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Optimized operational and structural solution for a TBM service shaft – Design and construction

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ABSTRACT: The Sydney Metro - Western Sydney Airport project incorporated a Tunnel Boring Machine (TBM) Service Shaft approximately 100 m beyond the Airport Terminal Station. The construction of a large elliptical shaft presented several unique challenges. The initial concept for structural solutions was a rectangular shaft supported by soldier piles and ground anchors. The 26 m deep excavation underwent several engineering design stages aimed to optimize the solution while accommodating the operational space required by the Station Box and Tunnelling (SBT) contractor. The final engineering solution adopted included a self-supporting elliptical shape shaft retained by secant piles. The successful implementation of innovative design resulted in a large strut-free shaft that provided an ideal clear space the smooth operation of two double shield TBMs. This shaft enabled early handover of the excavated station box to the permanent structure contractor and facilitated supply delivery and spoil extraction for the remaining 4.1-kilometer south tunnels excavation.

1 INTRODUCTION

The Sydney Metro - Western Sydney Airport (SM-WSA) is a new 23 km metro line currently under construction. The project is jointly funded by the Commonwealth and NSW Governments and will form the spine for the Greater Western Sydney. The new metro line will commence services from St Marys Station and will travel south through Orchard Hills, Luddenham, connecting to Airport Business Park and Western Sydney (Nancy-Bird Walton) International Airport (WSI) and ends at the new city of Bradfield. Along this alignment, it comprises of twin tunnels, travelling north and south for a total of 9.8 km and a central section at grade including viaducts, bridges and open-cut troughs.

In line with the procurement model adopted for the construction of the SM-WSA the scope was split between two contracts, namely:

- SM-WSA – Station Boxes and Tunnels (SBT) - tasked with design and construction of two sections of twin tunnels from St Marys to Orchard Hills for the North drive and from Airport Business Park Dive structure, underneath the new International Airport, to Aerotropolis for the South drive, the associated dive and portal structures and cross passages and the temporary support and excavation for the four underground stations at St Marys, Orchard Hills, Airport Terminal and Aerotropolis, two intermediate service facility shafts and one TBM service shaft near Airport Terminal station.
- SM-WSA - Stations, Systems, Trains, Operations and Maintenance (SSTOM) which follow on the construction of the permanent station structures the tracks and system along the entire length of the SM-WSA line.

Following a tender process held between April and August 2021, Sydney Metro appointed CPB Contractors and Ghella Joint Venture (CPBG JV) for the design and build of the SBT contract in

December 2021. Detail Design stage commenced in January 2022 and was completed in February 2023 while construction of SBT started in June 2023 and was completed in December 2024.

1.1 *TBM Service Shaft*

The TBM temporary Service Shaft is located 100 m past the Airport Terminal Station to enable an early handover of the excavated station box by the SBT contractor to the SSTOM contractor in charge of the station permanent structures contract and provide a convenient supply and spoils extraction point for the excavation of the remaining 4.1km of the South Tunnels drives. Upon completion of the South tunnel drives and cross passages, the TBM Service Shaft was going to be handed over to SSTOM contractor to build the cross passage permanent structure and backfilling. To this aim, a Design Life was 10 years was required in the project Particular Specification.

Ground conditions at site below the site establishment level around RL 84.5 m comprised of 3 to 4 m of General Fill (Geotechnical Unit S1) overlying 1.5 to 3 m of Residual Clay (S3) and the Bringelly Shale bedrock which was differentiated in extremely and highly weathered Shale V/IV (R1) 1-1.5 m thick, moderately weathered Shale III (R2) from approx. RL 77 m with a thickness varying between 4 and 10 m and slight weathered and fresh Shale II/I (R3) to the Final Excavation Level at approx. RL 58 m. The SLS design groundwater level was RL 78.0 m, approximately at the top of R1 unit.

The Bringelly Shale Formation is a sedimentary rock extensively outcropping in the western part of the Sydney sedimentary basin largely comprising claystone, siltstone with localized layers of higher strength sandstone, typically up to metric thickness. Bedding is typical sub-horizontal with four sets of joints, mainly with dip angle 50-60° and strike ENE-WSW and NNW-SSE. Similarly to the rest of the Sydney basin rocks, the Bringelly Shale has an in-situ horizontal stress higher than the vertical stress: the GIR recommended a major horizontal in-situ stress in the range ($0.3 + 1.3s_v$) to ($1.1 + 1.3s_v$) for Shale II/I (R1) and equal to the vertical stress for Shale III (R2).

Table 1. Design parameters for Bringelly Shale Formation rock mass.

Geotechnical Parameters	Unit R3		Unit R2	Unit R1	
	SH-I	SH-II	SH-III	SH-IV	SH-V
Point Load I_{50a} (MPa)	2.2 (1.4 – 3.3)	0.66 (0.5 – 1.2)	0.44 (0.3 – 0.8)	0.2 (0.1 – 0.2)	0.15 (0.06 – 0.17)
UCS (MPa)	20	14	7.1	2.9	1
Poisson's ratio, n		0.25		0.3	
Intact rock Modulus, E (MPa)	5,000	3,500	1,500	510	250
Unit weight, g (kN/m^3)			24		
m_i			8		
GSI	60	60	55	35	25
Rock Mass Modulus, E_m (MPa)	2,600	1,400	500	200	100

Critically for the project, Bringelly Shale was recognized to exhibit swelling potential due to the presence of swelling clay minerals. Testing conducted in 2005 by Williams suggested a rapid swelling process completed in a matter of few weeks whereas in the dedicated testing conducted for the WSA SBT samples were still swelling after a few months. The swelling testing program was fundamental to enable a swelling characterization for use in the UDSM – Swelling Rock model available in the commercial software Plaxis 2D.

1.2 *Reference Design*

The Sydney Metro Reference Design included a 25 m long, 20 m wide rectangular shaft 26 m deep supported by soldier piles 900 mm diameter and restrained by four rows of ground anchors as shown in Figure 1 below. The documentation provided as part of the Reference Design indicated an initial optimization implemented by the owner's Engineer. The TBM Service Shaft was in fact initially located just 20 m past the West headwall of the Airport Terminal Station where it was already serving the purposes indicated above but in the later states of Reference Design was moved to the location of Cross Passage XP-S06, approximately 100 m from the station headwall, so to realize savings in the excavation of one cross passage.

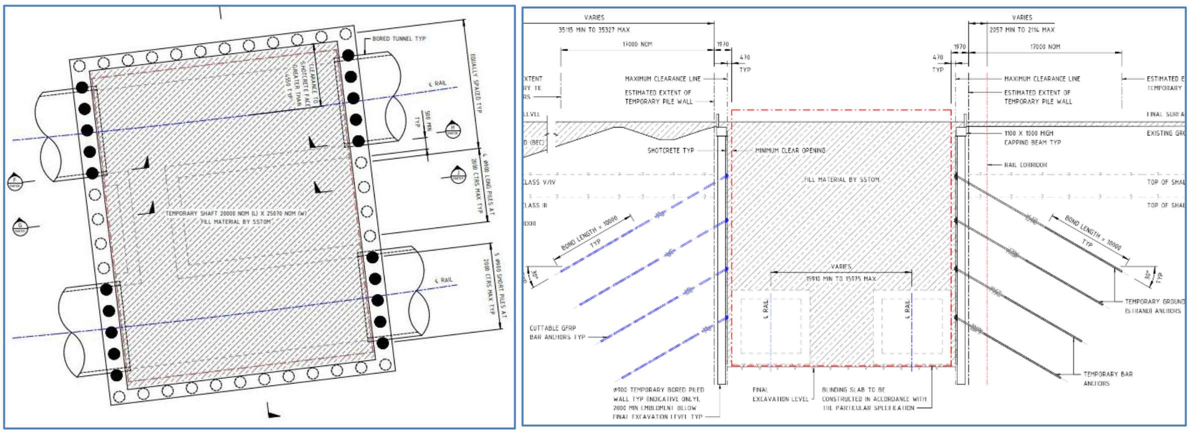

Figure 1. TBM Service Shaft - Reference Design plan and cross section

2 VALUE ENGINEERING

2.1 *Operational requirements driving Tender Design*

Early on during the Tender Design, CPBG JV had already clear ideas on the methodology to extract the material excavated by the two EPB TBMs boring the South drives using an inclined conveyor belt rather than a vertical one. The operational requirements set to the designers included a longitudinal dimension of 48.8 m and an opening in the retaining structure for the inclined conveyor belt 6 m high and 4 m wide immediately below the capping beam.

The required increase in length, doubling up the one in Reference Design, provided a double challenge for the designer: to excavate a larger shaft but reduce the time required for its excavation and support. It appeared clear that this would require to adopt a more structurally efficient curved shape self-supporting retaining structure for the TBM Service Shaft. Early consideration was given to two interlocking shafts – one with diameter of 32 m to encompass the Minimum Clear Opening (MCO) and the second smaller one to achieve the required 48.8 m length. However, this solution required the excavation of unnecessary volume of rock and provided an operational space with the constraint of the limited width and presence of concrete struts at the intersection between the two shafts.

The second idea was to fit an elliptical shaft to encompass the MCO and have the maximum major axis of the required operational length. A suitable ellipse geometry was determined with a major axis measuring 48.8 m and a minor axis of 27.8 m: the resulting eccentricity of 0.80 was still adequate for the hoop force to run all around the elliptical shape as other example in the literature indicated. This configuration allowed for a clear operational space inside the excavation facilitating the construction activities and it was adopted and a concept developed as part of the Tender Design activity.

The shaft structure consisted of a secant pile wall with 900 mm diameter piles, alternated hard-firm, spaced at 600 mm centres, extending to 5 m below the final excavation level. This solution provided a continuous wall with continuity of structural concrete and worked on the principle of arch structure to mostly transfer the external horizontal loads on the wall into axial (hoop) force in the retaining structure. The piled wall was surmounted by a capping beam 1.0 m deep x 2.0 m wide and fitted the 6.0 m by 4.0 m opening at the major axis on the side of TBM relaunch to allow for the passage of the inclined conveyor belt for the removal of the spoil coming from the excavation. For the areas where the TBM break in/out, the design included four concrete wedges - so to provide a planar surface for the machine to restart excavation.

The shaft was designed to remain largely undrained during construction, with drainage limited to that occurring through the base slab: the piled wall was therefore dimensioned to carry both rock and groundwater pressure.

Overall, the changes made at the tender stage reflected a practical response to site constraints, while also considering construction sequencing and TBM requirements.

2.2 *Options considered during Detail Design*

As part of the Detailed Design process, several value engineering options were developed to improve and refine the original tender design. These alternatives were driven by a need to improve constructability, optimize costs, and better align the design with the contractor's planned construction methodology and schedule and included:

- Terminate piles at 14 m below ground level to reach a minimum pile embedment into the Shale III (R2 geotechnical unit). The lower portion of the excavation in R2 and R1 would be now drained supported with conventional rock bolts and shotcrete.
- TBM break-in with short stub tunnels mined in advance and designed to match the TBM space-proofing requirements. This solution increased the operational space at FEL and eliminated the need for a thrust frame for the TBM re-launching operations. However, it also required additional excavation and tunnel lining, which needed to be weighed against the expected time and cost savings.
- Reduced excavated material by leaving unexcavated rock wedges at both TBM break-in and out simplifying the construction process and reducing excavated quantities.

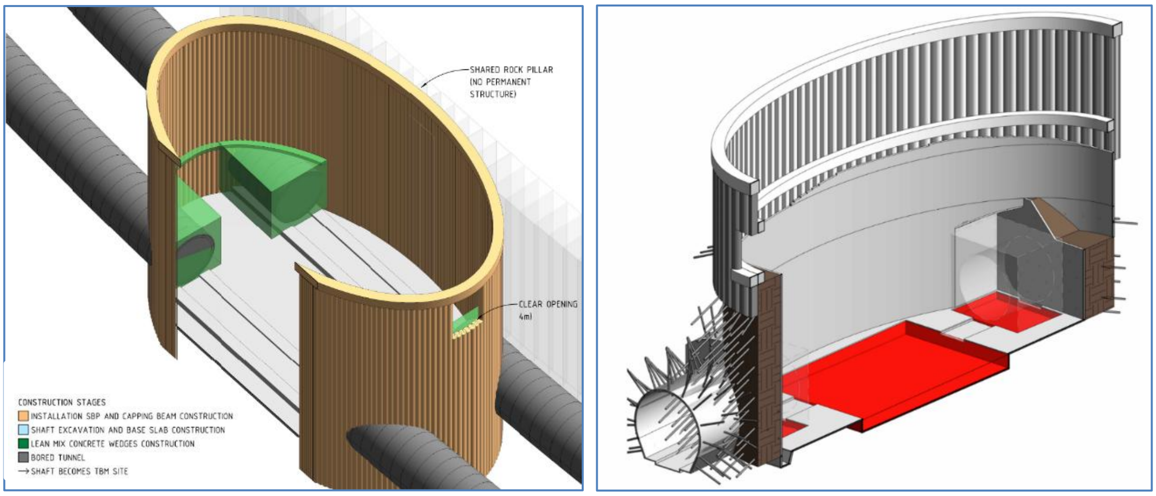

Figure 2. TBM Service Shaft - Tender design 3D view (left) and Detail Design solution (right)

2.3 *Detail Design solution*

The detailed design incorporated most of the value engineering options proposed during the value engineering and brought them even further. The resulting final solution, shown in Figure 2, featured secant piles extending 12 m below ground following the top R2 horizon, and a 1.2 x 1.2 m capping beam. The location of the opening for the TBM conveyor belt was revised and set at 8 m below ground level and required a deep trench to be excavated behind the opening for the conveyor to raise up to ground level. The lower part of the excavation was supported with rock bolts arranged in a 2 x 2 m pattern and 200 mm of shotcrete. The interface with the bored tunnels was revised adopting the two unexcavated rock wedges at the tunnel interface and two 9 m long stub tunnels at the TBM re-launch side, along with four niches on the shaft side wall to facilitate the TBM traverse and the casting of the final lining within the stub.

The detailed design also included a ring beam at RL 75 m to mitigate the risk of pile misalignment reducing the contact area between adjacent piles as well as rock bolts at the toe of the piles to ensure stability of the rock wedge below the toe.

3 DETAIL DESIGN CHALLENGES

The design process incorporated both geotechnical and structural finite element modelling (FEM), alongside UnWedge analyses, to address key challenges. Multiple Plaxis 3D and RS2 models were developed to ensure comprehensive coverage of all design aspects and risks.

3.1 *Axisymmetric Models with Non-axisymmetric Assumptions*

One of the challenges in the design process was the non-axisymmetric nature of various factors, including ground conditions (stratigraphy) across the site, structural openings (for the conveyor), and surface loading patterns (such as crane loads and TBM segment depot). Two main Plaxis 3D models which are illustrated in

Figure 3 were developed cutting along both major and minor axis of the ellipse to ensure that the structural integrity and stability of the openings were thoroughly analysed with the proposed asymmetric surcharge loading patterns, including crane loads and the TBM segment storage. To validate these models, a full model was later developed, and its results were compared with those from the initial stages.

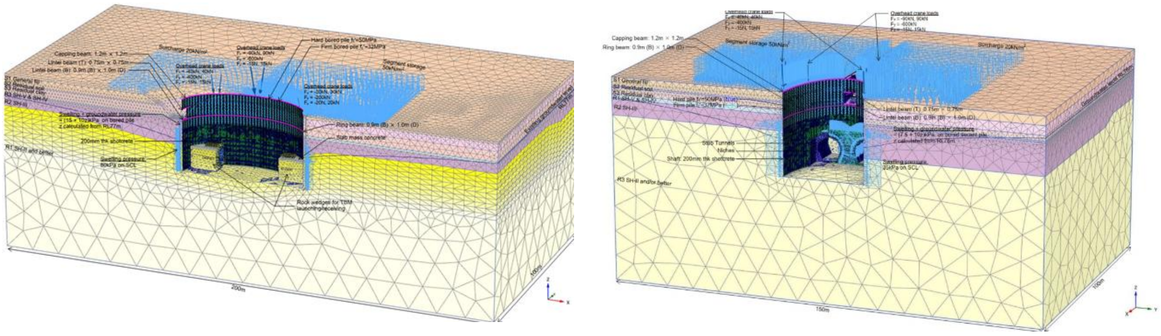

Figure 3. Numerical shaft models a) cut along major axis and b) cut along minor axis

3.2 *Hoop Load Transfer Between Hard and Firm Piles*

Competing requirements of ease of redrilling for the secondary piles and adequate concrete strength to carry the hoop force, resulted in adopting alternate hard (50 MPa) and firm (25 MPa) secant CFA piles. From modelling perspective, each individual pile was modelled as a plate with its own material properties to ensure that all critical interactions between piles were adequately captured, hence each plate was also given an "equivalent thickness” to achieve a realistic axial stiffness. For flexural characteristics, hard and firm piles would experience varying degrees of cracking depending on the design actions experienced which would result in a range of reduced stiffness from the nominal value. In line with the recommendation of Zdravković et al. (2005), the secant piled wall was modelled as anisotropic with reduced axial and bending stiffness of the structural elements in the horizontal direction. Figure 4 (a) and (b) below shows how the plate elements used to model hard pile and firm piles.

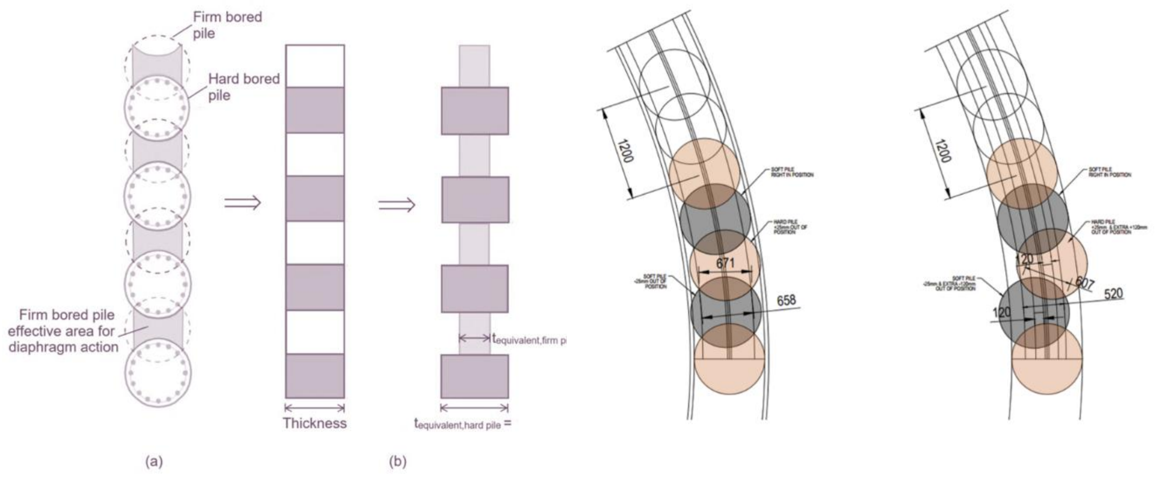

Figure 4. Secant pile wall: (a) as to be constructed; (b) modelled as rectangular slots as plate, (c) nominal pile position and (d) maximum allowed construction tolerance.

3.3 *Construction Tolerances consideration*

Pile construction tolerance of 25 mm position tolerance and 1 in 100 verticality tolerance were stipulated in the design. To account for these construction tolerances, the equivalent thickness for the firm pile elements was adjusted to reflect a further reduction in the width of the connecting section (or "throat") between firm and hard piles. This reduced width, set below the minimum geometric value of 520 mm, resulted in lower axial stiffness for the firm piles and consequently shifts more of the structural load onto the hard piles, which are designed to carry the greater share of demand and was the pinch-point of structural verification. The secant pile position configuration and the allowable construction tolerance is presented in Figure 4 (c) and (d).

3.4 *Composite Beam Behaviour and Flexural Stiffness Adjustments*

In PLAXIS, beam elements are modelled in the same horizontal plane as the pile plate elements. However, the ring and lintel beams will be constructed inside the secant pile wall and connected to the piles using dowel bars. When the secant pile wall undergoes compression in the circumferential direction, it forms a composite "T" beam. This configuration provides a larger effective bending depth and significantly higher flexural stiffness compared to rectangular beams modelled in the same plane as the piles. To accurately represent this increased flexural stiffness, the widths of the rectangular ring and lintel beams were adjusted as illustrated in Figure 5.

3.5 Sensitivity Analyses

In order to confirm robustness of the design solution, comprehensive sensitivity analyses were conducted across three key categories: structural, geotechnical and groundwater level. Each category's sensitivity analyses are detailed in the accompanying tables. In developing the design, a range of stiffness scenarios were considered to account for the likely variations in element stiffness. These scenarios are summarized in

Table 2. Geotechnical sensitivity analyses included the assessment of unbalanced groundwater pressure behind the piles, studied through different models. This approach ensured that all potential uncertainties were thoroughly covered in the design.

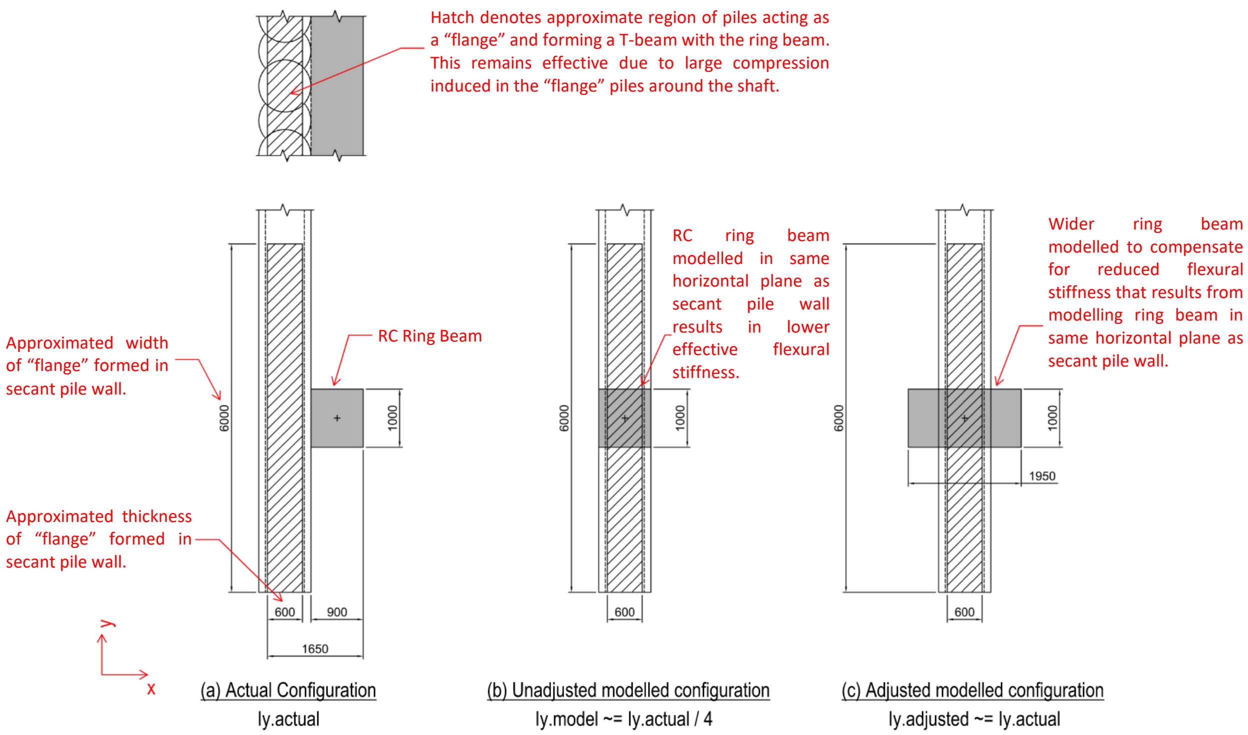

Figure 5. Ring beam showing: (a) Actual configuration; (b) Configuration in model with unadjusted width; and (c) Configuration with artificially increased beam width to achieve correct global bending stiffness.

Table 2. Structural sensitivity stiffnesses cases considered in PLAXIS 3D model and design.

Model	Secant Piles		Capping Beam	Ring, Sill & Lintel Beam
	E1 (ver)	E2 (hor)		
Base Case	70%E	70%E	70%E	70%E
SS 1: (Possibly critical for Capping Beam)	70%E	70%E	100%E	70%E
SS 2: (Possibly critical for Ring & Lintel Beams)	70%E	70%E	40%E	100%E
SS 3: (Possibly critical for Secant Pile Wall)	70%E	20%E	40%E	100%E
SS 4: (Possibly critical for Capping Beam)	50%E	70%E	100%E	40%E
SS 5: (Possibly critical for Ring & Capping)	70%E	20%E	100%E	100%E
SS 6: (Possibly critical for Lintel Beam)	70%E	100%E	70%E	70%E

Table 3. Sensitivity Analyses for Geotechnical parameters and stratigraphy (GS) and Groundwater (GWS)

Model	Description
GS1	Lower bound E module for S3 and R1 adopted; Interface ratio 0.5 applied behind piles.
GS 2	The effect of over-consolidated ratio (OCR) upper value of 3.5 considered in K_0 for S3.
GS 3	Top of R2 layer 1.5 m lower than considered in GIR thus This configuration would increase the soil load and reduce the passive support behind the piles at major axis.
GS 4	Top of R3 layer 1.5 m higher than considered in GIR. High locked-in stress in R3 results in unfavourable bending moment and shear at the bottom of the piles in the SE side.
GWS1	Groundwater at RL 83 m (78+5 m) on one long side and tapering to 0 at symmetry plane
GWS2	Groundwater at RL 83 m (78+5 m) on short side SW, opposite conveyor and reducing to 0

3.6 Design Adaptations for Swelling Pressure in Bringelly Shale

The solution with secant CFA piles only extending to 12 m below ground level already provided a mitigation against this risk as swelling pressure is higher in R2 and R1 when excavated.

Based on the results of swelling testing undertaken for the WSA SBT project, swelling pressure was evaluated using a 2D axisymmetric model that simulated different excavation phases, with the assumption that swelling occurred post-excavation. The swelling pressure acting behind the temporary piles was considered the difference between the pressure recorded at 10 days and the pressure prior to swelling activation and applied as a uniform load distribution.

4 CONSTRUCTION

Operational requirements within the shaft were already indicated as a driving factor for the selection of the elliptical shape of the structure. The activities and installations considered included: (i) most efficient operation of spoil extraction with the inclined conveyor system; (ii) tunnels ventilation ducts; (iii) MSV manoeuvring and loading space; (iv) segment lowering area, (v) portion of permanent cast-in-situ tunnels to be constructed by CPBG up to the MCO of the original Reference Design rectangular MCO; (vi) TBM cradle for retrieval and relaunch.

The 900 mm diameter and 12 m long CFA piles were installed at 600 mm centre-to-centre. Rock excavation was conducted in 1 m lifts, with each lift mapped by a geologist to confirm anticipated ground conditions and propose additional spot bolts, if adverse joint sets were found.

The shaft's structural performance was monitored using survey prisms positioned on both the pile wall and rock face. Permit to Excavate (PTE) meetings are conducted for each lift or weekly (whichever is sooner) to review mapping and monitoring data alongside construction progress, thereby ensuring safe and efficient shaft construction.

4.1 Construction Challenges & Solutions

Constructing a large elliptical shaft posed challenges in pile verticality, pile position, elliptical shape preservation, and accommodating reinforcement bars with varying curve radii for capping and ring beams.

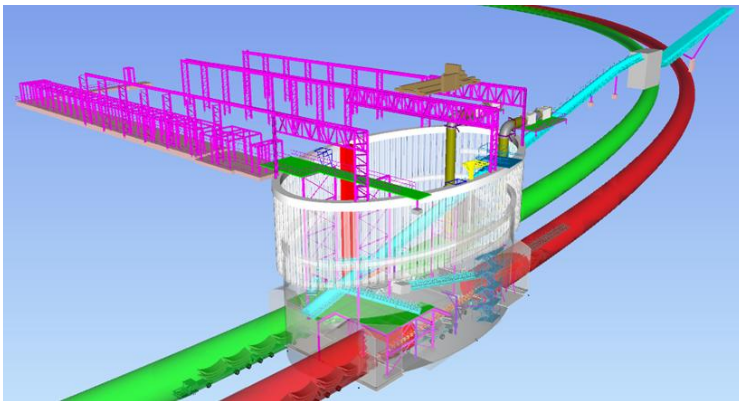

Figure 6. 3D view of the TBM Service Shaft in full operation with gantry crane and conveyor belt

Accurate surveying, guide walls, and maintaining rig verticality (within 1%), CPBG managed to achieve the accurate pile verticality, positioning and preserved the elliptical shape. But hard (secondary) piles' verticality posed difficulties due to drilling through differing material strength (35 MPa concrete firm pile and low strength Bringelly shale < 10 MPa).

Out of 212 piles, 16 exceeded tolerance and all of them are hard piles, primarily due to drilling through mixed materials. These were mitigated by localized minor trimming or filling during shaft excavation without affecting design and project requirements. From this project experience, complete elimination of out-of-tolerance issues in the hard pile is impractical; effective management can be achieved through quality control, regular surveys, and diligent checking of piling machine data to ensure verticality, thereby maintaining the shaft's overall performance and project requirements and/or selecting different piling technique with higher control on verticality such as bored piles. It is recommended that, when constructing complicated curved shafts, a larger verticality tolerance for hard piles may be considered to further reduce this issue.

Due to the elliptically shaped of the shaft, each main bar was required to be bent for varying curvature. This is impossible to do by a factory bar bending machine and required manual bending, and it is also not possible due to safety reasons. Therefore, in collaboration with the designer and reinforcement fabrication subcontractor, CPBG came up with a method for approximating the elliptical beams with a series of circles of constant radii. This allowed safe and effective reinforcement fabrication at the factory. It is recommended that, when designing complicated shape shafts special elliptical shaft, consideration is given to the bar scheduling requirement in the design and allow flexibility for the reinforcement placement to reduce construction RFIs and save time in trial-and-error exercises to come up with a suitable radius that satisfies the design and has less reinforcement placement error.

5 CONCLUSIONS

The paper provided an overview of the entire design development process for the WSA SBT TBM Service Shaft from Reference Design to Issue For Construction (IFC) and through construction highlighting how value engineering driven by contractor's operational requirements and the need for a more efficient structural solution led to the adoption of an elliptical shaft with optimized support system. To the authors knowledge, while this solution has been used in Australia on mining projects, it is the first application to an infrastructure project.

The design of the elliptical shaft solution provided a number of challenges which were comprehensively addressed to provide a solid design documentation which proved effective at the test of a fast-paced construction. The TBM Service Shaft was a key project element to ensure that the WSA SBT contract was delivered on time to a record 3 years from start of design to completion of the contract works.