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# Design and construction of the Woolloongabba station caverns for Brisbane's Cross River Rail project

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ABSTRACT: The Woolloongabba Station for Brisbane's Cross River Rail project comprises two caverns separated by a station building shaft. The caverns are D-shaped arched excavations of up to 25 m wide and 16 m high. The ground surface is approximately 8 to 16 m above the cavern crown. The site geology comprises Brisbane Tuff, overlying the Aspley Tingalpa formation, overlying the basement Neranleigh-Fernvale Group (NFG) beds. The presence of deep weathering profiles and tectonic deformation added further complexity to the ground conditions at the site. The initial primary support of the cavern comprised rock bolts and a thin shotcrete lining for the South Cavern and a passive arch lining for the North Cavern. The cavern permanent lining consisted of a steel fibre reinforced concrete crown, bar reinforced concrete sidewall with corbel and headwalls at either end of the cavern. This paper presents key challenges for the design and construction of the primary and permanent supports, adopted support solutions, the as-encountered ground conditions, and comparison of design predictions with measured monitoring data.

## 1 INTRODUCTION

Cross River Rail (CRR) is a new 10.2 km long metro rail line in Brisbane between Dutton Park in the south and Bowen Hills to the north, which includes 5.9 km long twin tunnels that traverse under the Brisbane River and the CBD. The Pulse consortium (including the CPB Contractors, BAM International Australia, Ghella and UGL Joint Venture, CBGU JV) was awarded the contract to design and construct the Tunnels, Stations and Development (TSD) works which includes construction of twin Tunnel Boring Machine (TBM) excavated and mined running tunnels; four new underground stations at Boggo Road, Woolloongabba, Albert Street and Roma Street; and dive structures at each end of the running tunnels.

## 2 WOOLLOONGABBA STATION

The new underground Woolloongabba Station is situated to the southeast of the Brisbane CBD and at the heart of a precinct undergoing major urban regeneration. The station will be at the new urban core which will be a destination and focal point of Brisbane's inner south as a place to live, work, play and learn.

The station comprises of a 33 m deep main station building shaft and two caverns, one to the north and one to the south. The caverns are 90 m (North Cavern) and 106 m (South Cavern) long respectively, with an excavation span of up to 25 m and excavated height of 16 m (Figure 1)

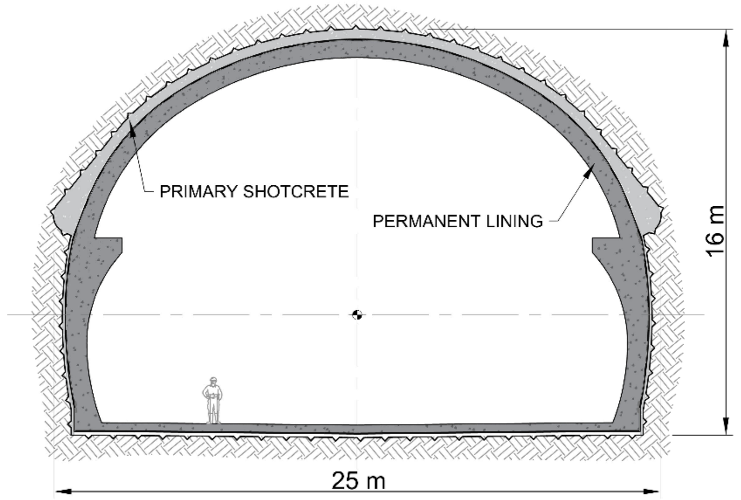



Figure 1. Station Cavern Profile

## 3 ENCOUNTERED GEOTECHNICAL CONDITIONS

The geotechnical conditions at the Woolloongabba site are complex with multiple rock lithologies that have undergone deformation associated with the Normanby Fault Zone (NFZ).

For design and construction, each of the lithologies encountered at Woolloongabba were classified into five rock mass classes ranging from class 1 (high to very high strength blocky rock mass) to class 5 (soil to very low strength disintegrated to disturbed rock mass). A sub-class of NFG 2 (denoted as NFG 2A) was included in the rock mass classification to represent a blockier rock mass due to fault disturbance in the NFG while the fault zone was sub-divided into a fault disturbed zone (FDZ) and fault crush zone (FCZ) (Cammack et al., 2022).

The mapped rock mass classes and key faults are presented in Figure 2 (North Cavern) and Figure 3 (South Cavern). The typical profile from surface down includes:

- Soil, including up to 4 m of Fill overlying 1.5 m of Alluvium.
- Brisbane Tuff (Tuff). A typical weathering profile was encountered, grading from Tuff 5 to Tuff 1 with depth. A horizon of variably deformed Tuff (jointed, sheared and variable strength) was encountered at the base of the unit. This horizon comprises Tuff 1 to Tuff 3 and the width is variable along the alignment.
- Unconformity zone 1 (UZ-1). A 300 mm (approx.) wide zone comprised of very low to low strength Tuff overlying a 50-100 mm thick medium strength sandstone bed. Clay seams (<100 mm thick) parallel to the UZ-1 are common both within the UZ-1 and several metres either side of the zone. Shearing is evident along some seams, and a paleosol origin is also possible. The overall shape of the UZ-1 is sub-horizontal.
- Aspley Tingalpa Formation (Aspley) – Sandstone and Siltstone (SD). SD 1 and SD 2.
- Aspley – Conglomerate and Sandstone (CD). CD 1 and CD 2.
- Unconformity zone 2 (UZ-2). This zone ranges from healed/intact, clean open defect, up to 50 mm clay (unclear if paleosol or sheared), and localised Tuffaceous beds.
- Neranleigh-Fernvale Group (NFG). The NFG encountered at Woolloongabba is significantly different to the NFG typically encountered in the Brisbane CBD. It is pale and dark grey, high to very high strength, foliated, weakly metamorphosed sandstone and phyllite. At Woolloongabba, two distinct NFG lithological types were encountered:
  - NFG "brecciated". This is a re-healed chaotic breccia with significant red and green alteration, likely re-healed fault gouge associated with the NFZ. Foliation is present in some areas, is highly variable in orientation and persistent only over several metres. The rock class is typically NFG 1 and NFG 2.
  - NFG "foliated". This is a foliated rock mass with foliation persistent on the cavern scale. Significant deformation and alteration have resulted in a beige and dark grey rock mass,

with pockets of quartzite. Foliation is orientated steeply towards the north-east. The rock class is typically NFG 1 and NFG 2.

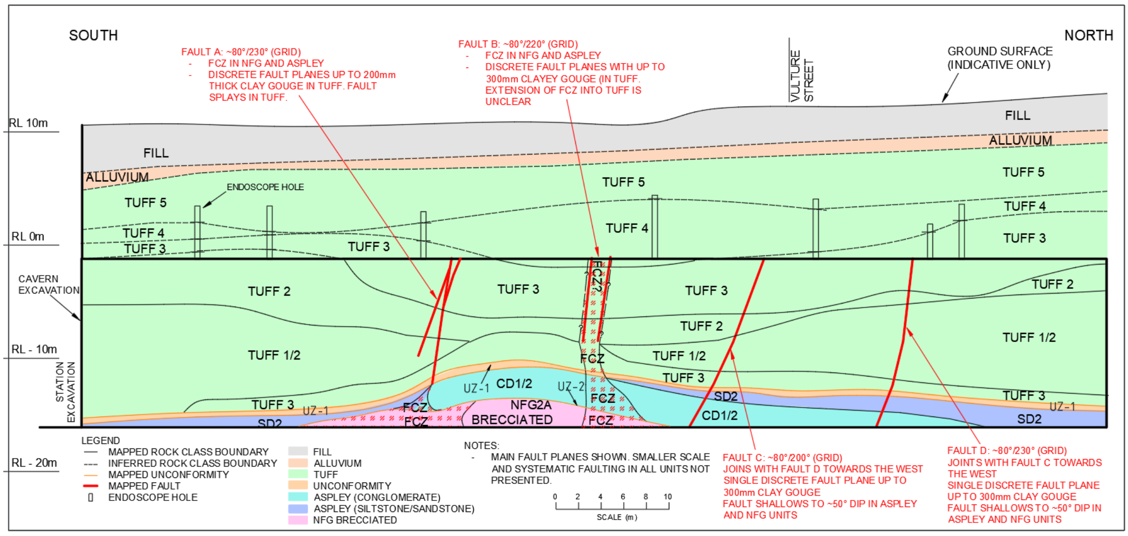



Figure 2. Mapped North Cavern Geotechnical Conditions

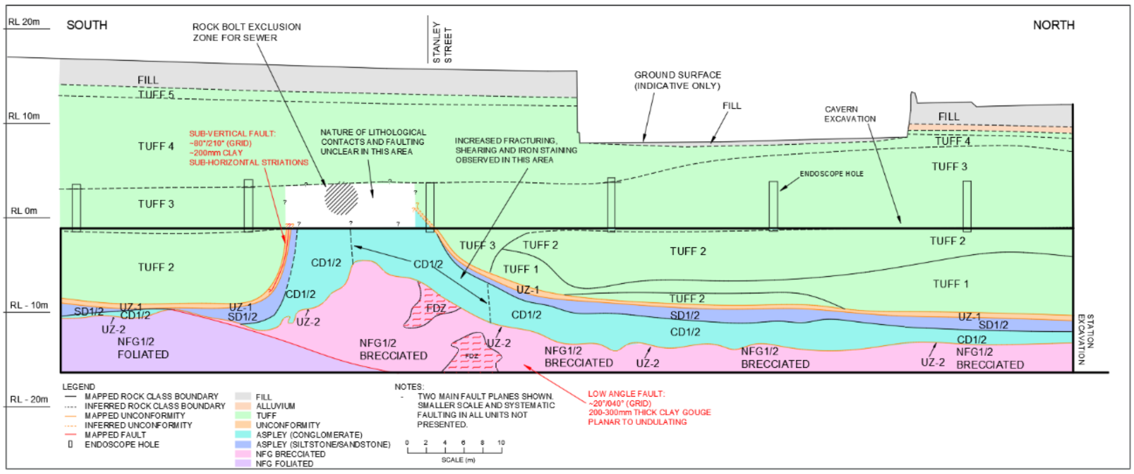



Figure 3. Mapped South Cavern Geotechnical Conditions

The Normanby Fault Zone (NFZ) is a major northwest-southeast (NW-SE) striking fault zone encountered in several CBD projects which can be traced from Normanby in the north, along the western edge of the CBD parallel to the Brisbane River, to Woolloongabba in the south. The NFZ has experienced numerous phases of deformation in its complex geological history. It has the characteristics of both a thrust and strike slip fault, but may have developed as a regional normal fault early in its existence. It is expressed as a wide "structural zone", where variably faulted rock could occur (Cammack et al., 2023). Deformation associated with the NFZ at the Woolloongabba site is detailed below.

A sub-vertical fault zone strikes NE-SW through the North Cavern and extends through the Tuff, Aspley and NFG units. The overall zone is approximately 50 m wide, and the rock class boundaries deepen in proximity to the fault zone with increased jointing, shearing and weathering. In the Tuff, there are distinct fault planes with up to 300 mm clay gouge that persist across the cavern scale and splay. The rock mass between the fault planes is variably damaged. The UZ-1 forms a domed shape, and it is unclear if this is a result of faulting or deposition. Limited vertical offset (<0.5 m) along the distinct fault planes is observed. The fault presents as zones of FCZ in the Aspley and NFG. The rock mass between the FCZ is variably deformed, including NFG 1, NFG 2 and NFG 2A. Evidence of normal, reverse and strike-slip faulting is observed on slickensides within the fault zone, however the overall sense of movement is interpreted as strike-slip.

A complex fault zone was encountered in the South Cavern, with evidence of multiple phases of deformation and re-healing of the rock mass. Two discrete geotechnical faults (i.e. weak planes) were mapped; a low angle fault and a sub-vertical fault. A zone of increased deformation is observed for approximately 25 m to the north of these two faults, with pockets of FDZ in the NFG, increased weathering, jointing and shearing in the CD unit, and a deeper Tuff 3 profile. The domed and uneven lithological boundaries is likely due to a combination of deposition and faulting. The low angle fault is a discrete fault plane oriented ~20°/040° (grid) with 200-300 mm clay gouge present in the NFG and Aspley units. The fault appears to terminate in the Aspley. Reverse movement is inferred, and the scale of movement is larger than the cavern scale. NFG "foliated" is present on the south side of the fault (footwall), and NFG "brecciated" is present on the north side of the fault (hanging wall) all the way through the station box and North Cavern. The sub-vertical fault is observed in the Tuff above the low-angle fault. It is a discrete plane oriented ~80°/210° (grid) with ~200 mm thick clay. The fault terminates within the Tuff, and the exact termination was not mapped. Sub-horizontal striations were observed, indicative of strike-slip movement.

## 4 PRIMARY SUPPORT

In good ground conditions, the primary support for the cavern comprises inflatable friction rock bolts and a thin synthetic fibre-reinforced shotcrete (SFRS) while a passive shotcrete arched lining was implemented where poorer ground conditions were encountered due to deep weathering within the Tuff (Figure 4). Table 1 presents a summary of the primary support types designed to cater for the range of expected ground conditions.

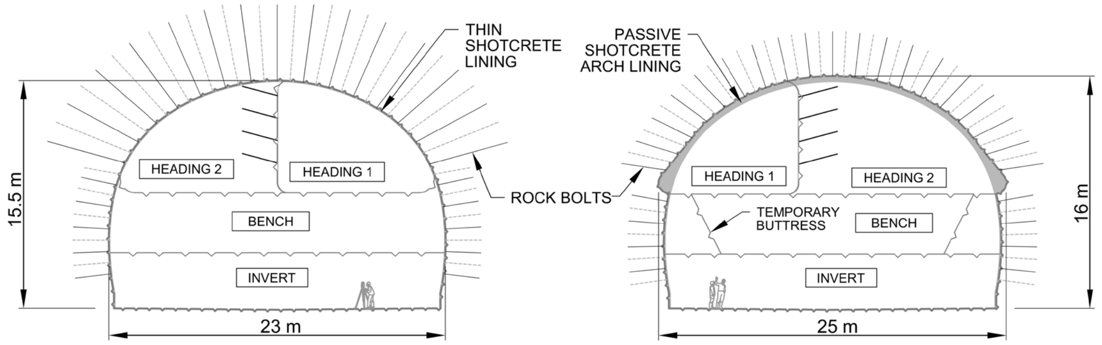
Table 1. Summary of primary support types.

| Support type | Bolt length (m) | Bolt spacing (m) | Shotcrete thickness (mm) | Applicable ground conditions |
|---|---|---|---|---|
| Type 1 | 5.4 | 1.75 | 50 | Tuff 1/2 or NFG 1/2 |
| Type 2 | 5.4 | 1.5 | 75 | Tuff 3 or NFG 3 or CD 1/2 or SD 1/2 |
| Type 3 | 5.4 | 1.25 | 100 | Tuff 1/2/3 or NFG 1/2/3 or CD 1/2 or SD 1/2 with adversely oriented faults and shears |
| Type 4 | 3.0 | 1.5 | 300 | Tuff 4 |
| Type 5 | 3.0 | 1.5 | 400 | Tuff 5 |

The design calculations undertaken to demonstrate the suitability of the proposed tunnel support design included preliminary assessments using empirical and precedence-based approaches followed by detailed assessments which included kinematic assessment of rock blocks, 2D and 3D wedge stability analyses, 2D and 3D finite element stress-deformation analyses. The analyses were undertaken for representative ground conditions along the alignment of the South and North Caverns.

The geotechnical assessments indicated the dominant failure mechanism for the South Cavern and the northern end of the North Cavern was structurally controlled rock block movement and falls (including wedge failures and sliding blocks). The primary support for this mode of failure is pattern bolting with thin shotcrete (Support types 1 to 3). Ravelling ground and crown failure are expected to be the dominant failure mechanisms for the southern half of the North Cavern. The primary support for this failure mechanism is a thick shotcrete passive lining (Support types 4 and 5).

The construction sequence for the bolted support types (Support types 1 to 3) is to advance the tunnel face to suit the encountered geotechnical conditions, install rock bolts and then spray shotcrete. The sequence for the passive shotcrete lining (Support types 4 to 5) adopts the same sequence as the bolted support type for the lead heading. The design provides an option for full thickness of passive linings to be constructed for the full span of the cavern such that lining connections are not required.




(a) Bolted Support Type (b) Passive Arch Lining Support Type

Figure 4. Primary Support Details

The two caverns were excavated using road headers from the central shaft towards the north and south directions. The cavern excavation for both the bolted and passive support types adopted a split top heading sequence where the trial heading is staggered from the lead heading by a minimum offset distance to suit the ground conditions. Following completion of the top heading, full width benches were excavated to invert level.

The main challenge for the design and construction of the primary support included risks associated with the presence of complex adverse ground conditions (Section 3) which included complex faulting due to tectonic deformation associated with the NFZ, deep weathering within the Tuff unit, and highly variable unconformity zone at the contact between the Tuff and Aspley unit. To manage the risks due to highly variable ground conditions, several sensitivity analyses were undertaken during the design stage to confirm survivability of the design under adverse ground conditions. In addition, the design included provision for additional stitch bolts where there is a potential to encounter a large scale adversely oriented structure. The construction stage measures implemented to manage the risks associated with complex adverse ground conditions included additional borehole drilling, logging of anchor drill holes for the shaft support, inspection of endoscope holes above the cavern crown and longitudinal probe holes drilled from the lead heading. The additional information from these investigations were used to identify location and characteristics fault zones, unconformity zones and other adverse ground conditions.

The design and construction of the primary support for the Woolloongabba station caverns was also constrained due to the presence of settlement sensitive critical infrastructure located directly above the cavern. These included a 600 mm diameter cast iron cement lined (CICL) water main and a 1500 mm diameter micro-tunnelled sewer trunk. Settlement risks at the CICL water main and the micro-tunnelled sewer were managed by limiting the excavation advance length when tunnelling directly below this sensitive infrastructure. The cavern primary support at the location of the sewer main required modification to avoid clashes with the bolt exclusion zone around the sewer. The modified support at this location comprises 300 mm thick shotcrete, 2.4 m long crown bolts inclined forward to avoid clashes with the sewer and 5.4 m long bolts on the shoulders away from the sewer exclusion zone (Figure 5).

The primary support design for Woolloongabba station caverns involved an iterative process with settlement analysis and predicted effects assessments to ensure the predicted effects are within acceptable limits for all the infrastructure within the influence zone of the cavern excavation. In addition, surface settlement monitoring was undertaken to enable review of the actual ground movements from the cavern excavation relative to the design predictions. Overall, review of the monitoring data indicated the measured ground movements were within the design predictions. The maximum surface settlement above the Woolloongabba caverns for the design cases was predicted to be up to 40 mm above the North Cavern, whereas the measured maximum surface settlement above the North Cavern was 35 mm. Figure 6 shows a good comparison between the measured and predicted surface settlement through a cavern section at the CICL water main.

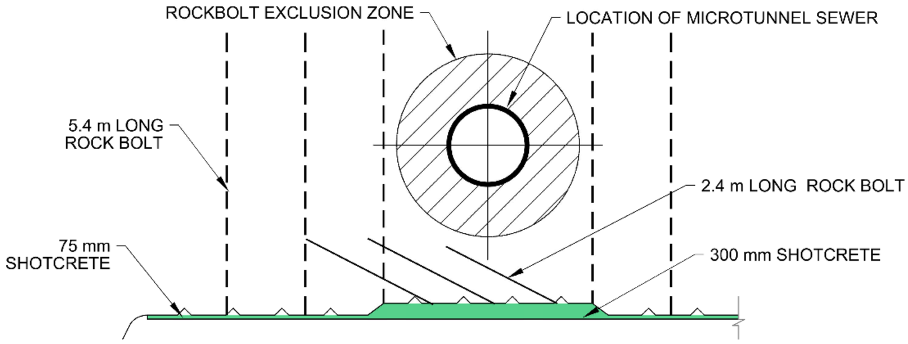



Figure 5. Longitudinal section showing the modified cavern primary support below the sewer trunk

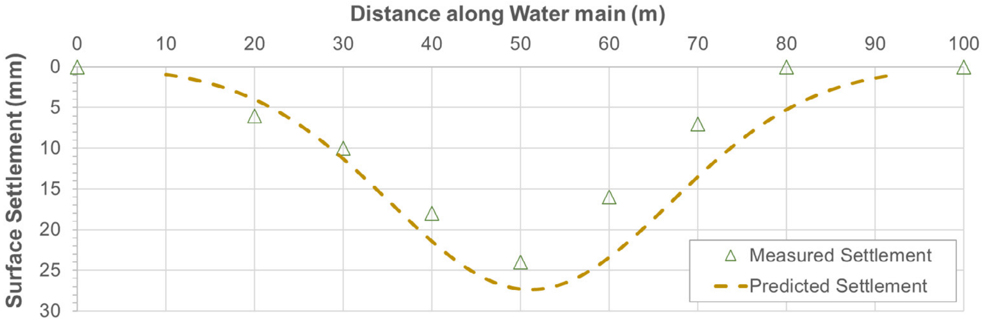



Figure 6. Comparison of measured and predicted settlements at the CICL water main

## 5 PERMANENT LINING

The permanent lining of the two caverns comprised bar reinforced concrete sidewalls with a Steel Fibre Reinforced Concrete (SFRC) crown. The sidewalls also incorporated a large corbel to support a concrete mezzanine slab, which spans across the cavern, imposing a working line load of up to 640 kN/m run. The cavern invert slabs were designed accounting for both bar and steel fibre reinforcement, with a thickness of 300 mm, based on the Contractor's preference to minimise material quantities. Bar reinforced concrete headwalls, 1 m thick, were located at either end of the cavern, with openings for the TBM tunnels at the northern end and the mined running tunnels at the southern end. Waterproofing, comprising sheet membrane and protective geotextile, was employed around the cavern sidewalls, crown and headwalls, with Cavidrain S60 installed under the cavern invert to facilitate a drained tunnel. Rearguard and hydrophilic waterstops were utilised at construction joints, which in conjunction with the membrane helped mitigate the risk of water leakage into the tunnel via the construction joints.

The thickness of the SFRC cavern crown varied depending on the geotechnical conditions, and corresponding ground loads for the permanent lining. The method to assess the design ground load was consistent with that outlined in Shen et al. (2022). As discussed in Section 4, the South Cavern utilised a bolted support type, whereas the poorer geotechnical conditions in the North Cavern required a passive shotcrete arch lining. The passive arch shotcrete was designed in accordance with the RMS B82 shotcrete specification to achieve a 100-year design life for the compressive strength of the shotcrete, allowing for a 'primary as permanent' approach where the ground load was shared between the primary lining (with degraded stiffness) and the permanent concrete lining.

The design vertical ground load for the cavern crown was estimated to be 80 kPa for the South Cavern, and 110 kPa for the North Cavern, with the horizontal ground loads (mostly associated with loosening rock wedges) for the cavern sidewalls and headwalls ranging from 10 to 25 kPa for the Tuff, NFG and Aspley units. A minimum SFRC thickness in the cavern crown of 600 mm and 700 mm was adopted for the South and North Caverns respectively.

Design of the SFRC lining was undertaken consistent with approaches outlined in AS5100.5 (2017) and the DAfStb Guideline (2015). Excavation of the cavern often resulted in localised areas of over-excavation, with the permanent lining over-poured to 'make-up' the difference, resulting in an irregular extrados profile and variable lining thickness. Finite element structural analysis within ATENA was undertaken accounting for the as-excavated primary lining face position to assess the risk of stress localisation causing undesired crack widths in the permanent lining prior to pouring. An example of such analysis is presented in Liu et al. (2025).

Poor geotechnical conditions were encountered in a number of areas of the cavern foundation, with FDZ, NFG 2A and SD 3 materials encountered. The combination of the mezzanine internal structure load and external ground loads resulted in an equivalent working load of approximately 2.9 MN/m run acting on the foundation below the cavern sidewall kicker. A tight tolerance for differential settlement of the internal structures (less than 3 mm) necessitated foundation treatment in most of the areas that poorer geotechnical conditions were encountered. Accounting for access and timeframe limitations, a 'remove and replace' foundation treatment solution was adopted as the preferred approach. The depth of removal was tailored to the encountered geotechnical conditions and the overlying load (which was less away from the cavern kickers), with 40 MPa concrete poured as the replacement material. Detailed geotechnical mapping of the invert during the cavern excavation as well as plate load testing of representative areas of poorer materials were undertaken to decide on foundation treatment requirements, with zones with an estimated Young's modulus of 700 MPa identified via the plate load testing. The foundation treatment varied between removal depths of up to 1.25 to 2 m under the cavern sidewall kickers and up to 0.75 m under the cavern invert, with an example of the design analysis approach undertaken presented in Shen et al. (2022).

Construction of the cavern headwalls was undertaken prior to the pouring of the adjacent cavern arch lining, which meant, that in combination with the thin 300 mm invert slab there was minimal passive resistance against overturning during construction of the headwall (which was constructed in a series of 'bottom up' horizontal pour lifts). In particular, during the higher lifts, the wet concrete hydrostatic forces generated significant overturning forces, that required additional temporary support to resist and enable construction. The South Cavern headwall was constructed using a significant A-frame to prop the lower portions of the headwall, with ground anchors installed through the invert slab to resist the A-frame uplift forces. The North Cavern headwall utilised a grid of 75 kN 'BA Anchors' with a minimum embedment of 500 mm into rock to support the formwork walers and resist the overturning forces. To achieve the 75 kN pull out capacity (which was verified via pull testing), a different system to the traditional BA Anchor was utilised, where a M20 steel bar was grouted into a hole drilled into the rock with HILTI RE-500. The bar was then integrated into the waterproofing system using a Bluey 'trumpet' system that 'sealed' onto the bar and then could be welded onto the waterproof membrane.

At the interface between the caverns and the station box shaft (located between the two caverns), a waterproofing detail was required between the cavern sheet membrane and the extrados of the shaft concrete lining, as shown in Figure 7. Over-excavation of the shaft however resulted in a zone of over-pour for the shaft walls, that the interface rearguard waterstop would tie into. There was a concern that over the design life, cracking could develop in this overpour concrete if it was unreinforced, effectively allowing seepage to bypass the waterproofing measures. To counteract this, a zone of localised reinforcement was installed in the 'over-pour' zone of the shaft walls, as shown in Figure 7, to mitigate the risk of cracking developing adjacent to the interface rearguard waterstop.

## 6 CONCLUSIONS

The primary and permanent ground support for Woolloongabba station caverns presented design and construction challenges due to highly variable and complex ground conditions and the presence of settlement sensitive critical infrastructures in close proximity to the cavern excavation, a zone for which details regarding its location and characteristics were limited prior to construction. A suite of design stage and construction phase measures were implemented to manage risks associated with geotechnical uncertainties without hindering the construction program. These

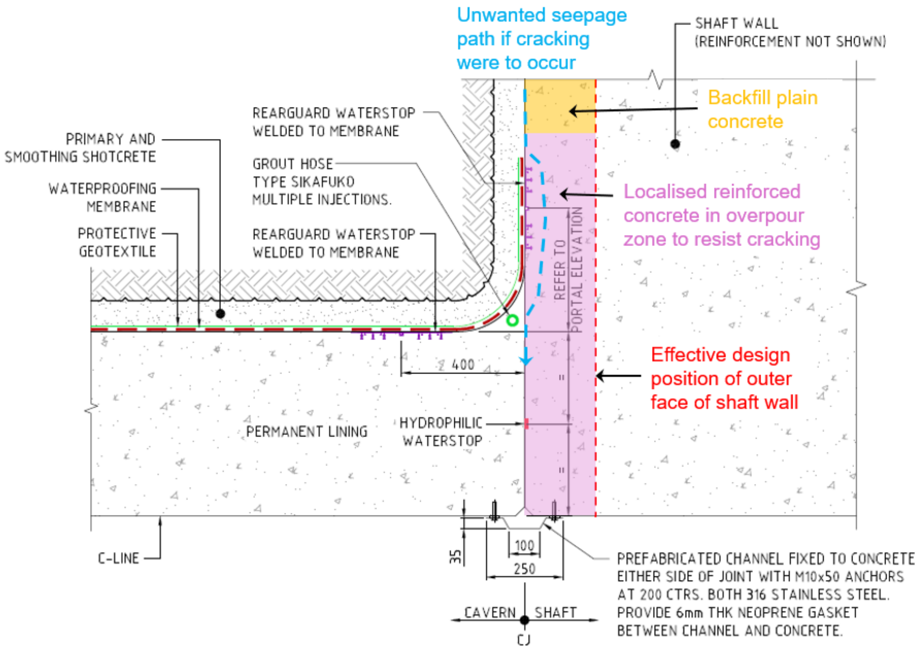



Figure 7. Cavern to Station Shaft waterproofing detail (long section)

measures included a range of support types to account for variable ground conditions, construction stage probing to identify adverse ground conditions, construction sequencing to suit ground conditions, and construction stage monitoring of ground movements to verify design assumptions.

The cavern excavation and primary support were completed on time to meet the construction program requirements for launching the TBMs from the North Cavern and commencing excavation of the mined running tunnels from the South Cavern.

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