Tunnelling within the Bunya Phyllite of Legacy Way, Brisbane, Queensland

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ABSTRACT
The Legacy Way Tunnel was constructed from Toowong to Kelvin Grove in Brisbane, and is the first large-scale underground excavation in the Bunya Phyllite in Brisbane. The Legacy Way Tunnel is 4.3 km in length, comprising two mainline tunnels excavated by a tunnel boring machine (TBM) with 46 connecting passages excavated between the mainline tunnels for egress provision and services. The Legacy Way Tunnel passes through two geological formations, the Bunya Phyllite and the Neranleigh Fernvale Beds. The Bunya Phyllite is the dominant formation of the Legacy Way Tunnel, extending for three quarters of the tunnel prior to intersecting the Normanby Fault Zone (NFZ) and the Neranleigh Fernvale Beds. The NFZ forms the contact between the two formations as part of the Brisbane Metamorphics, which underlies the majority of Brisbane City.

The development of the geological model and the understanding of the ground’s reaction to tunnelling was an iterative process. The tender phase investigation data has been supplemented with additional design phase investigation boreholes, geophysics and walk overs. Aerial photograph interpretation coupled with borehole data allowed the development of the domains along the length of the tunnel. Early excavations for the spoil conveyor tunnel and borehole data from subsurface instrumentation installation provided the first construction phase data followed by the commencement of tunnel boring machine (TBM) excavation. Routine cutterhead inspections coupled with ongoing reviews of the predicted geology resulted in clear response triggers to selection of segment types while detailed inspections in passage locations provide the initial classifications for segment removals.

INTRODUCTION
The Legacy Way Tunnel extends from the end of the Western Freeway at Mt Coot-tha to the Inner City Bypass at Kelvin Grove. The project comprises:
- two 4.3 km long, 12.4 m outer diameter, road tunnels excavated using double-shield Herrenkiclt tunnel boring machines (TBM)
- 46 passages excavated by conventional tunnelling techniques including mechanical rock hammers, and drill and blast; the connecting passages are made up of:
  - 35 cross passages
  - ten substation passages
  - one low point sump

The tunnels were excavated through the Brisbane Metamorphics comprising of the Bunya Phyllite and the Neranleigh Fernvale Beds (Holcombe, 1977), with the Normanby Fault forming the boundary between the two units in the Red Hill area (Bryan and Jones, 1954).

Five extensive geotechnical investigations were undertaken by Brisbane City Council along the proposed tunnel corridor between 2004 to early 2010. Further geotechnical investigations were undertaken during the detailed design phase to clarify the geological conditions at key locations, such as low cover zones, the Rosalie Village area and the NFZ. In total, 108 boreholes (five of these inclined), 11 downhole defect surveys (RAAX), over 1800 point load tests, 148 UCS tests, and 107 in situ permeability tests were undertaken over the six investigation phases. Notwithstanding the large amount of investigation information, sections of the tunnel alignment still had no direct investigation information. This was a result of the optimised tunnel alignment differing from the concept design over the western half of the tunnel alignment. These gaps in information were around the steep ridgelines in Paddington, the low cover zone within Martha Street rent and the expected NFZ. Therefore the development of the geological model was a progressive task from design through early TBM excavation and followed by later TBM and cross passage construction. The development can be separated into the following key tasks:
- Detailed design:
  - review of existing geotechnical investigation results
  - aerial photograph interpretation (API)
  - additional investigation including boreholes and geophysics in select locations
  - detailed analysis of rock mass characteristics (including strength, discontinuities, and kinematic details).
- Further geological data collection:
  - early identification of geology features during portal excavation through geological mapping
borehole logging of subsurface instrumentation installation for extensometers and inclinometers at all five low cover zones, including Martha Street

- TBM contact force data calibration
- rock face inspections through the TBM cutterhead openings particularly at future cross passage openings and collation of Q-values, RMR, groundwater inflow and discontinuity properties.
- Geological feedback and construction support:
  - forward prediction of geological zones for upcoming TBM tunnel excavation
  - initial primary excavation support requirements for cross passages using Q-values, RMR, groundwater and discontinuity properties from rock face mapping through the TBM.

LEGACY WAY GEOLOGY

The geology encountered along the Legacy Way Tunnel starts at the end of the Western Freeway within the Bunya Phyllite and extends through the eastern limb of the Indooroopilly Anticline to the NFZ and the Neranleigh Fernvale Beds. The start of the tunnel, including the Western Portal dive structure, consists of predominately phyllite rock with irregular rhyolite dykes from the Indooroopilly Intrusives.

West of the Legacy Way portal, including the conveyor tunnel, the geological structure comprises the hinge of the Indooroopilly Anticline which trends through the conveyor tunnel and the surface works area of the Western Freeway (Jones and Stevens, 1967). This was detailed for the project as Domain A (see Figure 1), and consists of phyllite, with areas of hornfels and intersecting dykes due to the intrusion of the Enogerra Granite. The analysis of project data shows Domain A having predominately shallow dipping foliation with an orientation of 20/245 therefore indicating it is located on the western limb of the anticline. Further analysis of the stereoplot of the conveyor tunnel discontinuity data from Domain A was undertaken, it showed a rotation of the foliation dip within the conveyor tunnel placing the hinge in the Mt Coottha Botanical Gardens near the National Freedom Wall.

At the Western Portal the phyllite is high in quartz content (50-65 per cent) due to a siliceous fabric within the rock from the contact metamorphism with the Enogerra Granite, with the phyllite additionally having numerous quartz veins within a foliated, high strength rock mass. The rock has a shallow depth of weathering (no more than 15 m), which follows the topography except when a shear/fault structure dissects the rock mass (see Figure 2). API undertaken using stereographic pairs from 1959 and 1965 identified large scale regional lineaments (west-east and northwest-southeast structures) across the tunnel area from Mt Coot-tha to Red Hill as detailed in Figure 1. At the Western Portal the lineament identified during API is associated with a rhyolite dyke as part of the Indooroopilly intrusives. The rhyolite is very high strength and discontinuities are widely spaced within fine grained porphyry. The Western Portal dyke is followed by rhyolite dykes in the Toowong Cemetery and between Thorpe Street and Gregory Street. After Birdwood Terrace (approximately 1 km into the tunnel, east of cross passages – XP8) no Indooroopilly intrusives were encountered within the Bunya Phyllite; however, it should be noted that a higher concentration of dykes are located (and can be seen) in the Western Freeway excavations from Moggill Road to the portal than within the tunnel itself. The largest intrusion encountered was a rhyolite dyke beneath Mt Coot-tha road which was 9 m in true thickness.

The high quartz content within the rock, identified during petrographic analysis (Figure 3), and the consistent foliation angle led to the classification of the phyllite from the Western Portal to approximately Payne Street as one geological domain (Domain B). Additionally in this zone a number of lineaments identified during API (Figure 1), were confirmed as shear zones during tunnelling. The shears were located along the first kilometre of tunnel at which point the quartz content decreases below 60 per cent, which we deemed for TBM construction activities as a key proportion for cutter wear. The decrease in quartz content is part of an overall downward trend within the Bunya Phyllite along the alignment, shown in Figure 3. The shear zones typically comprised a central geological structure with fault gouge, including clay and rock flour up to 1 m thick, surrounded by fractured rock up to 4 m to 20 m wide. The shear zones lead to minor collapse of the tunnel face in towards the TBM cutterhead during excavation.

EXISTING REGIONAL GEOLOGY AND KEY INVESTIGATIONS

Regional geology

The regional geology encompassing the Legacy Way Tunnel is known as the Brisbane Metamorphics within the D’Aguilar Block (Bryan and Jones, 1951), which consist of the Bunya Phyllite and the Neranleigh Fernvale Beds. The Bunya Phyllite has been interpreted as Cambrian to Silurian in age with the Neranleigh Fernvale Beds interpreted as younger than the Bunya Phyllite, likely Silurian in age. The Bunya Phyllite consists of phyllite and hornfels with igneous intrusion (namely rhyolite), with phyllonite located within the St Lucia Polymetamorphics (Jones and Stevens, 1967). The phyllite has undergone a series of deformation episodes with multiple folding events identified in the quartz veins and foliation of the phyllite (Holcombe, 1977). The Neranleigh Fernvale Beds consists of phyllite, meta-argillite, greenstone, chert, arenite and other meta-sediments which have differing amounts of foliation present with the rock mass and brecciation due to localised and regional shear structures.

The commonly agreed geological structure of the Bunya Phyllite and Neranleigh Fernvale Beds is that the rocks have experienced a series of deformation events which have resulted in a broad antiform structure known as the Indooroopilly Anticline (Dennead, 1928) with the Bunya Phyllite in the core of the fold and the Neranleigh Fernvale Beds on the flanks. Thrust faults have been suggested previously east of the anticline (Bryan and Jones, 1951) with the Normanby Fault also regarded as a thrust fault along the lithological boundary of the Bunya Phyllite/Neranleigh Fernvale Beds. Holcombe (1977) has detailed that the Bunya Phyllite/Neranleigh Fernvale Beds boundary with the Normanby Fault only coincide in the Red Hill area as elsewhere there are no abrupt changes in structure and lithology together (Holcombe, 1977). The subvertical nature of the geological structures north of the river in the Bunya Phyllite and Neranleigh Fernvale Beds are not noted elsewhere and therefore Holcombe (1977) questioned the presence of a fault structure, but did not categorically conclude one way or the other.

The Bunya Phyllite has been intruded by acid dykes specifically around the Indooroopilly area from the Enogerra Pluton (Houston and Tucker, 1965) and contact alteration of the phyllite has resulted in hornfels within the predominately phyllite rock. The dykes are predominantly located in the axial region of the Indooroopilly Anticline and are heavily concentrated in the St Lucia area near the University of Queensland mine (Jones and Stevens, 1967).
FIG 1 – Legacy Way Tunnel plan.

FIG 2 – Legacy Way Tunnel longsection.
(Figure 4). The discontinuities within the shear zones were undulating and polished, with some slickensided surfaces noted. The shear zones are considered as thrust faults as part of the folding process on the eastern limb of the anticline detailed by previous geological publications, (Houston and Tucker, 1965; Cranfield, Schwarzbock and Day, 1976; Holcombe, 1977).

The Bunya Phyllite from Payne Street to Given Terrace is deemed as Domain C (Figure 1) from the consistent strength, foliation and discontinuities with minor fractured and shear zones mainly associated with topographical relief. The foliation and defect spacing increased and therefore the excavability of the rock mass decreased, which was noted during TBM excavation with very high contact forces on the cutterhead and the cross passage excavation of the substation leading to drill and blast excavation. The reason for the decrease in discontinuities is not apparent however, it could be due to this area being distant to other geological boundaries and intrusions and therefore less deformation has occurred in the domain since initial folding deformation occurred. The intact nature of the foliation, which led to the reduction of excavation using mechanical machinery, was possibly formed during hydrothermal episodes as part of secondary folding as detailed by Holcombe (1977) and may have led to welding of the foliation and abundant quartz veining.

Foliation from the Western Portal through to the end of Domain C was shown to generally steepen and is consistent with the Brisbane Metamorphic geological publications (Bryan and Jones, 1954; Jones and Stevens, 1967; Holcombe, 1977). The foliation from Mt Coot-tha Road to Given Terrace rotates from 27/091 to 57/098 to 72/075, with a fold plunge and trend axis of 06/180 (Figure 5), hence confirming the geological understanding of the Indoooropilly Anticline, with the conveyor tunnel located on the western limb of the fold and the Western Portal being very close to the hinge of the fold structure. The shear discontinuities (crushed seams, sheared surfaces or shear zones) that occur in Bunya Phyllite and Neranleigh Fernvale Beds of the Legacy Way Tunnel intersect the foliation as either a conjugate set or are slightly oblique to a conjugate set. A small proportion of the discontinuities have the same orientation of the foliation.

The geological domain extending from Given Terrace to Cambridge Street (Domain D) is a transitional one associated with, what we have identified from tunnel excavation as the NFZ. This transitional domain consists of an increase in shear zones again with a predominant shear zone extending northwest from the NFZ at the Brisbane River (Figure 1). The shear zones increase in occurrence towards the gully and western edge of the NFZ at Cambridge Street.
At Cambridge Street API undertaken shows a curved set of lineaments (Figure 1 – lineaments associated with NFZ) forming a duplex shape and from observations during tunnel construction this has been defined as the NFZ. The left side of the duplex shape is a subvertical shear zone approximately 10 m wide within phyllite rock. An unconformable contact on the eastern side of the shear zone marked a change from dark grey phyllite to pale grey sericitic meta-argillite (Table 1) and therefore we consider the shear zone marks the unconformable contact of the Bunya Phyllite with the Neranleigh Fernvale Beds and the start of the NFZ. The rock mass from the western boundary of the NFZ to the eastern portal of the Legacy Way Tunnel (Domain E) consisted of multiple and regular shears at 50 m spacing on average and between 8–12 m traversed width (6–10 m true thickness). The shears through this area had one or more zones within the overall fractured rock mass with fault gouge, rock flour, disintegrated minerals and polished or slickensided discontinuities. Additional to the shears is a fractured rock mass beneath St Brigids church which consisted of two 40 m wide fracture zones with increased groundwater inflow and cubical blocks. The sequence of shears is intersected by a band of greenstone, which is very high strength with very widely spaced discontinuities and is derived from metamorphosed basalt (Table 1). The greenstone was 160 m true thickness and is subvertical in orientation through the tunnel. Shears located within the 200 m of the eastern boundary of the greenstone mark the eastern end of the NFZ through the Red Hill area and is noted on Figure 1 as the right solid line.

The shape of the two double-dashed curved lines in Figure 1, which define the NFZ is typical of strike-slip structural faults where a compressional duplex has formed a pop-up structure along the fault, as typically seen in Figure 6 (Davis, Reynolds and Kluth, 2012), due to a restraining bend in the Normandy Fault associated with the very high strength massive greenstone band, or just a change in geometry of the fault. The multiple shears identified within the Legacy Way Tunnel are consistent with a duplex structure of a strike-slip fault. It is noted that previously a nappe fold structure has been described (Houston and Tucker, 1965; Cranfield, Schwarzbuch and Day, 1976); however, due to the orientation of shear zones been recorded as 80/045 and later along the tunnel as 60/209, it is considered a strike-slip duplex more likely.

![FIG 6 — Compressional duplex (Normandy Fault looking from the north).](image)

When considering the strike-slip duplex structure, the adjacent fault structures and greenstone band, it is possible that the restraining bend structure has led to the single lineation of the Normandy Fault to the north and south of the Legacy Way Tunnel to become splayed through the Red Hill area, as shown in Figure 6. This would lead to multiple splays outward from a common fault plane, namely the Normandy Fault, and this was seen from the Bunya Phyllite/Neranleigh Fernvale Beds boundary beneath Cambridge Street, through the concentrated shear zones beneath St Brigids Church to the lithological boundary with the greenstone. The greenstone has been considered within the sequence as being within a single fault block within the compressional duplex as seen in the interpreted NFZ longsection in Figure 7. Additionally the longsection in Figure 7 shows the series of fault splays we believe was represented in the Legacy Way Tunnels as multiple shear zones in the TBM particularly from Cambridge Street to Musgrave Road. Therefore the Normandy Fault does exist through the Legacy Way Tunnel, as previously stated by publications (Cranfield, Schwarzbuch and Day, 1976), but more as a series of faulted zones that together make the NFZ (see Figure 7).

The greenstone lies within the Neranleigh Fernvale Beds between Musgrave and Kelvin Grove Roads and has a true thickness of approximately 160 m. The greenstone is bounded by shear zones within phyllite and meta-argillite rock. Through petrographic analysis the rock was confirmed as a low-grade, regional metamorphic greenstone, derived from previous pillow basalt. The greenstone is massive in nature.

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**TABLE 1**

Bunya Phyllite/Neranleigh Fernvale Beds rock descriptions.

<table>
<thead>
<tr>
<th>Location</th>
<th>Rock name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toowong Cemetery</td>
<td>Phyllite with quartz</td>
<td>Low-grade, dynamothermal, quartz veined phyllite with crudely planar foliation and abundant deformed quartz</td>
</tr>
<tr>
<td>Birdwood Terrace</td>
<td>Silicous phyllite</td>
<td>Low-grade, dynamothermal phyllite, strongly foliated</td>
</tr>
<tr>
<td>Martha Street</td>
<td>Phyllite</td>
<td>Low-grade, dynamothermal phyllite, that is kink foliated and folded</td>
</tr>
<tr>
<td>Cambridge Street</td>
<td>Sericitic meta-argillite</td>
<td>Low-grade, regional metamorphic, meta-argillite with strong foliation</td>
</tr>
<tr>
<td>Kelvin Grove Road</td>
<td>Greenstone</td>
<td>Low-grade, regional metamorphic greenstone, derived from previous pillow basalt</td>
</tr>
<tr>
<td>Normanby Terrace</td>
<td>Carbonated sericitic meta-argillite</td>
<td>Low-grade, regional metamorphic, meta-argillite with strong foliation</td>
</tr>
</tbody>
</table>
with very few discontinuities and very high strength. The lack of discontinuities, mineralogy and strength resulted in very high TBM contact forces of 17,000 to 18,000 kN and slow advance rates.

BUNYA PHYLLITE ROCK MASS CHARACTERISTICS

Rock strength
The Bunya Phyllite is characterised by a consistent foliation throughout the rock mass and irregular quartz veining from deformation phases throughout the development of the rock. In the case of the Bunya Phyllite along the Legacy Way Tunnel these foliations are well bonded and identified as intact for the majority of the rock mass. Where specimens failed along foliations the unconfined compressive strength (UCS) was below 40 MPa; however, not all failures below 40 MPa were due to foliation failures as shown in Figure 8. Specimen that had UCS greater than 40 MPa did generally not fail along the foliations. Where point load and UCS tests were carried out on immediately adjacent rock samples, the strength results have a correlation factor between the UCS and the point loads.

FIG 7 – Normanby Fault Zone geological longsection.

FIG 8 – Unconfined compressive strength / point load strength correlation.
of 8 for both diametric and axial point load tests with minor variations in the factor for intact or other failures (Figure 8).

Overall strengths of the Bunya Phyllite ranged from 4 MPa to 160 MPa (including point load testing). The greenstone within the Neranleigh Fernvale Beds has no foliations within the rock mass and rock strengths were identified as and strength from 55 MPa to 88 MPa. However, much higher strengths were encountered during tunnelling, with the TBMs having contact forces greater than 18 000 kN within the greenstone and an advance of 6–15 m in one 24-hour period. The spoil from the cutterhead during excavation of the greenstone was flint shaped, which differed from the well graded and elongated spoil throughout the phyllite. The spoil shape differed depending on the rock strength and foliations due to TBM using the foliation to form a weakness that could be exploited by the TBM disc cutters. For mechanical excavation bay hammer the high strength phyllite offer little or no planes of lower strength from which to advance mechanical excavation.

**Discontinuities properties**

The discontinuity properties of Bunya Phyllite were separated into material properties, orientation and persistence. The material properties considered from investigation data during design identified that the joints were planar and rough (JRC = 6) with no infill and a UCS of 30 MPa for the fresh rock.

Construction activities revealed a slight change in properties as joints were considered to be undulating and smooth while shear defects were undulating and polished.

The orientation of the discontinuities during design was based upon the RAAX downhole survey, oriented core and surface mapping. A re-analysis of the rock fracture data from drilling investigations was undertaken to ensure accuracy of the discontinuity orientation where possible. In particular, filtered discontinuity data was used wherever any discontinuity identified as a ‘foliation’ plane in the RAAX data, but not visible in borehole core, was removed from the data set. Also orientated core that showed the core had undergone rotation in the barrel and a loss in reference line was removed from the analysis so as not to scatter the stereoplot data. The design and construction geological discontinuity orientation data is shown in Table 2. Although the domain chainages have been refined slightly the orientations show alterations in some joint sets for Domain B, C, and D, as shown in Table 2.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Chainage</th>
<th>Design</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21 700 to 22 050</td>
<td>0/160</td>
<td>88/307</td>
</tr>
<tr>
<td></td>
<td>0/025</td>
<td>83/002</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0/160</td>
<td>88/216</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>22 050 to 23 200</td>
<td>69/316</td>
<td>80/335</td>
</tr>
<tr>
<td></td>
<td>52/297</td>
<td>72/288</td>
<td></td>
</tr>
<tr>
<td></td>
<td>73/175</td>
<td>78/178</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>23 200 to 24 700</td>
<td>15/240</td>
<td>77/349</td>
</tr>
<tr>
<td></td>
<td>73/175</td>
<td>81/173</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90/337</td>
<td>73/077</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>24 700 to 25 500</td>
<td>24/258</td>
<td>61/071</td>
</tr>
<tr>
<td></td>
<td>86/152</td>
<td>82/145</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85/251</td>
<td>89/174</td>
<td></td>
</tr>
</tbody>
</table>

**TUNNEL BORING MACHINE MAPPING AND FORWARD PREDICTION OF GEOLOGICAL STRUCTURE**

The acquisition of geological data was through a formulated approach validating known API, rock mass properties and identification of geological structures during the initial phases of construction with tunnelling data collected during the conveyor tunnel excavation and the initial sections of the TBM tunnels. The conveyor tunnel was excavated prior to the launch of the TBMs to allow transportation of tunnel spoil to the deposition area in the conveyor tunnel. The majority of the conveyor tunnel was excavated by drill and blast
through phyllite rock of the Bunya Phyllite. The mapping and documentation of the geological properties in the conveyor tunnel was similar to the TBM tunnel details with the following rock mass details documented:

- rock lithology, geotechnical rock unit
- rock discontinuities, including type, dip/dip direction, persistence, spacing
- strength, weathering, fabric, key minerals

- GSI, Q values, RMR
- groundwater inflow
- tunnel stability around persistent shear structures.

From the data collated from each stage leading up to the TBM excavation it was concluded that the majority of the tunnel would be constructed in generally medium to high strength, unweathered phyllite which would eventually intersect high strength, unweathered Neranieh Fernvale Beds at the Red

**TABLE 3**

<table>
<thead>
<tr>
<th>Rock eng unit</th>
<th>Weathering grade</th>
<th>Rock strength</th>
<th>Structure</th>
<th>Average discontinuity spacing (from RQD correlations)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP 4</td>
<td>HW to MW</td>
<td>Low</td>
<td>Foliated</td>
<td>Close</td>
<td>Phyllite, rhyolite, hornfels, with quartz veins</td>
</tr>
<tr>
<td>BP 3</td>
<td>Generally MW with minor amounts of SW</td>
<td>Generally medium (higher strength possible within quartzite and hornfels)</td>
<td>Foliated</td>
<td>Close to medium</td>
<td>Phyllite, rhyolite, hornfels, with quartz veins</td>
</tr>
<tr>
<td>BP 2</td>
<td>Generally SW, with minor amounts of FR</td>
<td>Medium to high (higher strength possible within quartzite and hornfels)</td>
<td>Foliated, Massive within the quartzite and quartz arenite</td>
<td>Medium, locally close</td>
<td>Phyllite, rhyolite, hornfels, with quartz veins</td>
</tr>
<tr>
<td>BP 1</td>
<td>FR with minor amounts of SW</td>
<td>High with some rock possibly very high</td>
<td>Foliated, Massive within the quartzite and quartz arenite</td>
<td>Medium</td>
<td>Phyllite, rhyolite, hornfels, with quartz veins</td>
</tr>
<tr>
<td>NF 4</td>
<td>HW with XW/MW</td>
<td>Medium</td>
<td>Foliated</td>
<td>Close</td>
<td>Phyllite, meta-greywacke, arenite, quartz arenite and quartzite with quartz veins</td>
</tr>
<tr>
<td>NF 3</td>
<td>MW</td>
<td>Medium to high</td>
<td>Foliated</td>
<td>Close to medium</td>
<td>Phyllite, meta-greywacke, arenite, quartz arenite and quartzite with quartz veins</td>
</tr>
<tr>
<td>NF 2</td>
<td>SW to FR</td>
<td>High to very high</td>
<td>Foliated</td>
<td>Medium, locally close</td>
<td>Phyllite, meta-greywacke, arenite, quartz arenite and quartzite with quartz veins</td>
</tr>
<tr>
<td>NF 1</td>
<td>FR</td>
<td>High to very high</td>
<td>Foliated</td>
<td>Medium</td>
<td>Phyllite, meta-greywacke, arenite, quartz arenite and quartzite with quartz veins</td>
</tr>
<tr>
<td>Spline</td>
<td>HW to FR</td>
<td>High to very high</td>
<td>Massive</td>
<td>Medium to wide</td>
<td>Greenstone</td>
</tr>
<tr>
<td>FWZ</td>
<td>SW to HW</td>
<td>Extremely low to low</td>
<td>Disintegrated/fractured</td>
<td>Very close to close</td>
<td>Highly fractured/fault/weakness zone (existing through all lithologies), exceeding 1 m in thickness</td>
</tr>
</tbody>
</table>
Hill area. The NFZ was anticipated to be shear zones (the extent which was unknown at the time) with a band of very high strength greenstone also in the vicinity. The interpreted rock properties for the Legacy Way Tunnel are presented as Table 3.

Refinement of the extent of geological conditions began once tunnelling commenced through routine mapping of the tunnel face through the TBM cutterhead ports and buckets (Figure 10). Mapping was mandatory when bad ground conditions existed or when the tunnel face corresponded with a cross passage opening to allow direct understanding of geological conditions. Each visit to the cutterhead was documented with a mapping sheet detailing discontinuity orientations, tunnel face and invert discontinuity properties (spacing, persistence, shape, roughness), groundwater inflow, identified large scale geological features with respect to the tunnel profile, and rock strength, that were all summarised in a live spreadsheet. This information was of particular use for assessing the future geological conditions in the TBM and construction conditions expected at the cross passages. The initial assessment at the cross passages formed the basis for the first support permit at the cross passage prior to segment breakout, and proved to be accurate for the first 3 m of excavation apart from spot bolt support requirements. The TBM contact force information from the cutterhead penetration was reviewed in these zones against the block size according to the Tunnelling Quality Index – Q (Barton, Lien and Lunde, 1974), assessed during TBM excavation (Figure 11). Figure 11 provided assessment on whether excavation would be relatively easy (low TCF and low block), difficult (high TCF and high block size) or variable (high TCF and low block size).

It was identified that for the Legacy Way TBMs contact forces of 8000 kN to 15 000 kN were normal operating forces within the Bunya Phyllite. Anything below 8000 kN showed a possible fractured rock mass and therefore the likelihood of a shear zone, while below 4000 kN identified a shear zone which would likely require heavy reinforcement within the segments. Correlation of the API lineaments, topography, rock mass, groundwater, TBM excavation data identified that the shear zones lay asymmetrical to the valley low points with the decrease in TBM contact force indicating the beginning of fractured rock prior to the weakest rock mass section. Therefore whenever the TBM contact forces dropped below 4000 kN the tunnel geologist was notified for an inspection of the tunnel face through the cutterhead and the spoil to determine segment lining requirements. If the TBM contact force dropped and stayed below 4000 kN for more than four segments the shift boss would request the tunnel geologist to inspect the face through the cutterhead buckets prior to locating the best location to start placing ‘heavy’ segments into the area of the shear zone. Through review of the contact force and the observed geology the number of rings with ‘heavy’ segments could be optimised as the TBM progressed through the shear zone.

Inflow of groundwater along the tunnel ranged from none to minor inflow at discontinuities to high inflow through fractured rock mass or even open joints. The inflow of groundwater was rapid prior to shear zones on the first TBM, with it occurring generally within a 2 m excavation advance. Once the rock mass surrounding the TBM was drained, limited recharge occurred before the second TBM excavated through the area (one to two months later). Drawdown at Rosalie was due to inflow of the groundwater within the alluvial sediments along discrete discontinuities

**FIG 10** – Tunnel boring machine rock face view during geological mapping.

**FIG 11** – Tunnel boring machine contact forces and block size.
which connected with the TBM. The drawdown began as the TBM excavated to a 60° zone of influence from the edge of the alluvial channel. Once inflow began the piezometers identified a steady drop in groundwater level. Inflow within the fractured and sheared rock mass within the NFZ was relatively constant and very high (150–300 l/min). The inflow was sealed following segmental lining of the TBM tunnels, and therefore high inflows were also encountered during cross passage excavation. The high inflow and presence of mineral deposition (calcite, manganese and iron) has resulted in the cross passages within the NFZ to be fissure grouted.

Tunnel stability around persistent shear zones during excavation was important as the double-shield hard rock TBM required an initial stand-up time of the rock prior to installation of the precast concrete segments. In the TBM tunnels when the initial shear zones were encountered beneath Toowong Cemetery, the rock initially would break away from the intact rock mass at the tunnel face immediately before a shear zone along an adjacent crushed seam or within a sheared seam in the shear zone, similar to Barton’s model within heavily fractures rock shown in Figure 12 (Barton, 2000). The collapse would at times extend 1–2 m outside the design profile in the crown for a small section of the tunnel with the remainder of the shear zone remaining intact after the initial collapse and tunnelling would progress through the shear without delay to ensure the ‘heavy’ segments were placed and the overbreak grouted. The geological mapping of these areas through the cutheading ports and buckets developed a model of discontinuity dip and orientation and the shear properties as described earlier.

CONCLUSIONS

The Legacy Way Tunnel is unique in Brisbane as a large-scale underground excavation through the Bunya Phyllite and its unconformable contact with the Neranleigh Fernvale Beds. The tunnel provided the detailed observation that the Bunya Phyllite along its eastern limb shows a steepening foliation as part of the Indooroopilly Anticline and multiple shear zones developed during regional deformation, which are consistent with the lineations identifiable through API. We believe that the contact between the Bunya Phyllite with the Neranleigh Fernvale Beds is unconformable and is followed by a series of shear zones making up the NFZ, which in the present day appears similar to a strike-slip pop-up duplex in the Red Hill area, with multiple discreet faults. The greenstone is situated within the series of faults and therefore is considered part of the Neranleigh Fernvale Beds. Beyond the Red Hill area it is likely the Normanby Fault returns to a thrust fault in nature as detailed in previous Brisbane geological papers.

Bunya Phyllite has been identified medium to high strength from point load and UCS testing with a correlation factor of 8, while inflow and permeability results identifies the majority of the rock as tight with flush inflows in the order of 5–25 L/s for a 24 m section of tunnel. Groundwater inflow was encountered during TBM excavation prior to shear zones and within a 60° zone of influence of the Rosalie alluvial channel. Inflow at the NFZ; however, continued after TBM excavation during cross passage excavation and lining.

Assessment of API early excavation works within the Bunya Phyllite and TBM excavation data was utilised for provide ongoing geological assessment of upcoming geology for forward prediction during tunnelling. Assessment of the tunnel face was important in developing support requirements for cross passages prior to breakout of the segments, also utilising TBM contact forces and block sizes to provide excavation predictions for the cross-passages.

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