A Comparison of EPB and Slurry TBMs Operating in Mixed Ground Conditions Resulting from Tropical Weathering of Rock

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ABSTRACT: Deep, but uneven, weathering of rock is common in tropical and sub-tropical areas. Infrastructure development in many Asian cities has required tunnelling through weathered rock profiles. The ground conditions for the tunnelling typically include saprolite, rock, and mixed faces of soil and rock. Where the rock is strong, and mixed ground is anticipated to be encountered over a significant proportion of the drive, slurry TBMs are typically specified in Singapore, based on local experience. Case studies of slurry and EPB tunnelling in mixed ground conditions, from Hong Kong, are presented, and compared, to illustrate the issues involved**.** For the EPB drive, there were very large increases in the Penetration Index and Specific Energy when working in pressurised EPB mode in ground conditions comprising >50% strong or stronger rock. In these ground conditions the rate of disc cutter replacement was significantly higher than when tunnelling in open mode in a full face of rock, on the same drive. Average progress rates fell to less than 3m per week in the most extreme conditions of 85% to 99% rock, with most of the time being spent on interventions, including a significant proportion of time required to cool the excavation chamber. It is postulated that these observations are related to the clogging of the cut chips of rock in the tool gap, ahead of the cutterhead, when the cut rock becomes the majority of the spoil. A slurry shield in comparable conditions in Hong Kong did not experience the spikes in Penetration Index, Specific Energy, or cutter wear, in mixed ground conditions, that were experienced during the EPB drive.

KEYWORDS: Weathering, Tunnel, TBM, EPB, Slurry

1. INTRODUCTION

Rapid urbanisation around the world has led to a massive increase in the demand for tunnels, as part of city infrastructure. Primary uses for tunnels in urban areas include: transportation (subways, railways and roads), utilities (water, sewerage, gas, and electricity) and storage caverns. Many of the rapidly developing cities are in tropical and sub-tropical regions. Examples include: Hong Kong, Singapore, Taipei, Guangzhou, Shenzhen, Bangalore and Sao Paulo. One of the differences between cities in tropical and sub-tropical area and those in temperate regions is the potential for deep weathering of rock. The weathering progressively weakens the rock, ultimately turning it into soil. There are specific issues associated with tunnelling in weathered rocks. In tropical and sub-tropical regions, the weathering often penetrates to a depth of 30m or more below ground surface level, but the rockhead profile is commonly highly variable in depth. Relic, corestone, boulders may be present above rockhead. The variable depth to rockhead and nature of the ground results in the potential to encounter mixed ground conditions during tunnelling at the typical depth required for infrastructure projects. The saprolitic soils derived from the weathering retain some relic structure of the original rock. The nature of the soils is also strongly affected by the particular processes involved in the weathering. Saprolitic soils can range from mainly granular materials that are potentially flowing ground, when encountered below the groundwater table, to collapsible soil to sticky clays.

2. GEOLOGY

2.1 General

Almost all rocks will weather, particularly in hot, wet tropical climates. The depth and nature of the weathering depends, inter alia on the nature of the parent rock, climatic conditions and topography. This paper will focus on experience in Hong Kong and Singapore, although reference will be made to some other experience. Information on tunnelling in weathered rock in Hong Kong and Singapore can be found in Shirlaw et al. (2000). Much of the information contained here post-dates that paper, but the earlier paper provides a reference for the general conditions and some of the historical experience in these conditions.

2.2 Classification

There are a variety of classification systems for weathering. Shirlaw et al. (2000) outline a classification system used in Hong Kong and subsequently adopted in Singapore (CP4 : 2003). References used here will be to that system.

2.3 Particular issues for tunnelling

Shirlaw et al (2000) listed a number of potential issues for tunnelling in weathered rock, including:

- Mixed face conditions, with rock and soil grades present in the face
- Abrasivity
- Instability/erodibility of the soil grades, when encountered below the water table
- Karstic conditions (Limestone and marble)
- Swelling clay
- Collapsible soils

An example of an exposed rockhead profile in weathered Singapore granite is shown in Figure 1; corestone boulders, also from the Singapore granite, are shown in Figure 2.

Figure 1 A rock head profile in weathered Singapore granite

In the Singapore granite, Zhao et al. (1995) record a depth of weathering of between a few metres to 70m. Also in Singapore, Zhao et al. (1999) record a depth of weathering in the meta-sedimentary rocks of up to 50m. In both cases the reference is to the depth of soil grades overlying the rock grades. In Hong Kong, Fletcher (2004) gives an example of rockhead in granodiorite that was over 100m below ground surface level.

Typically, it is the zone up to 40m below ground level that is most intensively used for utility and urban transport tunnels. However, with the increasing use of underground space, tunnelling is now required at greater depths to avoid the existing infrastructure.

In tropical and sub-tropical climates, the variability of the depth to rockhead and the nature of the ground, result in a high risk of encountering mixed ground conditions at the depth typical for tunnelling for infrastructure development.

Figure 2 Granite boulders at Gali Bukit depot, Singapore

Some general ranges for the geotechnical parameters of saprolites in Hong Kong and Singapore are provided in Shirlaw et al. (2000). Many of the saprolites have in-situ permeability in the range 10^{-5}m/s to 10^{-7}m/s. At the upper end of the range, the soils will behave as flowing ground if exposed below the water table. Prior to the introduction of Pressurised Tunnel Boring Machines (PTBMs), much of the tunnelling was carried out under compressed air.

3. TUNNELLING METHODS

3.1 General

Prior to the development of pressurised tunnel boring machines, tunnelling in mixed, weathered rock was typically by open face shield or sprayed concrete lining methods. Conventional mining methods, using timber and/or steel sets were also applied locally. Potentially flowing soil grades of weathered rock were stabilised by the application of compressed air, dewatering or chemical grouting.

Over the last thirty years, PTBMs have become a method of choice for tunnelling in weathered rock. Pressurised TBMs can be divided into three major categories:

1. Earth Pressure Balance machines (EPB), where the pressure is applied to the face by a spoil comprising a conditioned mass of the recently cut ground
2. Slurry TBMs, where the pressure is applied to the face through the medium of a bentonite slurry
3. Mixed mode PTBMs, which can be switched from EPB to slurry and vice-verse. This type of TBM includes the recently developed Variable Density TBM, which also has the capability of working with slurries of variable density

In weathered rock the TBMs are typically provided with a mixed ground cutterhead, equipped with both discs (for cutting rock, and scrapers (for cutting soil). A typical example is shown in Figure 3, from a slurry TBM in Hong Kong.

Figure 3 Typical mixed ground cutterhead used for a slurry TBM in Hong Kong

3.2 Experience from Singapore

The number of PTBMs used over the last 30 years and the wide variety of ground conditions have made Singapore a showcase for the use of PTBMs, particularly for their use in weathered rock.

The first Earth Pressure Balance Machine (EPB) used in Singapore was a 3.754m diameter TBM, employed to drive a 3 km long outfall pipeline from the Ulu Pandan Sewage works, between 1983 and 1985 (Balasubramanian, 1987). This was followed by two 5.910m diameter EPB TBMs used to drive the Mass Rapid Transit (MRT) tunnels between Lavender and Bugis Stations, in 1986-1987 (Elias and Mizuno, 1987). Subsequently, 14 EPB TBMs were used to drive the tunnels for the North East line (1999-2001), and 8 EPBs for the Deep Tunnel Sewer System (DTSS), between 2001 and 2005 (Marshall and Flanagan, 2007). Apart from the Ulu Pandan sewer TBM, all of these TBMs were mid-sized (4m to 9m diameter). Although a slurry TBM was first used in 1982, this machine and all subsequent slurry TBM drives up to 2005 (the commencement of tunnelling for Circle Line 3) were small diameter machines. Medium diameter slurry TBMs were not used in Singapore until the construction of parts of Circle Line 3 and 4, in 2005/6 (Nakano et al. 2007).

Table 1 A summary of the major projects involving medium sized PTBMs in Singapore

Major Projects		**PTBMs: Numbers used**	
Name	Tunnelling completed	EPB	Slurry
East-West Line	1987	2	None
North East Line (NEL)	2001	14	None
Deep Sewer Tunnels	2005	8	None
Circle line (CCL)	2009	19	8
Downtown Line (DTL)	2014	42	9
Deep Cable Tunnels	Tunnelling complete (2017)	3	11
Thomson-East Coast Line (TSL)	Under construction (2017)	28	23
	Total	116	51

A summary of the medium diameter PTBMs used for completed and current major projects in Singapore is provided in Table 1. Table 1 is not comprehensive, as a number of smaller projects, each requiring from one to five medium diameter PTBMs, have been omitted.

Table 1 shows a trend, with a change from all EPB TBMs before 2005, to increasing use of slurry TBMs since 2005. This trend is not simply related to time, but also geology. The majority of the tunnelling summarized in Table 1 was in weathered rock, but also included excavation in a variety of deposited soils. The rock types excavated ranged from the very strong Singapore granite to weak mudstone of the Jurong Formation. Generally slurry shields have been adopted where:

1. The tunnelling is largely or wholly in the Singapore granite, with multiple rock/soil interfaces, or
2. The tunnelling is deep, 45m or more below the groundwater table

EPB TBMs have generally been adopted where neither of these conditions apply. Where EPB TBMs have been used in mixed faces of rock and soil grades of weathered granite, the problems experienced have included:

- On early EPB drives in these conditions, conventional EPB face pressure could not be maintained consistently; as a result there were several sinkholes, Shirlaw et al. (2000).
- For some of the mixed face tunnelling, the TBM could only be operated in 'semi-EPB' mode, using compressed air above tunnel axis level (GEO 2014); semi-EPB mode is called 'transitional mode' in Anon (2016)
- Frequent damage to cutting tools (Figures 4 and 5), and interventions to replace the tools
- A new, and significantly redesigned, cutterhead for one TBM, installed during the tunnel drive by sinking a special shaft
- Major wear of a screw conveyor, requiring replacement during the tunnel drive (Figure 6)
- A number of sinkholes (Shirlaw & Boone, 2005); an example is shown in Figure 7
- High heat generated during some TBM advances; the heat, recorded locally at 60 to 80^{O}C, had an adverse effect on the time required for interventions, as the excavation chamber had to be cooled before access. The heat probably contributed to tool damage, due to the effect on the bearings of the disc cutters
- Serious delays to the tunnelling schedule; for one of the DTSS drives, mainly in weathered granite, Wallis (2004) records that the actual production rate averaged about one third of that planned

Figure 4 Damaged and abraded disc cutter, EPB TBM working in weathered Singapore granite

Figure 5 Damaged and abraded disc cutter, EPB TBM working in weathered Singapore granite

Figure 6 Badly abraded screw conveyor, DTSS, section in weathered granite

Figure 7 Sinkhole over an EPB working in mixed soil and rock grades of weathered Singapore granite

The slurry TBM tunnelling in Singapore in the weathered granite has not been without incident, as discussed Merrie (2009). In particular, there was:

- Frequent damage to cutting tools (Figure 8), and interventions to replace the tools

- Major modifications to a TBM that was part way through a drive, as discussed in Shirlaw and Hulme (2008)
- Several sinkholes (see Figures 9 and 10 for examples); these were mainly associated with interventions of long duration and/or multiple interventions over a short length of tunnelling, which typically occurred in mixed face conditions including Very Strong rock
- Delay to the overall tunnelling schedule

Figure 8 Damaged and abraded disc cutter, slurry TBM working in weathered Singapore granite

Figure 9 Sinkhole over a slurry TBM working in a mixed face of soil and rock grades of weathered Singapore granite

Excess heat has not been a problem for slurry shield tunnelling. The slurry circuit constantly supplies slurry, which will conduct any excess heat away from the excavation chamber.

Both EPB and slurry TBMs have encountered problems when excavating in a mixed face of soil and strong to very strong rock. Some of these problems have been overcome by improved design of the TBMs, improved choice of conditioning agents and cutting tools, and the experience gained in how to best manage the TBMs. Both types of TBM have completed a number of drives in mixed ground conditions. However, it is evident from Table 1 that despite the local problems with slurry TBM tunnelling in mixed ground conditions, there is still a strong preference for the use of slurry machines, rather than EPB TBMs, for tunnelling in the granite.

Figure 10 Sinkhole over a slurry TBM working in a mixed face of soil and rock grades of weathered Singapore granite

Over the last 15 years there have been significant improvements in both EPB and slurry TBMs, and in their operation, in relation to excavating in weathered rock. Merrie (2009) provides recommendations for improving slurry TBMs for these conditions. The Land Transport Authority of Singapore (LTA), in addition to indicating the type of TBM to be used for a project, provide specifications for EPB and slurry TBMs that set minimum standards, as part of the contract documents.

3.3 Other related experience

Similar issues, in relation to tunnelling through mixed face conditions resulting from deep weathering have been encountered in many cities over the last 30 years. Examples include: Bangalore, Kuala Lumpur, Sao Paulo and Hong Kong.

The tunnelling for the Bangalore Metro was largely in weathered granitic gneiss, which was very to extremely strong when fresh. Two lines were constructed, the NS and EW lines, with the tunnelling for the NS line planned to be by EPB TBM and the EW Line by slurry TBM. On the NS Line, one EPB drive, just 432m in length, required 22 months to complete, or an average rate of 4.53m per week; the parallel EPB drive took 12 months, at an average rate of 8.3m/week (Kenyon, 2016), Overall, the slurry TBMs for the EW (purple) Line took 34 months to complete the tunnelling; the EPB TBMs for the NS (green) Line required 48 months to complete what was originally a comparable length of tunnelling (Wallis, 2014, Wallis, 2016); in fact one of the slurry TBMs from the EW Line was reused on the NS line to reduce the delay to the EPB tunnelling. There was thus a marked contrast in the performance of the EPB TBMs with that of the slurry TBMs in the very difficult mixed ground conditions. A discussion on the basis of the choice of EPB or slurry TBMs for the EW (purple) line is provided in Moncrieff (2016).

In Kuala Lumpur, tunnelling for the MRT Line 1 has been through two main rock formations: the Kuala Lumpur Limestone and the Kenny Hill Formation, both formations being strongly affected by weathering. Ten pressurized TBMs have been used. For the relatively weak, sedimentary rocks and saprolites of the Kenny Hill formation, four EPB TBMs have been used (Kenyan, 2012). In the limestone, which is characterized by large karstic cavities, six Variable Density TBMs have been used. The Variable Density TBMs were specially developed for use in Kuala Lumpur, following experience with slurry TBMs during the construction of the SMART tunnel (Wallis and Kenyon, 2014); the tunnelling for the Kuala Lumpur MRT was the first use of Variable Density TBMs anywhere.

In Sao Paulo, as reported by de Oliveira and Diederichs (2016), an EPB TBM operated in a mixed face of crystalline rock and saprolite, for a tunnel on Line 5. In these ground conditions control of the face pressure was problematic, and there were major ground losses and sinkholes.

In Hong Kong, both slurry and EPB TBMs have been used for recent projects, such as the Express Rail link and the Shatin to Central line. However, the large diameter TBMs for the Tuen Mun to Chek Lap Kok tunnels are slurry TBMs (Robin, 2016); these tunnels are under relatively high water pressure. A Variable Density TBM has also been used for one section of the Shatin to Central line. The reason for using the Variable Density TBM was the need to tunnel with limited cover through variable fill and mixed ground (Reynolds, 2017). A detailed comparison is made, below, between the experience of slurry and EPB tunnelling in mixed ground of weathered rock in Hong Kong. The two case studies were in similar mixed ground conditions, resulting from the topical weathering of strong (or stronger) rock. The tunnels were driven within the last five years, using new TBMs that were designed for the respective projects and the anticipated ground conditions.

Overall, it can be seen that both EPB and slurry TBMs have been used for tunnelling in mixed face conditions resulting from tropical weathering; recently, Variable Density TBMs have been used for particular conditions, such as karstic limestone. The experience from Singapore and Bangalore suggests that slurry TBMs may have an advantage over EPB TBMs on drives where the tunnelling is frequently in mixed faces that include strong or stronger rock. However, the evidence presented above is largely qualitative, and does not show why slurry TBMs may be preferable in these conditions. Two case studies from tunnelling in Hong Kong are presented, below, in order to provide a quantitative assessment between slurry and EPB TBMs working in comparable conditions

4. COMPARISON OF TWO PTBM DRIVES IN HONG KONG

4.1 Ground conditions

Before assessing the interaction of the TBM and the ground, it is necessary to establish the actual ground conditions encountered during tunnelling. In weathered rock, boreholes alone are a poor indicator of rockhead, as shown in Fletcher (2004), Merrie (2009) and Shirlaw (2015). Predictions of the ground conditions made prior to tunnelling may be seriously in error. For the two case studies of EPB and slurry tunnelling, the actual ground conditions were established from all of the information available after the tunnelling was complete, as discussed below.

4.2 Assessing the actual ground conditions encountered during tunnelling

Weathered bedrock profiles are highly erratic, even over short distances. Occasional, offline boreholes can result in an inaccurate prediction of the actual rockhead profile (Shirlaw, 2015). Above the rockhead, corestone boulders have a major effect on tunnelling, but are notoriously difficult to identify on the basis of borehole data. Once the tunnel is driven, a significant amount of additional data is available to identify the ground conditions encountered. The information includes:

1. The original pre-construction boreholes and any additional boreholes drilled during tunnelling.
2. Face mapping; for PTBMs this can only be carried out during interventions into the excavation chamber
3. The TBM data, such as torque, thrust and rate of advance
4. Information from probing from the TBM, although this is rarely carried out during PTBM tunnelling
5. The nature of the excavated material

These are discussed further, below.

4.2.1 Borehole data

Boreholes provide a high degree of accuracy in terms of establishing the ground conditions at a particular location, particularly when double or triple tube core barrels are used to provide a continuous core through the rock encountered. However, boreholes are commonly located some distance from the tunnel alignment. Boreholes directly in the tunnel profile potentially create a path for slurry, compressed air or foam to reach the surface, if not securely grouted. For this reason boreholes are typically located slightly off the tunnel alignment. In urban areas, the presence of buildings, utilities and property boundaries often severely restricts where boreholes can be located, and it may be necessary to locate them some distance from the tunnel alignment.

4.2.2 Face mapping

It is standard practice to prepare a record of the face conditions during an intervention. This is normally the only time during pressurized TBM tunnelling that the face can be inspected directly. However, there are some limitations in the quality and nature of the data that can be obtained, including:

a) The face is visible only through the openings in the cutterhead. For a modern, mixed ground cutterhead, these openings typically comprise only 25% to 35% of the area of the cutterhead
b) Most interventions are 'half face' interventions, with the muck in the chamber only drawn down to axis level. If the rockhead is below this level, it will not be identified
c) It is common practice to form a filter cake on the exposed face, which may obscure the ground conditions; however, the filter cake will not form on massive rock
d) Unless the tunnelling team includes a geologist or engineering geologist who is fit and trained for work in compressed air, the quality of the mapping may be limited by the training of the personnel preparing the face map

Despite these limitations, the face mapping records are generally the most direct and most accurate record of the ground conditions encountered. However, these records can only be obtained at intervention locations, and provide only local 'snapshots' of the geological conditions encountered.

4.2.3 TBM data

The data captured during driving the TBM provides continuous evidence of the geological conditions along the tunnel drive. Numerous parameters are measured during TBM tunnelling. Three parameters that are affected by ground conditions are: contact force on the cutterhead, the torque required to turn the cutterhead and the advance rate, expressed either as mm /cutterhead revolution or as mm / minute. Two functions that combine some of these parameters, and that have been found useful for assessing tunnelling in weathered rock, are Penetration Index and Specific Energy. The derivation of these parameters is summarized below.

Penetration Index

The Penetration Index (PInd) can be calculated from:

$$PInd = CF/PRev \quad (1)$$

where:
PRev is the penetration rate in metres per revolution
CF is the average normal force on a disc cutter in MN

Specific Energy

The Specific Energy (SE) can be calculated from:

$SE = [(Fn.P) + (2.\pi.N.T)] / A.P \quad MNm/m^3 \text{ (or } MJoules/m^3)$ (2)

Where:
Fn is the normal contact force on the cutterhead, in MN
P is the penetration rate in metres/minute
N is the rotation speed in revolutions per minute
T is the Torque in MNm
A is the cross sectional area of the TBM in m^2

Although the Specific Energy includes terms that are based on contact force and torque, it is the latter that is generally dominant. Whereas the Specific Energy is related to the amount of torque required to drive the TBM at a given rate of advance, the Penetration Index is related to the average force applied to the disc cutters, for a given rate of advance. The Specific Energy is of particular interest when tunnelling in soil or weak rock, whereas Penetration Index is mainly useful when tunnelling in Strong or stronger rock; both are of interest in mixed ground conditions.

Some recent TBMs, such as those used for the Tuen Mun to Chek Lap Kok tunnels in Hong Kong, have been equipped with the means to monitor the load on each disc cutter. The information from this system can be used to establish a continuous interpretation of the proportion of rock in the face. However, this system was not used on either of the tunnels given as case studies here.

4.2.4 Probing

Typically, medium and large sized PTBMs are equipped with ports that allow probing ahead of the TBM. A full fan of peripheral grout ports typically allows drilling (and, if necessary, grouting) outside the tunnel extrados; these ports are placed just behind the pressure bulkhead. There are also usually a limited number of ports that allow drilling through the pressure bulkhead, directly ahead of the TBM; probing can only be accomplished when an opening in the cutterhead is aligned with the port in the bulkhead.

In practice, tunnel managers are invariably resistant to probing from PTBMs; the author has never experienced probing through the bulkhead, and only very rarely from the peripheral ports. A major concern with probing though the bulkhead is the risk of breaking the drill string, leaving steel ahead of the TBM and, potentially, skewering the cutterhead.

4.2.4 The nature of the excavated material

The nature of the excavated material may provide some information on the ground conditions. The value of the excavated material, as a basis for assessing the face conditions, is limited by a number of factors, including:

- Grinding and reworking of the material during cutting and then during the transport of the material from the tool gap, into the excavation chamber, through the rock crusher (in slurry TBMs) and then passage through the screw conveyor (EPB TBMs) or along the discharge pipe and through the slurry treatment plant (slurry TBMs).
- Time delay between excavation and discharge at the surface
- Addition of conditioning materials

These factors significantly limit the information on the geology of the tunnel drive that can be obtained from the excavated materials. Pieces of rock on the conveyor belt (for an EPB machine) or separated on the shakers (for a slurry machine) show that the TBM has encountered some rock, but it is generally not possible to tell the proportion of rock in the face with any degree of accuracy.

4.2.6 Summary, assessment of ground conditions after tunnelling

All of the sources of information listed above can provide information on the ground conditions that the tunnel has encountered. In weathered rock conditions, it has been found that the quality of the data can be ranked as follows, with the highest quality ranked as 1:

1. Face logs from interventions
2. Borehole data within 0.5 tunnel diameter from the tunnel extrados
3. TBM data, where calibrated against face logs and borehole data
4. Borehole data outside 0.5 tunnel diameter from the tunnel extrados
5. Data from probe holes and the excavated spoil

4.3 Case studies

Two case studies are presented: Tunnel A (a slurry TBM drive) and Tunnel B (an EPB TBM drive), both from Hong Kong. Tunnel A was driven through weathered granite with intrusive dykes of basalt and rhyolite, while Tunnel B was driven through weathered Tuff. Only a part of each tunnel drive is presented; these portions have been selected to include saprolite (soil grades of weathered rock), mixed rock and saprolite and full face tunnelling in rock.

The TBM information for Tunnels A and B is summarized in Table 2.

Table 2 The TBMs used to drive tunnels A and B

Item	Tunnel A	Tunnel B
TBM Type	Slurry	EPB
TBM cut diameter	7.46m	9.23m
Disc size	19” (482.6mm)	17” (431.8mm)
Number of discs	44	53
Opening ratio (%)	33	33

The Uniaxial Compressive Strength (UCS) and Cherchar Abrasion Index values for the fresh and slightly weathered rock are summarised in Table 3.

Table 3 The main characteristics of the main type of rock encountered during the driving of tunnels A and B

Item	Tunnel A	Tunnel B
Main rock type	Granite	Tuff
Range of rock strength (SI)	71 to 185.9 MPa	75 to 200 MPa
Range of rock strength (TBM)	36.6 to 169.4 MPa	46.5 to 192 MPa
Median rock strength (SI)	151 MPa	140 MPa
Median Rock Strength (TBM)	131.5 MPa	118 MPa
Cherchar Abrasion Index (range)	Average 4.6	3.5 to 4.5

In Table 3, the UCS values for the rock are quoted from the Site Investigation (SI) and as derived from the TBM data (TBM). The quoted values from the site investigation are derived from the Geotechnical Baseline Report or Geotechnical Engineering Report for the project. The ‘TBM’ values were derived from the TBM parameters, using the Colorado School of Mines (CSM) method; the relevant equations are in Rostaimi et al. (1996). The values given for the ranges of strength and median strength are reasonably comparable between those derived from the SI data and from the TBM derived values. Overall, the TBM derived values are slightly lower than the interpreted SI. This is probably because of a number of factors:

1. The CSM model does not take into account the fracturing of the rock; the effects of fracturing will be seen as an apparent reduction in strength. This is because it is easier to cut highly fractured rock than massive rock, for a given UCS value. This will lead to values derived from the CSM method

underestimating the UCS values where the TBM is in highly fractured rock

2. The SI values quoted are for Fresh and Slightly weathered rock. The TBM data probably includes a significant proportion of moderately weathered rock, which would be weakened by the greater degree of weathering compared with the Fresh and Slightly weathered rock.
3. There is a bias towards selecting relatively stronger samples rock for testing in the site investigation

Despite these factors, there is a reasonable degree of comparability in the UCS data between the assessed values from the site investigation and as back-analysed from the TBM data.

4.3.1 Summary of Tunnel A – Slurry TBM in weathered granite

The driving of Tunnel A from Ring 150 to Ring 600 is summarized here. Each ring was 1.5m in length. The face pressure at tunnel axis level was between 3.35 and 4 bar, providing a small overpressure compared with the water pressure where the tunnel was in soil or mixed ground; in rock the face pressure balanced the water pressure.

The actual ground conditions encountered are summarised in Table 4.

Table 4 Actual ground conditions encountered, Tunnel A

From (Ring No)	To (Ring No)	Ground conditions
150	291	Full face of rock grades of granite, except for mixed ground between R267 and R274, and local dykes of rhyolite and basalt.
292	321	Mixed ground (rock and soil grades of weathered granite)
322	600	Soil grades of weathered granite

As shown in Table 4, from R322 to R600 the tunnelling was generally in completely decomposed granite (cdg), a saprolite. However, a number of thin dykes of basalt and rhyolite crossed the tunnel alignment. The dyke rock within the cdg was generally also completely weathered, although some evidence of basalt rock and corestone boulders was found in samples from the slurry treatment plant. It was observed at the slurry treatment plant that there were a series of bands of ground that had relatively high clay content within the cdg (clayey cdg). The clayey cdg was associated with the weathered remains of dyke rock, and may have been a result of hydrothermal alteration of the granite associated with dyke formation. When the TBM was in 'clayey cdg', it was found that there was an increase in the average fines content of the spoil, compared with the more typical, granular, cdg. Evidence of clogging was also noted during interventions, when the face was in the clayey cdg. Many of the disc cutters damaged in the clayey cdg were flat, particularly the discs mounted in the central area of the cutterhead.

The calculated values of the Penetration Index for R150 to R600 are plotted in Figure 11; those for Specific Energy are plotted in Figure 12. The values for the Penetration Index and Specific Energy were high in the bands of clayey cdg, much higher than in the more typical, granular, cdg. The values for Specific Energy recorded in the clayey cdg were generally as high, or higher, than those recorded when tunnelling in the granite rock. In contrast, the values recorded when tunnelling in the cdg between the clayey cdg bands were very much lower. The bands of clayey cdg identified from the Specific Energy during tunnelling, typically 60m to 120m in thickness, correlated with where increased fines content was recorded at the slurry treatment plant.

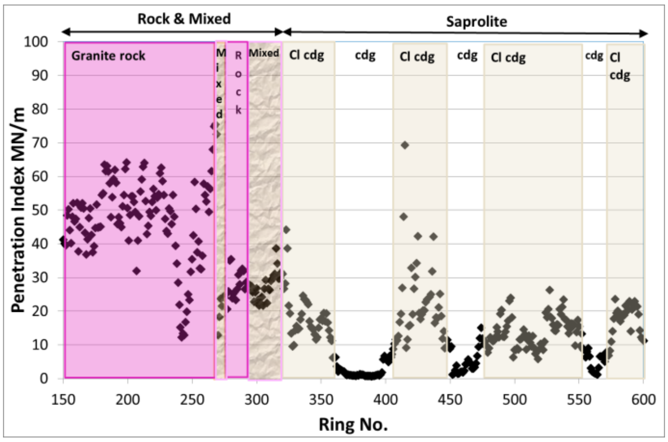

Figure 11 The Penetration Index for Tunnel A, Rings 150 to 600

Tunnelling in the mixed ground at the transition from rock to saprolite required a lower Penetration Index than tunnelling in the rock, but similar or slightly higher values for Specific Energy. The effect of the various ground conditions on the tunnelling can be assessed in relation to: average instantaneous advance rate, the frequency with which discs had to be changed, and the time required for interventions. These are summarised in Tables 5 and 6. The values given are averages over all of the rings assessed for a particular ground condition. The times given are average times per metre of tunnel constructed, and are only for advancing the TBM and interventions. These two activities comprise only part of the time required for tunnelling, but are the activities that are directly affected by the ground conditions encountered.

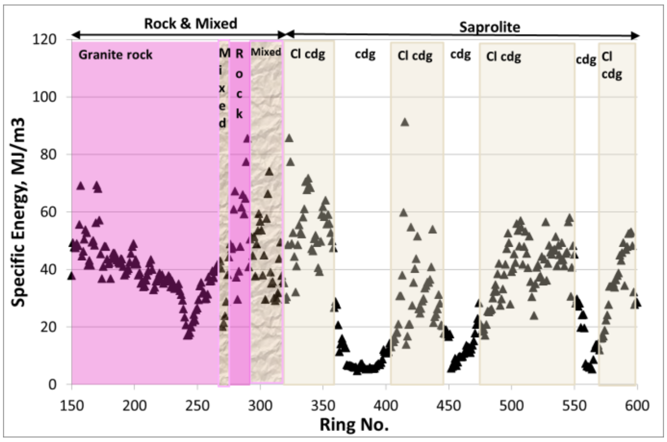

Figure 12 The Specific Energy for Tunnel A, Rings 150 to 600

The number of discs changed per cubic metre of ground excavated is presented in Table 5. In order to arrive at this figure, a simple assumption has been made that the wear of a disc is related to the ground conditions at the point where the disc is changed. This is imprecise, as the wear on the disc will be the result of the cumulative wear from the ground conditions since the disc was installed. However, over long lengths of tunnelling there will be a tendency for more discs to be changed in the more abrasive ground conditions. Over long lengths of tunnel, the value calculated in this way will provide an approximation of the relative rate of disc wear/damage per metre of tunnel in the different ground conditions. The highest rate of disc consumption was in the rock grades, but all conditions had high rates of disc consumption, showing how abrasive the saprolite derived from the weathering of granite is. Advance rates were significantly faster in the cdg than in the other three categories, where the rates were comparable.

Table 5 Effect of the actual ground conditions encountered on disc consumption and instantaneous rates of advance, Tunnel A

Ground conditions	Discs used (m^3/disc replaced)	Average Inst. rate of advance (mm/min)
100% rock	130.2	15.35
Mixed ground	191.7	15.80
Soil (Clayey cdg)	161.5	16.50
Soil (cdg)	146.5	27.00

The average time for interventions is presented in Table 6. Interventions were intermittent; to obtain this value, the total time for interventions in each category of ground was divided by the length of tunnel in that category. The time required for an intervention was calculated from the time that the TBM stopped advancing, prior to the intervention, to the time that the TBM resumed advancing. Some time for ring building or other maintenance may have overlapped with the time for the interventions.

The average time required for interventions in the clayey cdg was longer than that for normal cdg, as time was required to manually unclog the openings in the cutterhead in the sticky conditions.

The average time for interventions per metre is added to the average time required to advance 1m, to obtain a total for these two activities. Advancing the TBM and interventions are the activities during PTBM tunnelling which are directly affected by the ground conditions encountered.

Table 6 Effect of the actual ground conditions encountered on the average time required for interventions and the time for advance plus interventions, Tunnel A

Ground conditions	Average time to Advance, min/m	Av. Time for Interventions, min/m	Time for Advance plus Interventions, min/m
100% rock	65.1	54.20	119.3
Mixed ground	63.3	65.46	128.76
Soil (Clayey cdg)	60.6	45.64	106.24
Soil (cdg)	37.0	33.58	70.58

There was a reduction in the advance rate in clayey cdg, compared with the more typical granular cdg, of nearly 40%, on average. On average, there was little difference in the performance of the TBM between rock and mixed ground. The average advance rate was marginally faster in the mixed ground than the rock, but the average intervention time was longer in the mixed ground.

4.3.2 Summary of Tunnel B – EPB TBM in weathered Tuff

The tunnelling for part of the drive, from Ring 1 to Ring 600, is presented, comprising the first 1,080m of tunnelling. The tunnel lining rings were 1.8m in length. A full face of rock grades of weathered tuff was encountered between R284 and R405, and locally at R498 and R507. Most of the remaining drive was in saprolite (completely weathered Tuff), but with local areas of corestone boulders or mixed face conditions, which was defined for this tunnel as >15% rock in the face.

The tunnel was mostly driven in pressurized EPB mode, at up to 3.14 bar face pressure, but open mode was used between R284 and 405, where the tunnel was generally in a full face of rock. The ability to maintain EPB pressure in the mixed ground can be contrasted with the problems with maintaining pressure that was reported on the earlier North East Line tunnelling in similar conditions (Shirlaw, 2000). This suggests that there were substantial improvements in TBM design and the application of conditioners, for these ground conditions, since 2000.

The actual ground conditions encountered, as assessed after tunnelling, are summarised in Table 7.

Table 7 Actual ground conditions encountered, Tunnel B

From (Ring No)	To (Ring No)	Ground conditions
1	250	Completely decomposed Tuff, with some corestone boulders & local areas of mixed ground
251	283	Mixed ground
284	405	Rock; locally mixed ground towards the end of the section
406	449	Mixed ground
450	491	Completely decomposed Tuff, with some corestone boulders
492	521	Mixed ground with local area of full face rock at R498 and R507
522	600	Completely decomposed Tuff, with some corestone boulders & local areas of mixed ground

The Penetration Index along this section of the drive is shown in Figure 13, and the Specific Energy in Figure 14. Major areas of mixed ground (MG) and full face rock are indicated in Figures 13 and 14. For clarity, mixed ground is only shown where 10 rings (18m) of tunnel or more were continuously in mixed ground. Some locally relatively high values for Penetration Index are evident in Figure 13, such as at R47 to 52, R164 to R167 and R585 to R591. These represent local areas of mixed face conditions.

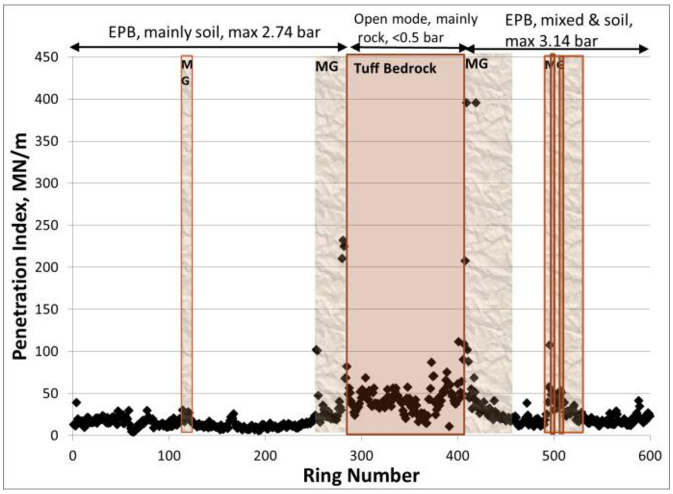

Figure 13 Penetration Index for Tunnel B, Rings 1 to 600

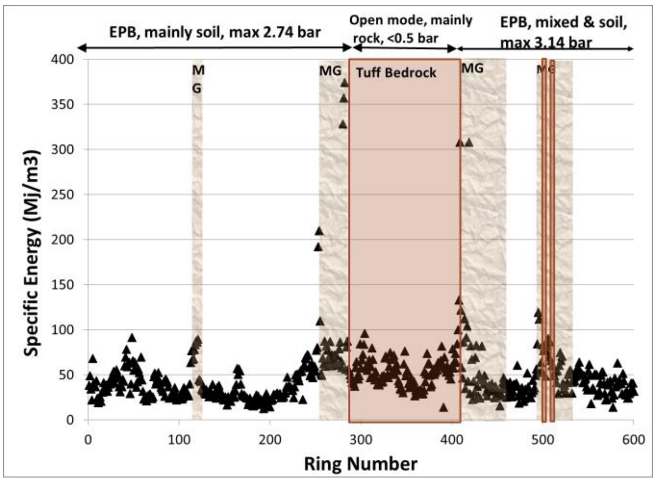

Figure 14 Specific Energy for Tunnel B, Rings 1 to 600

Some extreme values of the Penetration Index are shown in Figure 13, of up to 400 MN/m; much higher than the typical values of 40 to 60 MN/m recorded in a full face of Tuff bedrock. These values were also much higher than any value recorded in the slurry drive at Tunnel A. The extreme values for the Penetration Index generally occurred in mixed ground, close to where the TBM entered or exited the rock, in EPB mode. These very high values were recorded despite the use of very large quantities of conditioning agents, typically foam and/or bentonite slurry. In the mixed ground with less than 50% rock, the consumption of conditioner averaged about 60% of the volume of ground excavated. In mixed ground with greater than 85% rock, the average consumption of conditioner was 112% of the volume of the ground excavated.

There were also extreme values of the Specific Energy, up to 400 Mj/m^3, just as the TBM approached or exited full face rock, under EPB pressure (Figure 14). These values were also much greater than the typical values of 40 to 60 Mj/m^3 recorded in a full face of granite rock, in open mode.

The relationship between the ground conditions and the Penetration Index and the Specific Energy was explored further, by assessing the relationship between the percentage of rock in the face and the calculated values for that advance of Penetration Index and Specific Energy. In the assessment, locations where there was direct evidence of the actual ground conditions in the face were identified. This evidence came from boreholes located within half a tunnel diameter of the extrados of the tunnel and from the face maps prepared during interventions. Interventions had been very frequent in the mixed ground and rock sections of the tunnel, and interventions provided the majority of the information on the actual ground conditions.

The percentage of rock in the face was plotted against the recorded Penetration Index and Specific Energy for the relevant ring (Figures 15 and 16). There is considerable scatter in the data. However, within this scatter there is a clear trend. Up to 50% rock the data for Penetration Index and Specific Energy increases linearly between the values for 100% soil and 100% rock. The soil and mixed ground tunnelling with less than 50% rock was all carried out in EPB mode, whereas the rock tunnelling was in open mode. This shows that up to 50% rock, the application of the EPB pressure did not have a significant effect on tunnelling performance.

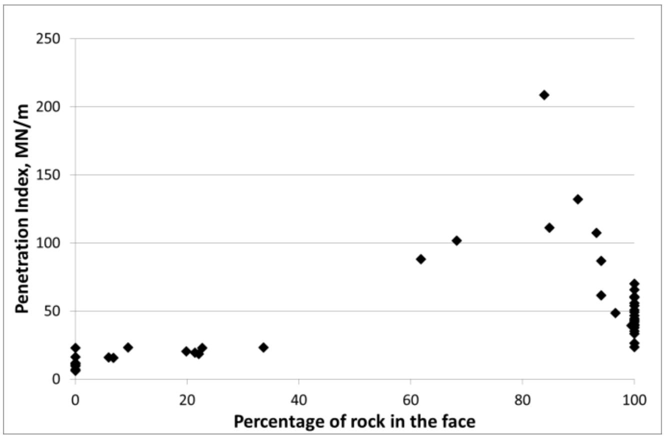

Figure 15 Penetration Index plotted against percentage of rock in the face, Tunnel B

When the proportion of rock in the face increased above about 50%, there was a dramatic increase in both Penetration Index and Specific Energy, well above trend. The peak values occurred just as the tunnel was transitioning from Mixed Ground conditions to a full face of rock, or vice versa; conditions where a high percentage of rock would occur, but the TBM would still generally be in EPB pressure. Typically, the maximum values in Figures 15 and 16 occur at 85% to 95% rock, with a drop in value at over 95% rock. Most of the rings with >95% rock were tunnelled in open mode, without EPB pressure. The extreme values for Penetration Index and Specific Energy recorded in Figures 13 and 14 are not captured in Figures 15 and 16, as there was no intervention or borehole at the relevant rings. However, it is known that the peak values occurred in EPB mode when the TBM was in a mixed face comprising mainly rock.

There were extremely frequent interventions where the TBM was in mixed ground conditions with over 50% rock in the face. High heat was generated when operating in EPB mode with a high percentage of rock, with the spoil temperature being measured at over 70^{O}C. In these conditions, the excavation chamber was initially too hot for safe man entry, and the chamber was flushed continuously with bentonite slurry to cool it down prior to the intervention. Where the machine required cooling, 12 hours to 36 hours of flushing were typically required to achieve safe conditions for man-entry. For nearly half of the interventions in these conditions, the face was found to be partially caved when the intervention could safely commence; it is likely that this caving was a result of the long period of flushing. The partially caved face could generally be maintained in a reasonably stable state, using compressed air, for short interventions. However, there were some further stability problems during long interventions. The initial caving of the face probably adversely affected the long term stability of the face under compressed air.

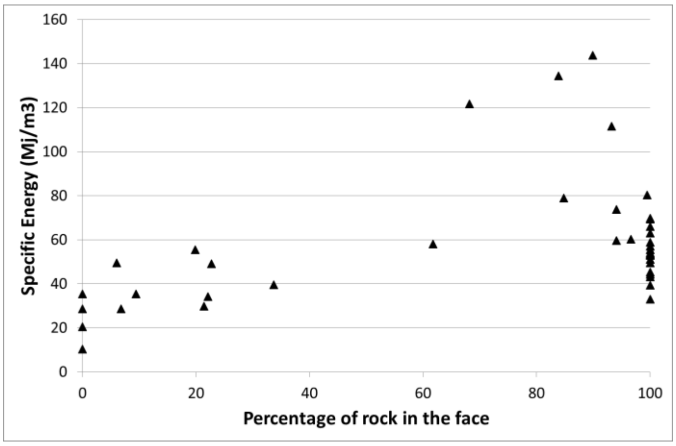

Figure 16 Specific Energy plotted against percentage of rock in the face, Tunnel B

The additional energy required to advance the TBM under EPB pressure in 50% to 95% rock was manifesting as heat.

For assessment purposes, the assessed ground conditions along the tunnel were divided up into five categories, as shown in Table 8. The disc consumption per m^3 of ground excavated and the average instantaneous advance rate are provided in Table 8.

Table 8 Effect of the actual ground conditions encountered on disc consumption and instantaneous rates of advance, Tunnel B

Ground conditions	Discs (m^3 excavated / disc replaced)	Av. Inst. Advance rate (mm/min)
100% rock	130.6	10.26
85-99%	18.3	4.6
50-85%	118.7	9.08
15-50%	365.6	15.16
<15%	803.9	26.23

The average time to advance 1m, based on the instantaneous advance rate, the average intervention time and the total of the two activities per metre, are provided in Table 9.

When the rock comprised over 85% of the area of the face, on average interventions were carried out at intervals of about 3m of tunnel constructed. Many of these interventions were of very long duration.

Table 9 Effect of the actual ground conditions encountered on the average time required for interventions and the time for advance plus interventions, Tunnel B

Ground conditions	Av. Time to Advance, min/m	Av. Time, Interventions, min/m	Advance + Interventions, min/m
100% rock	97.5	238.6	336.1
85-99%	217.4	2898.4	3,115.8
50-85%	110.1	139.4	249.5
15-50%	66	54.5	120.5
<15%	38.1	43.3	81.5

It can be seen from the data in Table 9 that the time required to advance the TBM and for the interventions were comparable in each category up to 85% rock, although both values increased significantly with increasing percentage of rock in the face. However, when the proportion of rock exceeded 85%, the time required for interventions became extreme, at over 2 days per metre of tunnel driven. In these conditions, with instantaneous advance rates of typically 2mm to 6mm/minute, and an average of 6 days of intervention time per 3m of tunnel driven, progress was extremely slow. Overall production in these conditions was about 3m per week, on average. Fortunately, only 1.65% of the total tunnel drive was in these conditions, as one third of the total time for TBM advance and interventions was required for this small proportion of the tunnelling.

There was one sinkhole recorded over Tunnel B; this occurred after an extremely long intervention in mixed face conditions with over 85% rock. The time required to recover and restart the tunnelling after the sinkhole is excluded from the average times given in Table 9.

4. DISCUSSION

The rock encountered at Tunnels A and B was approximately comparable, although the granite at Tunnel A had a slightly higher median strength and was more abrasive than the Tuff at Tunnel B. Where the two tunnels were in mixed ground, the major difference between Tunnel A, the slurry TBM drive, and Tunnel B, the EPB drive, was in the performance of the TBMs in conditions comprising >50% rock. The slurry TBM at Tunnel A passed from rock to soil without significant problems, as demonstrated by the relatively consistent values for Penetration Index and Specific Energy seen in Figures 11 and 12. In contrast, once the percentage of rock in the face exceeded 50% the EPB drive at Tunnel B exhibited rapidly increasing values for both Penetration Index and Specific Energy. These values increased to extreme values at about 85% rock. The practical effect on EPB tunnelling in these conditions is demonstrated by the slow average instantaneous advance rate, and number and duration of interventions recorded. As demonstrated in Table 9, in the most extreme conditions, in a mixed face with over 85% rock, each metre of tunnelling required on average about 4 hours of TBM advance and 2 days of intervention time. These values imply an average advance of less than 3m per week, although in practice the common pattern was to advance in short bursts of 3m to 6m over a few days, and then stop for an intervention lasting a week or more. For Tunnel B, it was fortunate that the most onerous conditions, 85% to 99% rock, were of limited extent. Other EPB driven tunnels have not been so fortunate. Shirlaw (2016) provides an example of an EPB driven tunnel which encountered similar conditions, in weathered granodiorite, over 256m of continuous tunnelling. There were 116 interventions, to replace a total of 513 No 17" discs over that 256m of tunnelling. It took 9.5 months just to tunnel those 256m, at an average of just over 6m per week; much of the tunnelling was in semi-EPB mode, as, generally, the TBM could not be advanced in EPB mode. Another example is the North-South line of the Bangalore Metro, which also used EPB TBMs in mixed ground of weathered rock (granitic gneiss which was extremely strong when fresh). One drive of 432m length required 22 months to complete, or an average rate of 4.53m per week; the parallel drive took 12 months, at an average rate of 8.3m/week (Kenyon, 2016).

One of the outward signs of these problems, with tunnelling in mixed face conditions with a high percentage of strong rock, is the high temperature of the spoil as it emerges from the screw conveyor. High spoil temperatures have been recorded on a number of EPB drives other than Tunnel B, including a drive in a mixed face of sandstone and soft clay under the Singapore River (Shirlaw et al. 2000).

Sometimes, an EPB TBM cannot be advanced in conventional EPB mode in these conditions, as the cutterhead cannot be turned without breaching the limiting values for the torque. A common expedient, if this occurs, is to switch to semi-EPB mode (GEO 2014), with the excavation chamber half empty, and the upper half of the face supported by compressed air. This mode was not used at Tunnel B, but was used locally for parts of the EPB tunnelling on several of the projects mentioned here, including:

- Tunnelling for the Deep Tunnel Sewer System in weathered Singapore granite
- Tunnelling on the Circle Line in the sedimentary Jurong Formation in Singapore (Venkta & Hoblyn, 2008)
- Line 5 of the Sao Paulo Metro (de Oliveira and Deiderichs, 2016).

The problems of high heat and exceptionally high torque during TBM advance appear to be limited to mixed faces including strong (or stronger) and abrasive rocks, when operating in EPB mode, and where the proportion of rock in the face is >50%. Despite the general trend of using slurry TBMs in the weathered granite, PTBM tunnelling in the Fort Canning Boulder Bed in Singapore has been entirely with EPB TBMs, on the Circle and Downtown Lines (Noh et al. 2016). The Formation comprises about 25% by volume of Strong or Very Strong and extremely abrasive quartzite boulders in a silty clay matrix (Shirlaw et al. 2003). The continued use of EPB TBMs in these conditions confirms the critical effect of the percentage of rock in the face.

At Tunnel B, the dramatic increase in the Penetration Index and Specific Energy when the face consisted of more than about 50% rock suggests that the problems are associated with a change from the spoil being mostly soil, with some chips of rock, to being mostly chips of rock with some soil. The high heat, high torque and rapid tool wear are suggestive of the spoil clogging in the gap between the face and the cutterhead (the tool gap). The discs will cut the rock into chips of typically 25mm to 100mm size, based on grading curves from hard rock TBMs (Bruland 1998). Coarse particle clogging can occur when the maximum size of the chips of rock is more than one third of the size of the tool gap. The tool gap with a 17" disc is about 150mm, so there is the potential for coarse particle clogging when tunnelling in a face that is predominantly rock. As the percentage of rock in the face increases, there will be an increasing proportion of rock chips in the spoil. This will increase the chance of local clogging. A local area of clogging will allow some of the contact force applied to the cutterhead to pass through the clogging particles onto the rock in the face, rather than through the tools. The clogging will also affect the torque, as torque is needed to break up the clogged particles. The pieces of rock are likely to be broken or abraded in this process.

Although a similar problem has been encountered locally in the moderately Strong to Very Strong Sandstone and meta-Sandstone of the Jurong Formation in Singapore, it has not been encountered in the weaker Mudstones and Siltstones of the formation. These weaker rocks are more readily broken or abraded, breaking up the larger pieces of cut rock. The effective use of EPBs in the Kenny Hill formation in Kuala Lumpur confirms that in relatively weak rocks similar problems do not occur.

The support pressure in an EPB TBM operating in full EPB mode is provided through particle to particle contact within the spoil and onto the face. While under these contact forces, the particles have to move relative to the cutterhead: passing from where they are cut towards the openings in the cutterhead. Where the particles are predominantly chips of rock within a narrow slot between the cutterhead and a face of strong rock, localized clogging can occur, leading to the high values of contact force and torque, but very slow advance rates, as seen at Tunnel B when the TBM was in a mixed face with a high proportion of rock. In a slurry TBM the face pressure is provided by the slurry, and the cut particles are transported within the slurry. The slurry TBM at Tunnel A did not experience comparable problems in mixed ground to the EPB at Tunnel B; it is suggested that this was in large measure because of the different operating principles of slurry and EPB TBMs. The slurry TBM at Tunnel A did experience some difficulty with clogging in unusually clayey cdg, but this was in relation to fine particle clogging.

As discussed above, since 2003 some major project owners in Singapore, including the Land Transport Authority (for MRT tunnels) and PowerGrid (for cable tunnels) have chosen to specify the use of slurry TBMs where the tunnel is likely to encounter a significant length of mixed face conditions. The example of Tunnel B, which were constructed after 2010 in Hong Kong, and the other examples such as the Bangalore N-S metro line, shows that this was a well-founded decision.

The use of semi-EPB mode can often allow an EPB TBM to advance, if it cannot advance in full EPB mode. In semi-EPB mode only half of the chamber is filled with spoil, reducing the area subject to local clogging. Also, much of the face pressure is provided by compressed air pressure, rather than by particle to particle contact, and the spoil is not confined vertically. There are, however, risks in the use of semi-EPB mode, as the compressed air alone cannot stabilize confined sand layers. This can lead to loss of ground and large surface settlement; Venkta & Hoblyn (2008) provide a case study on this.

As identified above, there has been a significant improvement since 2000 in EPB tunnelling in mixed ground conditions. However, further improvements still need to be made to EPB TBMs to improve their performance in mixed ground conditions comprising soil and strong (or stronger) rock. On the basis that the problem described above originates in local clogging of coarse particles (chips of rock) in the tool gap, and manifests as slow advance rates, heat, rapid tool wear and frequent, long interventions, possible improvements could include:

a) Flush with water or (preferably) slurry directly into the tool gap. EPB shields typically include a number of small nozzles to allow the injection of foam or polymer directly into the tool gap. Flushing with large volumes of water or bentonite, however, is normally only provided into the excavation chamber. The direct addition of water or slurry at the tool gap in front of the cutterhead will provide lubrication to the chips of rock, will assist in cooling, and (for flushing with slurry) will provide clay particles to aid the effectiveness of the foam.

b) Avoid creating unbroken 'walls' of cutters which can help to create clogging

c) Minimise the length of travel between the excavated particles and the openings in the cutterhead, and avoid creating significant areas of the cutterhead with no openings, or openings too small for the coarser chips of rock to enter

d) Use the largest discs practical: the larger the disc, the more robust it is; also the larger disc will increase the size of the tool gap, reducing the tendency for coarse particles to clog

e) Plan the compressed air locks and procedures to maximize the effective time that can be worked during an intervention: Merrie (2009) discusses the benefits of double sets of man-locks

f) Keep the intervention pressure to the minimum necessary. Shirlaw et al. (2015) discuss the use of the observational method to allow planned adjustment to the initially estimated compressed air pressure in Hong Kong

g) Provide a filter cake on the face (GEO 2014) prior to entry, and for long interventions or where the face is starting to cave or ravel, apply a sprayed membrane (Babendererde & Elsner, 2014)

However, it is not certain to what degree measures such as those listed above can improve EPB performance in these conditions. For the moment, the choice of a slurry shield where there is significant tunnelling in mixed ground comprising soil and Strong (or Stronger) rock would appear to be the safer option.

The adverse effect of clayey, sticky soil on slurry TBM advance rates is illustrated in the effect on Tunnel A (Table 6). The overall rate of tunnelling in the sticky clay was significantly slower than in the more granular cdg, but comparable with the mixed ground or rock.

5. CONCLUSIONS

The use of PTBMs in Singapore has a history stretching back over 30 years. Since 2005 there has been a general trend towards using slurry shields for tunnelling in the weathered rocks of the Singapore Granite, and, to a lesser extent, the meta-sedimentary rocks of the Jurong Formation. This change has been a result of project owners specifying the use of slurry TBMs for selected projects, after earlier problems with EPB TBMs. The selected projects are typically those where the tunnels are deep, or anticipated to include several soil/strong rock interfaces.

The detailed examples of Tunnels A and B, in Hong Kong, show how an EPB TBM (Tunnel B) can encounter severe difficulties in mixed ground conditions in the face, comprising greater than 50% of strong (or stronger) rock. This is consistent with the more general evidence from Singapore. The TBM at Tunnel B in Hong Kong experienced very slow progress in the most onerous conditions (>85% rock, in EPB mode), averaging about 3m per week. Much of the time was spent on interventions, with very rapid wear and damage to the discs. Similar problems, of very slow progress, heat and frequent interventions, have been experienced on EPB drives in mixed face conditions on other projects. In comparison, EPB TBMs have been effective in tunnelling in the Fort Canning Boulder Bed in Singapore, where the boulders are very strong and extremely abrasive, but the typical proportion of the boulders is about 25% of the ground. This is consistent with the critical effect on EPB tunnelling of the proportion of strong (or stronger) rock in the face.

The slurry TBM at Tunnel A did not experience the same degree of difficulty in similar mixed face conditions to those encountered in Tunnel B. Again, this experience from Hong Kong corresponds with the more general experience from Singapore.

It is postulated that the problems with EPB tunnelling in conditions of greater than 50% rock are related to local clogging by chips of rock produced by the TBM cutting the rock, in the gap between the cutterhead and the face. It should be possible to improve the design and operation EPB TBMs to improve their performance in these conditions. However, the use of slurry TBMs provides an effective means of tunnelling in these very difficult conditions. Mixed mode and Variable Density TBMs provide the option to switch operating modes in complex ground conditions, while the Variable Density TBM provides additional flexibility in terms of operating modes, for tunnelling in conditions such as karst.

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