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Melbourne's Metro Tunnel – City Square Rock Pillar Replacement Wall

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ABSTRACT: The Metro Tunnel is the biggest transformation of Melbourne's rail network since the City Loop opened in 1982, with twin 9km tunnels passing under Melbourne's CBD and five new underground stations. The City Square shaft is 90m long, 25m wide, 35m deep and runs length-ways against the mined cavern. Geotechnical analysis indicated that the capacity of the residual pillar of rock between the piles and the excavation line of the cavern presented a significant technical and construction risk when supporting the re-distributed stresses generated by excavation of the cavern – if this could not be overcome then the rail alignment and/or cavern width would need to change. An innovative and integrated approach incorporating design and construction thinking was required. The solution was to build a 70m long, 2.5m thick, 10.5m high reinforced concrete wall to replace the rock before the cavern side tunnel was excavated. This paper outlines the analysis, detailing, constructability and methodology considerations to successfully design and build this critical and complex component of the Town Hall Station.

1 INTRODUCTION

The Metro Tunnel connects the Cranbourne/Pakenham and Sunbury Lines, the metropolitan lines that service two of Melbourne's largest growth corridors to the southeast and northwest to create the Sunshine – Dandenong Line, shown in Figure 1. It comprises twin nine-kilometre tunnels and five new underground stations. A key part of the project was the Tunnels and Stations Package delivered by the Cross Yarra Partnership, incorporating John Holland, Lendlease Engineering and Bouygues Construction Australia as the D&C Joint Venture, hereafter described as D&C. Most of the engineering services, including the structures and tunnels were provided by the Arcadis/Arup/WSP (AAW) Design Joint Venture.

Of the five new stations, the greatest anticipated passenger demand is at the Town Hall Station, constructed within Melbourne's Central Business District (CBD), with City Square as its primary entrance. It is located under Swanston Street, extending from Collins Street to Flinders Street. Due to this location, several significant geometric constraints including The Melbourne Town Hall, St Paul's Cathedral, Young and Jackson Hotel and Flinders Street Station – all of which are heritage listed – a 5-Star hotel and one of the busiest light-rail corridors in the world.

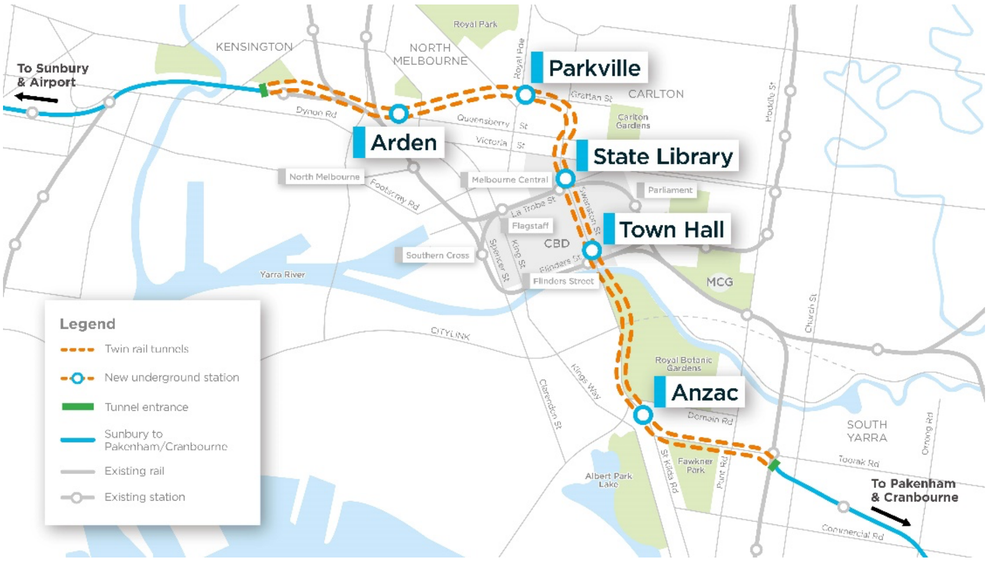

Figure 1. Metro Tunnel Alignment

The combination of these constraints, coupled with the width of the station platform resulted in minimal distance remaining between the cavern extrados and the City Square shaft retention system. The residual rock pillar between these elements was identified as potentially inadequate to support the vertical stresses transferred by the excavation of the tunnels, representing a significant public safety and construction risk. This paper outlines the analysis, detailing, constructability and methodology considerations to replace the rock pillar with a reinforced concrete wall to ensure the overall design could be achieved.

2 TOWN HALL STATION

2.1 *Overall Arrangement*

Town Hall Station comprises a mined trinocular cavern, three entrance shafts, four mined adits and a subterranean link connecting to the existing Campbell Arcade beneath Flinders Street, as shown in Figure 2.

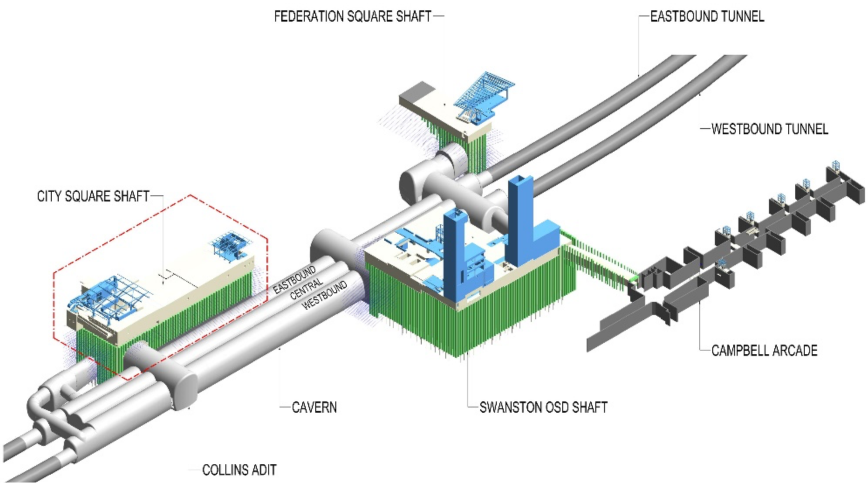

Figure 2. Town Hall Station Arrangement

The 230m long, 14m high, 29m wide cavern containing the platform and track is described as a trinocular due to the arrangement of three overlapping tunnels. It is located 18m below Swanston Street – one of the busiest light-rail corridors in the world. A mined approach was adopted to minimise disruption to the road. The four adits provide horizontal access from the shafts into the cavern, both during construction and permanently for passengers, services and emergency egress.

The City Square shaft is 90m long, 20-25m wide and 35m deep, with its long axis parallel to the cavern along its western side. It is constructed within a demolished portion of the Westin Hotel basement and abuts the hotel building and remaining basement, as shown in Figure 5. When complete, a new public square will be constructed on top of the station structure. To achieve the required pedestrian flows and services, the plan area of the station was maximised within the existing footprint.

The rail alignment at Town Hall Station was set to maximise separation from Young and Jackson Hotel, which was identified as sensitive to ground movements. This positioning left only 2.5 metres between the cavern excavation-line (E-line) and outer face of the City Square lining wall, which can be seen diagrammatically in Figure 4.

2.2 *Geology*

The geology at the City Square shaft comprises a layer of fill over weathered bedrock described as Melbourne Formation. The Melbourne Formation (also known as Melbourne Mudstone) is an anisotropic rock mass, both in terms of its intact properties and its structural geological features. Based on bore samples, the Melbourne Formation at the Town Hall Station comprises 77% siltstone and 33% sandstone.

The weathering profile of the Melbourne Formation at the Town Hall Station typically ranges from Extremely Weathered (classified as MF4) to Fresh/Slightly Weathered (classified as MF1). At the City Square shaft, the MF2 layer (Moderately Weathered) was anticipated to be encountered at between five and ten metres below surface level. Based on observations during the construction, an additional classification of MF1a was introduced for City Square to account for better than anticipated properties at the deeper portions of the shaft.

The Melbourne Formation is noted as comprising alternating layers of siltstone and sandstone of varying thicknesses, with sandstone typically interbedded within the siltstone. The bedding at Town Hall Station consisted of two distinct sets in at about 22 and 33 degrees, at WNW and NW respectively. It is also noted that joint sets are typically present in the Melbourne Formation. An example of this bedding can be seen in the excavated face shown in Figure 3.

These geological conditions are a key consideration in both the design and construction methodology of the Town Hall Station.

Figure 3. Excavated face of rock at top of wall

2.3 *Construction Sequencing*

The City Square shaft adopted a bottom-up construction methodology. This involved reinforced concrete piles being installed from the surface (within the bounds of the demolished Westin Hotel basement), with lateral retention provided by combination of steel struts and ground anchors in the East-West direction and rock bolts in the North-South direction. These retention elements were progressively removed or destressed during the build-out phase as the permanent walls and slabs were constructed.

Mining of the cavern was undertaken using roadheaders, commencing with the adits from the shafts. Once the heading and necessary benching of the adit was complete, the roadheaders turned 90 degrees and commenced excavation of the central tunnel. Excavation of the platform (side) tunnels could not commence until excavation of the central tunnel was complete, central base slab cast and temporary columns installed to support the transferred vertical load when the platform tunnel heading was excavated, refer to Figure 4.

The overall construction programme required works for the cavern and shafts to be undertaken concurrently with a minimum of constraints.

3 ROCK PILLAR

In simple terms, excavation of a tunnel in rock causes redistribution of stresses from the excavated region into the adjacent un-excavated regions. In the case of the trinocular cavern at CBD South, this redistribution happens twice. First into the rock either side of the central tunnel, then into the temporary columns and rock adjacent the platform tunnel, as represented in Figure 4 by the red arrows. This arrangement results in greatly increased stresses in the rock each side of the cavern. As noted above, there is only 2.5m between the E-line and outer face of the City Square lining wall. When the retention piles are considered, the residual rock pillar between the two structures is reduced to less than 1.5m and would be disturbed by both the piling and mining procedures. Early in the design phase it was identified that the rock pillar would be unlikely to provide reliable support for the transferred stresses and was thus identified as a substantial risk requiring mitigation by design.

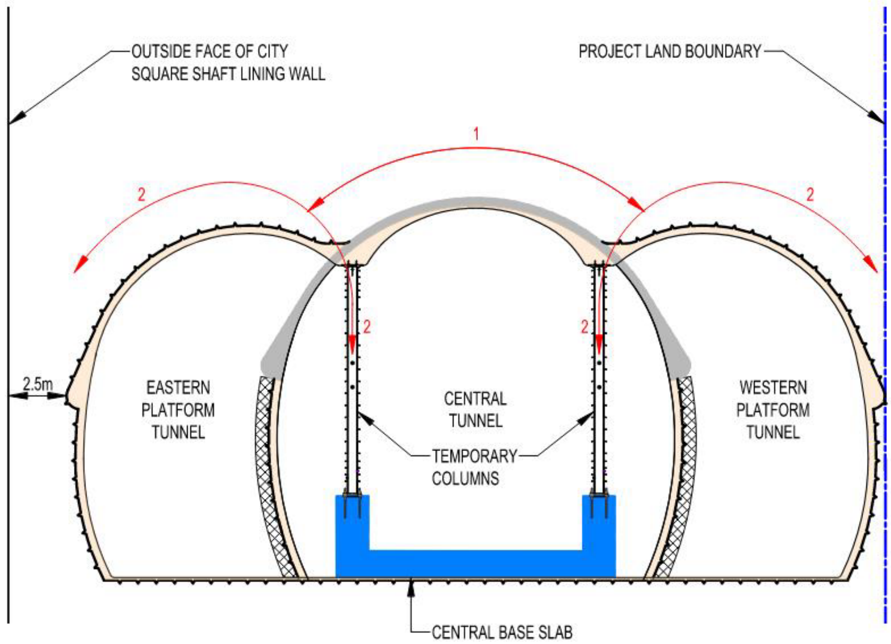

Figure 4. Cavern ground stress transfer sequence

As a reduction in the cavern width or change to the rail alignment were not possible due to constraints and project requirements, the adopted mitigation strategy was the replacement of the rock pillar with reinforced concrete.

Replacement of the rock while excavating the cavern was considered, but discarded for a combination of reasons including:

- Replacement needed to occur prior to excavation of the City Square shaft, introducing a substantial programme constraint as the Collins Adit could not be used to excavate the cavern; and,
- The platform tunnel would need to become wider, creating additional complexities for construction and design of the temporary support.

Therefore, the reinforced concrete pillar would need to be constructed from within the City Square shaft. The full interface between the shaft and cavern needed to be replaced, except at the Collins Adit interface, an extent of approximately 70m. The top of replacement was determined by the cavern geometry, nominally at RL -12.6m and extending to the base of the City Square shaft (which varies between RL -23.1 to -26.6), for a height of up to 14m. The relative position of the City Square shaft to the cavern with the narrow pillar in-between can be seen in Figure 5. Several surrounding constraints are also identified.

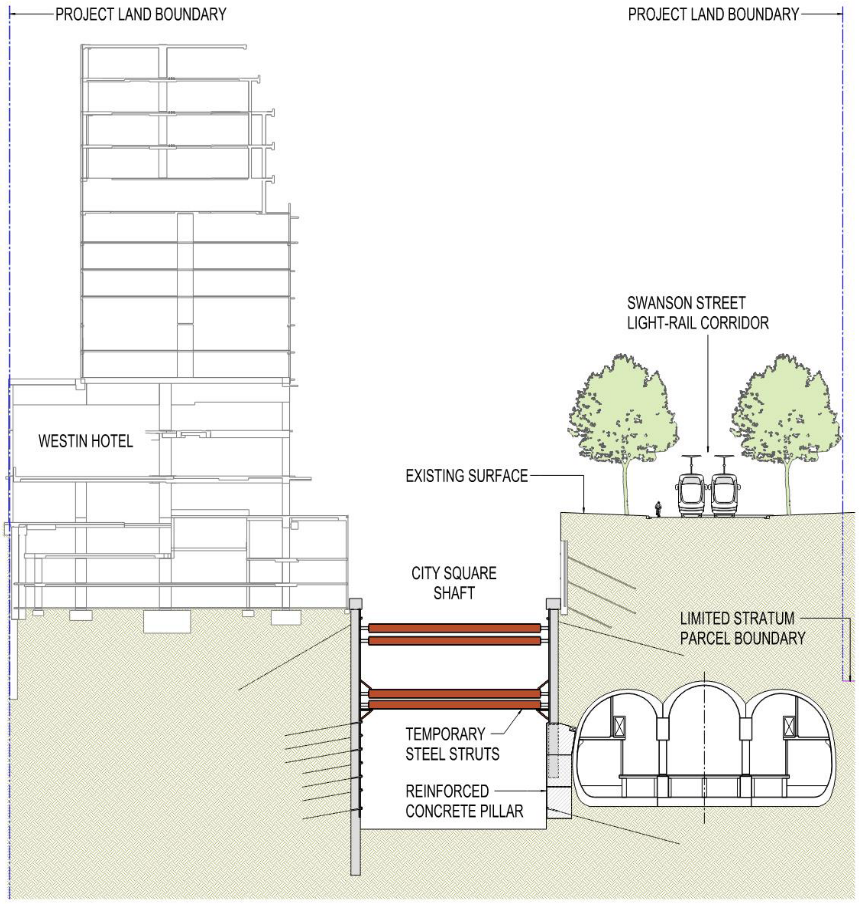

Figure 5. City Square Cross Section

Based on this arrangement, the rock pillar replacement needed to be constructed prior to commencement of excavation of the eastbound platform tunnel so it was in position to support the loads at transfer. This formed a key constraint in the overall construction programme of the Town Hall Station. However, this could be accommodated in the construction programme.

While this arrangement introduced a technical constraint for the platform tunnel excavation, it allowed for concurrent excavation of the central tunnel and the City Square shaft. Once the replacement was completed, it also de-linked excavation/construction of the cavern and shaft primary structure build-out, meaning each could progress independent of the other.

4 DESIGN/CONSTRUCTION METHODOLOGY

Although the overall construction methodology for City Square was bottom-up to allow swifter access for excavation of the adit and cavern, this approach was determined to be inappropriate for the rock pillar replacement wall due to its height and need to undermine the upper retention system to facilitate excavation outside the line of piles (see Figure 3). A bottom-up approach to construction of such an element would have been significantly slower and less safe, especially considering the 10.5m high vertical rock face which would have been exposed when the piles were demolished.

A top-down construction methodology was adopted for the wall. It was designed with three 3.5m high lifts, which were progressively excavated and constructed with the main shaft excavation.

4.1 *Sequencing*

Due to the depth of the shaft and cavern, the top of the wall is approximately 22.6m below the existing surface. It extends through the line of retention piles and a further 1.5m into the rock. The required excavation undermined the retention piles, compromising their stability and that of the construction deck supported on the capping beam.

To mitigate this issue and ensure vertical support is always provided, a hit-and-miss approach was adopted for each level of the wall. The first step was excavating and constructing the A-blocks – only when they had achieved the minimum required strength could excavation of the B-blocks commence. The final activity on each level was the C-blocks. This arrangement is shown in Figure 6: A-blocks are in red, B-blocks are in yellow, and C-blocks are in green. The Level 1 segments are typically 6.2m long, 3.5m high and 2.5m thick, while the Level 2 and 3 segments are 4.7m long.

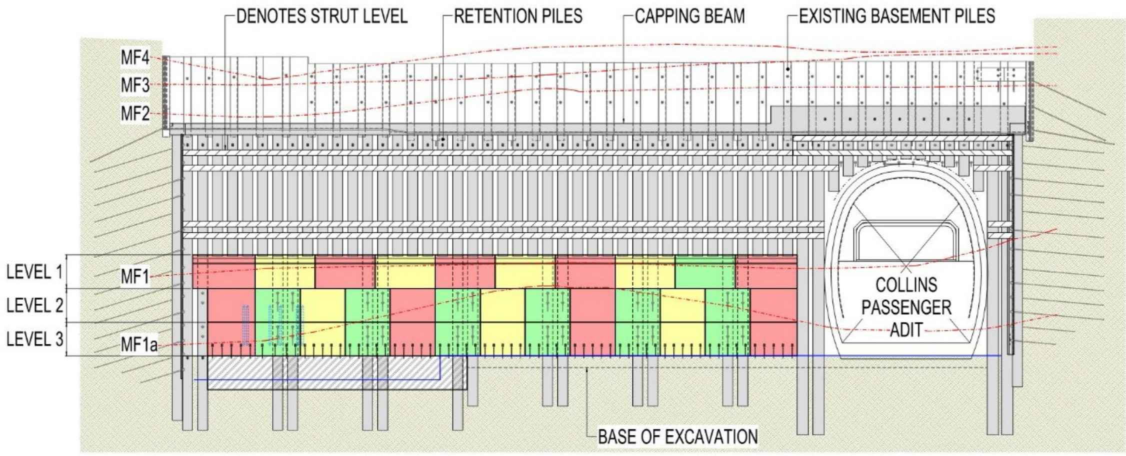

Figure 6. Wall Construction Sequence

This sequence was developed collaboratively by AAW with D&C over multiple workshops and iterations.

4.2 *Design Approach*

The wall was designed for three distinct conditions. A detailed cross-section of the wall can be seen in Figure 7, showing how it is positioned between the City Square primary structure and cavern permanent lining, with the cavern temporary support landing on the corner.

4.2.1 *Stage 1*

The first stage is vertical and horizontal support during excavation of the City Square shaft. During the excavation for Level 1 (excavated arrangement shown in Figure 3) the capping beam was designed to span over the demolished piles, this provided support for the construction deck on the beam, as well as any loads from the piles hanging on the beam.

During excavation for the subsequent levels, vertical support was provided by Level 1 of the wall. This level was designed as a deep beam with continuous horizontal reinforcement (via the use of couplers) and shear ligatures arranged for the vertical condition. Note the top left corner of Level 1 (see Figure 6) is extended onto an additional pile to ensure vertical support is maintained when that end of the wall was undermined. The Level 2 segments are designed to hang off the underside of Level 1 when they are undermined for the excavation and construction of Level 3.

Horizontal loads were not a significant concern at this stage as the platform tunnel was not being excavated. Restraint was provided by the steel struts against the piles over the wall and friction at the under-side of the wall.

4.2.2 *Stage 2*

The second stage is during excavation of the platform tunnels. This introduces a substantial vertical load on top of the wall with a large lateral component.

The vertical loads are resisted by the wall acting as a pillar, bearing on the rock at the base. The lateral loads are resisted by steel struts against the piles above the wall and regularly spaced stressed ground anchors which were sleeved through the wall at the base, extending beneath the cavern.

The wall was designed to span vertically from top to bottom in this condition.

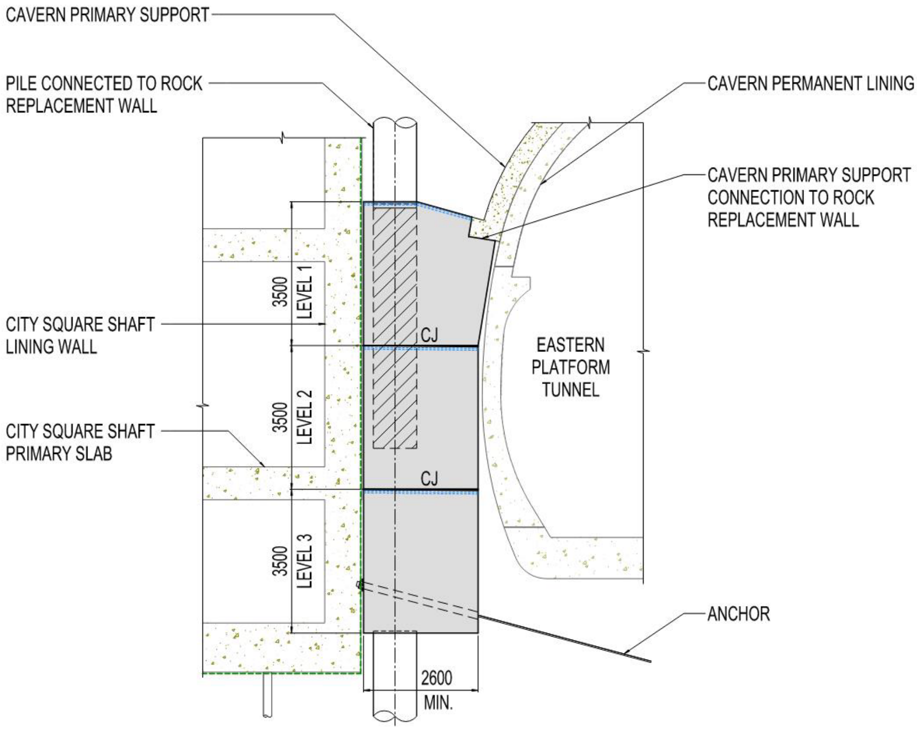

Figure 7. Rock Replacement Wall Section

The piles were installed from the surface with couplers included in the reinforcement cage to facilitate the future connection to the wall. When the piles were demolished to facilitate excavation for the Level 1 segment, the couplers were exposed for the installation of starter bars. The exposed couplers for this connection can be seen in Figure 3. The pile reinforcement for a selection of piles was extended to the toe as they could provide additional robust vertical support for the loads in the temporary condition as the levels were undermined.

Each segment included vertical reinforcement with couplers at the top and bottom to enable the provision of continuous vertical reinforcement. Shear ligatures were provided for the horizontal condition – in Level 1 this was in addition to the shear ligatures for the vertical condition.

Horizontal continuity was not provided between the segments at lower levels, in contrast to Level 1, as it was not necessary for them to span horizontally. They were designed to 'hang' from Level 1 when they were undermined. This approach was driven in part by Early Thermal Cracking (ETC) considerations, the omission altered the restraint of the concrete thus significantly reducing the area of reinforcement to limit the crack widths under ETC conditions.

4.3 *Stage 3*

The third stage is the final condition, when the cavern permanent lining and shaft primary structure are completed.

Any vertical and horizontal loads transferred into the wall by the cavern excavation are locked into the reinforced concrete wall, however lateral restraint is provided by the City Square primary structure following removal of the ground anchor and steel struts.

Figure *8* shows the wall on the right-hand side in its final condition, with struts at the top and stressed anchors at the base, before the construction of the shaft primary structure has commenced.

Figure 8. Construction Stage prior to stressing anchors

5 BUILDABILITY

The overall arrangement, dimensions and detailing were carefully developed by AAW in consultation with D&C.

5.1 *Tolerance*

The following considerations were incorporated into the design:

- The front face (against the City Square shaft) was set back from the outer face design line of the lining wall by 20mm to provide additional tolerance;
- The back face (against the cavern) reinforcement was provided with an additional 75mm of cover (150mm in total) to mitigate the risk of damage to reinforcement during excavation of the cavern;
- The connection of the pile to the top of the wall was checked for the potential omission of specific coupled bars to allow for on-site coordination of the circular pile reinforcement with orthogonal wall reinforcement in the event of clashes; and,
- The set-out of vertical reinforcement within the wall was adjusted in the design based on specific detailing feedback.

5.2 *Construction Sequence/Methodology*

The design documentation including construction sequencing drawings developed specifically for the wall segments. These clearly identified the anticipated approach which was considered in the detailing.

This also identified considerations intended to simplify construction, including:

- The use of cement-stabilised sand blinding at the underside of Level 1 and Level 2 for ease of excavation and better identification of the concrete face when excavating the level below;
- Provision of temporary spot bolts for rock face stability during installation of reinforcement;
- Provision of a timber void former at the interface with the cavern primary support for easier identification of the interface; and,
- Localised over-excavation to enable detailed placement of shotcrete to build out to the design face of the wall in a more refined manner.

5.3 *Detailing*

The reinforcement within the segments was detailed to be installed from the cavern side of the segment of the wall towards the shaft, see Figure *9*. This started with a vertical outer-most bar which was a continuation of the bottom reinforcement. This arrangement ensured there were bars against which the horizontal back-face reinforcement could be tied.

The shear ligatures were installed as loose 'candy-canes' at the ends, lapping with straight bars. This did not represent any concerns with detailing requirements to AS5100.5 as the laps were not in the cover zone. The outer 'closed' ligature was made up of individual ligatures with each hooked around a corner bar – this meant the near-face verticals could be one of the last bars installed allowing access to the inside for as long as possible. The horizontally placed shear ligatures were detailed to be inserted from the inside face once all other reinforcement was in place.

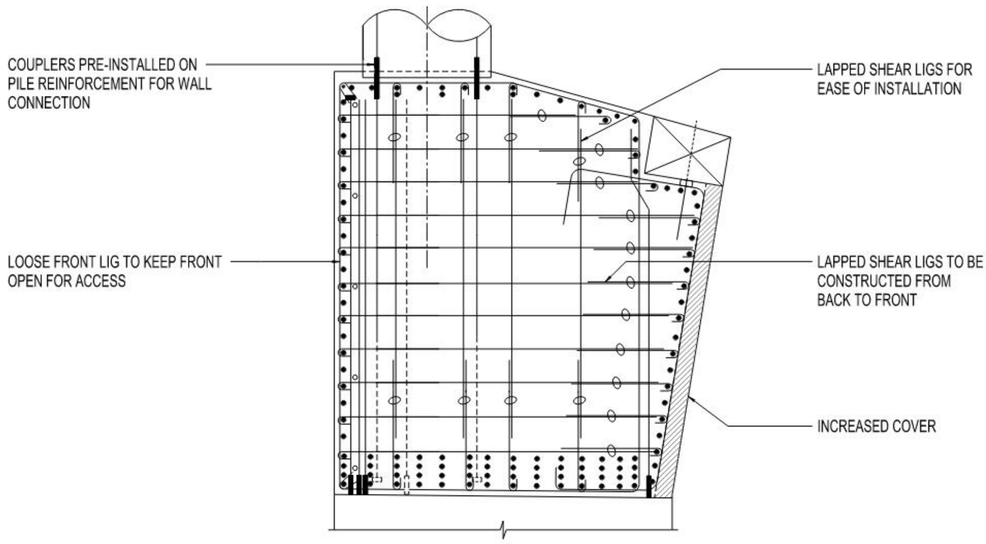

Figure 9. Level 1 Typical Reinforcement

The segment geometry and detailing was modularised as much as possible. This greatly simplified shop detailing, bar bending and installation on site.

5.4 *Shop Detailing*

Given the complexity of the reinforcement to meet design actions, construction methodology, Project Specification requirements and geometry, the shop detailers modelled the reinforcement in three-dimensions, see Figure 10. This model enabled a detailed review of constructability and resolution of clashes prior to fabrication and installation, greatly improving productivity on site.

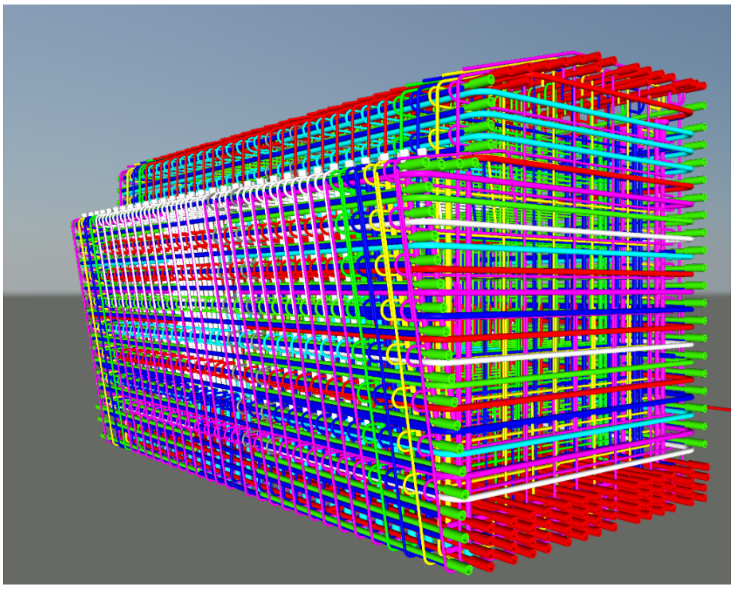

Figure 10. 3D Shop Detailing Model

6 CONCLUSIONS

The Rock Pillar Replacement Wall is an exemplar of how a bespoke design can holistically address major technical, construction, programming and safety challenges.

It highlights the importance of the Design and Construction teams working collaboratively to address a problem. Neither team had the ability to address their respective issues in isolation, it was only through a jointly developed solution for which all parties identified their challenges and constraints that a successful outcome was achieved. Regular workshops and challenge sessions were key to this.

As with all underground and complex structures, understanding the construction sequence is critical. The precise order in which activities can fundamentally change the loading and support conditions. It is important that this is communicated to the Construction team and confirmed as early as possible. The alternate approach would have been to provide a more conservative/expensive design solution which can accommodate multiple different sequences to account for potential challenges at a work front thus mitigating the risk of one problem delaying multiple areas. However, it is inevitable that the design team will not identify all potential construction sequences.

the construction was relatively unhindered as the design detailing carefully considered how each segment would be put together and included measures to enhance buildability and tolerance.

The Rock Pillar Replacement Wall was an ultimately successful solution to a complex problem. Due to attention paid during design and detailing the construction of the segments went smoothly on site, overall stability was maintained, and it was completed in time for excavation of the eastbound platform tunnel.

7 ACKNOWLEDGEMENTS

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