19th Australasian Tunnelling Conference – Acosta-Martínez, Stewart and Hudson-Smith (Eds.)
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Design and construction of the AS1 Shaft within the Albert Street Cavern, Cross River Rail, Brisbane

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ABSTRACT: Albert Street Station is one of the new Cross River Rail project underground stations in Brisbane's CBD. It is being constructed by the CPB Contractors, BAM International Australia, Ghella and UGL (CBGU) Joint Venture, with PSM designing the primary support and permanent cavern lining. To link the cavern under platform ventilation and services with the nearby 50 m deep Main Access Shaft, the AS1 shaft was excavated 12 m below the cavern invert level, with two adits connecting the two shafts. The AS1 shaft geometry, design constraints, interfaces, and construction sequence introduced unique challenges to its design and construction. The shaft was excavated from the cavern invert level via pre-blasting of the bedrock, with a substantial shaft capping beam constructed prior to removal of the blasted rock. The Kicker Beam (i.e. western capping beam) was undercut by the excavation, spanning 12 m across the AS1 shaft, and was subsequently subject to several significant temporary load cases. These included a temporary steel deck and plant loads, formwork loads associated with the largest cavern lining pour for the project, as well as acting, in conjunction with a capping slab, as the permanent 'bridge' to span the shaft and support the overlying track slab and train loads. Long-term ground load associated with AS1 included those from the narrow rock pillar remaining between the cavern and the Main Access Shaft. This paper presents the design and construction challenges for the AS1 shaft primary support and permanent lining, as well as the experiences and learnings gained throughout the project.

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 which pass below the Brisbane River and CBD. The Tunnel, Stations and Development (TSD) component of the project 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.

The Pulse consortium (including the CBGU JV) was awarded the contract to design and construct the TSD works.

Albert Street Station, located in the CBD of Brisbane, is constrained and surrounded by existing infrastructure. The 290 m long station cavern runs parallel to the alignment of the overlying Albert Street, with access to the station to be facilitated by the adjacent Lot 1 (i.e. Main Access) and Lot 3 shafts via adits linking to the mezzanine level of the station cavern. The cavern is the largest mined station on the project, with an excavation span of 22.6 m and excavated height of 16.7 m. PSM provided the design for the excavation primary support as well as the permanent lining, with Robert Bird Group (RBG) designing the internal structures within the cavern and AS1 shaft.

With the entire station developed as an underground structure, the pedestrian, maintenance and mechanical and electrical access is all facilitated via adits linking the cavern to the adjacent shafts. A total of seven adits are utilised, five linking to the 50 m deep Main Access Shaft and two to the Lot 3 Shaft. Of the adits linking to the Main Access Shaft, three link to the cavern mezzanine level, whereas the other two (AA2 and AA6) are located below the cavern invert level, linking with the AS1 Shaft, which is excavated 12 m below the cavern level for under platform ventilation and services. The Main Access Shaft and the AS1 shaft are some of the deepest excavations within the Brisbane CBD.

The geometry, interfaces, and construction sequence of the AS1 shaft introduced numerous unique design and construction challenges, the key ones of which are presented below.

2 SHAFT GEOMETRY AND GEOTECHNICAL CONDITIONS

Figure 1 shows a cross-section of the AS1 Shaft and key interactions with the station cavern and Main Access Shaft. The AS1 Shaft is 15.3 m by 12.1 m in plan, extending approximately 12 m below the cavern invert level, with a capping beam surrounding the top of the shaft, and the AA2 and AA6 adits extending out from the shaft southern and western sidewalls respectively.

On the western side of the shaft, the 'capping beam' is undercut by the AS1 Shaft (and AA6 adit), with this beam (referred to as the 'Kicker Beam') required to span the length of the shaft and support the overlying cavern permanent lining sidewall, as well as the permanent rail track slab (via a capping slab). A series of internal walls sub-divide the shaft into sectors for the under-platform ventilation, as well as providing support for the overlying platform units. The rock pillar that separates the AS1 Shaft and cavern from the Main Access Shaft is approximately 5.7 m wide.

Albert Street is underlain by the Neranleigh-Fernvale Group (NFG) rock mass. The NFG rock mass comprises weakly metamorphosed sandstone (meta-greywacke and arenite), phyllite and subordinate quartzite and meta-basalt. Meta-greywacke and arenite were typically high strength, whilst the phyllite was typically weaker. The foliation in the NFG dipped 40° to 50° to the north-east (i.e. dipping towards the cavern), with a 14° shallow angle, 0.3 m thick, contact fault (separating the phyllite and meta-greywacke), dipping to the east and cross-cutting through the rock pillar separating the cavern and Main Access Shaft above the level of the Kicker Beam.

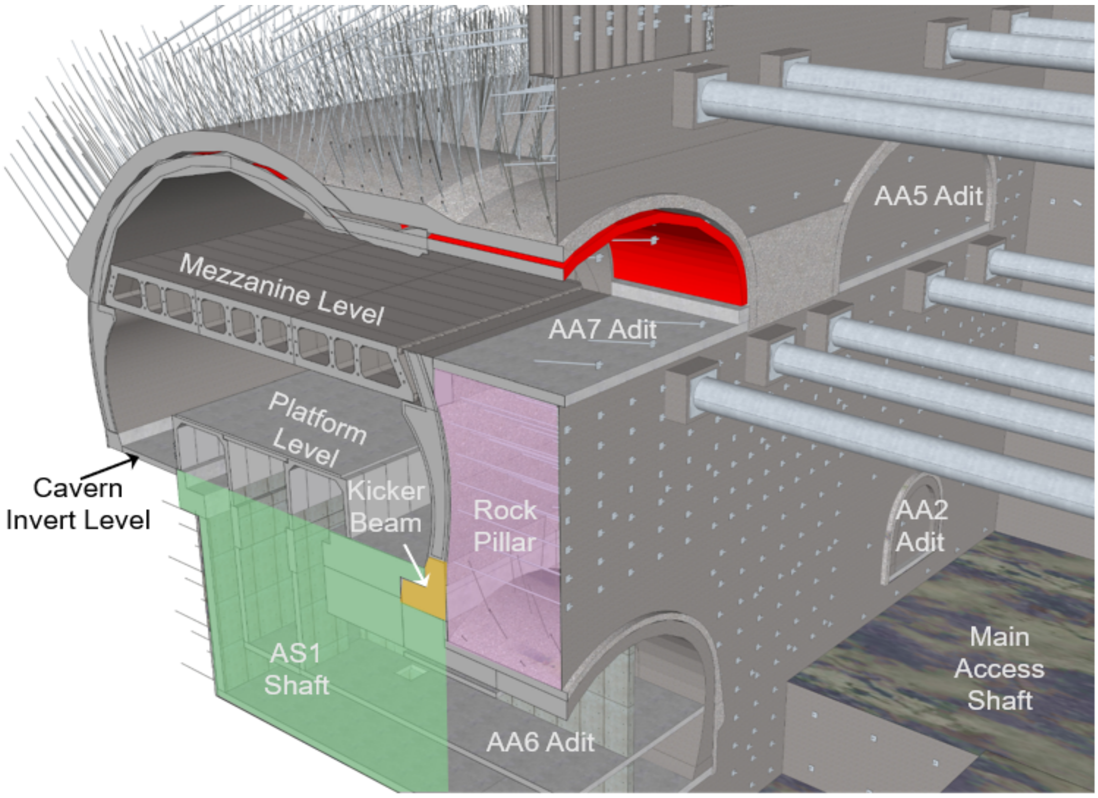


Figure 1. AS1 Shaft arrangement.

The geotechnical rock mass conditions within the AS1 shaft were typically mapped as NFG2 or NFG1, as per the definitions given in Cammack *et al.* (2022).

3 PROJECT SCOPE AND TECHNICAL REQUIREMENTS AND LOAD CASES

The Project Scope and Technical Requirements (PSTR) included key requirements related to the AS1 Shaft:

- Design in accordance with the Australia Standard (AS) 5100 series (2017).
- Minimum B2 exposure classification with crack widths estimated via the approach given in EN1992-1-1 and a crack width limit of 0.3 mm.
- Design life of 100 years for the permanent lining.
- Benefit of primary excavation active support (e.g. rock bolts) to be ignored in the design of the permanent lining.

The cavern (and AS1 Shaft) were designed as a drained tunnel, with Cavidrain S60 sheet drainage installed beneath the cavern invert slab and the AS1 Shaft invert (which collects groundwater inflows and conveys them to a sump in the Main Access Shaft), and a polyvinyl chloride (PVC) sheet waterproof membrane installed around the cavern and adit crowns and sidewalls and the AS1 shaft walls. This waterproof membrane was required to lap underneath the AS1 Shaft capping beam, resulting in a key design and construction challenge (refer Section 6.4).

The unfavourable foliation orientation (dipping to the north-east), thin rock pillar and the presence of faulted ground created adverse geotechnical conditions for the western cavern sidewall, AS1 Shaft walls and Kicker Beam foundation. These conditions were further complicated by the presence of the AA7 adit at the cavern mezzanine level, resulting in a complex and highly three-dimensional arrangement for the estimation of ground loads. Additionally, at the time of design, uncertainty in the excavation staging of the Main Access Shaft relative to the cavern and AS1 Shaft required sensitivity testing to ensure a robust design that could facilitate the range of potential construction sequences. For example, the existing Mantra building, on the western side of the Main Access Shaft has the potential to drive a large scale wedge sliding mechanism towards the shaft along the NFG foliation. During excavation, this wedge was supported by pre-stressed ground anchors, however, these were required to be considered as sequentially de-stressed as the permanent shaft structure was constructed from the bottom up, with load transferring through the Main Access Shaft structure, onto the rock pillar linking to the cavern, ultimately creating ground load for the cavern and AS1 Shaft permanent linings to resist. This scenario, in particular, resulted in complex load cases for the AS1 Kicker Beam.

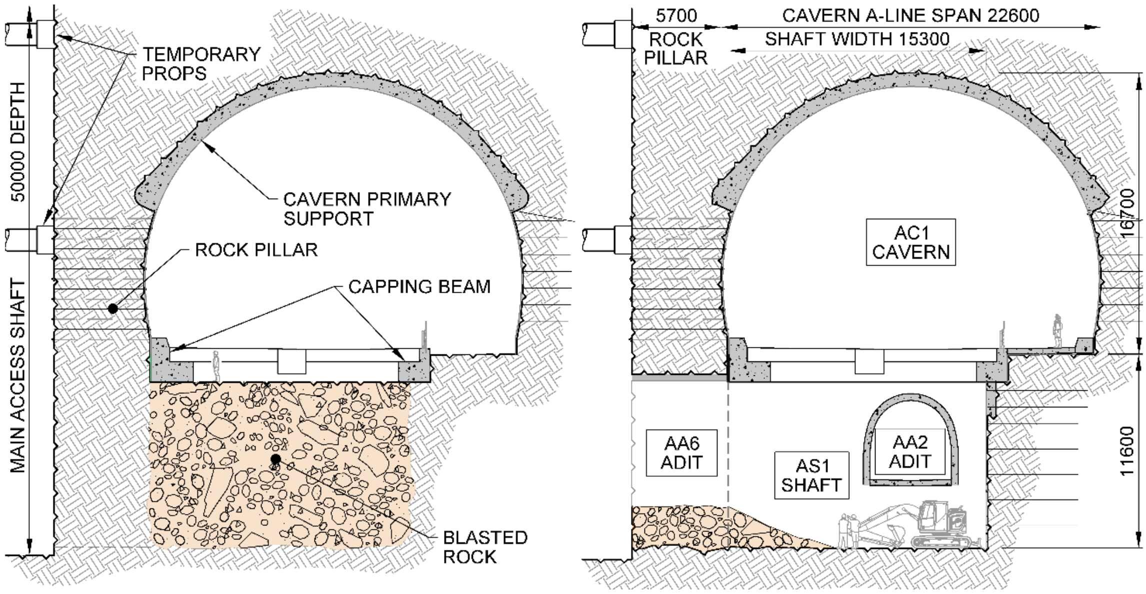
As shown in Figure 1, the AS1 Shaft underlies the rail track slab on the western side of the cavern. The Kicker Beam, capping slab (and underlying AA6 'headwall' lining), were required to act as a 'bridge' to support the track slab and associated live rail loads as well as a portion of the platform loads. In the final state, the internal shaft walls (designed by RBG) provided a degree of 'propping' to the shaft walls.

As a result of the construction sequence (as further discussed in Section 4), there were also several key construction cases loading the capping beam, shaft walls and Kicker Beam, including:

- Equipment loads on the cavern invert, adjacent to the shaft, creating lateral ground loads on the AS1 Shaft walls.
- A temporary steel deck, supported on the capping beam, that spanned the shaft and was required to support several construction load cases.
- The formwork for the cavern and AA7 intersection pour above the AS1 shaft was supported on the western side by the Kicker Beam, with this comprising the largest single pour in the mined tunnel packages.

4 PRIMARY AND PERMANENT SUPPORT

The construction sequence was complicated by the need to construct portions of the permanent tunnel lining structures as the shaft was being excavated (Figure 2).



(a) Blast shaft and partially excavate to construct capping beam.

(b) Excavate shaft, underpin capping beam then excavate and support adit AA2 and heading of AA6.

Figure 2. Abbreviated summary of shaft excavation sequence.

Due to the very high bedrock strength and that roadheader shaft excavation was impractical, the rock within the shaft was first blasted to permit excavation by hydraulic excavator.

The AS1 shaft was then excavated to a depth of a few metres to permit installation of the upper level of shaft waterproofing, followed by construction of the capping beam and cavern sidewall Kicker Beam. Excavation of the shaft continued, with the progressive installation of sidewall rock bolts and underpinning bolts beneath portions of the capping beam.

Once the excavation reached the invert level of adit AA2, the adit was excavated by drill and blast methods and primary support installed. The heading of AA6 was also excavated and supported prior to completion of the shaft excavation. Swinn *et al.* (2023) discusses challenges encountered during the excavation of AA2, and some damage caused to the overlying cavern invert slab that ultimately required remediation.

Due to critical program drivers for construction works occurring overhead in the mainline cavern, a temporary 100 tonne steel deck was erected across the shaft and supported by the capping beam and Kicker Beam. Construction of the AA6 adit permanent lining ‘headwall’ under the Kicker Beam span was also on the critical path, as it was required to withstand the largest load case associated with the formwork for pouring the overlying cavern permanent lining.

The shaft waterproofing was next installed and the permanent lining of the adits constructed, as well as shaft walls, headwalls, and internal shaft walls.

The shaft works were completed when the temporary deck was removed, capping slab constructed and contact grouting performed (see Section 4.2), precast station platform units installed, and track slab constructed.

4.1 *Excavation and primary support*

During cavern excavation and prior to blasting the AS1 Shaft, stitching of the approximately 5.7 m wide rock pillar located between the cavern and the Main Access Shaft was undertaken to improve the faulted rock bearing capacity. The stitch bolts comprised DN36 GEWI threadbars fitted with 300 x 300 x 50 mm anchors plates (Figure 1), prestressed to 500 kN prior to grouting. The stitch bolts were spaced at 1.2 m centres vertically, and between 1.2 m and 1.8 m horizontally.

Primary support for the shaft walls comprised 5.4 m long steel rock bolts spaced at 1.5 m centres with a thin shotcrete facing. Glass fibre reinforced polymer (GRP) rock dowels were available for the face support of the adits, however not required during excavation.

Underpinning of the capping beam was undertaken where the beam was required to resist substantial temporary construction loads. The underpinning bolts comprised 6 m long Dwyidag

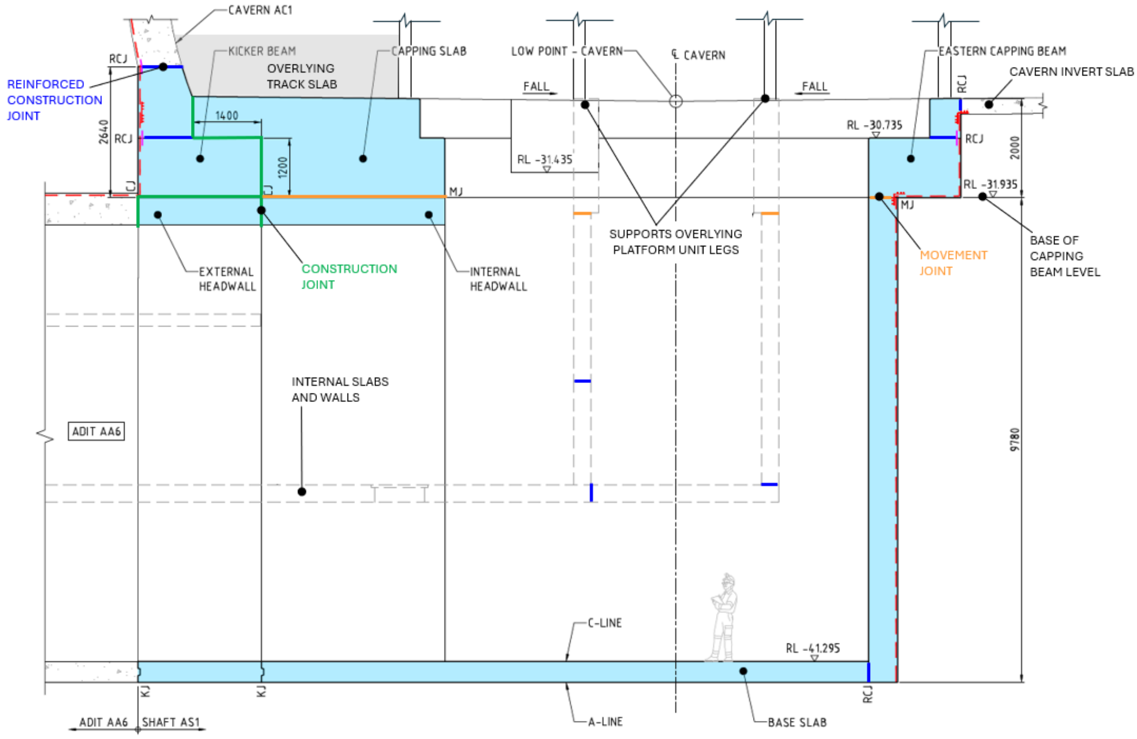


Figure 3. AS1 shaft permanent lining and movement joint locations.

WR36 threadbars with a 3 m free length and prestressed to 500 kN. An increased shotcrete thickness of 600 mm was adopted at the underpinned areas.

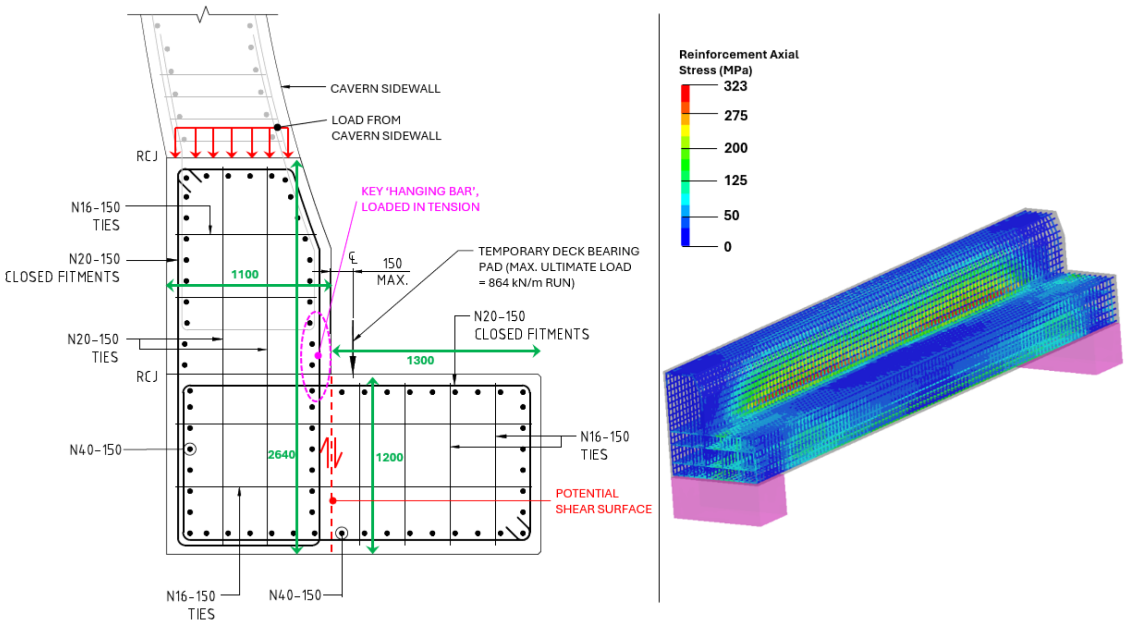
Primary support of the two adits leading from the shaft comprised a passive shotcrete lining with a design thickness of 400 mm.

4.2 *Permanent support*

The AS1 shaft walls were designed as 500 mm thick bar reinforced concrete with a characteristic compressive strength of 40 MPa. The capping and Kicker Beams have a thickness up to 2.4 m, partially to facilitate bearing pads for loading from the temporary steel deck during construction. The capping beams connected into the 300 mm thick cavern invert slab, which was a continuous slab along the length of the cavern with bar and steel fibre reinforcement. As shown in Figure 3, a reinforced concrete construction joint was utilised to connect the cavern invert slab to the capping beam. At the interface between the capping slab and the (north and south) capping beams, a series of ANCON DSD130 shear connectors were used to limit vertical and lateral (east/west) movements and help control deflections of the overlying structures and track slab.

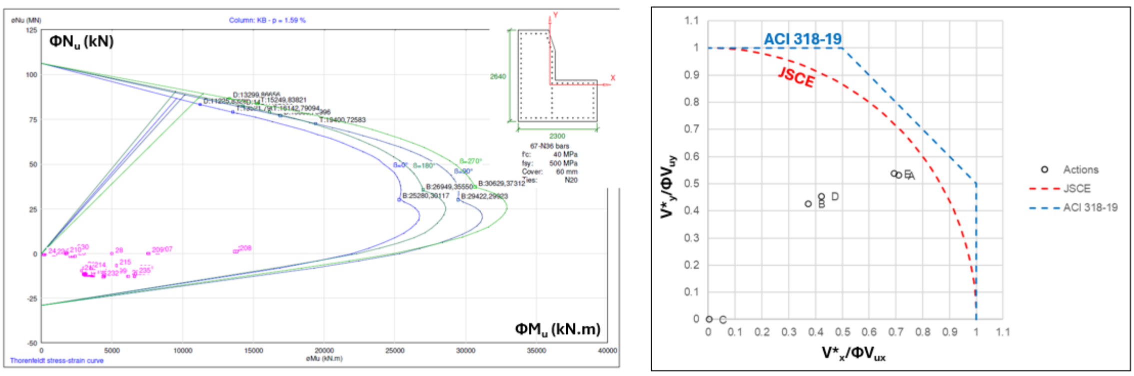
The construction of the permanent lining was highly sequenced, in line with the excavation and primary support sequence. The Kicker Beam and capping beams were constructed first, with the AS1 shaft walls and invert and capping slab constructed last, with a sequence of excavation stages in between. To help facilitate this sequence, a Movement Joint (MJ) was incorporated at the base of capping beam level (as shown in Figure 3), effectively separating the cavern invert and capping beam support system from the AS1 shaft walls and invert slab. A similar MJ was adopted in the internal shaft walls. A consequence of this was that the Kicker Beam and capping beam support and the AS1 shaft wall and invert support systems were designed to act independently.

In areas such as the Kicker Beam and the capping slab, the underlying 'AA6 headwall' ultimately provided additional support through an unreinforced construction joint interface. Given the requirement for the capping slab to support the overlying track slab, and be subjected to cyclical loading associated with the metro trains, a grid of grout tubes were installed through the capping slab to allow grouting of this joint interface following the critical initial concrete shrinkage stages to fill gaps that may have formed.



(a) geometry and reinforcement (b) flac3d analysis outputs.

Figure 4. Kicker beam geometry, reinforcement details and structural analysis.



(a) Bi-axial bending (b) Bi-axial shear.

Figure 5. Kicker beam analysis outputs

Following the completion of excavation, the waterproofing of the AS1 shaft was installed and connected to the waterproofing at the base of capping beam level (which had been installed prior to shaft excavation). Damage to the membrane at the base of capping beam level necessitated a remedial solution, as further discussed in Section 6.4. The AA6 headwalls were then constructed, followed by the shaft invert slab and the shaft external and internal walls, constructed in a series of bottom up jump form lifts. The capping slab was then constructed as a final 'puddle pour'.

4.3 *Other design interfaces*

The design of the internal shaft walls and slabs were undertaken by RBG, with the 50 MPa characteristic compressive strength internal structures connected to the external shaft walls, invert slab and capping beams via reinforced constructed joints. The internal structures consequentially provided a degree of 'propping' to the shaft and load transfer between the external permanent lining and internal structures. This degree of interaction was highly complex and was managed by both designers by developing and utilising a shared Strand7 structural design model to estimate design actions. For the design of the external walls, bookend scenarios for the stiffness of the internal walls (i.e. 'pre' and 'post' creep, estimated as 41.8 GPa and 13.9 GPa respectively) were accounted for to understand the potential range of load transfer under the spectrum of conditions that could occur over the design life of the structure.

5 KICKER BEAM

The Kicker Beam is a critical structure within the AS1 Shaft permanent lining, effectively acting as the foundation to the overlying cavern arch lining and part of the permanent support for the track slab. The range of load cases (including several critical temporary construction load cases), geometry of the Kicker Beam and variation in the surrounding support during construction resulted in a number of design and construction challenges.

5.1 *Design approach*

The design approach of the Kicker Beam needed to account for several key stages. During the excavation of the AS1 shaft, the Kicker Beam effectively acted as a 'bridge', spanning across the length of the shaft, and the temporary steel deck loading the 'lower flange' as a 'corbel' via a bearing pad. During this stage, the Kicker Beam was essentially 'simply supported' at the northern and southern abutments.

At later stages, the Kicker Beam became supported along its length by the underlying AA6 headwalls, and was subjected to loads from the capping beam, track slab (and trains) as well as long term ground loads associated with the cavern crown (transferred via the cavern sidewall) and lateral load applied by the 'rock pillar' between the cavern sidewall and the Main Access Shaft.

The differing loading combinations and support combinations resulted in numerous potential failure mechanisms and combinations of design actions. Two main design approaches were utilised to inform the design, namely:

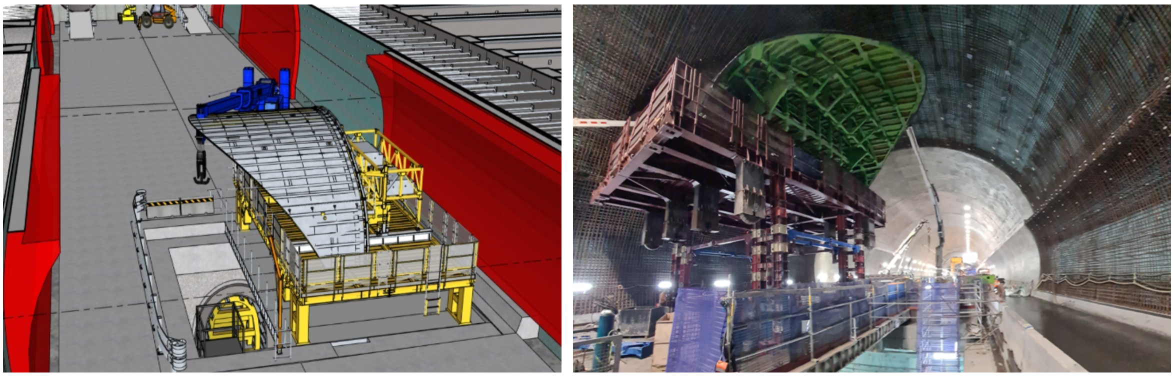
– Linear-elastic analysis for key cross-sections along the Kicker Beam, with calculated actions extracted from the Strand7 structural model
– Non-linear elastic analysis, complying with AS5100.5 Clause 2.3.6, undertaken with FLAC3D for critical load cases, with reinforcing bars discretely modelled.

Discussion of the above two approaches is outlined for the critical temporary construction load case, where the Kicker Beam was acting as a 'bridge', the temporary deck was supported by the lower flange and was carrying loads associated with the overlying cavern form, resulting in a total ultimate load of 864 kN/m run on the Kicker Beam.

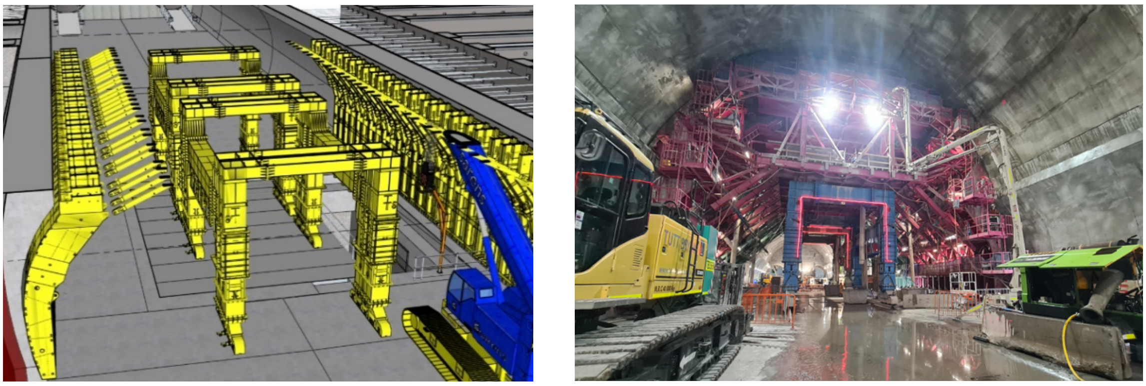
As shown in Figure 4(a), this generated potential mechanisms for bearing failure (where the bearing pad rested on the flange), shear failure of the flange from the web, generation of bi-axial bending forces and loading of the web intrados bar as 'hanging reinforcement' with significant tensile stresses. Local bearing failure was assessed using Clause 2.3.3 of AS5100.5, whilst the flange shear failure was assessed using a shear-friction capacity assessment, in line with Clause 8.4.3 of AS5100.5. The reinforcement design was assessed via a strut-and-tie check for the 'hanging bar', as well as by elastic analysis.

Within the Strand7 model, the Kicker Beam was modelled using plate elements, and equivalent beam actions were calculated at five cross-sections along the Kicker Beam. The eccentricity of the bearing pad, asymmetrical cross-section and support conditions resulted in significant bi-axial bending and shear actions being generated. Bi-axial bending capacity was assessed in line with AS5100.5 Clause 10.6.4 (as shown in Figure 5(a)) along with beam clauses for the combined effects of uniaxial shear and torsion. However, for bi-axial shear, as no methods were outlined within AS5100.5, interaction diagrams from ACI 318-19 Clause 22.5.1.10 and 11, and JSCE guidelines (2007) Clause C9.2.1 were utilised for the section checks (as shown in Figure 5(b)).

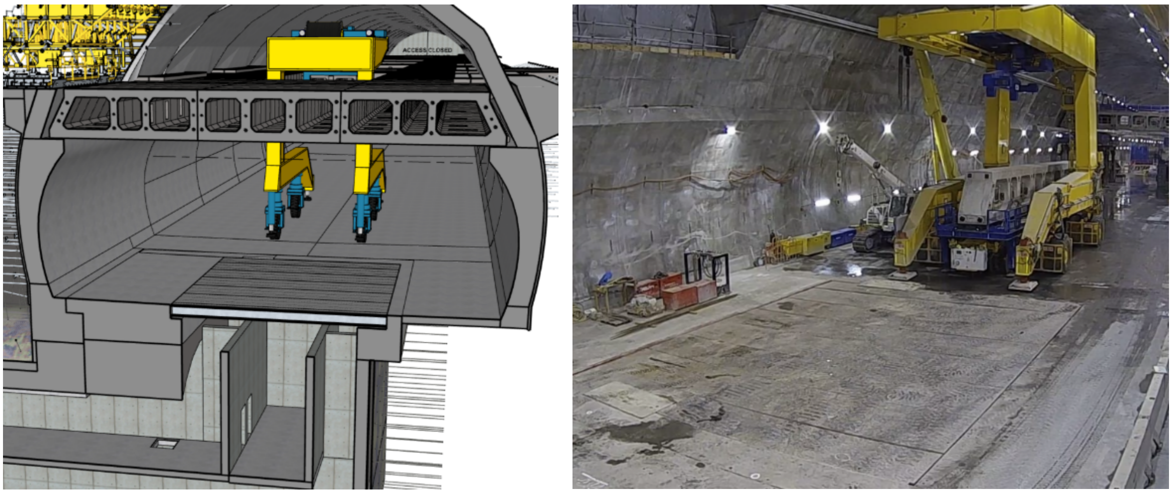
Following initial sizing of the reinforcement by the above approaches, a 3D model of the design reinforcement was created within the software package FLAC3D in combination with a constitutive concrete model to undertake non-linear elastic analysis. An example of the estimated bar stresses is shown in Figure 4(b). The method was undertaken consistent with the approach outlined in Tran *et al.* (2025), with results providing validation of the design.



(a) Upper Adit AA7 Stampella formwork



(b) Permanent Cavern Lining formwork system over the AS1 shaft



(c) Mezzanine loader traversing the AS1 shaft

Figure 6. Selected examples of stages required for the AS1 platform deck installation.

For the Serviceability Limit State (SLS) crack width estimation, section analysis was undertaken using the *RC Column* program, which implements the crack width estimation method outlined in AS3600 (2018). Due to the parameter differences, for typical sections and conditions, crack widths estimated via EN1992-1-1 (as required by the PSTR) typically estimate a crack-width 15% larger than those estimated via AS3600. Consequently, to allow for this, the 0.3 mm crack width limit was reduced to 0.26 mm when comparing against the *RC Column* outputs. Further crack width validation was provided by comparing SLS steel bar stresses against the maximum steel stress limit of 280 MPa, given in Table 8.6.1(B) of AS5100.5.

An SLS deflection limit of 1/640 of the span was adopted, in line with AS5100.2 Clause 9.10.

The resulting final reinforcement configuration is shown in Figure 4(a).

5.2 *Temporary construction load cases*

The AS1 temporary steel deck was critical to de-couple critical path activities in the mainline cavern from the permanent lining activities in the AS1 shaft and adits below. The steel deck was designed and manufactured to be utilised in different positions over the shaft, moving from east to west multiple times (Figure 6), to facilitate mainline cavern works. These activities included:

- Working at heights access to waterproof the mainline cavern, and steel fixing cavern lining.
- Stampella formwork for the upper AA7 adit (Figure 6(a)).
- Ability to traverse the two (2) rolling TFI cavern formwork systems across the shaft under dynamic loading through the rails placed on the cavern invert (Figure 6(b)).
- Formwork and concrete loadings for the mainline cavern arch pour.
- Mezzanine loader for both traverse and static installation setups (Figure 6(c)).

The temporary load cases varied for 22 different construction scenarios, all being transferred through the main steel deck centre beam to a bearing plate on the east and western (i.e. Kicker) beams. These loads on the deck ranged from 682 kN point loads from the mezzanine loader, to 270 kPa track loads from a crawler crane. Careful permit systems and signage were implemented to manage loads and stacked activities on the platform deck during construction.

6 OTHER KEY DESIGN AND CONSTRUCTION CHALLENGES

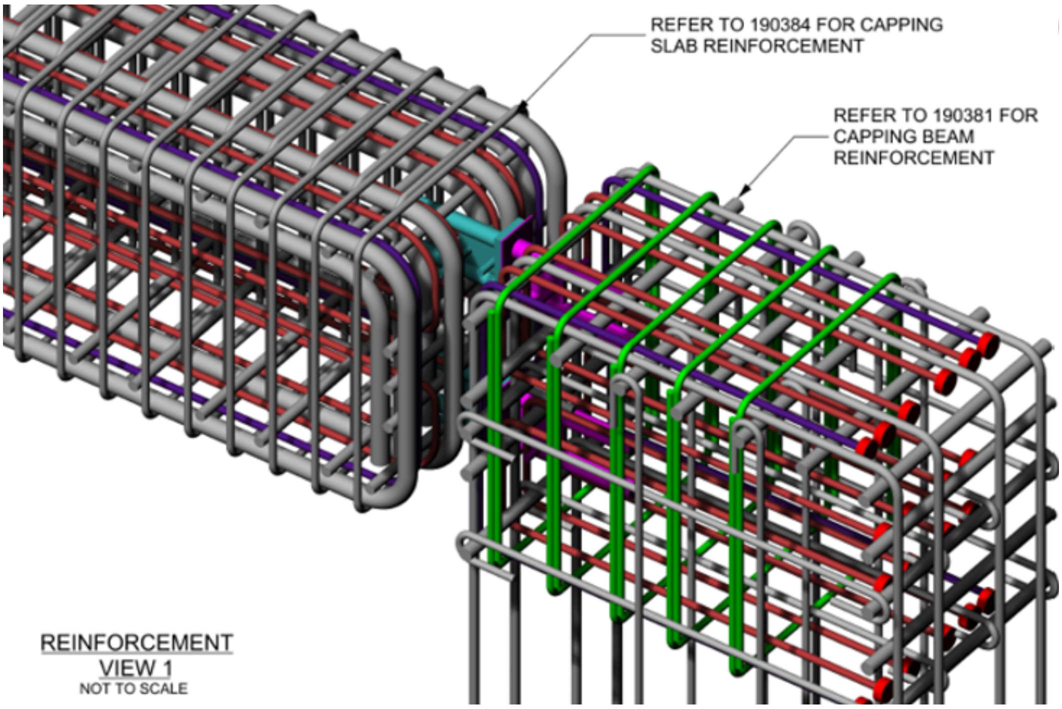
6.1 *Capping slab*

The capping slab is supported by the Kicker Beam flange on the western side and otherwise sits on the AA6 headwall, with the track slab constructed on top. Shear dowels were installed between the capping beam and capping slab to minimise differential displacements between the two structures for the overlying internal structures. As the capping slab supports the rail track, it is subject to cyclic rail loading and was designed for fatigue as per AS5100.2 and AS5100.5.

The design of the 2 m thick capping slab incorporates zones with closed shear ligatures (required to resist torsional actions) as well as shear ligatures cogged at each end. An acceptable alternative detail to closed shear ligatures from ACI 318-19 Figure R9.7.7.1 was utilised in some locations to aid constructability.

The overlying track slab supports the rail tracks, which have a ±5 mm maintenance tolerance for both horizontal and vertical directions. Partly due to the restriction from the PSTR that the rock anchors in the rock pillar between the Main Access Shaft and the cavern sidewall could not be relied upon, there was the potential for horizontal ground loads to develop against the extrados of the cavern sidewall. To help mitigate this, a 30 mm to 40 mm layer of Class L / SL Polystyrene (EPS) to AS1366.3 (1992) was installed at the vertical interface between the Kicker Beam / cavern sidewall and the track slab, allowing horizontal movement of the cavern sidewall in response to the ground load prior to loading the track slab.

Figure 7. Kicker and capping beam assembled reinforcement



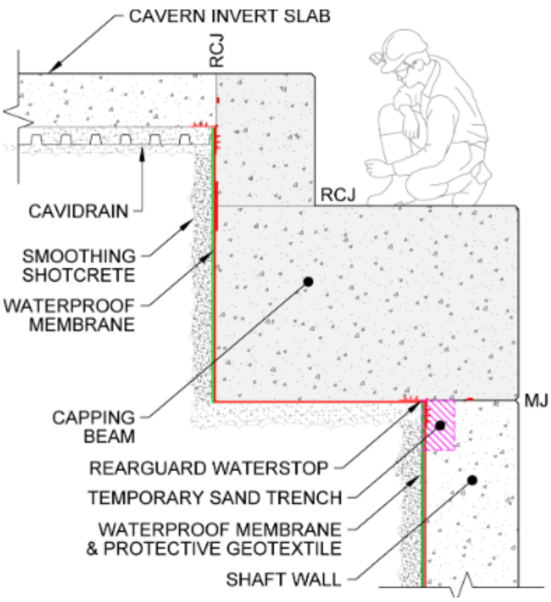
(a) Reinforcement 3D model

Figure 8. Capping Beam reinforcement details.

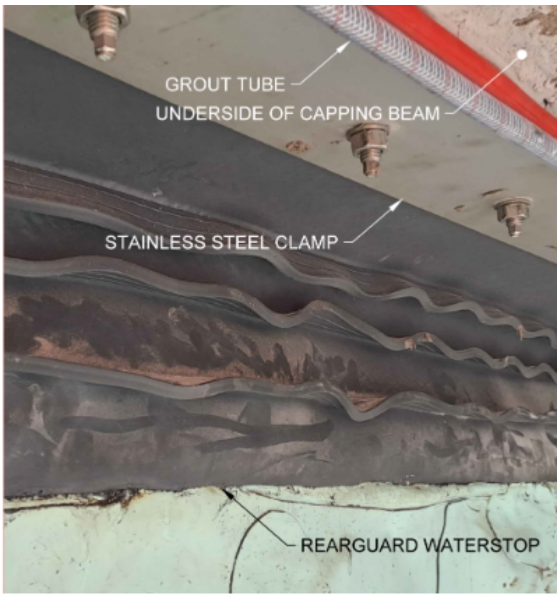
6.2 *Steel-fixing construction challenges*

Due to the depth and geometry of the large Kicker Beam, and the large diameter bars inducing longer lap lengths, the steel-fixing required careful planning to successfully schedule and assemble the reinforcement in line with the design requirements. The steel reinforcing cages for the corners were prefabricated, weighing approximately 6 tonnes each, and landed into the waterproofed excavation.

As the capping beam and Kicker Beam was a single sided form (i.e. cast against the primary lining) access was only available from the front face (Figure 7), further emphasising the need for planning and progressive inspections.



(a) Sand trenches and sawcut protection



(b) Remedial rearguard waterstop

Figure 9. AS1 Waterproofing

6.3 *Capping beam reinforcement congestion*

Sixteen ANCON DSD130 shear dowels were installed at the interface between the northern and southern capping beams and the capping slab. The required shear dowel local reinforcement and the capping beam web upstand geometry resulted in significant reinforcement congestion.

During the design phase, this was managed by discussing opportunities with ANCON to utilise some of the capping slab global reinforcement as part of the required local reinforcement (where possible), as well as developing a detailed 3D model of the reinforcement to identify clashes.

For some of the local reinforcement, shown in red and purple in Figure 8(a), there was insufficient length in the capping beam upstand to provide an effective development length, or sufficient space to cog the bars. Shear studs were utilised for these bars to provide adequate anchorage.

Despite the 3D clash detection model an additional reinforcement congestion issue was encountered during construction. The cavern invert slab longitudinal bars required anchorage (via an L-bar attached to a coupler) within the capping beam upstand. As the cavern invert slab was constructed ahead of the capping beam, the coupler positions for the L-bars where effectively set, and in several areas created complications for the installation of the shear dowels and associated capping beam reinforcement. To overcome the clashes in these areas and provide gaps between the bars for concrete placement and access for probe vibrators, a few of the cavern invert L-bars where cut and welded to adjacent bars as a welded splice (still providing development length), but improving steel congestion.

Figure 8(b) shows the final reinforcement positions in the capping beam upstand prior to pouring. Despite the dense reinforcement, the capping beam was successfully poured, which would have been extremely difficult without the clash detection modelling during design.

6.4 *Waterproofing*

As part of the MJ detail at the base of the capping beam, an allowance for vertical movement was required for the waterproofing, with half of the rearguard waterstop at the MJ required to be cast into the base of the capping beam at the initial excavation stage, 18 months prior to the other half being cast into the rear face of the shaft walls. This required significant efforts to protect the membrane and waterstop during the various construction activities.

The protection method involved excavating a trench to cast half of the rearguard waterstop into the capping beam initially and protect the membrane within a temporary sand trench during the concrete pour (Figure 9(a)). Once shaft excavation began, the rearguard was ‘released’ from the sand and suspended under the capping beam overhang until ultimately being cast in the wall pour.

Despite the efforts some sections of the rearguard were damaged during the excavation of the remainder of the shaft, with the waterproofing subcontractor performing repairs where possible. In some areas, an extra remedial solution was required to provide an acceptable waterproofing solution for the 100 year design life, which incorporated a fresh rearguard waterstop to be cast into the shaft walls, which was then pinned to the underside of the capping beam via a clamping detail (M12 stainless fasteners at 200 mm spacing) and welded onto the remaining waterproofing under the capping beam, a re-injectable grout tube was also included to add additional redundancy and accommodate the expected joint movement range (Figure 9(b)).

7 CONCLUSIONS

The AS1 Shaft is a complex structure, which provided numerous design and construction challenges. These challenges included construction sequencing, impacts of temporary loads, ground loads and interactions with the nearby Main Access Shaft, impacts from cyclical train loads, waterproofing and components of the shaft designed by different designers.

A suite of design stage and construction phase measures were implemented to manage risks associated with the above challenges. These measures included utilising movement joints to facilitate the construction sequence, protection of earlier constructed elements against impacts from the subsequent excavation of the shaft, sensitivity testing at the time of the design to de-risk Main Access Shaft construction timeline interactions, detailed clash detection modelling of congested reinforcement areas, use of a shared structural analysis model between designers and detailed assessment of ground loads.

Despite the numerous challenges, the AS1 Shaft was successfully constructed.

8 ACKNOWLEDGEMENTS

The authors would like to acknowledge the Pulse consortium together with CPB Contractors, BAM International Australia, Ghella and UGL Joint Venture for granting permission to publish this paper. The authors also wish to express their appreciation of the professionalism and technical expertise provided by colleagues at PSM in the development of a practical design solution and the CBGU construction team for implementing the complex design to a high standard.

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