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Design challenges on western harbour tunnel mega TBM segment and cross passages

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ABSTRACT: The Western Harbour Tunnel project in Sydney consists of twin three-lane tunnels driven under Sydney Harbour by tunnel boring machines (TBMs), which provide design challenges that smaller tunnels do not face. These include increased thrust forces applied to relatively thinner linings. The project tunnels will be the largest diameter TBM tunnels in the southern hemisphere and the largest diameter TBM tunnels with Steel Fibre Reinforced Concrete (SFRC) only segmental lining worldwide. Solutions for cross passage opening design include cored shear keys to transfer loads around the segment opening, including a cast-in bond-breaker to minimise damage. The collar structure of the cross passage is configured to maximise the opening width. This paper describes the design philosophy, engineering challenges and the associated engineering solutions for the segment and cross passages design for this mega TBM tunnel project.

1 INTRODUCTION

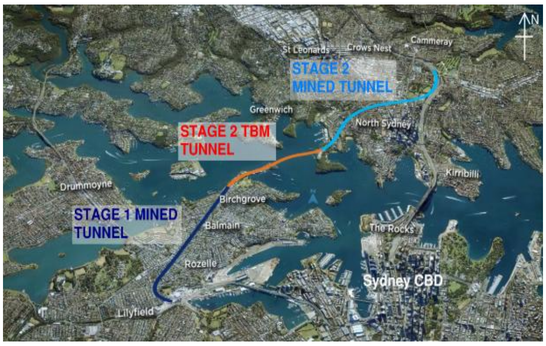
With the needs of urban road network development and development of the tunnelling technique, the use of mega tunnel boring machines (TBMs) with a cut diameter of more than 14 metre rapidly increases. Up until 2024, more than 40 tunnelling projects worldwide have used a mega TBM. The segmental linings for most of these mega TBM tunnels have traditional steel rebar reinforcement (FHWA2020). However, the mega TBM tunnels recently completed or being constructed in Australia and New Zealand, including Auckland's Waterview Tunnels, Melbourne's West Gate Tunnels (WGT) and North East Link (NEL), and Sydney's Western Harbour Tunnel (WHT), are constructed/ lined with Steel Fibre Reinforced Concrete (SFRC) lining (Chau et al. 2024).

WGT and NEL linings are the largest diameter SFRC-only TBM lining without rebar ever completed (WGT tunnel excavation and lining completed in mid-2023, NEL tunnel excavation and lining partially completed 2025 – due for completion mid-2026). WHT is being constructed and will, upon completion, be the largest diameter TBM tunnel with SFRC-only segmental lining in the world.

This paper focuses on the engineering challenges on the mega TBM tunnel segment and cross passage design of the WHT Project.

2 PROJECT BACKGROUND

2.1 *General*



a) WHT overview (image from https://caportal.com.au/rms/wht/)

b) WHT TBM tunnel and cross passage layout plan

Figure 1. WHT overview and TBM tunnel layout plan

Western Harbour Tunnel (WHT) is a new crossing under Sydney Harbour, linking Rozelle Interchange to the Warringah Freeway in Sydney, Australia. The twin 6.5-kilometre motorway tunnel will have three lanes in each direction and will create a western bypass of the Sydney CBD, taking pressure off the Sydney Harbour Bridge, The Sydney Harbour Tunnel, Anzac Bridge and Western Distributor corridors. WHT is being delivered in two stages (Figure 1a). Stage 2 of the project is being delivered by ACCIONA for Transport for NSW, with the designer AECOM AURECON Joint Venture (JV). Stage 2 will use several roadheaders to excavate the northern section and two TBMs to construct the southern section. The 1.5 kilometre long twin TBM tunnels are located between Birchgrove and Waverton and pass beneath Sydney Harbour. Figure 1b shows the TBM tunnel and cross-passage layout plan.

2.2 *Geology and Hydrogeology*

The inferred geology along the alignment of the TBM tunnels is shown in Figure 2. The TBM tunnels will be excavated mostly in Hawkesbury Sandstone, except for a short 180m section of soft ground (alluvial soil of Pleistocene age), where the tunnels cross a paleochannel under the harbour. Marine boreholes have identified geological features, including laminite beds, dykes, open joints and thrust faults in Hawkesbury sandstone, due to stress relief from valley bulging in the eroded paleovalley.

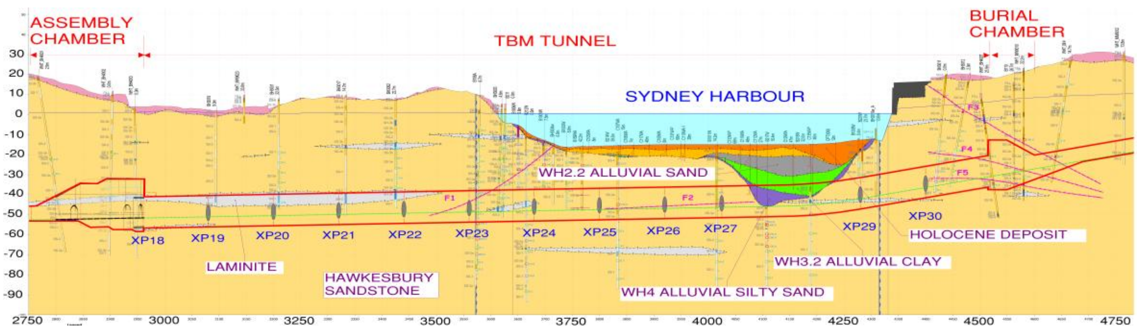


Figure 2. Inferred Geology along TBM Alignment

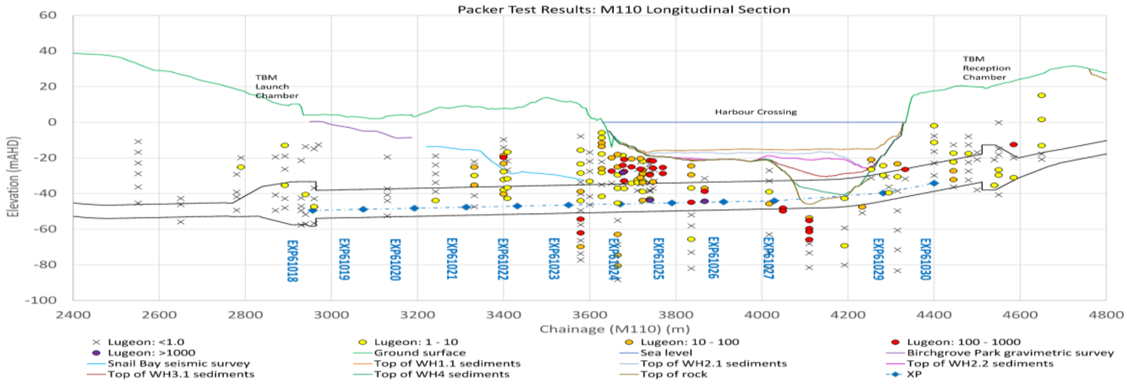


Figure 3. Packer test results along TBM Alignment

The groundwater head to tunnel crown ranges from 35m to 45m (40m to 50m to cross passage crown). Hawkesbury Sandstone is a dual porosity aquifer where groundwater flow potential is dominated by secondary features, such as joints, fractures, faults and bedding planes, whilst the intact Hawkesbury sandstone is mainly impermeable.

Figure 3 illustrates the magnitude and variability of rock mass permeability along the tunnel alignment. Rock mass permeability is higher around the valley that forms the Harbour, where the rock has experienced stress relief and valley bulging (>100 Lugeons). In these areas, existing open discontinuities and rock joints developed at the harbour valley-sides increase the defect aperture, potentially increasing groundwater flow.

2.3 *TBM Tunnels and Cross Passages*

The TBM tunnels have an ID of 14.15 metres and lining thickness of 500 millimetres and will be constructed by two 15.7 metre mixshield (slurry) machines, both advancing from the assembly caverns at the south and will be entombed in reception chambers at the north. It accommodates a three-lane traffic envelope, with a box culvert for facilitating tunnel construction logistics, future-proofing and subgrade backfill to the road level. Figure 4 shows the TBM tunnel and cross passage cross-section.

The TBM section has eleven cross passages with a typical spacing of 120 metres (Figure 1b). Cross passages in road tunnels are for emergency pedestrian movement from the incident tunnel to the non-incident tunnel. The spaceproofing of the cross passages provides the following elements:

- Civil/ Structural: segment opening and collar, emergency egress, comms pit, wall elements, fire-rated doors, internal structures, and drainage.
- MEP (Mechanical, Electrical and Plumbing): Deluge main, Deluge manifold, electrical equipment room (EER), mechanical ventilation equipment, ITS, and lighting.

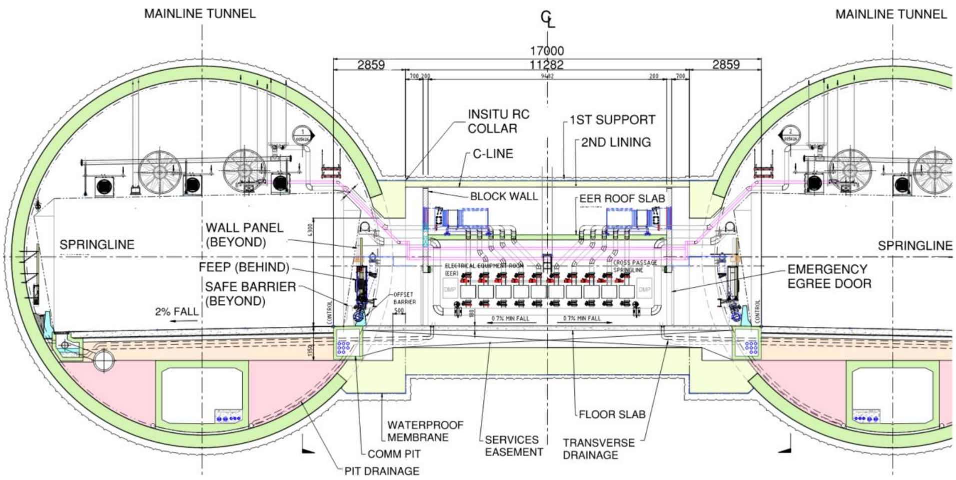


Figure 4. WHT TBM tunnel and cross passage cross-section

3 UNDERSEA TBM TUNNEL STABILITY CHALLENGES

The reference design construction method for the WHT harbour crossing section was immersed tube tunnel (IMT). According to Brown 2023, one of the reasons was to reduce the risk of deep tunnelling (e.g. TBM) through the expected poor geology under Sydney Harbour. Confirming the closed face slurry TBM tunnels altering the IMT for constructing the WHT harbour crossing, there were many other concerns on the environment, construction risks, programme and cost associated with the IMT and cofferdams. However, a crucial technical challenge for TBM tunnel feasibility is understanding the soil/ ground cover to achieve subaqueous tunnel stability regarding structural integrity, tunnel flotation resistance and construction phase blowout prevention.

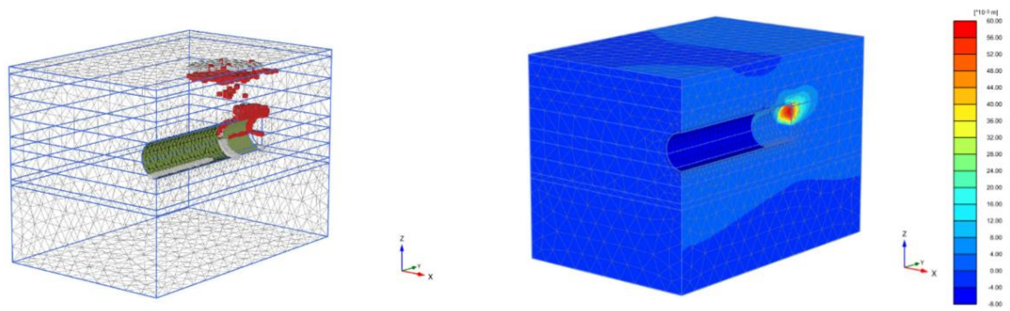
3.1 *Tunnel Flotation, Face Pressure and Blowout*

The minimum soil cover to tunnel crown at soft ground section is approximately 19 metres. Chau et al 2024 has described the methodology and analysis for flotation and blowout checking, including:

- Adopting the model and formulas from Lo et al. 2012 for flotation check, with partial factors derived from PAS 8810:2016 Table 11 and 12 (Limit State UPL).
- Using DAUB 2016 guide to determine the lower face pressure limit to prevent tunnel face cave-in failure and the upper face pressure limit to avoid blowout of the support medium.
- Alternatively, developing a limit equilibrium model including soil shear strength as suggested by Lo et al. 2012 to estimate the maximum face pressure against blowout.
- Undertaking 3D numerical analysis to verify the minimum and maximum face pressure.

3.2 *Annulus Grout Pressure*

Effective annulus grouting of the rings is essential to achieve tunnel safety and ring quality, as well as preventing slurry leaking through the tail shield seals. To achieve this, the primary grout pressure is set to be two bars above the hydrostatic pressure. The tunnel lining has been designed for a maximum annulus grout pressure of two bars plus hydrostatic pressure from the highest water table. The TBM tunnels will be excavated mostly in rock, which is stable for the grout pressure. However, the tunnel and ground stability challenge remain at the soft ground section, at which the maximum grout pressure should be calculated to avoid blowout failure. The maximum grout pressure can be verified same as the maximum face pressure, as checked by Lo et al. 2012 and is 1.2 times the proposed grout pressure. The numerical analysis by 3D Plaxis (Figure 5) has demonstrated this limit with a factor of safety (i.e. phi/c' reduction) of 1.072 against the stability.



a) Plastic points (indicated in Red zones) b) Ground movement shading (heave of 3mm at seabed)

Figure 5. 3D face pressure model results (ultimate face pressure = 2 bars plus hydrostatic pressure)

3.3 *Cutterhead Intervention*

Compressed air pressure for cutterhead intervention is calculated for planning purposes according to the GEO249 guide (GEO 2009). The construction strategy is to carry out interventions in rock geology under atmospheric or low-pressure hyperbaric conditions. It is planned to avoid undertaking interventions in soft/mixed ground zone, a cutterhead inspection and tool re-dress will be carried out before entering this zone, and a similar exercise will be undertaken approximately 180-200m later when the TBM is back within the full face of rock.

Following the groundwater inflow monitoring, compressed air pressure is set as low as possible without compromising the excavation face stability. Should high-pressure hyperbaric interventions be required, suitably trained hyperbaric workers and supervisors, including mixed gas trained/certified personnel, will undertake the work.

4 SEGMENT DESIGN CHALLENGES

Mega TBM tunnels are always associated with huge hoop forces and TBM ram thrust forces and linings are normally RC segments or SFRC segments with joint reinforcement. In WHT, more challenges for SFRC segment design include high groundwater pressure and a section of soft ground under Sydney Harbour. This required consideration of appropriate design codes, SFRC properties specification, using different empirical and numerical analyses on segment joint design to overcome the design challenges and to confirm the SFRC only lining design.

4.1 *SFRC Segments*

The WHT segmental lining design follows a similar design philosophy to WGT (Ireland et al. 2019, Chau et al. 2020) with project-specified considerations, to overcome the technical challenges to verify the SFRC segment capacity. It mainly includes:

- Adopting PAS8810 code for lining design.
- Using FIP Model Code 2010 for SFRC behaviour.
- Undertaking FEM models to model plastic behaviour of SFRC – validated empirical formulae derived from joint test results for segment joints design.
- Specifying material and segment testing to verify the design approach and assumptions.

WHT adopts SFRC-only segments for the tunnel alignment, except for RC segments at cross-passage opening locations. Upon completion, the WHT tunnel will be the world's largest diameter SFRC-only segmental lined tunnel. The design compressive strength of the concrete segment is 65 MPa. The design characteristic residual flexural tensile strengths of the SFRC are fR1 of 4.0 MPa and fR4 of 4.0 MPa. The characteristic splitting strength is 6.0 MPa. All the design parameters for the SFRC are to be verified by testing.

4.2 *Ring Configuration and Rhomboidal Segment*

The mega TBM tunnels in recent years mostly adopt ring configuration of 9-12 numbers segments with equal subtended angles. WHT tunnels have 10 segments in a ring at an even 36-degree angle subtended by rhomboidal segments (8 nos.) and two trapezoidal segments, the key and the counter key. The nominal length of a ring is 2400 millimetres. The radial joint angle for the rhomboidal segments is 5 degrees, and the radial joint angle for the key and adjacent segments is 10 degrees, with a key segment insert variant angle of 7.5 degrees to achieve a workable key draw distance. The segment ring is a universal taper ring with a taper of 60mm (+/-30mm) so that the key can be built in all 20 possible locations. The schematic developed plan view of the ring arrangement and segment joint arrangement is shown in Figure 6.

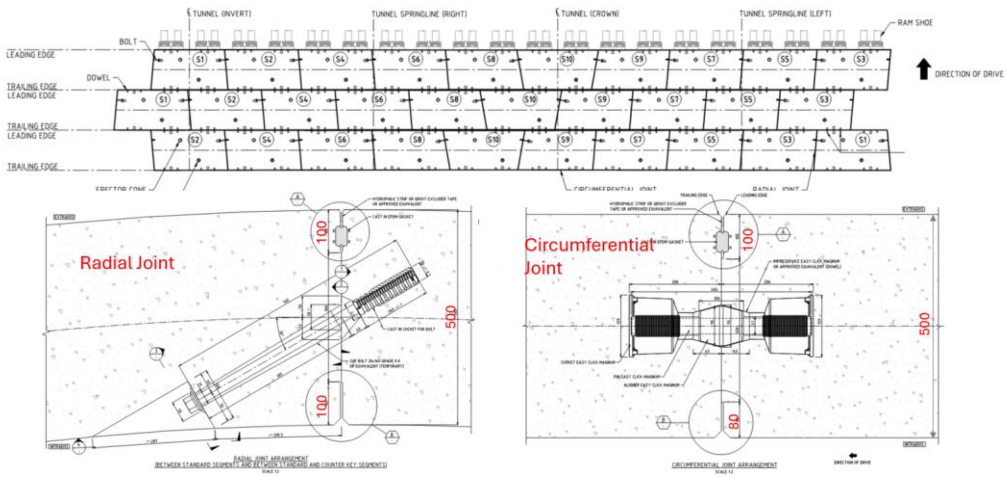


Figure 6. Ring configuration and segment joint arrangement

Based on the available information, the segments of mega TBM tunnels are more commonly rectangular, including the WGT, NEL and Waterview tunnels. For WHT, the preferred ring configuration was to use rhomboidal segments together with circumferential joint dowels to improve the precision of the ring build and to lessen the potential for leakages through the lining joints under high water pressures. WHT is the second largest TBM tunnel with a rhomboidal segment ring arrangement, after the Santa Lucia Tunnel in Italy. A detailed study has been undertaken to compare the rectangular and rhomboidal segment arrangements regarding ring stiffness and bursting stresses at circumferential joints. Chat et al. 2024 have described the details and results, which are summarized below:

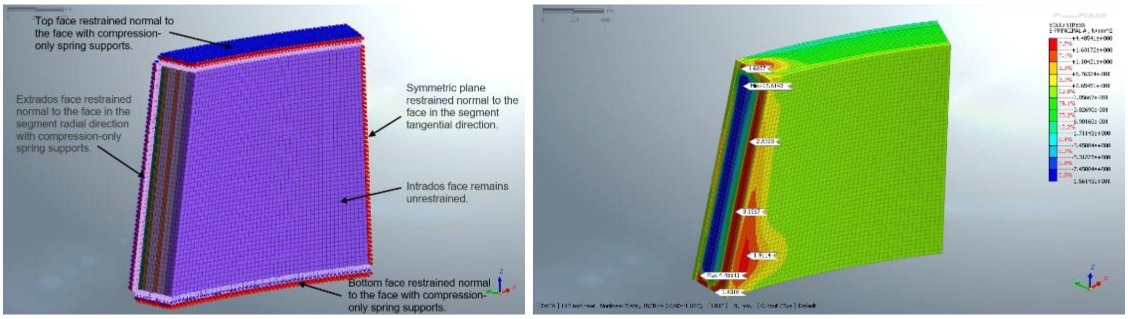
- Rhomboidal segment has a slanted joint, the axial force acting perpendicular to the joint is slightly less than a flat joint, as a result, the slanted joint reduces the maximum moment and therefore, the equivalent rotational stiffness is slightly reduced.
- Ram load impact analysis by Midas (non-linear model FEM software) and ATENA (concrete specialist software) indicates that both rhomboidal and rectangular segments are within acceptable limits for estimated cracking.

4.3 *Segment Joints*

The WHT tunnel radial and circumferential joint design has eliminated the joint steel ladder/ reinforcement requirement. Figure 6 shows the joint details. The WHT Mega TBM lining is subject to bursting stress from high hoop loads and ovalisation on the radial joint and high TBM ram forces on the circumferential joint, compared to metro size tunnels. The gasket groove is long enough to accommodate the larger gasket size and hydrophilic strip or grout excluder tape and to resist concrete corner failure due to gasket compression force. Caulking groove in radial joints is designed to avoid segment intrados corner contact damage due to ring ovalisation. In circumferential joints, the larger the joint contact area, the higher joint capacity is to resist TBM ram load.

The WHT radial and circumferential joints design and analysis has followed the approach developed from the WGT projects (Chau et al. 2020, Ireland & Chau 2025), which mainly includes:

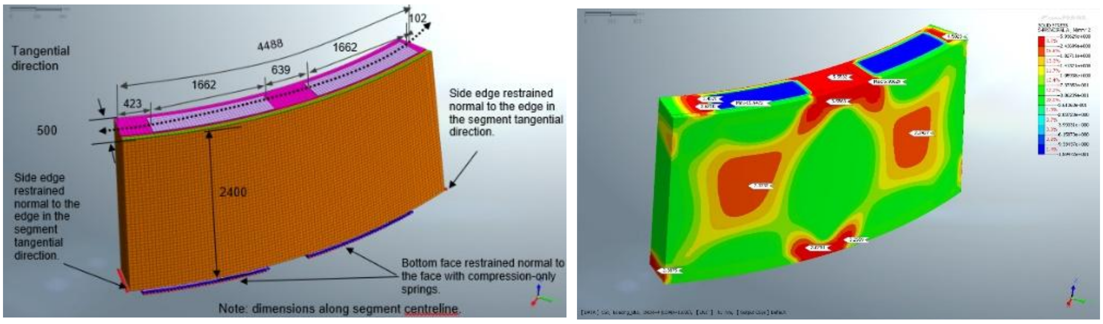
- Use of empirical Curtis equations to calculate splitting forces crushing resistance etc.
- Elastic analysis by Guyon 1972 method – this has been developed for post-stressed concrete structures and deals with the transmission of high forces through the surface of an elastic body – to check that cracking (SLS) does not occur.
- FEM analysis by Midas - A non-linear analysis is performed with elasto-plastic behaviour for compressive (crushing) and tensile (cracking) of the SFRC material. These models run for both SLS case to determine crack widths and ULS case to confirm structural capacity. Figure 7 and Figure 8 show the 3D analysis for radial joint and circumference joint respectively.



a) Radial joint model input

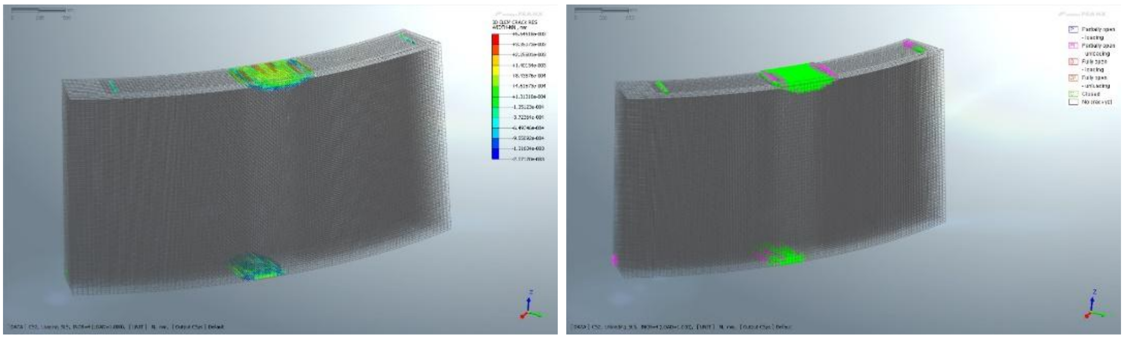
b) Calculated bursting stresses

Figure 7 3D Midas radial joint model



a) Circumferential joint model input

b) Principal tensile stress



c) Calculated cracking pattern (colour shading = cracks with RAM load but within crack limits)

d) Calculated cracking pattern (green areas = cracks closed after removing RAM load)

Figure 8. 3D Midas ram load and circumferential joint model

5 CROSS PASSAGE DESIGN CHALLENGES

5.1 *Segment Opening and Shear Keys*

Cored and grouted heavy shear keys are described in Della Valle et al 2014, Walter 2019 and Chau et al 2023. Figure 9 shows the shear keys in relation to the opening in the ring arrangements. Bicones are also shown in the joints of the opening sets; four bicones per segment, as well as shear dowels, two per segment.

The action of breaking out the core may lead to damage to the gasket joint. Under Sydney Harbour, this damage would be difficult to repair with potentially five bar of water pressure behind it. To avoid such damage, a solution has been chosen to install a semi-circular bond-breaker in all segments in the opening set and post-core only at the required locations. Site trials of this concept have demonstrated that this approach works; the core to the remaining segment is removed easily without damage (Figure 10).

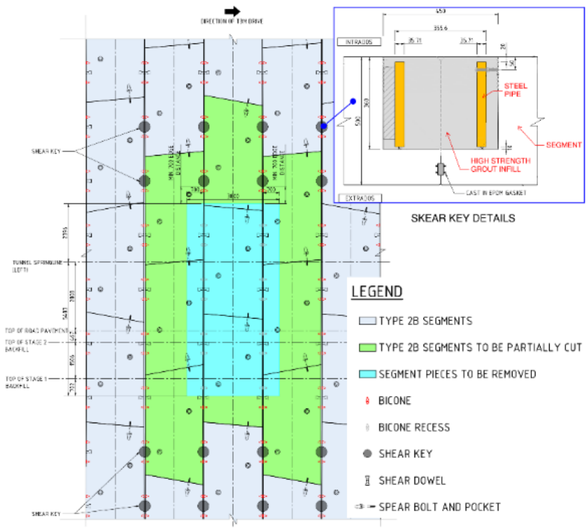


Figure 9. Shear keys and bi-cones arrangement in the segment opening

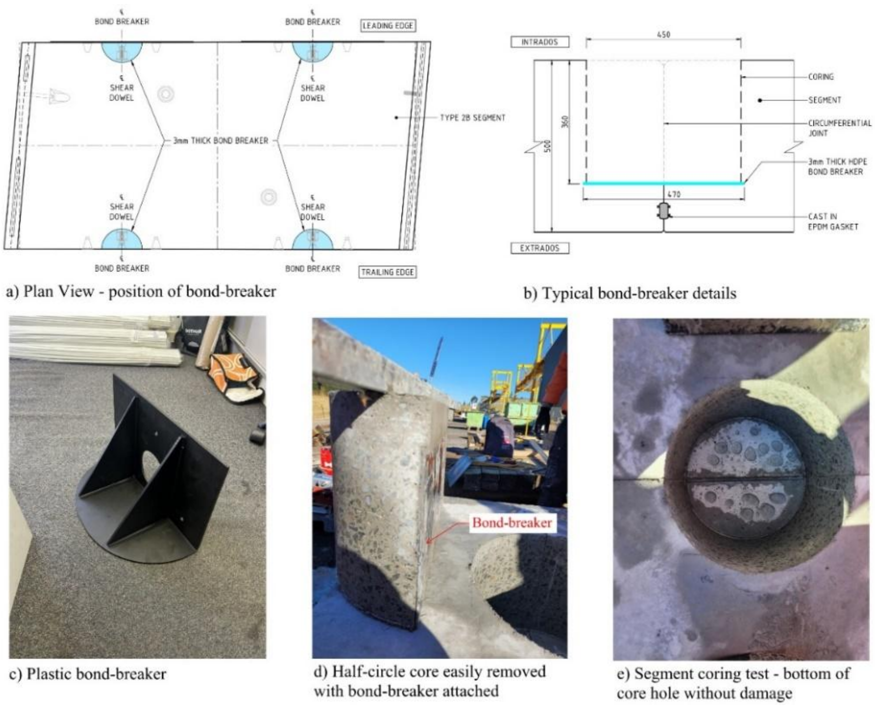


Figure 10. Shear key/ bond-breaker arrangement and bond-breaker installed for cored shear keys

For the cross passage opening rings, traditional reinforced concrete (RC) segments are adopted to resist the high lining hoop forces from tunnel lining opening that is transferred through the opening ring shear keys. The steel bars around the shear key areas have been arranged to avoid clashing with the bond-breaker.

The analysis of the opening set adopts the conservative consideration that, while the area in front of the opening has the water pressure relieved, the pre-grouting has been effective in limiting water movement and the full water pressure remains around the segment away from the opening. Due to the possibility of intersecting with a high-volume water bearing fissure, pre-drainage around the cross passage has not been considered to be feasible. The segment opening support system had been designed for unbalanced water pressure, full at crown and non-opening side and 5 rings away from opening and varying to zero at opening.

5.2 *Cross Passage Lining and Collar Structure*

The cross passages are in rock, generally Hawkesbury sandstone, or in some locations, also intersect a shale band. Probing and grouting are designed to control water to minimise construction impacts, except at some of the cross passages where areas with high ground permeability will still require a high level of water control. Excavation of cross passages will be by rock hammer. The primary support includes pattern rockbolts and shotcrete.

The secondary lining is designed to be undrained to carry the full external water pressure; this load predominates. The shape of the secondary lining has been chosen to minimise the bending moment generated by the water loading, and the invert and bases of the walls are reinforced with conventional bar reinforcement. In contrast the walls and crown of the lining are SFRC-only.

The collar structure carries the proportion of the permanent load imposed on the cross passage opening after construction is completed; the segments and shear keys carry some of the permanent loads. To maximise the opening space, the lintel beam carries the load in torsion and bending behind the segments to the jamb member located behind the segments (Figure 11). The load distribution on the collar structure in the permanent case is three-dimensional and is primarily influenced by the change in water pressure as the water table returns to its original level post-construction. Structural analysis for the construction stages, with the permanent collar introduced after the temporary opening stage and disregarding the temporary bi-cones and shear dowels (Figure 9), has been undertaken to determine the degree of load sharing between segments, shear keys and collars in the permanent case.

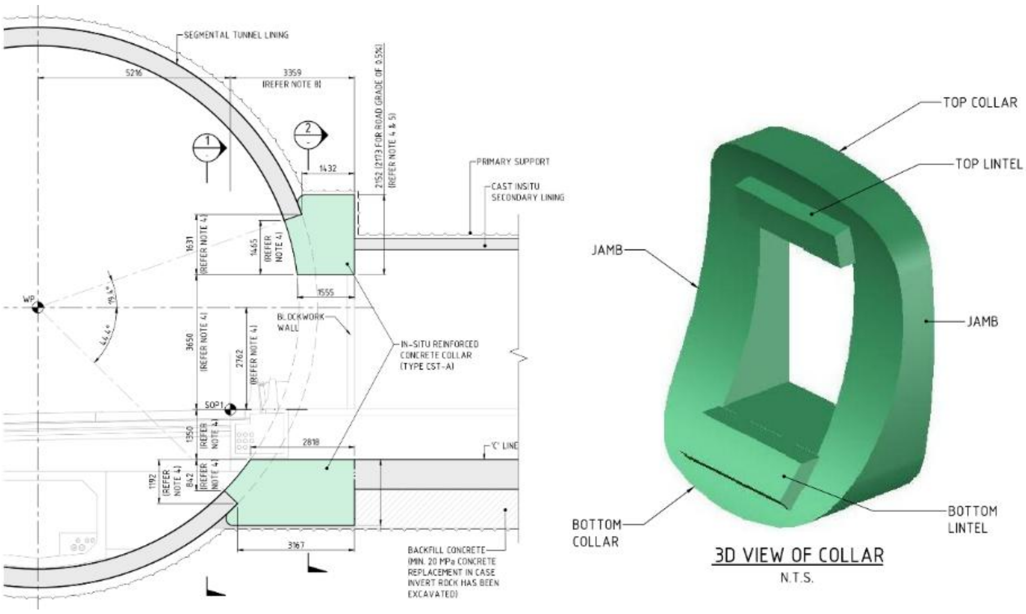
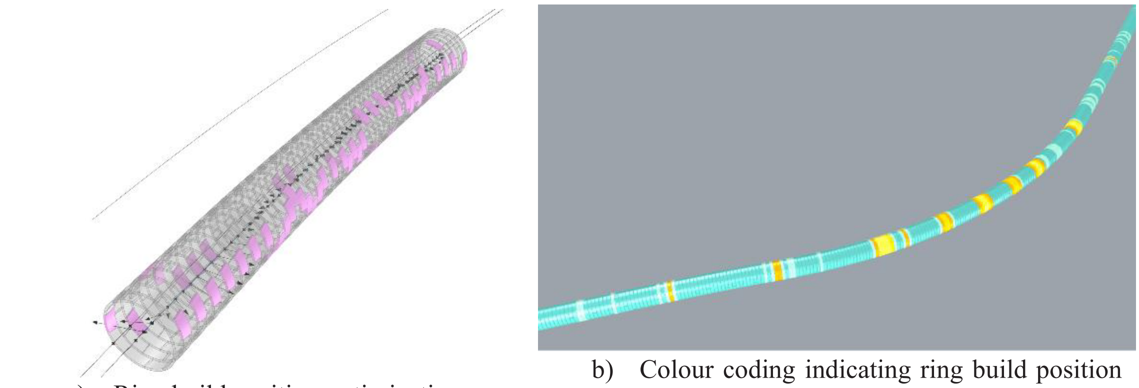


Figure 11. Collar structure showing jamb behind the segments

6 DIGITAL TUNNEL DESIGN

There are a few geometrical complexities in road alignment and cross passage design. The road alignment of the TBM tunnel is generally an “S” shape consisting of two (~960m) curves. However, TBM launch starter rings need to be straight. At cross passages the opening set rings follow the curved road alignment with limited allowable ring build positions, due to an undesirable key segment steeper angle in relation to the opening. Segment creep/ shrinkage normally happens in mega TBM tunnels that affect the actual cross passage locations.

Digital tunnel design (Figure 12) has been carried out to check and verify the above geometrical challenges. A ring model with all segment configuration is created and all 20 ring build positions are defined. The proposed ring build positions at TBM starter rings (for straight alignment) and at cross passages locations (to follow road alignment) based on opening support requirements are assigned. The digital platform automatically selects the optimum ring build positions to meet the tunnel alignment curve and calculate the ring build position tolerance, with colour coding output. Although there had been many trial runs on different proposed ring build positions, the digital design were efficient and confirmed the allowable ring build positions for TBM launching and at cross passages, which also facilitated the construction planning.



a) Ring build position optimization

b) Colour coding indicating ring build position tolerance amount

Figure 12. Digital tunnel design

7 CONCLUSION

This paper describes the main design challenges associated with Western Harbour Tunnel's mega TBM segments and cross passages. A comprehensive analysis of the stability of the TBM tunnel undersea has demonstrated the feasibility of TBM tunnelling through the soft ground conditions under Sydney Harbour. The segment design has used different empirical and numerical analyses to overcome many design challenges and confirmed the SFRC lining design for the tunnel alignment. Segment opening is designed to be supported by cored shear keys to transit the opening forces, with a bond-breaker at the base of the cored hole to minimise segment damage. Staged construction 3D modelling for segment opening and collar structure allows structural optimisation so that the jambs of collar structure are located behind the segment opening to maximise the opening size while keeping a line of thrust within the cut segments. Digital engineering tools are also used to facilitate tunnel design and construction planning.

8 ACKNOWLEDGMENTS

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