Starting the Journey – Launching of the Legacy Way Open Face Tunnel Boring Machines in Mixed Face Ground Conditions

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ABSTRACT
The mainline running tunnels for Legacy Way comprise two tunnel boring machine (TBM) driven tunnels. Both TBM drives commenced at the Launch Portal adjacent the Mt Coot-tha Road. Excessive surface settlement arising from tunnelling would have had a significant impact to the road infrastructure. The geological structure above the tunnel springline is a mixture of fill, residual soil and weak rock. Given the combination of low ground cover and weak ground materials, along with the use of an open face TBM, an oversize pipe umbrella system has been installed above the tunnels. This pipe umbrella system is similar to that commonly adopted in conventional mined excavation support in soft ground except that the steel pipes are substantially larger in geometry and filled with concrete. It is acknowledged that similar systems with oversize pipe umbrellas have been adopted elsewhere in the world in others projects. These systems often comprise of a full arch formed by conjoining oversize steel pipes (in contact only). By aligning the pipes in contact, the arching behaviour of the steel pipe would have been enhanced. However, this poses a degree of construction difficulty due to excavation and installation method of the pipes. The Legacy Way pipe umbrella system only consists of a partial arch at the tunnel crown and each pipe is spaced approximately 1200 mm apart with 900 mm diameter pipe, leaving a gap of approximately 300 mm between pipes. A reinforced concrete portal block was used to support the exposed ends of the pipes.

This paper reviews the design analysis, the recorded deflections from the pipe umbrellas and surface monitoring during TBM launch and revisits the analysis using the newly available RS3 program, from Rocscience for 3D analysis of geotechnical structures.

INTRODUCTION
The mainline running tunnels for Legacy Way comprise two tunnel boring machine (TBM) driven tunnels. The tunnels run approximately parallel to each other over some 4250 m. Both TBM drives commence at the launch (western) portal sharing common logistical support infrastructure. This TBM portal was excavated and supported by sheet piles in soft ground and by rock bolts and shotcrete at the lower levels in rock.

The relatively low ground cover (approximately 10 m) at the western portal indicates a section of the TBM crown will be in the extremely weathered rock mass as it passes below the Mt Coot-tha Road. The Mt Coot-tha Road is an important infrastructure item both for the surrounding traffic movement and for site access. The pipe umbrellas have been installed to limit the surface settlement due to TBM tunnelling activity on this road and surrounds. The elevation through the TBM portal below the road provided in Figure 1 illustrates the low cover situation.

The pipe umbrellas were tied into a permanent portal block at the tunnel entrance to create a fixed connection at the outer extent of the pipe umbrella. The portal block also forms the upper surface and face of the cut and cover tunnel section. The western connection is made up of the trough and cut-and-cover structures up to the TBM portal.

WESTERN PORTAL ARRANGEMENT
The western portal is located adjacent to the Western Freeway and Mt Coot-tha Road, Toowong. The area is bordered by the Botanic Gardens to the north and northwest and the Western Freeway to the south. The western arterial bikeway is located at the south-eastern corner of the site and consists of an earth embankment supporting a concrete bikeway.

The western TBM portal, located immediately adjacent to Mt Coot-tha Road is formed by the east face of the cut and cover tunnel that is configured as a TBM launch box during construction. The two TBM portal faces are offset to maximise the proximity to Mt Coot-tha Rd and shorten as much a practical the length requiring presupport. The sides

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of the launch box are supported by secant piles with two lines of tie backs while the east end of the box is supported by a combination of sheet piles tied back with anchors through concrete walers then rock bolts and shotcrete at lower levels. The arrangement of the cut and cover support structure with the TBM portal and a pipe umbrella is shown in Figure 2. The sheet piles are driven down to the highly weathered rock horizon with the use of preboring to ensure the pile toe levels are achieved. This places the toe of the piles into the top third of the TBM excavation profile that subsequently requires the sheet piles to be trimmed to outside the TBM profile once the pipe umbrellas have been installed and before the portal block is cast. Given the shallow cover over the TBM and the proximity of the two TBM drives the location for the tie back anchorages is restricted with the anchors having to be installed near horizontal above the tunnels intersecting with the rising rock head on the opposite side of Mt Coot-tha Rd. The top line of anchors were designed and installed as removable anchors so as to leave only the fixed end of the 20 m long anchors in place upon anchor removal following completion of the cut and cover roof backfill.

WESTERN PORTAL GEOLOGY

The western connection is located within the Bunya phyllite, which is a low-grade metamorphic rock with igneous intrusions from the Enoggera granite. The Bunya phyllite consists of phyllite, hornfels and rhyolite dykes, with the phyllite containing quartz veins throughout. At the portal, the surface layer consists of fill associated with Mt Coot-tha Road overlying stiff to hard residual soil and extremely weathered (XW) rock extending to approximately 10 m depth. The residual soil and XW rock has an increased depth at the eastbound tunnel which is associated with weathering above and at the contact with a rhyolite dyke that extends through the portal area. The rhyolite dyke cuts through the tunnel portal from the eastbound tunnel to the west bound tunnel dipping approximately north and is 9 m true thickness. The rhyolite dyke was exposed during portal excavations in the eastbound tunnel beneath the sheet piled wall, and due to its orientation extends into the tunnel face, to intersect the westbound tunnel between 7 m to 22 m from the sheet pile wall (15 to 28 m into the TBM tunnel).
The phyllite is highly weathered (HW) to moderately weathered (MW) in the upper half of the TBM portal face with unweathered rock in the lowest edge of the portal face. The weathering rises into the tunnel within the phyllite rock with the east bound tunnel becoming unweathered after the dyke at approximately 35 m into the tunnel. In the westbound tunnel the weathering also rises in the phyllite towards the dyke, with the rhyolite being slightly weathered before a 'baked zone' occurs at the contact being the rhyolite and the phyllite. This zone is weathered and heavily fractured initially, with the weathering extending for 1 m before the phyllite becomes only fractured due to the dyke intrusion. The fractured zone extends up to 20 m in the east bound tunnel from the sheet piled wall and 30 m in the west bound tunnel.

The strength of the phyllite within the portal face was estimated between 2 to 40 MPa, while compressive strength tests within unweathered rhyolite beneath Mt Coot-tha Road were recorded up to 77 MPa and 83 MPa. Quartz content within the phyllite ranges from 55-65 per cent, and the phyllite is foliated with close spaced joints and widely spaced shear discontinuities.

During construction of the pipe umbrella the cutting from the augers indicated that once through the high strength rhyolite rock, a highly weathered zone approximately 1 m wide was encountered with the phyllite decreasing in weathering towards the end of the auger bore and the last 7 m was socketed into moderately weathered rock. The highly weathered material was further into the tunnel on the westbound tunnel resulting in a inferior socket of the pipe umbrellas than in the eastbound tunnel.

The degree of fracturing within the socket of the pipe umbrellas was not identified during the umbrella installation process due to the nature of the auger excavation, and this led to the pipes remaining as per design, while the increased competency of the ground due to the rhyolite dyke was recorded but the pipes were not reduced in length or number due to this.

**TUNNEL BORING MACHINE LAUNCHING OPTIONS**

Given that the TBM's available for the project meet the requirements for the entire tunnel excavation except the first 20 m, options to excavate the first section of tunnel are quite simple, excavate by other means before the TBM's arrive or carry out ground improvement allowing the TBM's to safely excavate this first 20 m of each tunnel.

The use of a pipe umbrella replaced the option of stub tunnels at the western portal that was considered in the tender concept. The stub tunnels would have required additional logistics and control associated with the sequential excavation and installation of support using conventional large diameter tunnelling methods for a very short length. This made the option unattractive when compared with the launching of the TBM directly into the portal face (part rock face, part concrete block).

The TBM launch methodology had to be revised to enable the launch of the TBM using the auxiliary thrust cylinders with the gripper pads offering torque stability only. The design analyses of gripper loads on the rock pillar, as well as the incorporation of the thrust ring into the portal block were all elements of the same design package.

The TBM excavation would leave a 25 m long, 200 mm deep unsupported annulus between the TBM cutter face and the location where the full grouting of the segmental lining annulus is completed. This length of unsupported ground is shown in Figure 1. Due to the relatively low ground cover (approx. 10 m) at the western portal a section of the roof will be in the XW rock mass as it passes below and in close proximity to Mt Coot-tha Road. The presupport required needed to prevent collapse of this weak ground over this length of 20 m for a period that may include TBM stoppages and delays due to the TBM being operated for the first time.

**DESIGN**

**Development of the concept**

The challenge set by constructors was to eliminate the requirement of any form of stub tunnel though the installation of presupport over the TBM crown. More conventional options such as forepoling did not have the structural capacity to span the long length between the portal block and the sound rock.

Horizontal steel pipes installed by auger boring will be filled with concrete to span the XW and MW rock material as a pipe umbrella in the roof of the tunnel over the first 28 m. This will reduce the magnitude of settlement anticipated on Mt Coot-tha Road due to the delay in grouting the annular gap between the TBM cut profile and the installed segment extrados.

The function of the pipe umbrella is twofold. Due to the large diameter of the pipes and their spacing they provide improved arching around the tunnel acting in a similar manner as ground improvements such as jet grouted horizontal columns. Secondly the pipes provide longitudinal spanning support, between the reinforced concrete portal block and the more competent rock deeper into the tunnel.

The portal block was conventionally reinforced to provide crack control and distribution ensuring the 100 year design life of the permanent structure was met. The portal block also had additional reinforcement where tensile stress capacity was required. The transfer of load into the portal block from the umbrellas required reinforcement slings to relocate load from the inside face of arch to outside compressive face.

Due to the novel design approach the concept also had to consider a less than optimal outcome, of the end restraint of the pipe umbrellas in the MW rock. While the geometry and length of the pipes took into account the ability of the pipe to span over wedges formed by the mapped joint sets from the portal face excavation, consideration had to be given to higher than anticipated convergence to the ends of the umbrellas. In this situation the key benefits of the double shield arrangement come into play. As in poorer quality ground traversed by double shield TBMs the final critical element is to achieve adequate stand up time between the rear of the shield and the grouted segmental lining. The minimum length of the pipe umbrellas ensured that the 12 m length between the back of the rear shield and the grouted segments is always bridged by the pipe umbrella in the poorer ground.

**Method of analysis**

This design method is based on the iteration of multiple 2D cross-section models and an asymmetric model to produce corresponding tunnel deformations and hence assess both surface settlements and pipe stresses with some confidence.

Steel pipes are installed by horizontal auger boring to span from the concrete portal block to the MW to SW rock. At the furthest extents the more competent rock provides embedment and support for the pipes as the TBM passes underneath. In the less competent rock mass the pipes will support the excavation and reduce the deformation into the excavation.
An initial settlement assessment of the rock mass with and without pipes has been undertaken by 2D analysis with sections cut every 5 m. Pipes are installed in position with no longitudinal load transfer along the pipes, followed by the excavation and tunnel lining installation.

No core replacement was modelled at cross-sections representing sections where the 1.5 m thick rock arch between the umbrella and the TBM cut profile is thought to provide end support to the pipe umbrella. In sections where the pipes support the weaker material above the pipe umbrella core replacement is used at a very low level preventing large deformation in these areas and allowing the model to converge without the core material providing actual support to the umbrellas.

The pipe convergence in the 2D analysis is compared to an axisymmetric model which captures the longitudinal load transfer along the pipes.

Spanning actions applied to the pipes in the 2D model are derived from back calculating longitudinal shear forces calculated in the axisymmetric model. At the near end the pipes are shown to be supporting the rock mass, while at the far end the rock arch between the TBM excavated profile and the pipe umbrella supports the pipes.

Each pipe in the pipe umbrella has been modelled as a composite member formed from the concreting of the steel pipes.

**Modelling details**

**Multiple 2D slices**

Slices were set-up at 5 m spacing along the tunnels using the material geometry from the 3D ground model (other software) and the proposed tunnel and umbrella arrangement. Each model includes the following staging:

- apply initial loading
- apply vehicle loading above tunnels
- install pipes above both MCA and MCB tunnels and portal block for first section
- core softening (excavation) and application of radial loading to pipes (in later iterations)
- install support from segmental lining in westbound tunnel
- core softening (excavation) and application of radial loading to pipes (in later iterations)
- install support from segmental lining in east bound tunnel.

Pipe umbrella convergence has been extracted from the 2D models by subtracting the edge pipe vertical settlement from the centre pipe vertical settlement as shown in the Figure 3.

**Axisymmetric model**

An axisymmetric model of the MCA tunnel entry was created with the following staging:

- initial loading
- install pipes
- install mass concrete wall
- 4-14 - excavate tunnel in 2 m stages
- 14-40 - excavate tunnel in 2 m stages and install final lining 24 m behind.

Field stress is taken as the depth of overburden plus traffic load. As the pipe umbrellas do not from a continuous structural cylinder the pipes are represented in the model as a continuous liner using three main inputs, elastic modulus equivalent to the steel concrete composite, 1 wall = 1 eq x 1000 mm/spacing mm and an area A = 1E-20 (to ensure no axial hoop transfer).

**Iterations**

The axisymmetric model replicates a rotated slice forming a closed circle. Displacements resulting from such an analysis replicate convergence in the tunnel roof where vertical stress is approximately equal to radial stress. The 2D analyses are gravity based models which undergo settlement in addition to convergence. Convergence has been isolated in the 2D models as discussed above and is shown in Figure 3.

As the tunnel face moves away from the pipe umbrella the rock loads acting on the umbrella reach a settled state. These loads have been evaluated by buck calculation of the shear force appearing in the pipe umbrella with the following results. The 2D model has been re-assessed incorporating longitudinal pipe forces into the 2D model. This load allows the pipes in the 2D models to reflect the load transfer along the pipe umbrella. In each 2D section radial loads are applied to the pipes upon face softening. The resulting loads applied to the pipes to achieve convergence between the two models is shown in Table 1 for a given load case.

![Figure 3 - 2D umbrella settlement analysis. Where: edge pipe vertical settlement = (ΔA + ΔB)/2; and convergence = centre pipe vertical settlement - edge pipe vertical settlement.](image)
A coming together of the convergence in the attuned 2D models and the convergence in the axisymmetric has taken to indicate a solution has been reached. The revised 2D results have been extrapolated to produce expected surface settlement at each slice. The converged results from one of the design cases is shown in Figure 4.

### Results and reviews

The results from the 2D model are taken forward for use in settlement predictions, while the moments and shear forces from the axisymmetric model are used in the structural design of the pipe umbrellas. The high shear at the entrance to the portal block required the incorporation of an addition smaller diameter steel casing into the composite element to achieve the required ultimate shear capacity.

Given that the entire design was novel, the project specification required an independent proof engineer review of the completed design to be undertaken. This was carried out by an approved independent tunnel engineering consultancy. The proof engineer undertook their own analysis using Plaxis 3D and arrived at results similar to the base design and confirmed the structural adequacy of the design based upon the information available.

### CONSTRUCTION OF PIPE UMBRELLA

To eliminate the amount of falsework required the Constructor elected to progressively excavate working platforms within the open cut and cover box on which the auger bore rigs could be set-up, so that only simple packing was required under the auger bore track to position the bores. The means that the excavation was taken down in a number of steps between completion of the top bores and commencement of the lower bores. The temporary thrust walls for the bores comprised of king pile posts loaded by a spreader beam. The pipe umbrellas were installed using to auger bore rigs set-up with 15 m of track travel to allow the pipes to be installed in two lengths with only a single site butt weld to join the pipes to form the full length of the umbrella. The arrangement of the auger bore rig for the top level of pipes is provided in Figure 5.

Careful set-up using the long auger track and length of pipe was the primary method of alignment control but due to intersecting dipping rock some wedging of the cutting tool support spindle was required to correct alignment as the bore progressed. The aim was to install the augers with minimal disturbance to the surrounding ground which required prompt grouting of the pipe annulus upon completion of the pipe installation. Given the tight time frames and stable bore annulus grouting was undertaken before the adjacent bore was undertaken and before the working platform was lowered for the next round of pipe installation. Grouting was undertaken using a thick cement grout, with superplastiser for improved flow, batched on-site.

Cuttings and face inspections of the bores were undertaken progressively and records checked to ensure that the pipes socketed into the required 6 m of moderately weather rock. Boring of the 11 pipe umbrella above the westbound tunnel was undertaken with two changes, one of the second lowest pipes deviated enough to contact the pipe above at a length of 26.5 m, where this pipe was then terminated and the lowest pipe on the north was stopped short due to auger refusal. Boring of the 12 planned pipes above the eastbound tunnel was more varied, with the three northern pipes, the first hitting two misaligned tieback anchors, the second requiring realignment to avoid the adjacent pipe and the third being omitted due to program constraints in consideration of better ground conditions on that boundary.

Once all pipes were installed the six instrumented pipes were fitted out with inclinometers and the pipe ends fitted with the additional short casings and backfilled with a super workable (self-compacting) structural concrete though a delivery line fixed in the pipe and a series of breathers. Filling was similar to rock bolt grouting with pumped volumes of concrete being checked against theoretical volumes and discharged concrete from breathers being confirmed as of same consistency as the injected concrete. The concrete filled umbrellas are seen in Figure 6 ahead of construction of the portal block.
MONITORING

Planned monitoring
Mt Coot-tha Road is an important item of infrastructure both for the surrounding traffic movement and for site access. Monitoring of surface settlement and ground movement was an intrinsic part of ensuring the success of the tunnelling operation and the limiting the risk to third party infrastructure.

Ground monitoring elements that were specific to the Mt Coot-tha Road tunnel crossing include the following:
- inclinometers vertical from the surface between the two bores
- settlement points on surface but also the face of the portal block
- extensometers above the tunnel bores.

Transcity was also required to monitor the performance of the pipe roof above the TBM excavation using horizontal inclinometers.

Results
The first TBM to be launched was the westbound tunnel, and initially excavation took place within phyllite rock leading into the 9 m band of high strength rhyolite. The higher strength rock caused difficulty with TBM excavation due to the reduced gripper loads allowed on the excavated sidewalls, limiting the amount of thrust available for the TBM. Once through the rhyolite the extent of the fractured rock became apparent through the lack of stability of the tunnel face which collapsed back into the cutterhead leaving an approximate 2 m void in front of the cutterhead within the fractured phyllite rock. This collapsed section extended into the roof of the tunnel beyond the end of the pipe umbrellas and was grouted during a secondary grouting operation after the segments and annulus grout had been installed.

The reduced competency in the rock at the end of the pipe umbrella on the westbound tunnel resulted in significantly more convergence at the ends of the westbound umbrella that anticipated. The monitoring from the westbound pipe inclinometers is shown in Figure 7. The eastbound umbrella on the other hand performed in accordance with the design predictions. The monitoring from the westbound pipe inclinometers is shown in Figure 8. Overall surface settlement of the road and the subsurface extensometers is shown in Table 2 compared with the design trigger levels.

With the real time monitoring in place, design amendments were made to extend the length of heavily reinforced segments with addition shear connectors between segments further into the westbound tunnel along with a secondary grouting program through the segments to ensure any over excavation was backfilled.

POST-CONSTRUCTION 3D ANALYSIS
The new RS3 software, from Rocscience, for 3D analysis of geotechnical structures provides an additional tool to undertake this form of analysis for future projects. As
the models in RS3 are built by extruding 2D slices either horizontally or vertically it is not possible to accurately follow sloping ground surface of material surfaces. To model this problem in RS3 where there are both of these type of sloping surface requires some simplification to the model geometry. Replacing sloping ground surfaces with flat surfaces and adding imposed loads is a simple workaround. The step in the material boundaries can also be softened by introducing a transitional material between existing materials than bridge the steps in the slices.

**TABLE 2**
Surface settlement predicted and actual values.

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**CONCLUSIONS**

The TBM portal configuration of the Legacy Way tunnels is unique and the application of a similar system of ground improvement on other projects may be difficult. The need to provide a stable zone for the commencement of tunnelling in an urban environment is always high and ground improvement is common placed for closed face TBM launches in soft ground.

The ground improvement measures put in place did reduce significantly the impact from tunnelling on third party...
infrastructure and the possible loads on the segment rings ahead of grouting.

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