The largest cavern on Sydney Metro, Victoria Cross Station

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ABSTRACT

Victoria Cross Station in North Sydney is one of the new stations on the Sydney Metro City & Southwest project. John Holland, CPB Contractors and Ghella are building the 15.5 km long twin railway tunnels between Chatswood and Sydenham and excavating six new metro stations.

The underground Victoria Cross Station excavation was completed in September 2019 as part of the Tunnel and Station Excavation (TSE) Works.

The station cavern is the largest underground structure constructed for the project, with an excavated length of 265 m, height of 19 m and span of 26 m.

Although the station cavern was excavated in a favourable tunnelling medium comprising fresh, high strength Hawkesbury Sandstone, the underground excavation posed significant design and construction challenges due to its wide span and station configuration with connecting smaller tunnels (adits) and adjacent shafts. This included a complex junction at the southern end resulting in a slender pillar being formed. In addition, the cavern lies between 17 and 33 m beneath a busy street lined with high rise buildings with basements between three to six levels deep.

The primary support of the cavern and adits comprised rock bolts, cable bolts and a thin synthetic fibre reinforced shotcrete liner.

This paper considers the challenges in the primary support design of the station cavern and adits including risk mitigation measures considered in design. It concludes with a summary of the completed excavation works and primary support performance.

INTRODUCTION

The Sydney Metro City & Southwest project comprises new 15.5 km twin rail tunnels from Chatswood, continuing under Sydney Harbour and through Sydney's CBD to Sydenham. The John Holland, CPB Contractors and Ghella Joint Venture was awarded the contract to design and construct the tunnel and station excavation works. The project includes twin TBM bored running tunnels, three open cut stations, three underground stations, dive structures and a crossover cavern.

PSM designed the primary and permanent support for the underground Victoria Cross Station (SVC) in North Sydney. The station comprises of a 265 m long cavern, two pedestrian access adits, an underground lift shaft, three service adits, nozzle enlargements and associated open cut shafts (Figure 1).

The station cavern is the largest underground structure constructed for the project, with an excavation span of 26 m and height of 19 m, resulting in a face area of 405 m^2. The mined cavern and adits involved excavation of approximately 125 000 m^3 of bedrock comprising fresh, high strength Hawkesbury Sandstone.

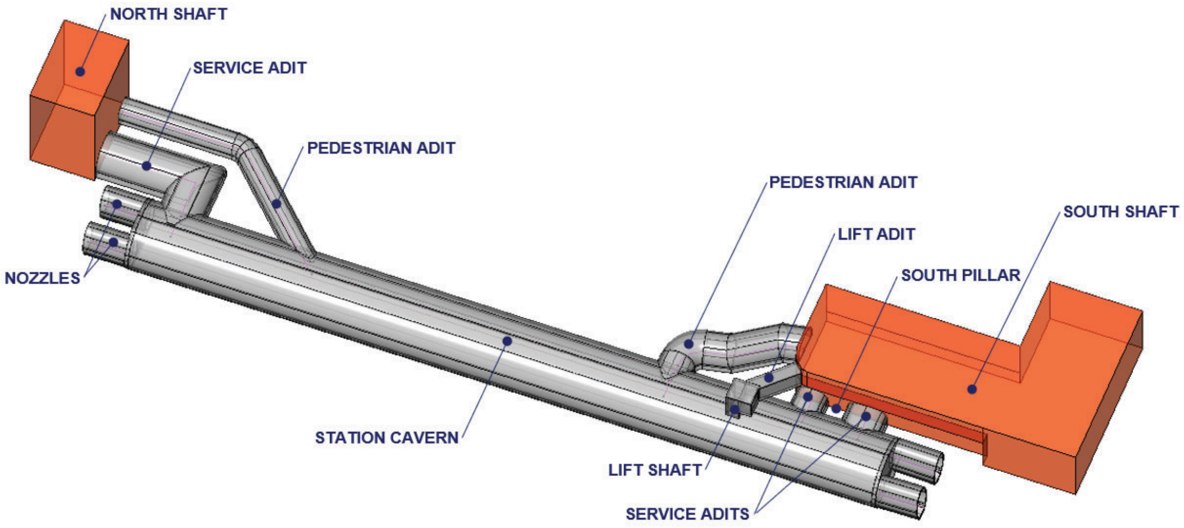

FIG 1 – Victoria Cross Station.

GEOTECHNICAL CONDITIONS

The project is situated in the Sydney Basin, which comprises a thick sedimentary sequence of Permian-Triassic aged rocks dominated by Hawkesbury Sandstone and the Wianamatta Group within the project area. At SVC, the subsurface conditions comprise surficial fill and residual soils overlying weathered low strength sandstone (Class V) grading to fresh high strength sandstone (Class I) (Figure 2). Ground cover above the cavern crown ranges from 17 m to 33 m.

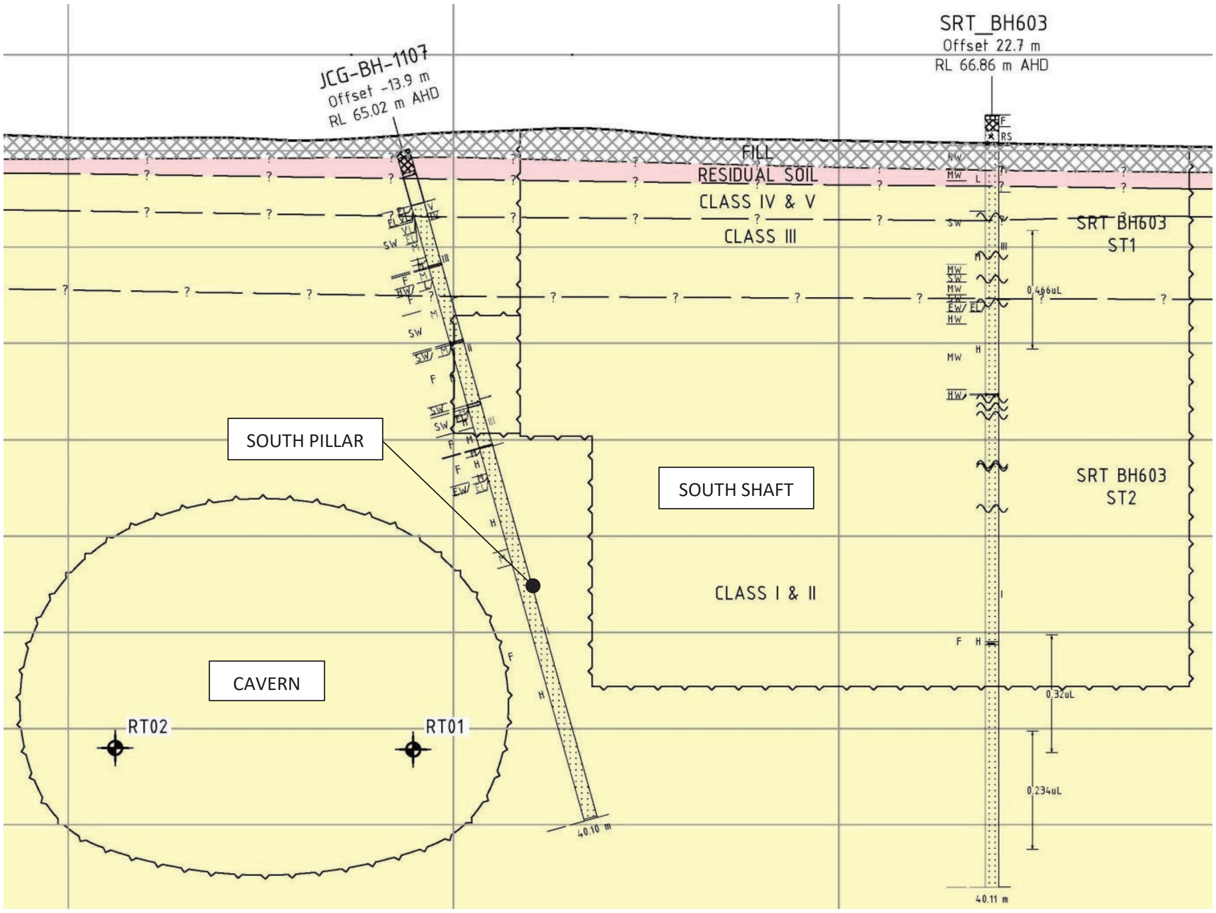

FIG 2 – Cross-section of the cavern adjacent to the south shaft through the South Pillar.

Based on published literature and the geotechnical investigation at SVC, no major regional geological structures were anticipated to intersect the SVC mined tunnels. Geological structure observed from the boreholes and mapping of rock exposures at SVC comprise bedding and joints, typical to Sydney geology.

Bedding is typically subhorizontal with an average dip of less than 10°, persistence greater than 20 m with typical defect spacing of between 1 m to 3 m.

Joints in the sandstone are typically subvertical with the predominant joint set striking north-east. A minor set is also present dipping typically 40° from horizontal and striking north-east-east.

In situ stress testing was carried out within the fresh, high strength sandstone at 13 m to 49 m depth and the results indicated that the stress regime is consistent with the expected range in Sydney. A range of *in situ* stresses were considered in design consistent with that adopted in recent tunnelling projects in Sydney.

The geotechnical conditions of Class I and II sandstone generally provide favourable tunnelling conditions. Geotechnical risks at SVC were largely related to particular areas where the station configuration resulted in slender pillars and thin tunnel crown rock beams with failure mechanisms controlled by geological structures rather than overall rock mass.

DESIGN

Primary support

The primary support comprised rock bolts, cable bolts and synthetic fibre reinforced shotcrete. The primary support was designed to provide adequate support to allow construction of the permanent tunnel support structure, comprising a variety of cast *in situ* bar reinforced, steel fibre reinforced or plain concrete linings for different areas of the cavern and adits as described by Clarke (2019). Design of the primary support elements was based on precedence and empiricism together with detailed numerical analysis.

Rock bolts ranging from 3.5 m to 5.5 m in length were used for the adits with spans ranging from 5.5 m up to 16 m with local effective spans in excess of 20 m. In the cavern, a combination of rock bolts and cable bolts were used. For lengths of the cavern away from intersections, 7.5 m long cable bolts were used in the side drifts and 5.5 m long rock bolts were used in the central pillar (Figure 3). At cavern intersections, 8 m long cable bolts were used for the cavern heading.

Synthetic fibre reinforced shotcrete was applied following each advance to provide support of rock blocks that could form between the bolts. Shotcrete thickness ranged from 75 mm to 100 mm depending on the encountered ground conditions.

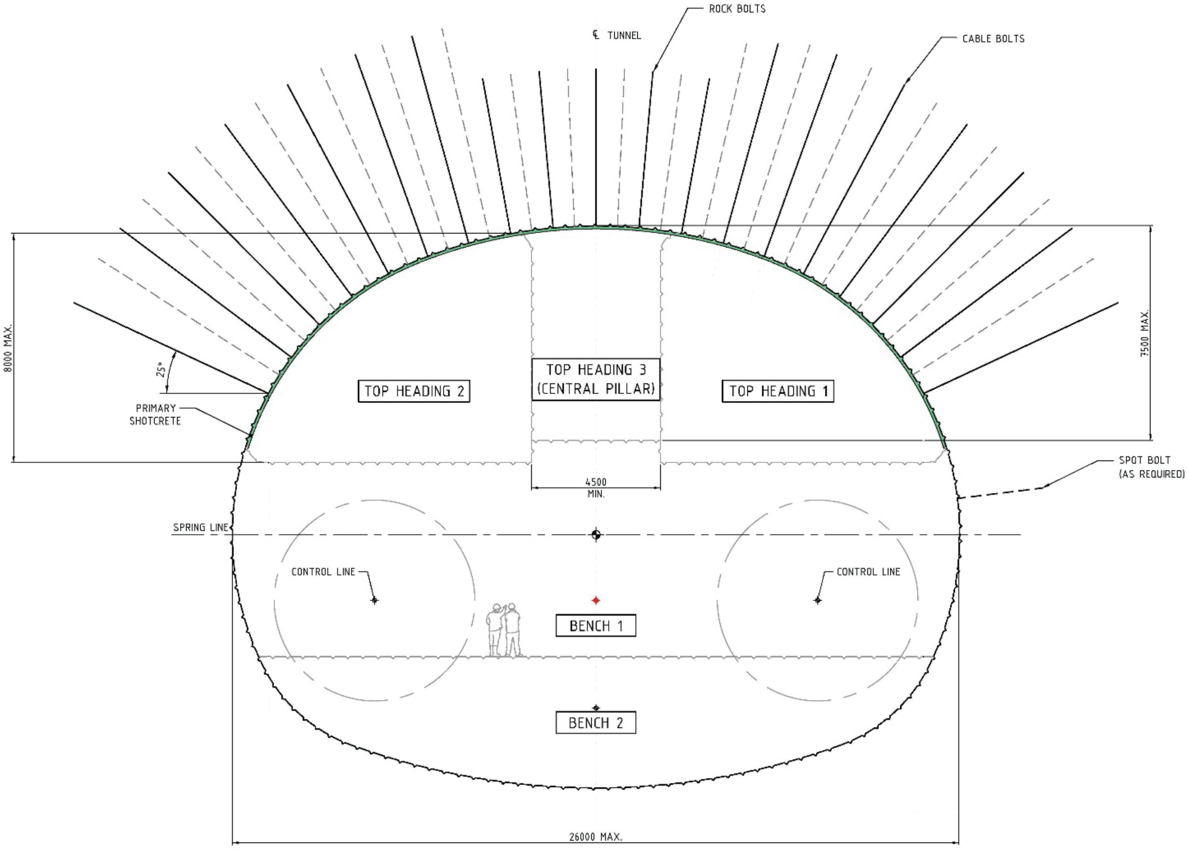

FIG 3 – Station cavern primary support.

Construction sequence

The excavation of the station cavern and adits was carried out predominately with Mitsui Mike SLB-S300S roadheaders. The primary support was installed systematically as the tunnel face advanced. Purpose-built equipment was used with appropriate sequencing implemented for personnel to work under supported ground at all times away from the unsupported crown and face. This ensured that the safety of workers was maintained throughout construction. Spot bolting of isolated rock blocks or wedges was undertaken as required based on observation and direction by the geotechnical engineer or engineering geologist.

The cavern excavation was sequenced as a staggered, three heading advance comprising two leading side drifts with a trailing central pillar (Figure 3). Following completion of the cavern heading, full width benches were excavated to invert level. Adits were excavated full face and where required; bench excavations were undertaken.

DESIGN CHALLENGES

Impacts to existing infrastructure

There are inherent risks when tunnelling in an urban environment associated with existing infrastructure. At SVC, the risks to infrastructure include the impacts on Miller Street (which the station cavern runs directly beneath) and surrounding buildings with basements up to six levels deep (Figure 4).

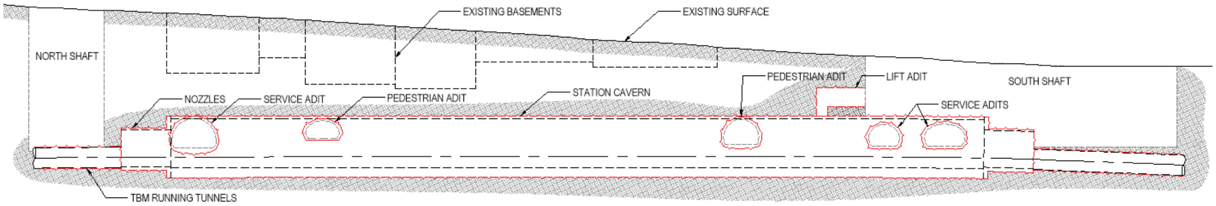

FIG 4 – Schematic of basements at SVC (edge of basements offset 15 m from cavern centreline).

The north service adit and pedestrian adit were excavated directly beneath three building basements with adit to basement separation ranging between 13 m to 15 m. Ground conditions between the adits and basements comprised Class I/II sandstone.

To mitigate these risks, detailed 2D and 3D finite element analyses were completed to assess impacts of tunnelling to existing infrastructure and impacts on tunnel design due to building loads. The results indicated that the ground deformations were within acceptable limits for the proposed bolt and shotcrete primary support and construction sequence including adopting efficient tunnel advance rates. Impacts on buildings were individually assessed based on the predicted ground deformations. It was concluded that the predicted effects were not governing the design of the primary support.

Station configuration

The station configuration included a lift adit that is located above the cavern connecting the south shaft to the cavern crown via a lift shaft (Figure 5). The lift adit (at the lift shaft location) has relatively shallow rock cover of approximately 5 m (below the intersection of Miller Street and Berry Street).

Due to the location of the lift adit and shaft, part of the rock arch or beam above the cavern crown which is typically relied upon for tunnel stability is partially removed. The rock arch is locally reduced to a thickness of approximately 1.8 m at the thinnest point (Figure 5).

FIG 5 – Excavation of cavern central pillar under lift shaft and lift adit.

As a result of the geometry, higher stresses were expected to distribute through this thin rock beam and as such the integrity of the rock beam had to be maintained. In addition, cavern crown bolting was not possible due to the lift adit void above the cavern. The cavern primary support had to be revised to accommodate the station configuration in this area. The thin rock beam was stitched with grout encapsulated 36 mm diameter high tensile threaded bars spaced at 1.5 m centres, pretensioned to 50 kN and plated at both ends. Floor bolts, 4 m in length, were also installed from within the lift adit prior to cavern excavation beneath the adit. The design requirements also included hold points to complete detailed mapping of the adit floor and shaft walls, downhole endoscope inspections and point load strength testing to verify that the thin rock beam met the assumed design ground condition.

Pillar stability

It was identified during design that rock pillars would be formed at several locations and pillar stability assessments were required to be completed. Pillars were formed between adjacent adits, nozzles, shafts and the cavern. Pillar stability assessments were completed based on empirical methods and detailed finite element analysis. Stability was assessed by interrogating the behaviour and stresses developed within the pillars and compared against the adopted rock mass strength criterion (yielding) and UCS. In addition, the principal stresses at the pillar faces were also assessed against a Damage Initiation and Spalling Limit (DISL) strength envelope for Hawkesbury Sandstone to understand if damage and spalling of the pillars could be expected. This is appropriate for assessment of rock capacity under low confinement (as in the case of a pillar).

The South Pillar (Figure 1) formed between the twin service adits, the cavern and the South Shaft on the southern side of the station was identified as having a particularly elevated risk due to the significant excavation on all four sides (Figure 6). In addition, the reduction in lateral restraint of the cavern rock arch due to the adjacent shaft excavation (Figure 2) had the potential to compromise the cavern arching action.

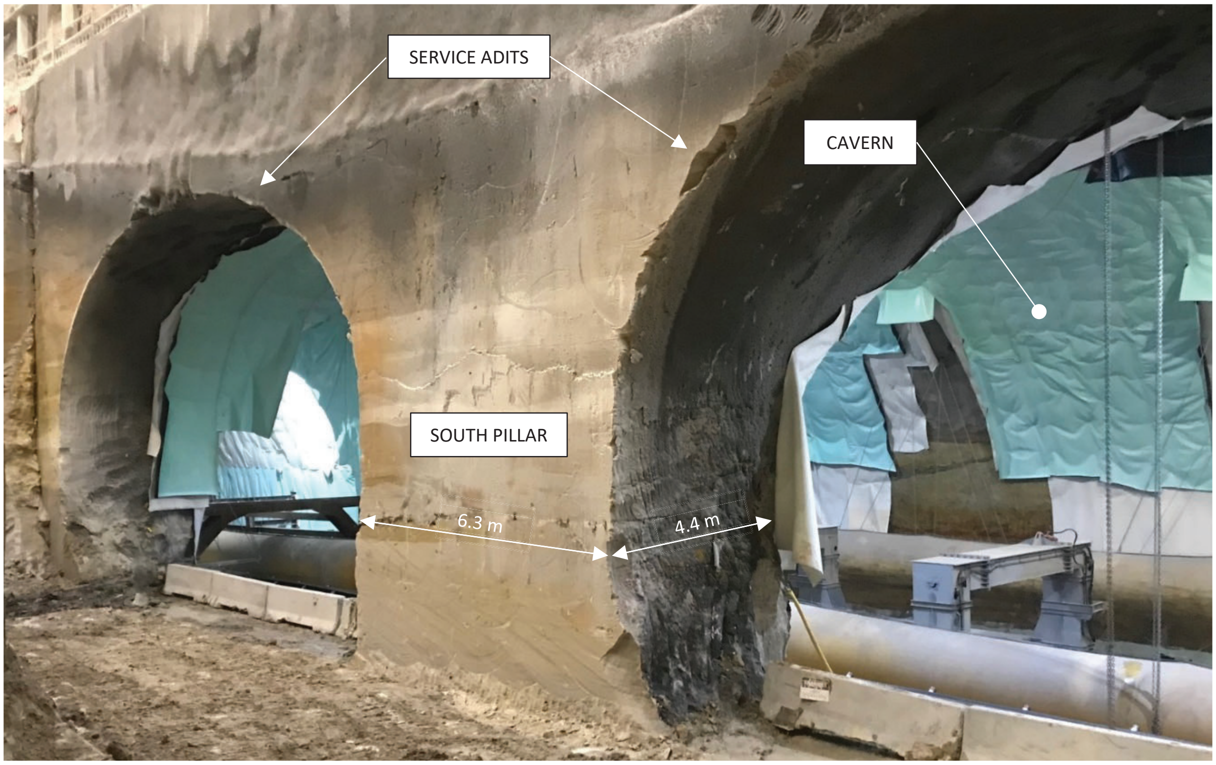

FIG 6 – South Pillar formed by twin service adits, south shaft and cavern.

During the design phase, early client collaboration through value engineering workshops positively resulted in the South Pillar size increasing. At the designer's request, the client optimised the profiles of the southern twin adits to allow more rock to be left in place for the South Pillar. The size increased from initially being 3 m × 3 m to 6.3 m × 4.4 m (Figure 2) which meant that a rock pillar could feasibly be left in place whereas otherwise, the South Pillar would have required replacement by concrete.

The completed assessment indicated that the South Pillar would be stable and the induced stresses would be well below the rock strength. Consideration was given to the concentration of stresses in the South Pillar, damage/crack initiation and the presence of adversely oriented defects. Based on the pillar stability assessment, the design expectation was that minimal pillar treatment would be required. The resulting South Pillar support comprised 4.5 m long rock bolts at 1.5 m centres installed from within the cavern.

Heavier support (eg pillar stitching, passive shotcrete liner etc) or pillar replacement was assessed not to be required unless in the unlikely scenario that the ground conditions differed significantly from design expectations.

Risk mitigation measures implemented in design include:

- Value engineering workshops with client resulting in optimisation of the twin adits to increase pillar size
- Additional site investigation at the South Pillar
- Detailed construction sequence and staging requirements
- Requirement for detailed mapping and appropriate hold points for release by the designer
- Pillar specific instrumentation and monitoring (pillar inclinometer, survey etc).

The encountered ground conditions at the South Pillar comprised Class I sandstone with subhorizontal bedding partings. There were no adversely oriented defects observed during the progressive formation of the South Pillar.

SUPPORT SELECTION

Selection of appropriate tunnel support to be adopted for the encountered conditions is part of the well-established Permit to Tunnel (PTT) procedure adopted for many tunnelling projects in Australia. The PTT is (partly) informed by the ground type classification which has been developed specific for this design based on Bertuzzi and de Ambrosis (2017). This ground classification considers the potential failure mechanisms, the key controls for tunnel stability and the suggestions of Nash *et al* (2017) for practical and robust geotechnical verification. The result of such an approach is less variability in the assessed ground type, greater confidence that the appropriate design support type is installed and simplicity in application.

PREDICTED SETTLEMENT

The zone of influence extends approximately 40 m either side of the cavern centreline. The predicted settlement along Miller Street was approximately 10 mm to 15 mm with a maximum settlement of 28 mm occurring locally at the southern end of Miller Street (south of Berry Street) due to combined excavation effects of the cavern, south shaft, service adits and lift adit. Settlement at existing basement level was also assessed as part of the design for assessment of building effects due to tunnelling and shaft excavations. The schematic in Figure 4 shows the existing basements along the eastern side of the station cavern.

Settlements in the order of 60 mm were calculated for some of the sensitivity analysis cases. Analysis resulting in this order of displacement was associated with unexpected adverse ground conditions, where support ‘survivability’ was investigated (ie ensuring the support system maintains tunnel stability when unexpected adverse ground conditions are encountered) rather than presenting the design prediction.

All predicted settlements were assessed to be within acceptable limits. Monitoring of the actual effects was completed during construction under a robust monitoring and protection plan. The monitored actual effect was then compared to both the predicted effects and the acceptable effects.

MONITORING AND DESIGN VERIFICATION

As part of the design verification and infrastructure protection strategy, monitoring was carried out using instrumentation installed before and during tunnelling. Monitoring instrumentation comprised surface settlement points, in-tunnel convergence and crown sag optical survey arrays, borehole inclinometers and endoscope inspection holes. Monitoring arrays (in-tunnel and surface) were spaced at nominally 20 m intervals. Additionally, building monitoring comprising survey and tiltmeters was undertaken for selected buildings. The monitoring and protection system included identified triggers and response plans for various alert levels.

The monitoring results indicated stable conditions during excavation of the cavern and adits. Surface settlement measured along Miller Street directly above the cavern ranged from 8 mm to 12 mm which compared well with the predicted settlement presented in the section above. In-tunnel survey monitoring measured a typical crown sag of 10 mm (up to 20 mm at intersections) and typical convergence of 20 mm. The inclinometer that was installed through the South Pillar measured a maximum lateral displacement towards the south shaft of up to 35 mm at the completion of all excavation in the vicinity of this pillar. The measured pillar displacement was within the design predicted displacement of 25 mm to 40 mm (depending on the *in situ* stress case considered). In summary, the measured displacements due to cavern excavation indicated good agreement with the predictions. The monitoring results also indicated that effects on existing infrastructure due to tunnelling were within acceptable limits.

Geological mapping of ground conditions encountered during excavation was undertaken where actual conditions were compared with the expected ground conditions as part of design verification. The encountered conditions were consistent with design expectations with the design primary support being applicable for the observed conditions.

CONCLUSION

While the station was constructed in favourable tunnelling ground conditions, the combination of the cavern size and complex station configuration resulted in several design challenges. The risks were mitigated by developing a thorough appreciation of the geological conditions, particularly in areas where the rock mass had the potential to be overstressed (eg at the South Pillar and where the cavern interacted with the lift shaft). Design was supplemented by development of support selection criteria that was practical and which provided a high confidence that the appropriate support type was installed.

Another aspect that was beneficial to the project was the early engagement with the contractor which resulted in a robust design solution that considered the contractor’s preferred methodologies, proposed construction plant and program. The design also provided adequate flexibility to facilitate changes in construction methodologies and sequences during the tunnelling. Client consultation through value engineering workshops during the design stage also proved to be valuable in design development and risk mitigation.

Finally, the importance of developing a well thought out, appropriate instrumentation and monitoring plan as part of the overall risk mitigation strategy is emphasised. Apart from monitoring the performance of the works, quality monitoring data can in some instances be used to refine the design during construction which could result in substantial economic benefits to the project. In this instance, the monitoring provided flexibility in construction which allowed sequencing to be changed during construction to improve overall efficiency.

The cavern was successfully completed on time for the TBMs to traverse through the station on their way towards Sydney Harbour and the city followed by permanent lining construction (Figure 7).

FIG 7 – TBMs traversed through completed cavern.

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