sandstone margins. The dyke was associated with a structurally complex zone which comprised an increase in subhorizontal bedding shears and low-angle shears and faults. The faults observed during tunnelling had clay or rock fragment infilling. The dyke was encountered in nine tunnels throughout the Rozelle Interchange project area, including ventilation facilities and road caverns.

A photograph of Dyke B as encountered in the top heading of ventilation facility VF04 is presented in Figure 6. Figure 7 is a 3D model showing Dyke B and Fault 1 intersecting Caverns 3, 4 and 12.

Figure 6. Dyke B encountered in the top heading of ventilation facility VF04.

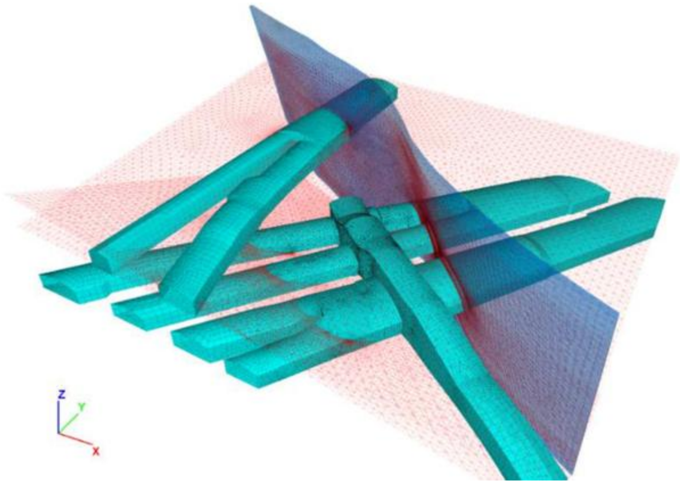

Figure 7. 3D model of Fault 1 (shallow dipping red structure) and Dyke B (near-vertical red structure) intersecting Caverns 3, 4 (lower caverns) and 12 (upper cavern).

High horizontal in situ rock stress was observed at some locations of the project, which resulted in rock bolt shearing during road cavern heading excavation and ventilation facility deep benching. Bai et al (2023) provide a comprehensive summary of rock bolt shearing at Rozelle Interchange, including uphole photographs of 54 shearing events.

Although all 11 road caverns and 4 ventilation caverns were excavated in Hawkesbury Sandstone, ground conditions varied considerably. A summary is provided in Table 2.

Table 2. Cavern ground conditions as encountered.

Cavern no.	Category	Ground classification(1)	Remarks
Cavern 1	Competent ground	Sandstone Class II	
Cavern 2	Competent ground	Sandstone Class II	
Cavern 3	Poor ground	Sandstone Class II Faults and joints	Structurally complex zone with faulting and jointing encountered; Dyke B intersected in mainlines and ramps beyond permanent pillar
Cavern 4	Poor ground	Dyke Faults and joints	Dyke B (3 m thick dolerite core) and structurally complex zone with faulting and jointing encountered
Cavern 5	Poor ground	Faulted ground	Encountered Fault 1: 3.5m thick fault core equivalent to Sandstone Class IV/V with associated damage zone with increased jointing and faulting
Cavern 6	Intermediate ground	Sandstone Class II Siltstone rip-up clasts	Cavern in proximity to paleovalley; stress-induced rock bolt shearing led to re-bolting
Cavern 7	Intermediate ground	Sandstone Class II Siltstone rip-up clasts Bedding shears	Cavern under paleovalley; increased water inflows and grout takes for rock bolts observed
Cavern 8	Competent ground	Sandstone Class II	Pillar replaced due to its small size
Cavern 10	Competent ground	Sandstone Class II	Cavern under paleovalley
Cavern 11	Intermediate ground	Sandstone Class II Faults and joints	In proximity to Dyke B; structurally complex zone with faulting and jointing encountered
Cavern 12	Poor ground	Dyke Faults and joints	Dyke B (3 m thick dolerite core) and structurally complex zone with faulting and jointing encountered
VF01	Competent ground	Sandstone Class II	
VF02	Competent ground	Sandstone Class II	
VF03	Poor ground	Dyke Faults and joints	Dyke B (3 m thick dolerite core) and structurally complex zone with faulting and jointing encountered
VF04	Poor ground	Dyke Faults and joints	Dyke B (3 m thick dolerite core) and structurally complex zone with faulting and jointing encountered

Notes: 1. Sandstone classification is in accordance with Pells, Mostyn, Bertuzzi & Wong (2019).

3 GROUND SUPPORT DESIGN

The ground support design philosophy for the caverns was largely the same as for the smaller tunnels. As the span increases, convergence is expected to increase, and a greater extent of ground is mobilized that needs to be reinforced. This led to the requirement for longer and higher-capacity crown bolts. Fully grouted rigid rock bolts and cable bolts were installed in combination with sprayed shotcrete. Up to 5.4 m long rock bolts were routinely used for tunnel spans up to approximately 21 m. For cavern profiles with span between 21 m and 29 m, longer and higher-capacity cable bolts were required.

Shotcrete thickness in good ground was unaffected by tunnel span. Shotcrete was designed to span between rock bolts to support small blocks of rock between bolts. When in competent ground, a design thickness of 110 to 130 mm was adopted with a total of 165 mm sprayed locally at bolt heads to provide cover to steel elements. This was the same regardless of tunnel span since the rock bolt spacing in narrower tunnels was equal to that in the caverns. The widest 29 m span cavern was supported with the same thickness of shotcrete as a 6 m wide cross passage.

A typical road cavern ground support cross section (in good ground) is presented in Figure 8. The face is shown split into three headings and a bench. Initial span rock bolts and final span cable bolts are indicated. The left half of the sketch shows the permanent primary shotcrete lining (green) without a waterproofing membrane. The right half of the sketch shows the permanent secondary shotcrete lining (grey) with a waterproofing membrane (red), which was installed if groundwater conditions required it or where project requirements specified membranes to be installed.

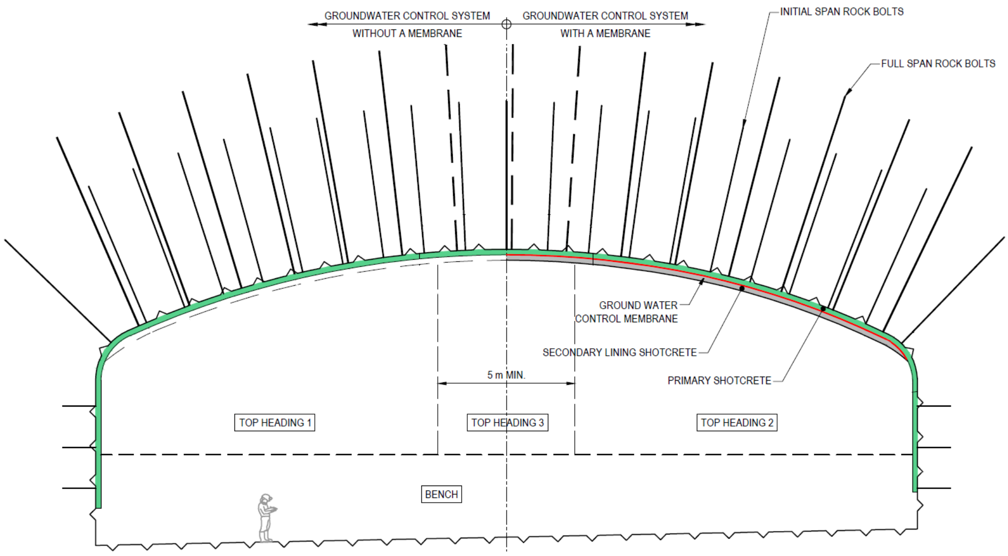

Figure 8. Typical road cavern ground support cross section in good ground.

A different approach to shotcrete was adopted for the high ventilation caverns. Thicker crown shotcrete was considered necessary there due to potential stress-induced fracturing and formation of loose blocks of rock in the crown during deep benching operations.

The construction program was a critical input to support design. Due to plant limitations, it was not possible to install cable bolts at the tunnel face remotely in all instances. Installation of cable bolts by hand under supported ground takes considerable time. Therefore, it was important to adopt an excavation sequence and support design to take installation of cable bolts out of the typical excavation and support cycle.

The sequence adopted involved excavation of three headings with the two side drifts (headings 1 and 2) excavated first and supported with remotely installed rock bolts. Cable bolts in headings 1 and 2 were then installed behind the heading face, off critical path. This enabled construction to pass through the cavern quickly and access other parts of the project. The temporary central pillar (heading 3) was excavated following cable bolt installation in headings 1 and 2.

The ground support installed in headings 1 and 2 before removal of the central pillar is referred to as the initial span support in this paper. The cable bolts installed behind the face prior to excavation of the temporary central pillar and opening up the full span is referred to as the full span support. The initial span rock bolts were considered permanent bolts, which reduced the demand and quantities for the full span cable bolts. Double corrosion-protected (DCP) rock bolts and cable bolts with a protective plastic sheath were used to achieve a 100-year design life.

A photograph showing a Rozelle Interchange motorway cavern under construction with a roadheader in heading 1 and a bolting rig operating in heading 2 is presented in Figure 9.

Figure 9. cavern under construction, showing a roadheader in heading 1 (left) and a bolting rig operating in heading 2 (right). The temporary central pillar (heading 3) is still in place.

Support designs were provided for a range of ground conditions. A selection, referred to here as “favourable” (fav.), “expected” and “adverse”, is presented in Table 3.

Table 3. Selected range of design ground conditions.

Ground conditions	Favourable	Expected	Adverse
UCS	≥ 30 MPa	≥ 25 MPa	≥ 10 to 15 MPa
Defect spacing	≥ 1.5 m	≥ 1.0 m	≥ 1.0 m
Geological structure	Zero to one clay seam in bolted zone above crown	One to two thin clay seams in bolted zone above crown	Two to four clay seams in bolted zone above crown; or joint swarm, thin subvertical fault or thin low angle shear in bolted zone

Notes: 1. The tabulated design ground conditions are simplified for the purpose of this paper. Selection criteria vary across design packages.

Typical support details for the road caverns under these ground conditions are summarised in Table 4 for the various cavern spans. Ventilation cavern support details are included in Table 5.

Table 4. Typical ground support details for road caverns (bolt lengths, types & spacing).

		Initial span		Full span			Shotcrete thickness (mm)	
Ground type	Span (m)	Bolt length and type[1] (m)	Spacing (m) (Trans. x Long.)	Bolt length and type (m)	Bolt length and type (m)	Spacing (m) (Trans. x Long.)	Primary [3]	Secondary [4]
		H1 & H2		H1 & H2	H3[2]			
Fav	22		1.75 x 1.75		-	2.0 x 1.75		
Expected	to		1.50 x 1.50	6.5 R	-	2.0 x 1.50		
Adverse	23		1.25 x 1.25		6.5 R	2.0 x 1.25		
Fav	23		1.75 x 1.75		-	2.0 x 2.5		
Expected	to	5.4 R	1.50 x 1.50	7.5 C	-	2.0 x 2.5	110	200
Adverse	26		1.25 x 1.25		7.5 C	2.25 x 1.75		
Fav	26		1.75 x 1.75			2.50 x 1.75		
Expected	to		1.50 x 1.50	8.5 C	8.5 C	2.50 x 1.50		
Adverse	29		1.25 x 1.25			2.25 x 1.25		

Notes:
1. Rock bolts (R) had ultimate tensile strength of 310 kN. Cable bolts (C) had an ultimate tensile strength of 580 kN.
2. Full span bolts were not required in top heading 3 for favourable and expected ground conditions.
3. At the bolt heads a total of 165 mm of primary shotcrete lining was sprayed locally to provide cover to steel elements.
4. The primary shotcrete lining is a permanent lining. the secondary lining was only installed in areas where a waterproofing membrane was provided. a waterproofing membrane was not required in the majority of the caverns.

For ground conditions poorer than "adverse", including major faults and dykes, a hybrid support system with rock bolts and a thick (up to 350 mm) structural shotcrete arch was adopted.

A summary of PTT-directed ground support details (refer to Section 4.1) for the 15 road and ventilation caverns is given in Table 5 at their widest span, unless indicated otherwise.

Table 5. Cavern support details per PTT.

Cavern no.	Bolt length and type[2] (m)	Bolt spacing (m)	Primary shotcrete thickness[1] (mm)	Pillar replacement
	Initial span support[3] (Full span support, if applicable[3])			
Cavern 1	5.4 R (8.5 C)	1.5 trans x 1.5 long (2.5 trans x 1.5 long)	110	No
Cavern 2	5.4 R (8.5 C)	1.5 trans x 1.5 long (2.5 trans x 1.5 long)	110	No
Cavern 3	8.5 C	1.25 trans x 1.25 long	175	No
	Cable bolts installed at face without initial span rock bolts			

Cavern no.		Bolt length and type[2] (m)	Bolt spacing (m)	Primary shotcrete thickness[1] (mm)	Pillar replacement
Cavern 4	Fault (27.6 m span)	4.5 R (8.5 C)	1.25 trans x 1.25 long (1.0 trans x 1.25 long)	175	No
Cavern 4	Dyke (25.8 m span)	5.4 R (7.5 C)	1.0 trans x 1.25 long (2.0 trans x 1.25 long)	150, passive arch (350, SL81 mesh, passive arch)	N/A
Cavern 4	Dyke (25.8 m span)	Concrete strip footing underpinning heading elephant's foot and founded below cavern invert			
Cavern 5		5.4 R (7.5 C)	1.5 trans x 1.5 long (1.0 trans x 1.25 long)	110	Yes
Cavern 6		5.4 R (8.5 C)	1.5 trans x 1.5 long (2.5 trans x 1.5 long)	110	No
Cavern 7		5.4 R (8.5 C)	1.25 trans x 1.25 long (2.25 trans x 1.25 long)	110	No
Cavern 8		5.4 R (7.5 C)	1.5 trans x 1.5 long (2.0 trans x 2.0 long)	175	Yes
Cavern 10		5.4 R (8.5 C)	1.5 trans x 1.5 long (2.5 trans x 1.5 long)	110	No
Cavern 11		5.4 R (7.5 C)	1.25 trans x 1.25 long (2.0 trans x 2.0 long)	175	No
Cavern 12		4.5 (7.5 C)	1.0 trans x 1.25 long (1.5 trans x 1.5 long)	250	Yes
VF01		5.4 R	1.25 trans x 1.25 long, or 1.5 trans x 1.5 long	160	N/A
VF02		5.4 R	1.5 trans x 1.5 long	200	N/A
VF03	Class II SST	5.4 R	1.5 trans x 1.5 long	200	N/A
VF03	Dyke	5.4 R	1.0 trans x 1.25 long	200	N/A
VF04	Fault	5.4 R	1.0 trans x 1.0 long	250	N/A
VF04	Dyke	5.4 R	1.0 trans x 1.25 long	175, SL81 mesh	N/A

Notes:
1. Unless indicated as a passive arch, shotcrete is designed as a hanging lining, spanning between and pinned by rock bolts.
2. Items outside brackets indicate initial span support elements. Items inside brackets indicate full span support elements. Where no brackets are provided, the initial span ground support was used to support the full span.
3. Bolt lengths outside brackets (initial span) indicate rock bolts with a capacity of 310 kN. bolt lengths in brackets (full span) indicate cable bolts with a capacity of 580 kN.

It is noted that no design changes were made at the PTT. Support directed at the PTT relied on a pre-approved toolbox of support options. Where design changes were made, these followed the approved design changes process. Refer to the paper by Salcher et al (2023) for details on the PTT and design change process adopted at Rozelle Interchange.

A fit-for-conditions groundwater control system was part of the design but is not the subject of this paper. It consisted of a toolbox of groundwater control measures to meet the project inflow requirements, ranging from local flushable strip drains to a waterproofing membrane with a thick secondary lining resting on abutments or hanging off additional rock bolts.

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

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