The effects of ground conditions on TBM performance in tunnel excavation - A case history
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ABSTRACT

This paper reviews the effects of ground conditions encountered in the S1 Sewer Tunnel excavation in Brisbane. The tunnel was excavated through a complex geological sequence consisting of metasedimentary rocks, tuff and fluvial breccia with intervening unconformities, and some deeply weathered, altered and faulted zones. A 3 m diameter hard rock tunnel boring machine (TBM) was used in the excavation.

Analysis of tunnel machine performance in relation to geological conditions encountered revealed that the performance of the TBM was highly dependent on the geology that it traversed. Rock mass weathering, strength, geological structures and the frequency of these occurrences appeared to have had an impact on machine downtime and on both instantaneous and average advance rates. Rock mass classification (using the Q system) quantified the extent of deterioration due to weathering. This was reflected in Q parameters mapped in the tunnel, especially in RQD, Jn, Jr and Ja values. Tunnelling conditions and TBM performance were sensitive to the effects of increased degrees of weathering.

Various geological conditions encountered along the hard rock tunnel were compared with the mechanised tunnelling difficulties (or otherwise) and this information was then related to TBM performance.

1 INTRODUCTION

The S1 Main Sewer Augmentation project involved the construction of a new sewer tunnel from the Brisbane Central Business District to Hamilton, north of the city (Figure 1). It involved the construction of a 4.6 km tunnel, two cross connection tunnels and seven shafts. The main entry/exit to the tunnel was via a 20 m deep large diameter shaft located at Perry Park. About 3.6 km of the main tunnel was excavated through hard rock using a hard rock tunnel boring machine (TBM), and the rest in soft ground was excavated using an earth pressure balance TBM. The 3.0 m diameter tunnel was concrete lined to a finished diameter of 2.4m. This was the first TBM tunnel constructed in Brisbane.

A Robbins double shield TBM was used for the excavation of the hard rock tunnel. It had a maximum thrust capacity of 22.7 kn/cutter, with a total installed power of 520 kW. The cutterhead was dressed with 21 cutter discs of 482mm diameter. Muck disposal was via a continuous conveyor system. Temporary tunnel support consisted of friction bolts, mesh and steel sets.

In this paper, the geology and various ground conditions that were encountered during tunnel excavation and its effect on the TBM performance in hard rock section are presented. The ground conditions were systematically mapped in the tunnel. References to locations along the tunnel route were made either based on chainages from the Perry Park Shaft or to the nearest road/intersections on the surface.

2 GEOLOGY

2.1 General Geology

The hard rock tunnel was excavated through weakly metamorphosed sedimentary rocks of the Neranleigh Fernvale Beds (NFB) of late Devonian to early Carboniferous age, and the Brisbane Tuff (BT) of Late Triassic age. NFB rocks consisted of meta-argillite, chert, greywacke and intermediate and basic volcanics. The BT consisted of mainly stratified to massive, rhyolitic ignimbrite. This ignimbrite was deposited on a palaeo landscape developed on NFB and Bunya Phyllite bedrock (Cranfield et al., 1976).

2.2 Tunnel Geology
Preconstruction information on the geology, geotechnical and planning aspects of the S1 Tunnel is outlined in publications by Mobbs (1996) and Stewart & Waters (1996).

During tunnelling, predominantly phyllite, quartz arenite, arenite, argillite and minor basalt of NFB were encountered. BT was encountered at two locations along the tunnel. Fluvial breccia (approximately 50m tract, interbedded with mudstone) was encountered in the unconformity zone between the BT and the NFB at Barry Parade.

The NFB can be divided into two general sections based on the degree of deformation identified in the tunnel. From Perry Park to School Street, the NFB was highly deformed as a result of faulting and shearing. From Perry Park to North Quay the deformation was far less (except at the vicinity of the North Quay Shaft). These two sections were separated by a 25 m wide deeply weathered (HW-CW) fault zone (referred as the School Street Fault zone hereafter) striking in a north-westerly direction bounded by a 25m wide zone of graphitic phyllite on north. From Perry Park to School St, the NFB was frequently faulted and sheared with 9-13 m wide fault zones containing fault gouge and breccia. The foliation dip angle varied from as low as 15° around Perry Park to 35° at the School St Fault zone. The foliation was often crenulated and marked by quartz segregation bands. North of the School St Fault zone the foliation was steeper (dipping up to 70°) and there was no crenulation.

The deformation had resulted in a vast difference in the rock mass properties (weathering, degree of fracturing, strength, discontinuity properties) between these two sections.

The BT at the first section (Ch695-780), was predominantly SW-MW, and fractured with at least 3 joint sets. In the second section (Ch1030-1870), it was mostly fresh to SW with clusters of open vertical joints. Depositional stratification (bedding) was not common. Two fault zones (altered to clay, 10 and 15 m wide) were encountered in the tuff. The unconformities between BT and NFB were sharp but highly variable.

2.3 Ground Water

Most of the ground water ingress was in the form of minor seepages which decreased rapidly with time. Seepages occurred mostly below spring line as an old sewer tunnel parallel to the S1 Tunnel had already lowered the local ground water table. Immediate water ingress was less than 0.05 l/s. The most significant water ingress occurred in BT at Ch1710, from a 1.5m deep bolt hole at a rate of 1l/s. This decayed to a trickle over a period of 4 months. Only minor seepages occurred at NFB-BT unconformities. At completion, water flowing from tunnel was approximately 0.5 l/s.

3 EFFECT OF GROUND CONDITIONS ON TBM TUNNELLING

3.1 Weathering

The weathering in S1 Tunnel was identified following the ISRM (1981) method. Where more than a single grade was identified in a zone, a range of weathering grades was applied based on predominant grades. The average rock mass properties (Q parameters i.e., RQD, Jn, Jr and Ja) identified in each zone is presented in Figure 2a and 2b for NFB and BT respectively.

From the results, it was obvious that the RQD was reduced, and joint number (Jn) and joint alteration (Ja) increased (non linearly) with increased weathering. The joint roughness (Jr) decreased linearly. This was apparent in both NFB and BT. The decrease in RQD was drastic from...
The deteriorating rock mass conditions with weathering in S1 Sewer Tunnel resulted in various tunnelling problems. The effects of weathering on TBM performance in the S1 Sewer Tunnel is demonstrated using results from weathered and fresh sections from NFB (Table 1).

In weathered weaker rock, the thrust was reduced to avoid bogging of the cutterhead. Although the instantaneous (specific) penetration rate was 100% higher than the fresh rock, the production rate was much lower.

The poor production rate in weathered sections was as a result of downtime due to various causes such as increased ground support, mucking difficulties (eg. frequent electrical tripping as a result of added power requirements), repeated weak sections and difficulty in controlling the TBM. This is illustrated in Figure 3 (also refer to Figure 4 for rock mass and tunnelling condition variation along the tunnel).

### Table 1. Comparison of TBM performance in weathered and fresh sections in NFB

<table>
<thead>
<tr>
<th>Weathering</th>
<th>Weathered</th>
<th>Fresh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chainage (m)</td>
<td>120-480</td>
<td>2425-2800</td>
</tr>
<tr>
<td>Schmidt Rebound Number, N &amp; Is50 (MPa)</td>
<td>43.9 &amp; 0.97</td>
<td>49.8 &amp; 3.60</td>
</tr>
<tr>
<td>Average cutting time/stroke, (minutes)</td>
<td>11.3</td>
<td>13.4</td>
</tr>
<tr>
<td>Average Penetration per revolution, (mm/rev)</td>
<td>5.61</td>
<td>5.02</td>
</tr>
<tr>
<td>Average Normal Force per cutter Fn, (kN)</td>
<td>77.4</td>
<td>124.4</td>
</tr>
<tr>
<td>Average Specific Penetration Rate, Ps(Prev/Fn)</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Average production per shift, (m)</td>
<td>12</td>
<td>19</td>
</tr>
</tbody>
</table>

#### 3.2 Other conditions

Unconformities, faults, blocky ground and an unexpected hydrocarbon contaminant inflow into the S1 Tunnel also resulted in downtime. The conditions encountered at various tunnel sections are summarised in Table 2.

The width of unconformity along tunnel varied from 0.5 to 30m. Often there was a 0.5 m thick soft to firm carbonaceous clay in between the NFB and the BT. The geometry of these unconformities was highly variable. Major downtimes at the unconformities were due to TBM steering difficulties, ground support, mucking and blockage of cutterhead & buckets.

In fault zones, breccia and soft fault gouge, together with weaker materials which formed as a result of deep penetrative weathering into the adjacent wall rock and chemical alteration (in BT) resulted in similar tunnelling problems as above. Blocky ground was experienced in the BT intermittently, resulting in the frequent slowing down and stopping of the TBM. The Q parameters compared in the blocky and non blocky ground identify distinctively the rock mass conditions encountered in both these conditions (Table 3).
The tunnel). Illustrated in Figure 3 (also refer to Figure 4 for added power requirements), repeated weak sections and difficulty in controlling the TBM. This resulted in similar tunnelling ground support, mucking and blockage was highly variable. Major downtimes at the unconformities were due to TBM steering difficulties, to firm carbonaceous clay in between the NFB.

The deteriorating rock mass conditions with weathering along the S1 Tunnel were captured in Q. (Barton 1974), the effects of weathering on TBM performance in the S1 Sewer Tunnel is higher than the fresh rock, the production rate (e.g., frequent electrical.

The low overall TBM utilisation was generally poorer advance rates and changes in rock mass conditions on advance rate can directly be read from the plot. For example, tunnelling advance rates of 30-40 m per shift were achieved in sections where the rock mass was predominantly fresh, stronger least deformed and where Q>1. Frequent changes in rock mass conditions resulted in poorer advance rates.

4 TBM PERFORMANCE

The data gathered from the tunnel and delays recorded from shift reports are shown in Figure 4. This includes the geology traversed by the TBM, weathering, Q-values, shift advance rates, downtimes such as electrical, mechanical, conveyor, and rock strength. The influence of the ground conditions on advance rate can directly be read from the plot. For example, tunnelling advance rates of 30-40 m per shift were achieved in sections where the rock mass was predominantly fresh, stronger least deformed and where Q>1. Frequent changes in rock mass conditions resulted in poorer advance rates.

4.1 TBM utilisation

The overall TBM utilisation for S1 Tunnel was 32%. The low overall TBM utilisation was generally related to geotechnical and non-geotechnical factors. Downtime related to geotechnical factors were installation of ground support (11%), cleaning of TBM buckets and cutterhead (3%), conveyor...
Figure 4. Ground conditions as encountered (weathering, Q & strength) and its effect on tunnelling performance (advance & downtime).

- Fig 4a. Long section showing weathering along tunnel
- Fig 4b. Q value as mapped in tunnel
- Fig 4c. Schmidt Hammer (L-Type) rebound number tested along tunnel wall
- Fig 4d. Shift advance rate (m/shift)
- Fig 4e. Conveyor downtime due to mechanical, electrical and geotechnical issues
- Fig 4f. Downtime - cutterhead/bucket blockage/cleaning
downtime (14% including geotechnical related and removing of rocks off the TBM conveyor) and guiding of the TBM and survey (5%). Downtime due to TBM mucking occurred in poor ground conditions where Q was generally < 1. Fines generated from weak zones resulted in substantial conveyor downtime. The mucking system had to be frequently cleaned and more power had to be utilised to continue running the mucking system. The higher power demand resulted in frequent electrical trips (Figure 4e).

Unexpected hydrocarbon contamination (7%), mechanical & electrical (9%), booster breakdown (2%) and, industrial disputes and other (17%) were among the non-geotechnical related factors that contributed to a significant downtime. Overall, the weekly utilisation of the TBM varied from 0 to 55%.

4.2 Tunnelling rates

The TBM penetration rate (PR) ranged from 2.55 m/h to 4.28 m/h in the various geological domains identified in tunnel with an average rate of 3.42 m/h. The advance rate (AR) ranged from 0.14-0.98m/h with an average of 0.91m/h.

The advance rates were highly dependent on the ground conditions traversed by the TBM (Figure 4c). Overall, ground conditions improved markedly from the School St Fault to North Quay. It was along this tract of the tunnel that the highest rates of advance up to 65m were achieved. The average daily advance rate was 14 m. When the weighted Q was around 30, the shift advance rate approached 20 m.

5 CONCLUSIONS

The Brisbane geology is complex and varied. Some of the difficulties encountered during the tunnelling of S1 were due to this geological complexity. Observations, tunnel mapping and data analyses showed that the TBM performance was significantly influenced by the ground conditions encountered along the tunnel route. Rock mass weathering appeared to have had dominant influence in this particular TBM tunnel excavation. The changing quality of the rock mass due to weathering was captured in the Q parameters i.e. RQD, Jn, Jr and Ja. Q parameters reflect tunnelling conditions and therefore can be used to predict TBM performance.

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REFERENCES


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