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# The interaction of the TBM and the ground during tunnelling through weathered Kowloon Granite

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ABSTRACT:
Tunnelling from Diamond Hill Station on the Shatin to Central Link (SCL) in Hong Kong involved twin, 1.7km long, slurry TBM drives in the direction of Lion Rock. The tunnelling encountered soil and rock grades of weathered Kowloon granite, and mixed ground conditions. A swarm of dykes of basalt and rhyolite had intruded into the granite, and the granite adjacent to the dykes was hydrothermally altered. During tunnelling it was found that the weathering of the dyke rock and the hydrothermally altered granite had resulted in the development of swelling clay minerals. As a result, a significant proportion of the soil grades of weathered rock were 'sticky'. The contact force and the torque applied to the cutterhead were measured throughout the drive, as was the drag at the tail of the TBM. The friction on the TBM skin was calculated from the measurements. The values were used to study the relationship between the TBM parameters and the ground conditions encountered. The data was also used to derive the Field Penetration Index and Specific Energy for each ring of advance. The values of these two parameters are compared with the assessed ground conditions. It is found that plotting these two parameters provides insight into how the TBM and the ground interact, and how changes made to the TBM for the second drive affected the performance of the TBM in the varied ground conditions. It is found that the average unit friction on the TBM skin and tail seals reduced as the TBM passed from saprolite to mixed ground to rock.

## 1 INTRODUCTION

The MTR Corporation's Shatin to Central Link (SCL) in Hong Kong connects the existing Ma On Shan, West Rail and East Rail Lines. It will also cross the harbour to Admiralty Station on Hong Kong island. When fully opened, it will form a new north-south and east-west corridor with five new stations, four major station modifications and an interchange station at Hung Hom. SCL Contract 1103 is one section of the line. It included the construction of 3.75km of running tunnels between Hin Keng and Diamond Hill stations. The tunnels run under Lion Rock, an iconic peak to the north east of the Kowloon peninsula. The tunnelling was in two major parts: a 2,175m long section under Lion Rock constructed by drill and blast methods, and a 1,700m section of twin tunnel constructed through soil, mixed ground and rock by two slurry TBM drives.

The TBM tunnels were driven from a launch shaft at Diamond Hill Station to a reception chamber formed at the end of the drill and blast tunnel. The Up-Track was driven first; the TBM was then removed back down the constructed tunnel and rebuilt with a new shield skin and cutterhead. The Up-Track TBM tunnel was driven between August 2014 and June 2015, while the Down-Track was driven between September 2015 and April 2016. During the rebuilding of the TBM, significant modifications were made, following the experience of the first drive. The cut diameter of the TBM was 7.46m and it was operated in closed mode along the entirety of both drives.

The alignment of the TBM tunnels is shown in Figure 1. The tunnelling for both drives started at Diamond Hill, passed on either side of Fung Tak emergency escape shaft, through a ventilation shaft at Ma Chai Hang and finished at a cavern constructed at the end of the Lion Rock drill and blast section.

The wide range of ground conditions encountered and the modifications to the TBM provide the opportunity to study the interaction of the ground and the TBM, using the parameters measured on the TBM during tunnelling. This paper will review the relationship between the ground conditions and the TBM parameters, and how this changed because of the modifications made to the TBM between the Up- and Down-Track drives.

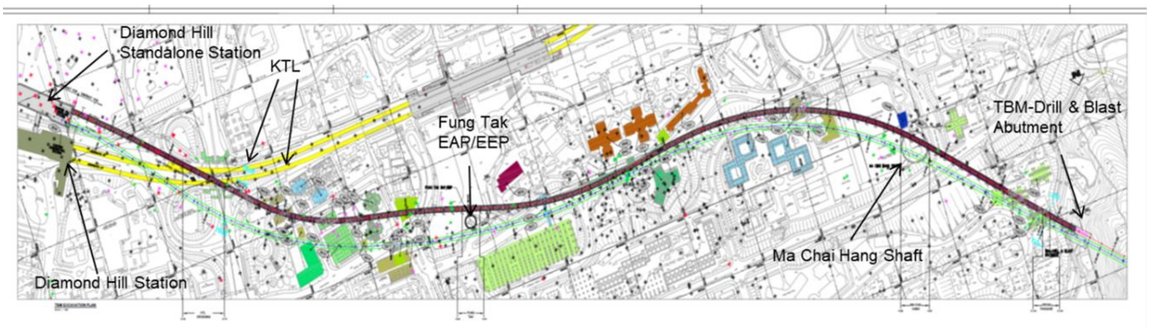


Figure 1. The horizontal alignment of the TBM tunnels

## 2 GROUND CONDITIONS

### 2.1 General Geological conditions

The regional geology comprises general superficial deposits of fill, alluvium and colluvium overlying solid geology of Kowloon Granite. As illustrated in Figure 2, the tunnels were driven through variably weathered granite, ranging from Grade V (completely decomposed) to Grade II (slightly decomposed). The Kowloon granite is a medium-grained granite with two to three major joint sets. The TBMs encountered two sections of full-face rock, one near the start of the drives and one at the end. Within the first section of granite encountered there was a swarm of basalt and rhyolite dykes, as identified from the ground investigation.

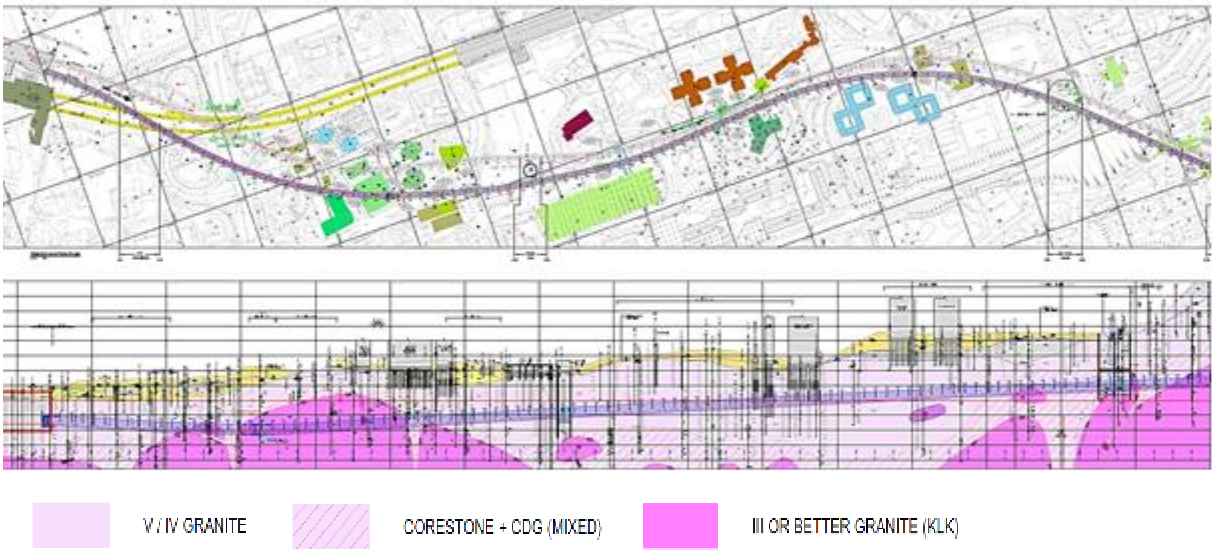


Figure 2. The interpreted ground conditions along the TBM tunnel drives.

The cover over the tunnel varied from 19m to 98m. The groundwater pressure at tunnel axis level, obtained from standpipes and/or piezometers, varied from 23m head to 66m head. The piezometric pressure increased with increasing cover over the tunnel and reflected the rising ground surface towards Lion Rock.

As outlined in GEO Guide 3 (2000) and Shirlaw et al (2000), the classification system used in Hong Kong has six material grades of weathered granite, with Grades I to III being classified as rock, IV to

V as soil (saprolite) and VI as Residual Soil. Residual Soil was not encountered in the tunnelling. The ground investigation for SCL 1103 showed a wide range of measured strength for the granite rock, from 12.5 MPa to 200 MPa. The Cherchar Abrasivity index of the rock is typically between 4 and 5, with a quartz content of 21% to 35%. The effect of the weathering is largely on the feldspar minerals in the granite; the quartz weathers more slowly than the felspars. As a result, the Grade IV and V weathered granite also have a significant quartz content and are highly abrasive.

### *2.2 Identification of face conditions during tunnelling*

The general geological conditions along the alignment of the twin tunnels, as illustrated in Figure 2, were identified from the ground investigations carried out prior to contract award. However, due to the dense urban environment, many of the boreholes were significantly off the line of the tunnels. During tunnelling the actual ground conditions encountered were established from the additional information available from the tunnelling. The primary sources of this additional information were:

1. Logging of the tunnel face during interventions to inspect and change cutting tools
2. Inspection of the nature and relative quantity of the scalpings at the slurry treatment plant

An example of a face log prepared during an intervention is presented as Figure 3.

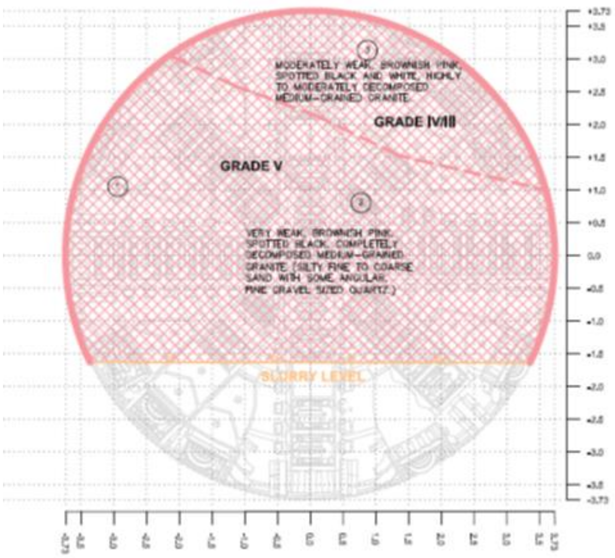


Figure 3. Example of a face log prepared during an intervention for the Up-Track tunnel

There were 149 interventions during the Up-Track tunnelling and 107 during the Down-Track, giving an average spacing of 11.3m and 15.8m between interventions for the two tunnels, respectively. As all grades of weathered granite are significantly abrasive, interventions were frequent and the quantity of face logging available was unusually high for pressurised TBM tunnelling. The record of direct observation of the face provided by the logs represents a major source of high-quality information on the ground conditions encountered. One limitation was that most of the interventions did not involve emptying the excavation chamber fully, so the lower portion of the face could not be observed, as in the example in Figure 3.

The bentonite slurry used in the tunnelling was treated at the slurry treatment plant (STP) to remove the ground excavated during tunnelling (scalpings). The STP involved several processes, including shakers, hydro-cyclones and filter presses. Each phase of treatment involved removing particles of a different range of sizes. Inspection of the nature of the scalpings and the relative proportions of the various size ranges provided qualitative information on the general nature of the ground conditions encountered. The assessment of ground conditions at the STP was approximate, due to the treatment sequence and the time lag between TBM excavation and slurry treatment.

Within the saprolite, the tunnels encountered a succession of subvertical bands of completely and highly weathered, hydrothermally altered, rock, associated with dyke formation. Unlike the more common completely weathered granite, which behaves like a silty sand, the weathering of the hydrothermally altered granite resulted in the formation of swelling clay minerals, including beidellite and montmorillonite. The TBM encountered 'sticky' conditions in these bands of weathered hydrothermally altered rock, which adversely affected rates of TBM advance and required additional interventions to manually remove the sticky material. The material was termed 'clayey completely decomposed granite' or 'clayey cdg'. The nature of the 'clayey cdg' is illustrated in Figure 4 which shows a block of this material that had been extruded through an opening in the cutterhead and was revealed during an intervention. The 'clayey cdg' was also evident at the STP. The relatively high clay content and presence of swelling clay minerals required additional plant installation and treatment to produce a suitable slurry for reuse, compared with the more typical saprolite of the Kowloon Granite. Additional filter presses were also added to process the larger volumes of degraded bentonite produced by the clayey cdg.

Dykes of intrusive rock (basalt and ryolite) were identified striking across the tunnels in the first area where the tunnels were in rock. The proximity of the dykes within the rock and the adjacent bands of clayey cdg within the more typical granitic saprolite suggested that the clayey cdg was the result of the weathering of dyke rock and the associated hydrothermally altered rock. This was confirmed when chips of basalt were found in the scalpings at the slurry treatment plant during excavation of some of the areas of 'clayey cdg'.

Figure 4. 'Clayey cdg' being extruded through an opening in the cutterhead

### *2.3 Categories of face condition in weathered granite*

The information on the ground conditions from the ground investigations, face logging and slurry treatment plant were combined to produce 'as-built' geological long sections along the two tunnel drives. These 'as-built' sections were used to categorise each ring of advance into one of four categories:

i. A full face of saprolite, including completely and highly decomposed rock but excluding ground assessed as 'clayey cdg'
ii. A full face of 'clayey cdg'
iii. Mixed ground, where the face comprised both soil (saprolite or clayey cdg) and rock grades of weathered granite
iv. A full face of rock, including slightly and moderately decomposed rock

These simple categories were not arbitrarily determined. Typically, the contract documents for tunnelling projects in Hong Kong and Singapore include a Geotechnical Baseline or Geotechnical Interpretative Baseline Report. The Baseline Report provides a summary of the anticipated ground conditions and is the reference point to determine whether the ground conditions encountered were different from those anticipated. For tunnelling projects in weathered granitic rock, it is common for the baseline statements to include the anticipated length or proportion of the tunnel in soil (saprolite), mixed ground and rock. Tunnelling in these three categories will have different advance rates and tool consumption, and so significant changes in the length of tunnel in each category will affect both the cost and duration of the tunnelling.

For SCL 1103, the unusual 'clayey cdg' caused by the weathering of hydrothermally altered granite had tunnelling characteristics that were sufficiently different to the normal granitic saprolite to form a fourth category.

The record of the tunnelling for SCL 1103 provided an opportunity to study how the TBM and the ground interacted, and how this interaction was changed by the modifications to the TBM. In particular, the range of ground conditions encountered and the modifications provide an opportunity to compare the interaction in various contrasting conditions. Understanding how the TBM and the ground interact and the effect on the TBM parameters of different ground conditions has the potential to assist in resolving contractual and financial disputes, It may also assist in developing improved contract documents aligned with modern contact forms such as the NEC or FIDIC Emerald book.

### *2.4 Limitations in the assessment of the actual face conditions*

Because of the frequency of the interventions the amount of information on the actual ground conditions encountered was relatively high for a pressurised TBM. However, the resulting 'as-built' geological profile on which this study is based is unlikely to be a precise representation of the actual ground conditions. Apart from the limitation in the accuracy of the interpretation of the actual ground conditions, there is also a conceptual issue related to dividing face conditions into four simple categories in a material as complex as a weathered rock profile. Dividing the ground conditions into four categories implies that these categories are separate and distinct, as illustrated in Figure 5.

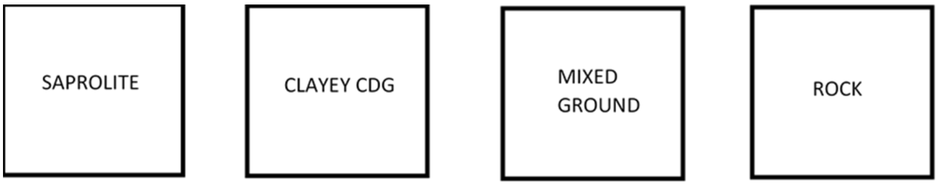


Figure 5. Categories of weathered granite used in the study

While it is common to place weathered rock into categories for engineering purposes (Hencher 1986), the reality is more complex and less differentiated than these simple categories would imply. Rather than the simple, differentiated categories of Figure 5, it would be more appropriate to consider the four categories as represented in Figure 6.

The differentiation between rock and saprolite is based on strength at a material (hand sample or core) scale. The weathering of granite involves progressive weakening. Field logging relies on simple field tests; in this case the ability to break a core or a large piece by hand (saprolite) or not (rock). Such a test, while simple and practical, is clearly not precise. In terms of uniaxial compressive strength, this boundary has been defined variously from 2 MPa to 'a few MPa' (Martin and Hencher 1986) to 12.5 MPa (Hencher 2006). The testing equipment for the field test, a pair of human hands and arms, is subject to a wide range of possible variation. Consequently, the boundary between rock and saprolite is blurred by the lack of precision in the categorisation even in ideal circumstances, and more so when carrying out the assessment with the limited access to the face afforded by a pressurised TBM.

Mixed ground refers to a face where there is both saprolite and rock. This single category covers a wide range: from the face being almost entirely saprolite to almost entirely rock. In weathered Kowloon granite, the rock may be of any strength from a UCS value of a few MPa to 200 MPa; generally, but not always, the rock in a mixed face is likely to be significantly affected by weathering and therefore towards the lower end of the possible range of strength. Mixed ground conditions may refer to corestone boulders within a matrix of saprolite, or to tunnelling at engineering rockhead, with part of the face in saprolite and part in rock with a defined contact surface.

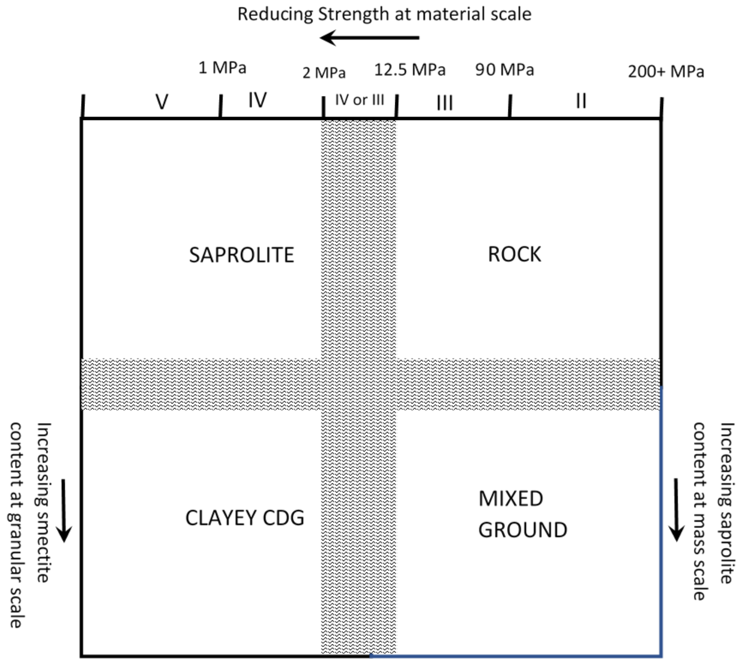


Figure 6. Categories of ground conditions, showing continuity and the scale of changes

The ‘clayey cdg’ category refers to completely decomposed granite which is unusually sticky because the weathering of dyke rock and hydrothermally altered rock produced swelling clay minerals. From measurements made during the construction of SCL 1103, the proportion and type of clay minerals present varied significantly. Consequently, the degree of ‘stickiness’ also varied significantly within this category. It is likely that some of the mixed ground also included clayey cdg. The variation in the clay mineralogy that distinguishes clayey cdg from saprolite occurs at a granular scale.

It is evident from the above that:

- There is a very large degree of variation within each of the four generalised face categories.
- The boundaries between the four generalised face categories are imprecise, and there is likely to be significant overlap in the data
- The distinction between the different face categories occurs at different scales, as illustrated in Figure 6.

Because of these factors, combined with the varying quality of the information on which the face conditions were assessed, it can be anticipated that there will be considerable scatter and overlapping of the TBM data between the four face categories.

## 3.0 THE TUNNEL BORING MACHINE

### *3.1 TBM for the Up-Track drive*

The Up-Track TBM was of the mixshield type, manufactured by Herrenknecht AG, using bentonite slurry to support the face. The pressure of the slurry was regulated by use of a compressed air bubble. Some of the key features and dimensions of the TBMs are summarised in Table 1. The cutterhead is shown in Figure 7 and was equipped for excavation in soil, rock and mixed ground.

The TBM was equipped to allow the forces applied at various points to be measured. These measurements included:

- The thrust force applied at the back of the shield by the shove rams
- The force applied to the cutterhead and main bearing assemblage.
- The torque applied to the cutterhead

- The slurry pressure
- The force required to drag the trailing gear (tail drag)

Table 1. Key features and dimension of the TBM

| Item | Value |
|---|---|
| Excavated diameter | 7.46m |
| Shield skin diameter | 7.41m to 7.39m |
| Shield length | 11.67m + 0.735m cutterhead |
| Opening ratio | 27% |
| 19" discs | 36 single + 4 double |
| Scrapers | 52 + 4 back |
| Bucket lips | 12 No. |
| Pressure limit, static | 8 bar |
| Pressure limit, advance | 6.25 bar |
| Electrical power | 1750 kW |
| Maximum thrust | 4940t |
| Nominal Torque | 4510 kNm |

Figure 7. The cutterhead, equipped with discs, scrapers and bucket lips

The measurements of Force and Torque are summarised in Figure 8.

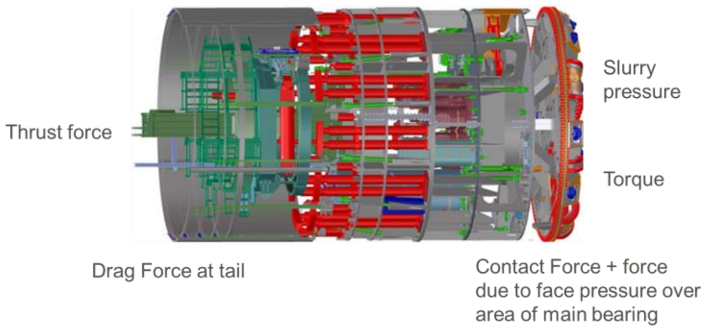


Figure 8. Measurement of force and torque at the TBM

There were three pairs of jacks holding the main drive and the articulated cutterhead. The total force on the main bearing and cutterhead could be calculated from the hydraulic pressure in the three jacks. There was another jack between the trailing gear and shield. The drag force was derived from the measured hydraulic pressure in this jack.

### *3.2 TBM for the Down-Track drive*

The clayey cdg encountered during the construction of the Up-Track drive caused some adverse effects on the tunnelling, including reduced advance rates, additional interventions and contributed to high rates of wear on the cutting tools. The TBM would be reassembled within a new shield skin and with a new cutterhead for the Down-Track drive. As a result, there was the opportunity to modify the TBM and the STP to mitigate these issues for the second drive. The relevant parties, including the owner (Mass Transit Railway Corporation), contractor (Vinci Construction Grand Projets) and TBM manufacturer (Herrenknecht AG) collaborated to assess the experience during the first drive and agree appropriate measures to improve the TBM and STP for the second drive. Golder Associates provided analysis of the data in support of the changes, in addition to providing the face pressure calculations for both drives.

The modifications made for the second (Down-Track) drive included:

- Altering the slurry circuit in the area of the cutterhead. For the Up-Track TBM slurry was fed to the back of the excavation chamber, with a typical flow rate of 1,600m$^3$/hr. For the Down-Track TBM this was altered so that up to 240m$^3$/hour of the slurry could be fed, via additional pipework, into the tool gap in front of the cutterhead, as illustrated in Figure 9. This increased the clay “flushing” at the center of the cutterhead.
- Reducing the rate of rotation of the cutterhead. When the clayey cdg was first identified during the Up-Track drive, the first response was to reduce the rate of rotation of the cutterhead from 2.5 rpm to between 1.5 and 1.7 rpm. Analysis of the data showed that this was beneficial in terms of increasing both the rate of penetration and the overall advance rate. The rate of rotation for the Up-Track and Down-Track drives is summarized in Table 2. There is limited difference, as the reduction in the rate of rotation in the saprolite and clayey cdg from the planned 2.5rpm rpm had already been implemented early in the Up-Track drive.
- Optimising cutter disc selection. Various types of disc were trialed during the Up-Track drive. On the basis of these trials, for the Down-Track standard discs with a ¾” tip were used as far as practicable in the rock and mixed ground, while Tungsten Carbide Insert (TCI) discs, as shown in Figure 10, were used in the saprolite and clayey cdg.
- The operation of the STP was modified by adding coagulant to the return slurry and by adding an additional filter press. Both modifications were made to increase the ability of the plant to treat slurry from the tunnelling in the clayey cdg.

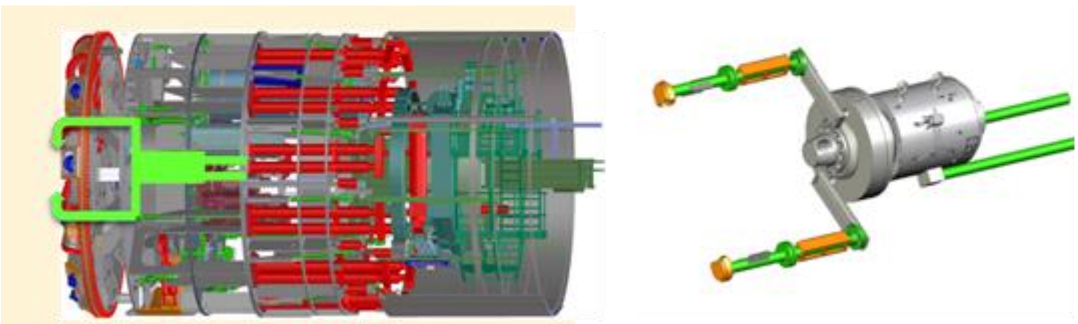

Figure 9. Modification to the flushing system for the Down-Track TBM, to feed some of the slurry flow into the tool gap at the cutterhead.

Table 2. Comparison of the average rates of rotation of the cutterhead between the Up- and Down-Track drives

| Drive | Parameter | Saprolite | cl cdg | Mixed ground | Rock |
|---|---|---|---|---|---|
| UT | RPM | 1.84 | 1.74 | 1.84 | 3.3 |
| DT | RPM | 1.71 | 1.69 | 1.71 | 3.09 |

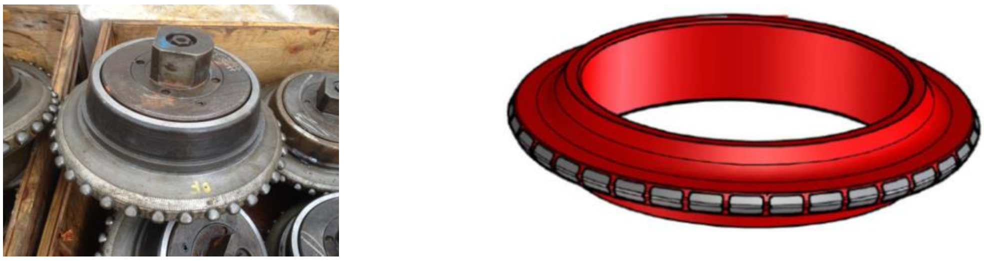

Figure 10. TCI disc used for tunnelling in the saprolite and clayey cdg for the Down-Track drive

## 4.0 HORIZONTAL FORCES AND OTHER TBM PARAMETERS

### *4.1 Horizontal forces on the TBM*

The horizontal forces imposed on a TBM during the advance of the TBM are summarised in Figure 11; the TBM applies equal and opposite forces on the ground. The immediate contact between the ground and the TBM is at the cutterhead, particularly the cutting tools. Force is applied to the tools on the cutterhead to push them into the face, as part of the cutting action (the 'contact force'). Torque is applied to turn the cutterhead, also as part of the cutting action and to overcome frictional forces on the cutterhead. For a slurry TBM the frictional forces on the cutterhead are generally small but may increase if there is clogging in the gap between the main cutterhead structure and the excavated face (the 'tool gap'). The face pressure is applied at the main pressure bulkhead. There is friction along the TBM shield and at the tail seals where they bear on the rings. There is a drag force at the tail of the TBM as the TBM tows the trailing gear. The combined normal (in the direction of tunnelling) forces applied to the TBM have to be overcome by the thrust applied through the thrust rams at the back of the TBM.

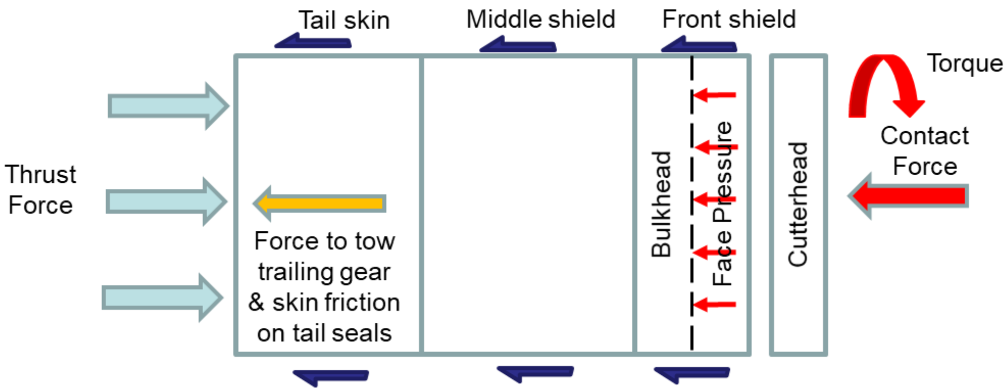


Figure 11. Horizontal forces and torque on a slurry TBM

For a more detailed review of the forces on a TBM, including vertical forces and moments as well as horizontal forces and torque, see Festa et al. (2020).

The TBM for SCL1103 was designed so that there was measurement of the force applied to the cutterhead plus the slurry pressure over the area of the main bearing. The force due to the slurry pressure on the area of the main bearing could be calculated, and the contact force applied to the cutterhead derived.

Balancing the normal forces on the TBM requires that:

$$F_{total} = F_{fp} + F_c + F_{fr} + F_d \qquad (1)$$

Where:

$F_{total}$ is the total thrust force
$F_{fp}$ is the force due to the face pressure
$F_c$ is the contact force

$F_{fr}$ is the force due to the friction along the shield and the friction between the tail seals and the lining rings
$F_d$ is the tail drag

The values for $F_{total}$, $F_{fp}$, $F_c$ and $F_d$ were provided by the measurements made during tunnelling, so the combined value of the friction along the TBM and at the tail seals could be obtained from equation 1.

Measurements of the forces were made every 5 seconds during tunnelling. The data used in this paper was averaged over each approximately 1.5m long advance between building successive rings, excluding measurements made during any temporary stoppages in the TBM advance.

### *4.2 Other measured parameters*

Other parameters measured during TBM advance and used in this paper are:

The Torque (T) applied to the cutterhead of the TBM

The penetration rate (PR), expressed as mm/minute

The rate of rotation of the cutterhead (RPM). The number of times the cutterhead was rotated for each advance was measured and recorded, and the rate of rotation was calculated using the time required for the advance

The rate of penetration (ROP), expressed in mm/revolution, was calculated from the length of advance and the number of cutterhead rotations required.

The average normal force per disc cutter (Fn). Fn is the Contact Force divided by the number of cutters. Although there was a total of 44 No. discs installed on the cutterhead, 10 of these were concentrated on the gauge (Figure 7). The cutters on the gauge were placed at a varying angle to the direction of drive, and the tracks on the gauge cutters were closely spaced. To calculate Fn, the number of discs was taken as 40 No., giving an average disc spacing of 93.25mm.

### *4.3 Derived parameters*

In addition to the forces and other common parameters obtained from the measurements made during TBM tunnelling, three parameters were derived from the data:

Specific Energy (SE), calculated from equation 2:

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

Where:
$F_c$ is the contact force 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 $m^2$

In equation 2, the first term, $F_c.P$, is generally small in comparison with the second term, and is often ignored. If it is ignored, the value for SE = (approx.) 2 x Torque / $r^2$ x ROP, where r is the radius of the TBM.

The Field Penetration Index (FPI), calculated from equation 3:

$$FPI = Fn / ROP \quad kN/mm/rev \text{ (or MN/m/rev)} \qquad (3)$$

Equation 3 can also be written as FPI = $F_c$ / (Number of discs x ROP)

For a particular TBM, where the radius and the number of discs are constant, the Specific Energy is proportional to the unit torque divided by the rate of penetration, while the Field Penetration Index is proportional to the unit contact force divided by the rate of penetration.

Specific Energy (Miramahdi et al. 2017) and the Field Penetration Index (Hassanpour, 2016) are commonly used in the assessment of hard rock TBMs. However, the Field Penetration Index is not directly related to the strength of the rock, so a modified Field Penetration Index is proposed, based on the relationship between Fn and rock strength developed at the Colorado School of Mines (Rostami 1997). The modified Field Penetration Index (mFPI) is calculated from equation 4:

$$mFPI = \sqrt[3]{(Fn^3/ROP)} \quad (4)$$

The values for mFPI quoted in this paper were obtained from Fn in kN and ROP in mm/rev. The derivation of mFPI does not consider the effect on cutting of the joints in the rock and is only suitable for use in strong or stronger rock with a wide joint spacing.

### *4.4 Completeness of TBM data sets*

The Up-Track tunnel comprised 1122 complete ring advances, while the Down-Track drive required 1125 ring advances, for a total tunnel length of 1,683m and 1,687.5m respectively. Each advance was categorised into one of the four categories of ground condition, based on the site records. The resulting division by ground condition for the two tunnel drives is summarised in Table 3. The greatest difference between the drives was in the classifications saprolite and clayey cdg, with the Down-Track apparently encountering much less clayey cdg and much more saprolite than the Up-Track drive. It is likely that the measures taken to modify the TBM and slurry treatment for the Down-Track drive made a substantial difference to the TBM performance in the clayey cdg and that this resulted in some material that would have been classified as clayey cdg during the Up-Track drive being classified as saprolite during the Down-Track drive, as it became more difficult to distinguish the two categories.

Table 3. Number of rings of advance in each ground category for the two drives

| Drive | Unit | Saprolite | cl cdg | Mixed ground | Rock | Total |
|---|---|---|---|---|---|---|
| **UT** | Rings | 163 | 432 | 222 | 305 | 1122 |
| **DT** | Rings | 307 | 217 | 240 | 361 | 1125 |
| | % change | 88.3 | -49.8 | 8.1 | 18.4 | |

During the drives there were some local problems with the measuring devices for some of the TBM parameters. Often, these problems were with the device used to record the number of revolutions of the cutterhead. The data from each advance where there was an incomplete or missing record of any of the assessed parameters was discarded, and only complete records were considered in the assessment. The number of remaining data sets considered is summarised in Table 4.

Table 4. Number of rings of advance for each drive for which there was complete data, with percentage of rings for which the data was incomplete

| Drive | Unit | Saprolite | cl cdg | Mixed ground | Rock | Total |
|---|---|---|---|---|---|---|
| UT | Rings | 147 | 413 | 222 | 304 | 1086 |
| DT | Rings | 296 | 213 | 237 | 353 | 1099 |
| UT | % loss | 9.8 | 4.4 | 0.0 | 0.3 | 3.2 |
| DT | % loss | 3.6 | 1.8 | 1.3 | 2.2 | 2.3 |

Overall, a complete data set was available for 96.8% of the Up-Track drive and 97.7% of the Down-Track drive.

## 5.0 PURPOSE AND SCOPE OF STUDY

### *5.1 Purpose of the study*

The purpose of the study was to assess:

1. How does the TBM data change with different ground conditions?

2. What combination of measured parameters or derived parameters best reflect the changes in the ground conditions?

3. Can TBM data be used to interpret the ground conditions encountered during tunnelling, and, if so, on what basis should such an interpretation be made?

4. Can the effect of the changed TBM design be measured in the selected parameters?

### *5.2 Study procedure*

The first step of the study was to determine the value of the parameters and derived parameters listed in Table 5, for each ring of advance on each of the two TBM drives. Each advance, and the related parameters, were then allocated to one of the four face ground categories, based on the assessment made during tunnelling.

There were two stages of study: the initial study and the detailed study. The initial study compared selected aspects of the two drives, to confirm whether there was a significant difference between the two. The initial study involved an overall comparison of the Up-Track and Down-Track drives in terms of the total duration, number of interventions and tool consumption. The average values of the forces, other parameters and derived parameters for the four ground categories were also compared between the two drives.

Table 5. Parameters and derived parameters for the TBM tunnelling

| **Parameters** | |
|---|---|
| $F_c$ | Contact Force |
| T | Torque |
| $F_{fr}$ | Friction (including friction on the tail seals |
| $F_d$ | Tail Drag |
| ROP | Rate of penetration (mm/rev) |
| PR | Penetration rate (mm/minute) |
| RPM | Revolutions per minute |
| Fn | Average force per disc |
| $F_{total}$ | Total Thrust |
| **Derived Parameters** | |
| SE | Specific Energy |
| FPI | Field Penetration Index |
| mFPI | Modified Field Penetration Index |

The detailed study involved plotting the parameter combinations listed in Table 6 for each of the four face categories, separately and in combination, for the Up-Track drives. This was to investigate general relationships and determine which combination(s) provided the clearest distinction between the ground categories. The procedure was then repeated for the Down-Track drive, and the results of the Up-Track and Down-Track drives compared, to see whether the effect of the changes made to the TBM were evident in the results.

Table 6. Plots of parameters and derived parameters prepared as part of the detailed study

| x-axis | y-axis |
|---|---|
| Torque | Contact Force |
| Contact Force | Friction |
| Torque | Friction |
| Contact Force | Rate of Penetration |
| Torque | Rate of Penetration |
| Specific Energy | Rate of Penetration |
| Specific Energy | FPI |
| Specific Energy | mFPI |

## 6.0 INITIAL STUDY

### *6.1 Tunnelling duration*

The Down-Track drive was very slightly longer than the Up-Track, by 3 rings (4.5m), but for the purpose of an overall comparison the difference is immaterial. The tunnelling progress for the Up-Track drive has been superimposed on the progress of the Down-Track drive in Figure 12. As shown in the figure, the total time required for the Down-Track drive was 3.2 months less than for the Up-Track.

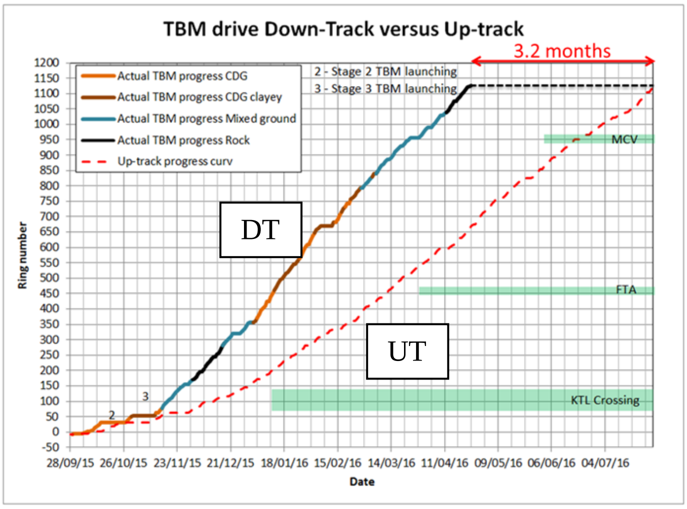


Figure 12. Comparison of the tunnelling duration between the Down-Track and Up-Track TBM

### *6.2 Interventions and tool consumption*

The number of interventions and cutting tools changed on each of the drives is summarized in Table 7.

Table 7. Comparison of the number of interventions and the number of cutting tools changed for the Up-Track and Down-Track drives

| | Unit | UT | DT | Change, % |
|---|---|---|---|---|
| Interventions | No. | 149 | 107 | -28.2 |
| Single discs | No. | 577 | 429 | -25.6 |
| Double discs | No. | 27 | 17 | -37.0 |
| Bucket lips | No. | 193 | 108 | -44.0 |
| Scrapers | No. | 96 | 57 | -40.6 |

In every category listed, the number for the Down-Track drive was significantly less than for the Up-Track drive: the number of interventions reduced by 28.2%, the number of tools that required changing was consistently less, with reductions that varied from 25.6%, in the number of single discs changed, to 44% in the number of bucket lips changed.

### *6.3 Comparison of average and maximum values for parameters*

The average and maximum values of selected TBM parameters for the whole of the Up-Track and Down-Track are compared in Table 8. The average penetration rate increased by 15.6% for the Down-Track tunnel, but the average values for thrust, contact force, torque and friction reduced, by between 8.9% and 21.3%.

Included in Table 8 are the limiting values for thrust, torque and contact force. The limiting value for contact force was established by multiplying the number of discs by the recommended limiting force as stated by the manufacturer (300 kN). The maximum values for thrust and torque were 87% and 93% of the limiting values, respectively, for the Up-Track tunnel, but 69% and 80% for the Down-Track drive. For the Up-Track drive the limiting value for the Contact Force was locally exceeded but was never more than 80% for the Down-Track drive.

The target face pressure was adjusted between the Up-Track and Down-Track drives, reducing the average and maximum face pressure required. See Shirlaw et al. (2017) for detail on the basis of the face pressures and adjustment to the face pressures.

Table 8. Average and maximum values of TBM parameters

| **Drive** | **Item** | **Unit** | **Installed maximum** | **Average value** | **Maximum value** | **Ground Class. Max. value** |
|---|---|---|---|---|---|---|
| UT | Penetration rate | mm/min | | 18 | 38 | Saprolite |
| DT | Penetration rate | mm/min | | 21 | 50 | cl cdg |
| UT | Thrust | kN | 49,400 | 27,386 | 42,895 | Rock |
| DT | Thrust | kN | 49,400 | 21,966 | 34,219 | Rock |
| UT | Contact Force | kN | 13,200 | 5,681 | 14,147 | Mixed Ground |
| DT | Contact Force | kN | 13,200 | 4,644 | 10,386 | Rock |
| UT | Friction | kN | | 3,997 | 13,715 | cl cdg |
| DT | Friction | kN | | 3,144 | 10,442 | cl cdg |
| UT | Torque | kNm | 4,510 | 2,131 | 4,359 | Mixed Ground |
| DT | Torque | kNm | 4,510 | 1,942 | 3,772 | Rock |
| UT | Face pressure at axis | Bar | | 3.88 | 6.48 | Rock |
| DT | Face pressure at axis | Bar | | 3.21 | 4.20 | Rock |

### *6.4 Comparison of average forces, parameters and derived parameters by face category*

The average value of the forces applied to the Up-Track TBM in each of the four face condition categories is shown as a histogram in Figure 13, while the values for the Down-Track TBM are provided in Figure 14.

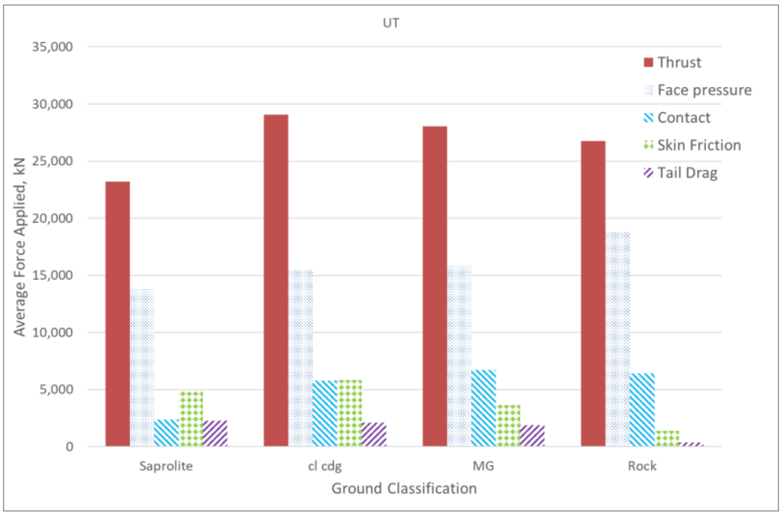


Figure 13. Average distribution of forces on the Up-Track TBM in the four ground categories

For both drives:

The majority of the thrust force, about 60%, was required to balance the face pressure for both drives and in all face categories. There was a reduction in the force required to balance the face pressure in the Down-Track drive, due to some fine-tuning of the face pressures based on the experience of the Up-Track drive. Saw et al. (2017) provide the basis of the face pressures and the changes between the pressures used for the Up- and Down-Track drives.

The lowest average Contact Force was applied in the saprolite, on both drives.

The average Friction Force was lowest in the rock and highest in clayey cdg.

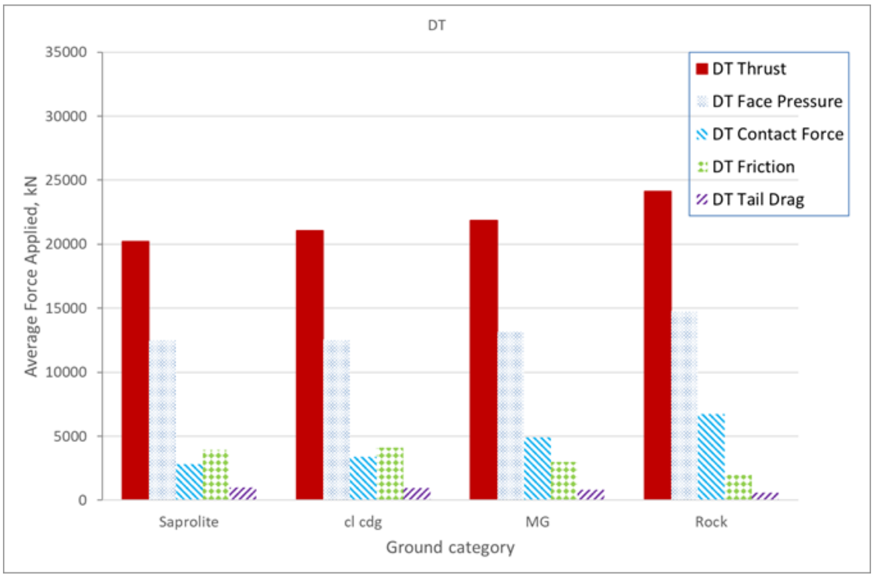


Figure 14. Average distribution of forces on the Down-Track TBM in the four ground categories

The average values of forces and other selected parameters used for the two drives, divided by face category, are summarized in Table 9, and of the derived parameters in Table 10. The percentage change is also provided in Tables 9 and 10. The average rate of penetration increased for all four face categories for the Down-Track tunnelling. In the clayey cdg and the mixed ground the increase in the rate of penetration occurred despite a marked reduction in the average values for, particularly, contact force, torque, specific energy and field penetration index.

Table 9. Average values for Rate of Penetration and forces for each ground category compared for the two drives.

| Drive | Parameter | Unit | Saprolite | cl cdg | MG | Rock |
|---|---|---|---|---|---|---|
| UT | ROP | mm/rev | 13.60 | 11.40 | 8.70 | 4.60 |
| DT | ROP | mm/rev | 15.17 | 13.85 | 9.88 | 6.90 |
| | | % change | 11.54 | 21.49 | 13.56 | 50.00 |
| UT | Contact Force | kN | 2,343 | 5,759 | 6,728 | 6,417 |
| DT | Contact Force | kN | 2,832 | 3,414 | 4,903 | 6,749 |
| | | % change | 20.87 | -40.72 | -27.13 | 5.17 |
| UT | Torque | kNm | 1,145 | 2,814 | 2,734 | 1,271 |
| DT | Torque | kNm | 1,783 | 1,811 | 2,330 | 1,910 |
| | | % change | 55.72 | -35.64 | -14.78 | 50.28 |
| UT | Friction | kN | 4,782 | 5,843 | 3,637 | 1,378 |
| DT | Friction | kN | 3,945 | 4,107 | 2,987 | 1,991 |
| | | % change | -17.50 | -29.71 | -17.87 | 44.48 |

Table 10. Average values for the derived parameters for each ground category compared for the two drives.

| Drive | Parameter | Unit | Saprolite | cl cdg | MG | Rock |
|---|---|---|---|---|---|---|
| UT | SE | Mj/m3 | 16.1 | 44.9 | 55.3 | 45.6 |
| DT | SE | Mj/m3 | 18.6 | 21.1 | 38.5 | 42.7 |
| | | % change | 15.5 | -53.0 | -30.4 | -6.4 |
| UT | FPI | $MN/m^2/rev$ | 4.8 | 14.2 | 21.8 | 39.2 |
| DT | FPI | $MN/m^2/rev$ | 5.2 | 7 | 13.8 | 29.5 |
| | | % change | 8.3 | -50.7 | -36.7 | -24.7 |
| UT | mFPI | | 25.3 | 65.8 | 84 | 99.3 |
| DT | mFPI | | 29.6 | 36.9 | 58.5 | 92.9 |
| | | % change | 17.0 | -43.9 | -30.4 | -6.4 |

The Specific Energy for tunnelling reduced in every category for the Down-Track drive, except in the saprolite. The total energy required reduced from 884.85MWh for the Up-Track to 637.24 MWh for the Down-Track. The 28% reduction reflected the saving in the electrical energy required for the tunnelling.

### *6.5 Review of the results of the initial study*

The initial study showed that there was a major difference between the tunnelling for the Up- and Down-Track drives. The overall duration was significantly shorter, with fewer interventions and tool changes. The average penetration rate was higher on the Down-Track than the Up-Track drive, while the average contact force and torque were significantly lower. This confirmed that, overall, the modifications to the TBM had made a significant difference to the tunnelling, and that a more detailed study was justified.

The summary of average forces and parameters summarized in Tables 9 and 10 shows that the reduction in forces, torque and derived parameters was particularly concentrated in the clayey cdg and in the mixed ground.

The average data showed a pattern of reducing friction on the shield as the TBM moved from clayey cdg to mixed ground to rock, for both drives. The average friction in the clayey cdg and mixed ground also reduced between the Up-Track and Down-Track drives. The change in the value for friction on the shield between different ground conditions and between the Up-Track and Down Track drives was included in the detailed study.

While the maximum value of the contact force locally exceeded the recommended value on the Up-Track drive, the average values used for tunnelling in the rock were 48.6% for the Up-Track drive and 51.1% for the Down-Track. These values are low compared with data from hard rock TBMs and is considered suitable for further study. However, a study of the interaction of the TBM and the rock, including the variation of rock strength and its effect on the tunnelling performance, was considered beyond the currently planned work and this paper. It is intended to address this in as a further phase of the study.

## 7.0 REVIEW OF TBM DATA, UP-TRACK DRIVE

Graphical examples of the relationships are shown in three groups:

Contact Force vs Torque vs Friction
Rate of Penetration vs Contact Force or Torque
Specific Energy vs Friction, Rate of Penetration, Field Penetration Index or modified Field Penetration index.

Most of the examples presented show the data for the full drive, with different symbols and colours used to distinguish the data from each category of face condition. As there are almost 1000 data points on the graphs for each drive, some of the details are obscured by the sheer number of data points. For clarity, selected graphs are used to show and contrast the data in particular face condition categories.

### *7.1 Up-Track, Contact Force vs Torque vs Friction*

The data for contact force and torque are presented in Figure 15.

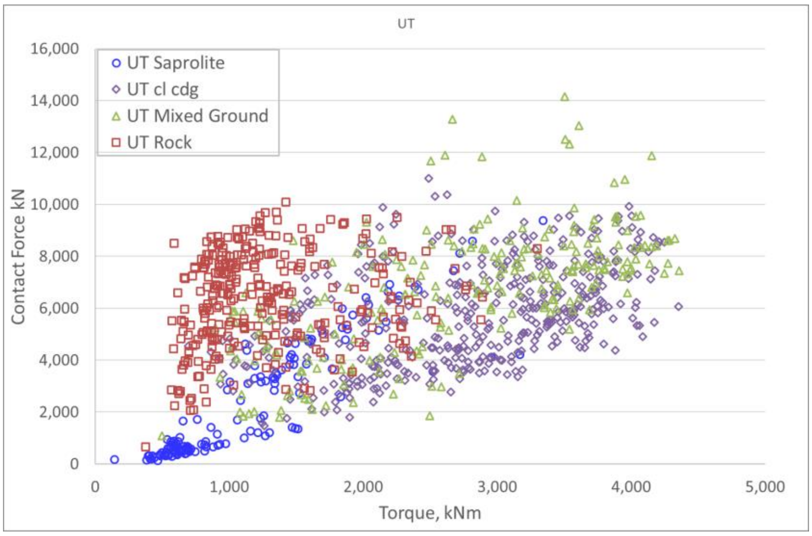


Figure 15. Torque plotted against Contact Force, Up-Track tunnel

Generally, the various face conditions are characterized by:

Saprolite: low contact force and low torque
Rock: high contact force and low to moderate torque
Clayey cdg and mixed ground: high contact force and high torque

Although this pattern is evident for most of the data plotted, there is significant scatter and overlapping of data.

The information presented in Figure 15 can be interpreted in relation to the nature of the ground categories and the action of the cutting tools.

Saprolite is weak. The grade V (completely weathered rock) portion of the saprolite behaves like a silty sand and is easily excavated. In hand mined tunnels, the Grade V granite was typically excavated with pneumatic spades. The soil would have been easily excavated by the action of the scrapers. The cutting action of the scrapers (Figure 7) primarily involves torque, with some contact force to push the cutting edge of the scrapers into the ground. Although the primary cutting action in soft ground is by the scrapers, the discs lead the scrapers on a mixed ground cutterhead, by 50mm in this case. As a result, in soft ground some additional contact force is required to push the discs into the ground ahead of the scrapers.

The granite was typically strong to very strong. The rock would have been cut by the action of the discs. The cutting action of the discs involves mostly contact force. As the discs are free to rotate, only limited torque is generally required to excavate the rock.

In the clayey cdg the sticky nature of the ground required both more contact force, to help extrude the material through the openings in the cutterhead, and more torque, due to the clogging of the material, than the tunnelling in the saprolite. In mixed ground the transition between soil and rock would have resulted in impact on the discs, causing additional torque compared with tunnelling in a full face of rock; it is likely that some of the mixed ground involved a combination of rock and clayey cdg, which would have also required additional contact force and torque to advance the TBM. There was significant evidence of discs getting jammed and not turning on the Up-Track drive, causing excessive disc wear. Jammed and damaged discs would also have increased the required torque in the mixed ground.

Although the typical location of data for the four categories of ground, as presented in Figure 15 is consistent with the nature of the ground and the cutting action of the tools on the TBM, there is significant intermingling of the data for the four ground categories.

The data for contact force and friction are presented in Figure 16.

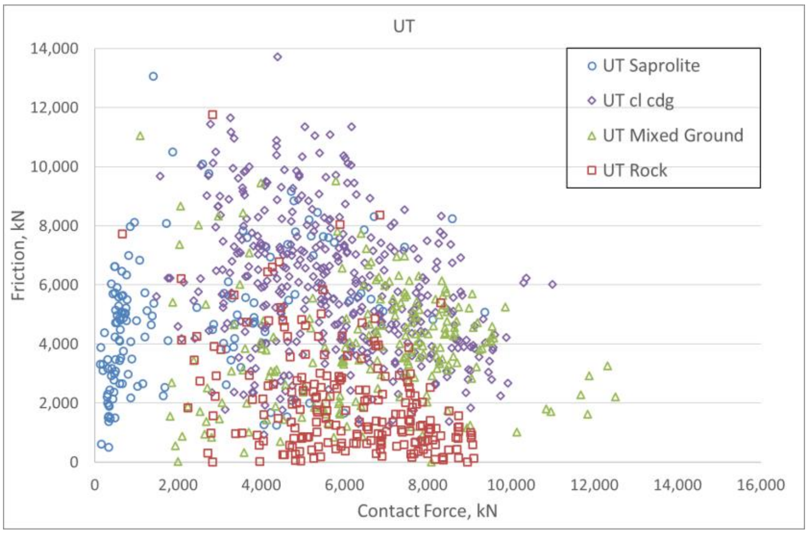


Figure 16. Contact Force plotted against Friction, Up-Track tunnel

There is a lot of scatter for all ground categories, but, generally, the various face conditions are characterized by:

Saprolite: low contact force
Rock: high contact force and low friction
Clayey cdg and mixed ground: high contact force and high friction

A similar general pattern can be observed in the relationship between torque and friction, as presented in Figure 17.

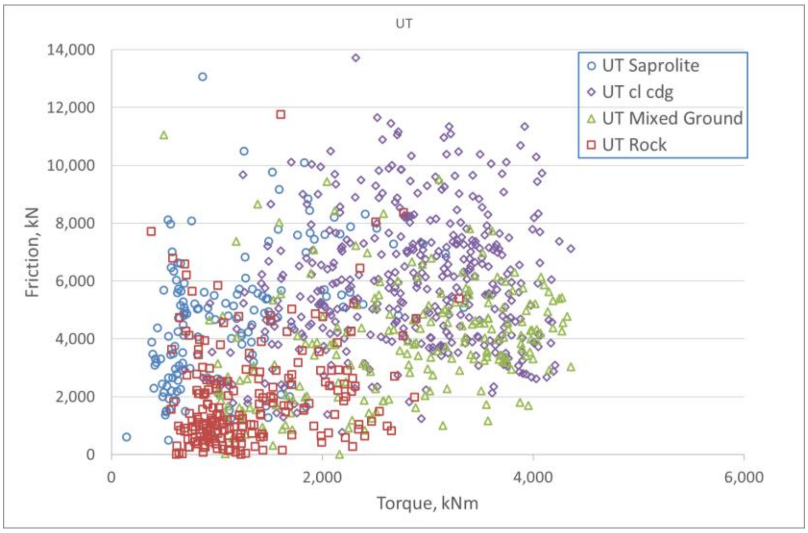


Figure 17. Torque plotted against Friction, Up-Track tunnel

The friction on the TBM will be discussed further later in the paper.

### *7.2 Up-Track, Rate of Penetration vs Contact Force or Torque*

Maximising the rate of penetration is a significant factor in progressing the tunnelling as rapidly as possible. The relationship between the contact force and rate of penetration is presented in Figure 17.

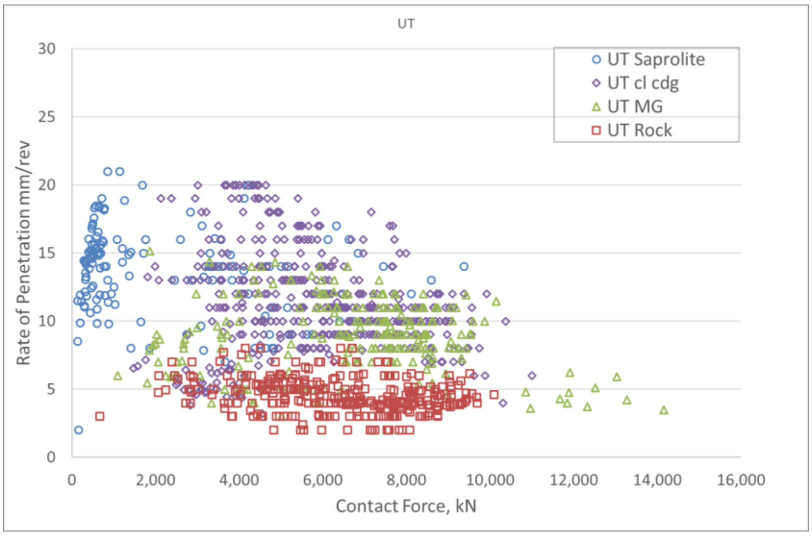


Figure 18. Contact Force plotted against Rate of Penetration, Up-Track tunnel

Generally, the various face conditions are characterized by:

Saprolite: low contact force and moderate to high rate of penetration
Rock: high contact force and low rate of penetration
Clayey cdg and mixed ground: high contact force and low to high rate of penetration

Although this pattern is evident for the majority of the data plotted, there is significant scatter and overlapping of data.

The relationship between the torque and rate of penetration is presented in Figure 19.

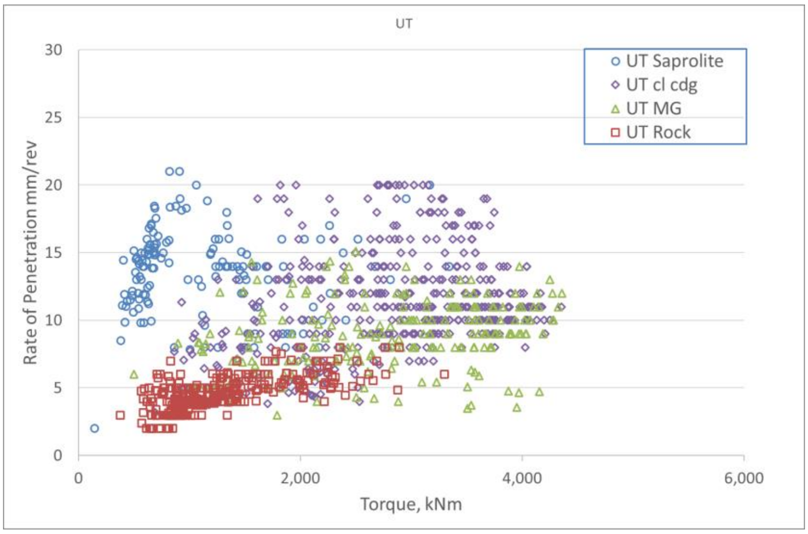


Figure 19. Torque plotted against Rate of Penetration, Up-Track tunnel

Generally, the various face conditions are characterized by:

Saprolite: low torque and moderate to high rate of penetration
Rock: low to moderate torque and low rate of penetration
Clayey cdg and mixed ground: high torque and moderate to high rate of penetration

Although this pattern is evident for most of the data plotted, there is significant scatter and overlapping of data.

### *7.3 Specific Energy vs Friction, Rate of Penetration, Field Penetration Index or modified Field Penetration Index*

Specific Energy is widely used in the assessment of hard rock TBMs (Mirahmadi et al. 2017), including for differentiation between rock strata (Purwodihardjo 2011). Graphs were prepared to compare the values for Specific Energy with those of a number of other parameters, including Friction, Rate of Penetration and another widely used parameter in the assessment of hard rock TBM performance, the Field Penetration Index.

The relationship between the Specific Energy and friction is presented in Figure 20.

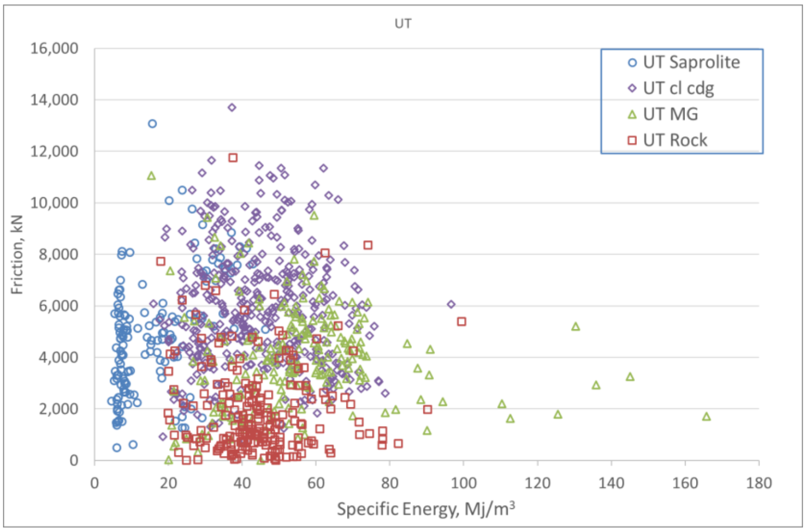


Figure 20. Specific Energy plotted against Friction, Up-Track tunnel

Generally, the various face conditions are characterized by:

Saprolite: low Specific Energy and low to moderate friction
Rock: low to moderate Specific Energy and low friction
Clayey cdg and mixed ground: high Specific Energy and high friction

Although this pattern is evident for the majority of the data plotted, there is significant scatter and overlapping of data

The relationship between the Specific Energy and rate of penetration is presented in Figure 21.

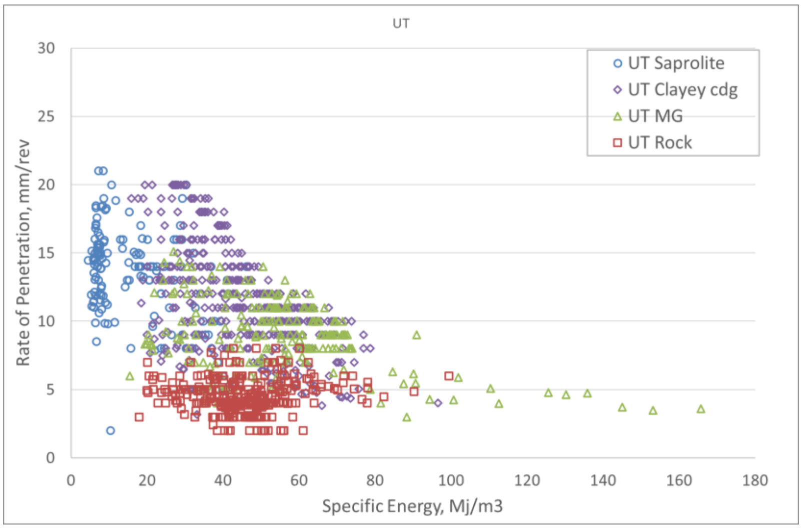


Figure 21. Specific Energy plotted against Rate of Penetration, Up-Track tunnel

Generally, the various face conditions are characterized by:

Saprolite: low Specific Energy and moderate to high rate of penetration
Rock: low to moderate Specific Energy and low rate of penetration
Clayey cdg and mixed ground: low to high Specific Energy and low to high rate of penetration

Although this pattern is evident for the majority of the data plotted, there is significant scatter and overlapping of data

The relationship between the Specific Energy and Field Penetration Index is presented in Figure 22.

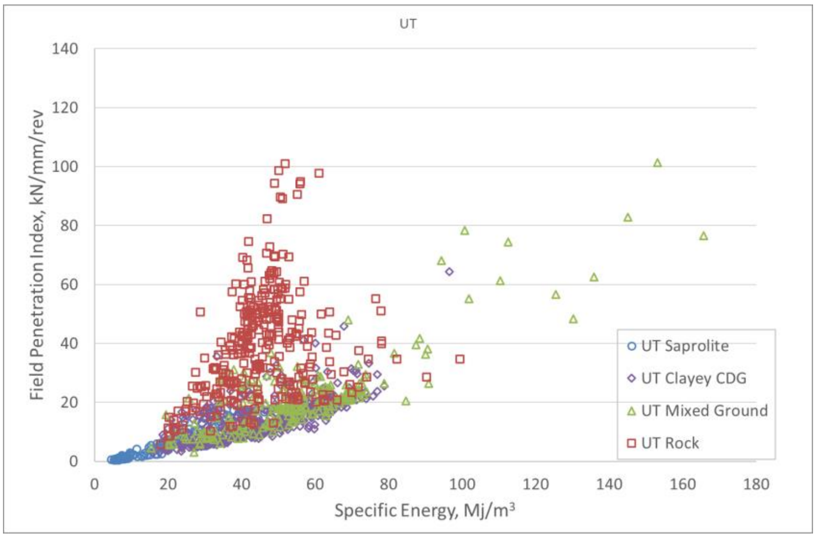


Figure 22. Specific Energy plotted against Field Penetration Index, Up-Track tunnel

Figure 22 shows saprolite, clayey cdg and mixed ground following a generally common trajectory with a similar ratio of Field Penetration Index to Specific Energy. The linear interpolation of the ratio is 0.35 for saprolite, 0.32 for clayey cdg and 0.41 for mixed ground. While the values for saprolite, clayey cdg and mixed ground form successive groups along approximately the same trajectory, the data for rock forms a distinct group. The data for rock is bounded at the lower end by the mass of the data for the other face categories. The general trajectory of the data for rock is upward on the graph, with increasing values for Field Penetration Index, but limited change to the range for Specific Energy. The number of points and the scale required to fit in all the points makes it difficult to distinguish the values for saprolite, clayey cdg and mixed ground. The average value of Specific Energy for these three categories was 16.1, 44.9 and 55.3 MJ/m$^3$, respectively, for the Up-Track drive. To assess whether the three categories of ground could be identified from the data, normal distribution curves for the values of Specific Energy have been plotted in Figure 23a. There is considerable overlap between the range of values for clayey cdg and mixed ground, but limited overlap between saprolite and mixed ground. A similar chart for Field Penetration Index is plotted in Figure 23b. The more typical conditions in weathered granite include only the three general categories: saprolite, mixed ground and rock. Based on Figure 23a, there would be would be limited overlap between the values for Specific Energy for saprolite and mixed ground. Comparing Figure 23a and 23b, Specific Energy provides slightly better distinction between the categories than Field Penetration Index.

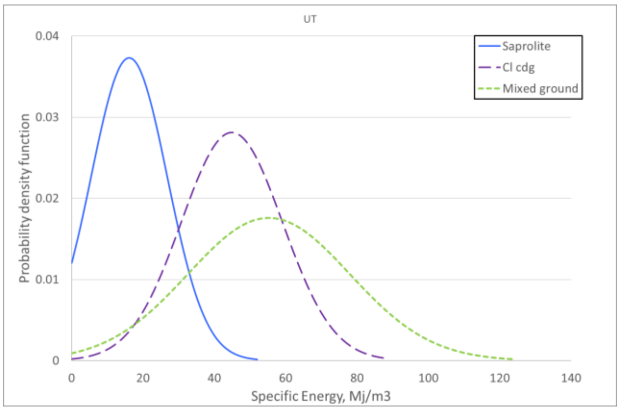


Figure 23a. Distribution of values for Specific Energy for saprolite, clayey cdg and mixed ground, Up-Track tunnel

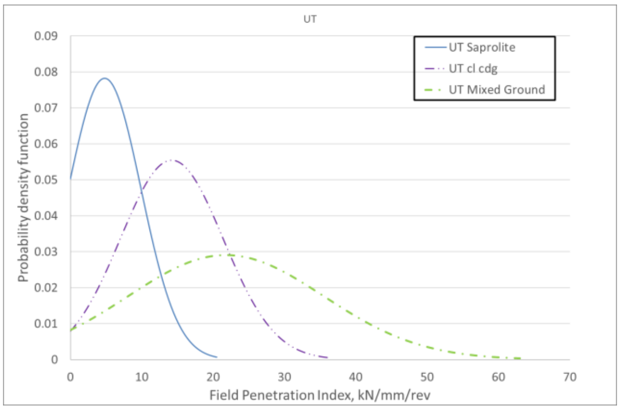


Figure 23b. Distribution of values for Field Penetration Index for saprolite, clayey cdg and mixed ground, Up-Track tunnel

The relationship between the Specific Energy and modified Field Penetration Index is presented in Figure 24 and can be contrasted with the data in Figure 21.

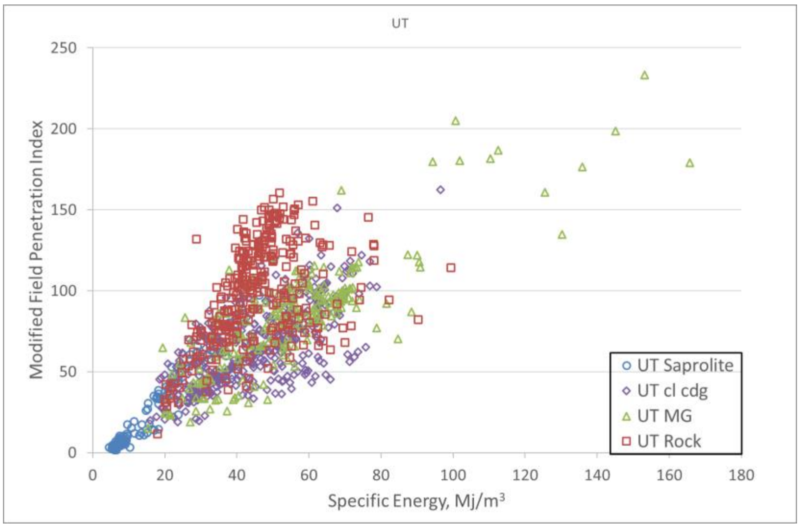


Figure 24. Specific Energy plotted against modified Field Penetration Index, Up-Track tunnel

The majority of the data from saprolite and rock align around a general relationship of:

mFPI = 2SE

While the data for the clayey cdg and mixed ground lies between

mFPI = SE and 2SE, and is centred on mFPI = 1.5 SE.

The ratios quoted above are for values based on the units given in Section 4.3.

### *7.4 Comment on Up-Track data*

Reviewing the graphs presented in 7.1 to 7.3, the most consistent distinction between the various ground categories is provided in Figure 22, Specific Energy plotted against the Field Penetration Index. There is some overlap between the data for tunnelling in rock and the other categories of saprolite, clayey cdg and mixed ground. However, some overlap is inevitable due to, inter alia:

1. The imprecision with which the boundaries between the materials can be defined using the simple field tests used for classification
2. The limited exposure of the ground in the face available during the interventions
3. The limited accuracy of the interpretation of the ground conditions between the interventions based on the scalpings at the STP

The degree of overlap between the data was assessed by establishing criteria for the boundary between the data for the saprolite and the mixed ground, and between the mixed ground and the rock. The crite-ria are illustrated in Figures 25 and 26 and summarized in Table 11.

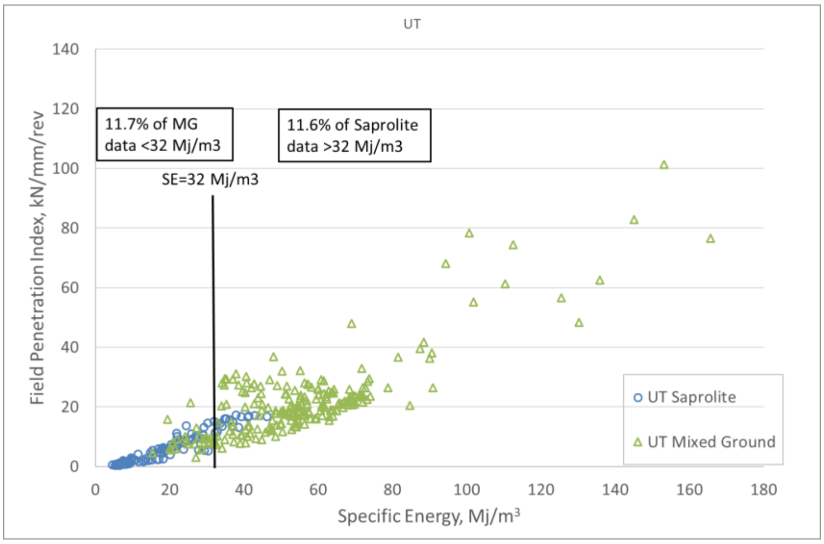

Figure 25. Overlapping of the data from the saprolite and the mixed ground, Up-Track

Table 11. Criteria for distinguishing ground categories and percentage overlap

| Ground category | Criterion | Number of points beyond criterion | Percentage of points beyond criterion |
|---|---|---|---|
| Saprolite | SE<32 | 17 out of 147 | 11.6% |
| Mixed Ground | SE>32 | 26 out of 222 | 11.71% |
| Mixed Ground | FPI/SE<0.492 | 37 out of 222 | 16.7% |
| Rock | FPI/SE>0.492 | 51 out of 304 | 16.8% |

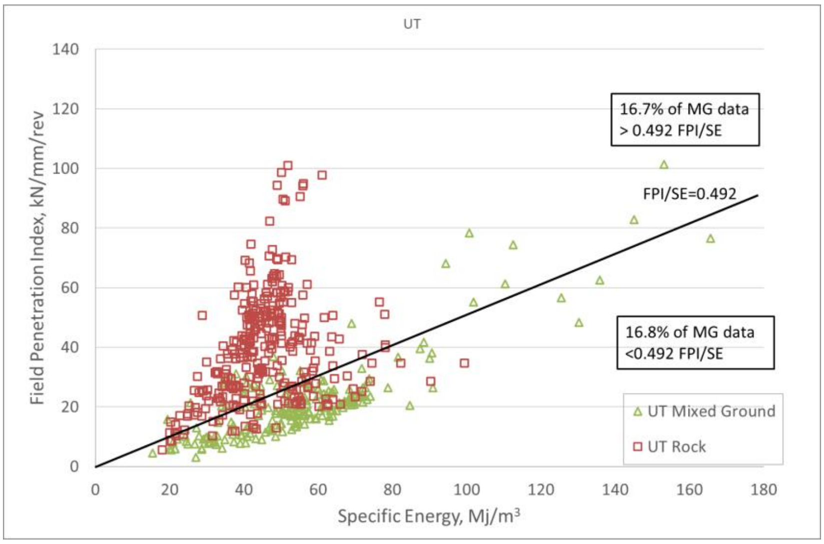


Figure 26. The data from the Up-Track drive for mixed ground and rock, with the criterion for the ratio of the Field Penetration Index to the Specific Energy and percentage of overlapping points.

It is considered likely that much of the overlap between the values for the various face categories was due to imprecision in the ground classification assessed during tunnelling and used as the basis for this analysis.

Theoretically, there is value in plotting Specific Energy against modified Field Penetration Index, as shown in Figure 23. This is the figure that is most consistent with the general concept of the weathered rock categories presented in Figure 6: the data for saprolite and rock are approximately aligned. This is consistent with saprolite and rock being a continuum distinguished by strength on a material scale. The clayey cdg and the mixed ground deviate from this general trend, with generally greater values of Specific Energy for a given value of Field Penetration Index. This is also consistent with the general concept, as clayey cdg would clog, so requiring more torque to turn the cutterhead and more Specific Energy than the typical granitic saprolite. The mixed ground would also present more resistance to torque than a rock of comparable average strength, due to the need for additional torque at the saprolite/rock boundaries. However, in the resulting diagram there is significantly more overlap between the data for the four categories than there is for the plot of Specific Energy against Field Penetration Index. The latter is therefore preferred as a basis for relating the TBM parameters to the face conditions.

## 8.0 REVIEW OF TBM DATA, DOWN-TRACK DRIVE

Graphical examples of the relationships are shown in the same three groups as for the Up-Track drive, although a smaller number of figures are shown. Each graph is juxtaposed with the graph from the Up-Track. The reduced scale results in some loss of clarity due to the number of data points involved, but direct comparison allows easy comparison of how the graphs change between the two drives. The comparison is made only for selected examples.

### *8.1 Down-Track, Contact Force vs Torque vs Friction*

The data for contact force and torque are presented in Figure 27.

Compared with the Up-Track, on the Down Track there was a general reduction in the Torque required for tunnelling in the clayey cdg and the mixed ground. The particularly high values of contact force observed in the clayey cdg and the mixed ground of over 10,000kN for the Up-Track tunnel were not present in the data for the Down-Track tunnel.

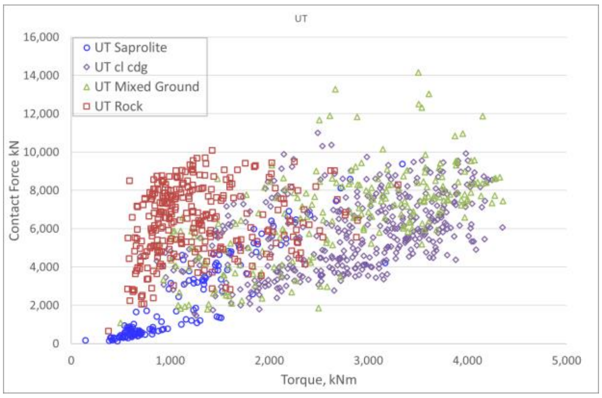


Figure 27a. Torque vs Contact Force, Up-Track

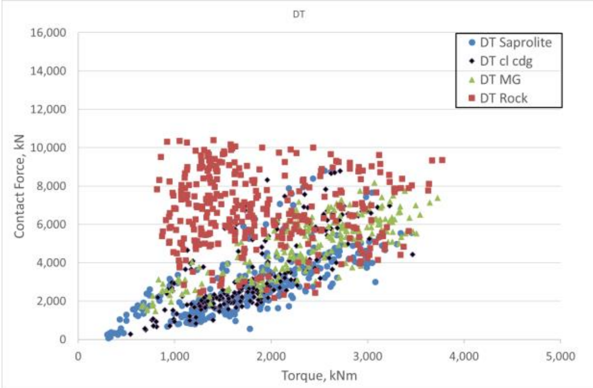


Figure 27b.Torque vs Contact Force, Down-Track

The data for contact force and friction is presented in Figure 28. The higher values of both forces for clayey cdg and the mixed ground have reduced from the Up-Track to the Down-Track drive. For the Down-Track there is a general pattern of reducing friction with increasing contact force.

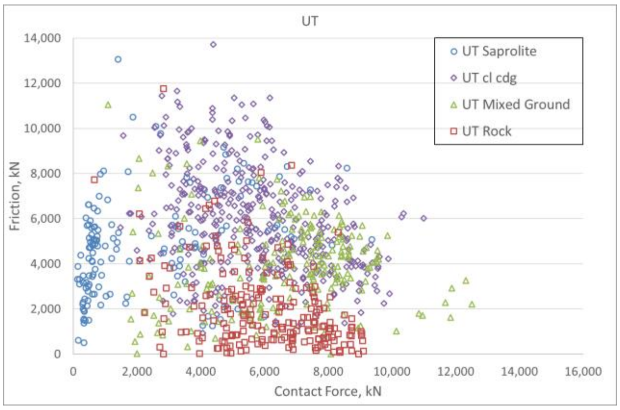


Figure 28a. Contact Force vs Friction, Up-Track

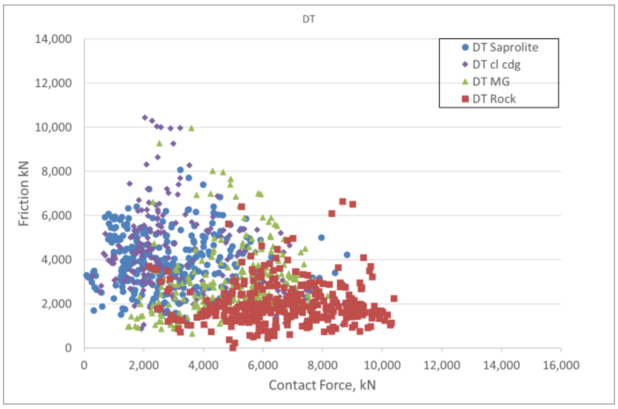


Figure 28b. Contact Force vs Friction, Down-Track

### *8.2 Down-Track, Rate of Penetration vs Contact Force*

The relationship between the contact force and rate of penetration is presented in Figure 29.

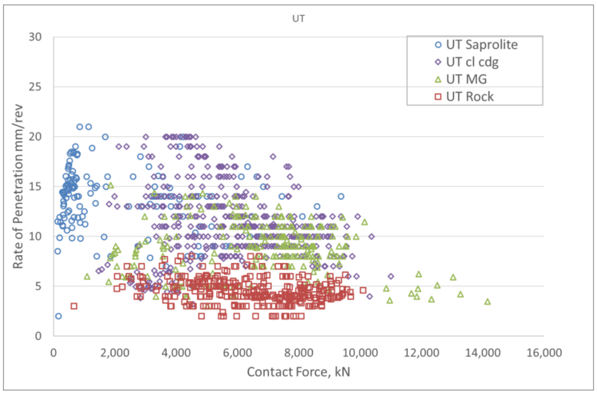


Figure 29a. Contact Force vs Rate of Penetration, Up-Track

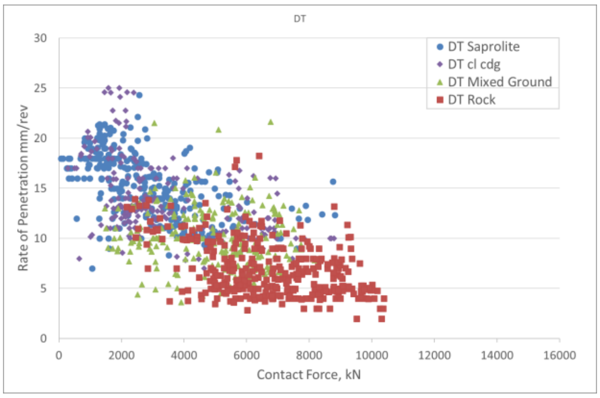


Figure 29b. Contact Force vs Rate of Penetration, Down-Track

In the Up-Track plot (Figure 29a) the data for the saprolite, rock and clayey cdg/mixed ground generally occupy distinct locations on the graphs, albeit with some scatter and overlapping. In the Down-Track data (Figure 29b) the values for the clayey cdg and mixed ground have been pulled into a more general group with the saprolite and the rock, with less distinction between the data from the four ground categories. However, there is a general trend of increasing contact force and reducing rate of penetration with increasing resistance to penetration as the ground type changes from saprolite to clayey cdg to mixed ground to rock.

### *8.3 Down-Track, Specific Energy vs Rate of Penetration, Field Penetration Index or modified Field Penetration Index*

The relationship between the Specific Energy and rate of penetration is presented in Figure 30. In the Up-Track plot the data for the saprolite, rock and clayey cdg/mixed ground generally occupy distinct locations on the graph, albeit with come scatter and overlapping. In the plot from the Down-Track tunnelling the values for the clayey cdg and mixed ground have been pulled into a more general group with the saprolite and the rock, with less distinction between the data from the four ground categories. For the Down-Track data there is a general trend of increasing Specific Energy and reducing rate of penetration with increasing resistance to penetration as the ground type changes from saprolite to clayey cdg to mixed ground to rock.

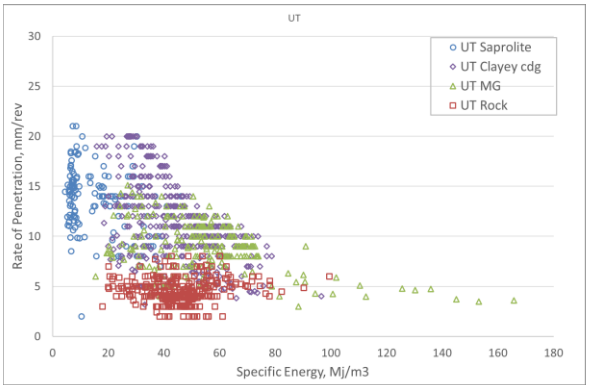


Figure 30a. Specific Energy vs Rate of Penetration, Up-Track

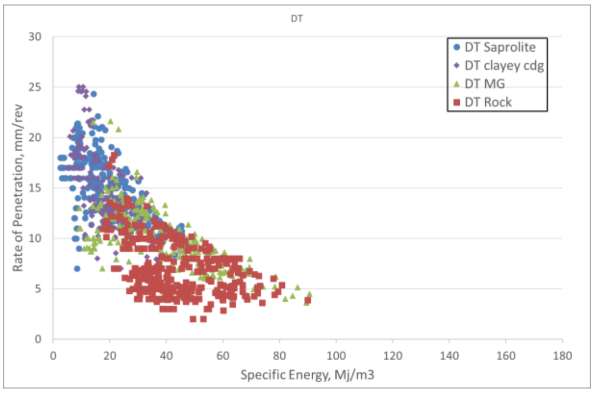


Figure 30b. Specific Energy vs Rate of Penetration, Down-Track

The relationship between the Specific Energy and Field Penetration Index is presented in Figure 31.

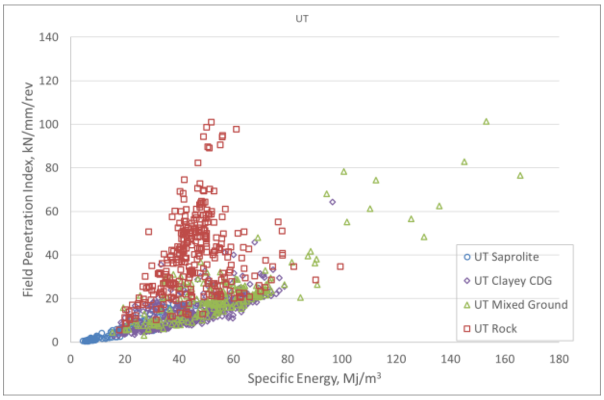


Figure 31a. Specific Energy vs Field Penetration Index, Up-Track

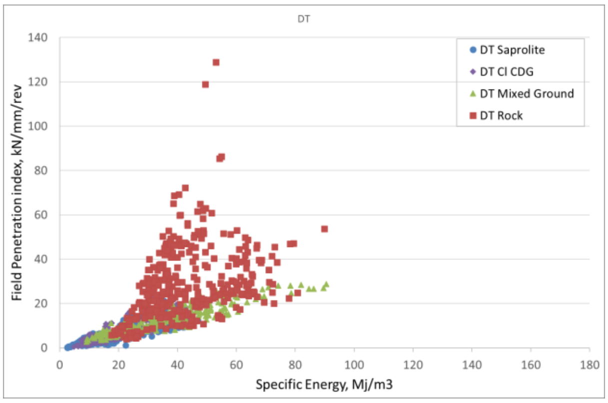


Figure 31b. Specific Energy vs Field Penetration Index, Down-Track

Unlike the graphs presented previously, the graphs for this combination follow a remarkably similar pattern. The data for the saprolite, clayey cdg and mixed ground follows a general trend, with most of the data from the rock plotting above this general trend. One obvious difference between the two charts is that the extreme values in the mixed ground that were present in the Up-Track data were not evident in the Down-Track data. A linear interpolation of the data provides values for the ratio of the Field Penetration Index to Specific Energy summarised in Table 12.

Table 12. The ratio of the Field Penetration Index to the Specific Energy based on linear interpolation of the data

| Drive | Parameter | Saprolite | cl cdg | Mixed ground |
|---|---|---|---|---|
| UT | Ratio FPI/SE | 0.35 | 0.32 | 0.41 |
| DT | Ratio FPI/SE | 0.29 | 0.35 | 0.36 |

The values for saprolite, clayey cdg and mixed ground form successive groups along approximately the same trajectory. Normal distribution curves for the Specific Energy data for the three categories are presented in Figure 32a. Comparing this with Figure 23a, the data for the clayey cdg has become almost indistinguishable from that for the saprolite for the Down-Track drive. The average value for the mixed ground has shifted downwards, increasing the overlap between the data for the saprolite and the mixed ground. There is slightly less overlap between the data for the saprolite and clayey cdg for the Field Penetration Index (Figure 32b) than for Specific Energy.

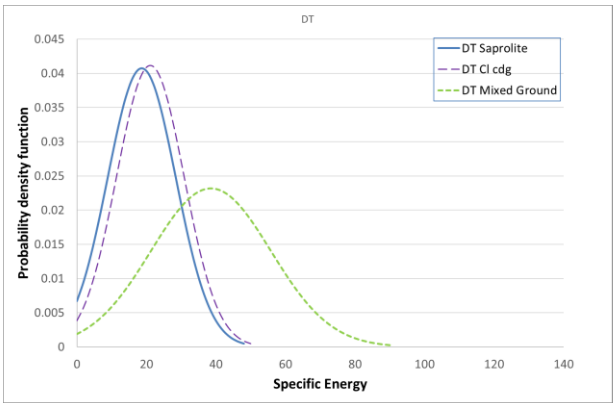


Figure 32a. Distribution of values for Specific Energy for saprolite, clayey cdg and mixed ground, Down-Track tunnel

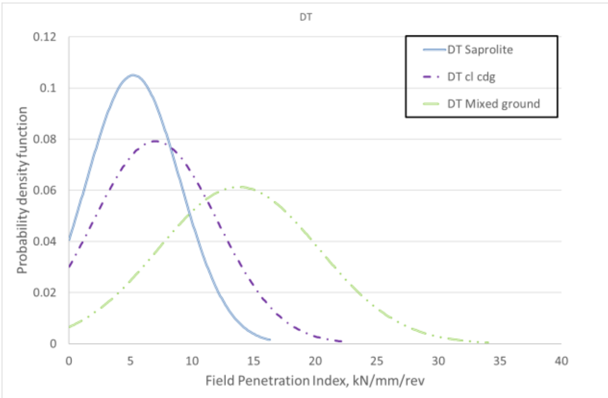


Figure 32b. Distribution of values for Field Penetration Index for saprolite, clayey cdg and mixed ground, Down-Track tunnel

The relationship between the Specific Energy and modified Field Penetration Index is presented in Figure 33.

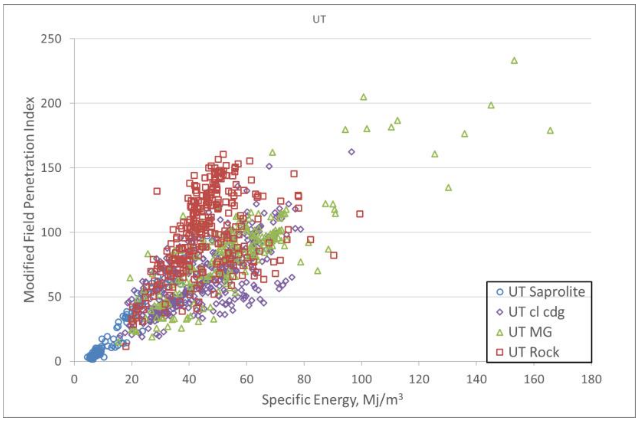


Figure 33a. Specific Energy vs modified Field Penetration Index, Up-Track

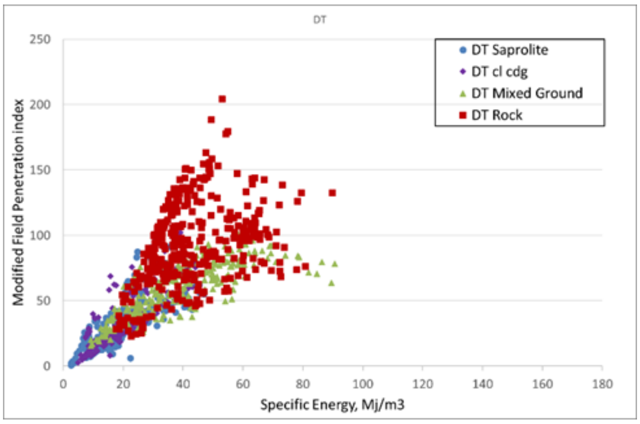


Figure 33b. Specific Energy vs modified Field Penetration Index, Down-Track

The data plotted as Specific Energy vs modified Field Penetration Index occupies the same general area of the graph for both drives, but the extreme values seen for the mixed ground on the Up-Track are not present in the Down-Track drive.

### *8.4 Review of comparison of Up-and Down-Track data*

The graphs relating contact force, torque, friction and rate of penetration all show significant differences between the Up- and Down-Track drives. The greatest change was for the tunnelling in the clayey cdg and the mixed ground. During the Up-Track drive, these ground categories were characterized by high values of both contact force and torque; this was not evident in the graphs for the Down-Track drive. The graphs for rate of penetration against contact force, torque, friction and Specific Energy all show significant changes between the two drives. While any of these graphs may have value for investigating the TBM performance, none of them is ideal for determining how the performance changed between the ground categories because of the changes made to the TBM for the Down-Track drive. It is concluded that the three variables torque, contact force and rate of penetration all need to be considered in comparing the two drives. This can be achieved by plotting Specific Energy against Field Penetration Index or modified Field Penetration Index, as these terms include the three variables. The plots of Specific Energy against Field Penetration Index are chosen for further study as they appear to provide the clearest distinction between the four ground categories, although the plots of Specific Energy against modified Field Penetration Index arguably provide greater consistency with the geological concept provided in Figure 6.

## 9.0 DETAILED COMPARISON OF THE UP- AND DOWN-TRACK DRIVES

From Figure 31 and Table 12, the data from the saprolite, clayey cdg and mixed ground follow a general trend when plotted as Specific Energy against Field Penetration Index. However, the number of data points obscures the exact location of the data from the three ground categories, and how the data changed between the Up- and Down-Track drives. Each of the ground categories will be considered separately, below.

### *9.1 Saprolite*

The data for the saprolite is shown with expanded scales relative to Figures 31a and 31b. The data from the Up-Track drive is presented in Figure 34a and the Down-Track data in Figure 34b. The two plots are similar, as shown in Figure 35, where the two sets of data are combined.

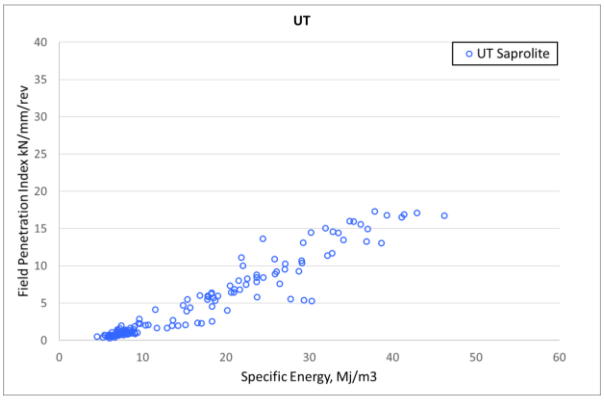


Figure 34a. Specific Energy vs Field Penetration Index, saprolite, Up-Track

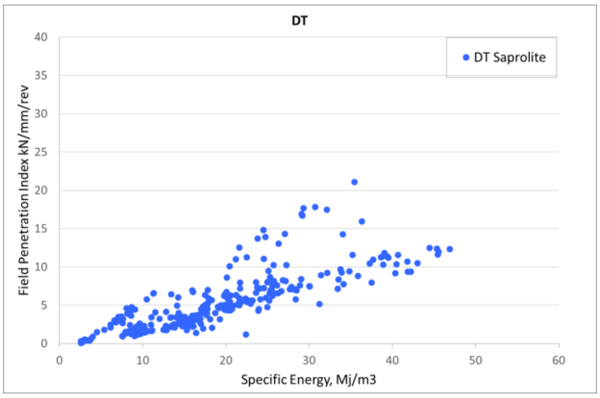


Figure 34b. Specific Energy vs Field Penetration Index, saprolite, Down-Track

Although the scales of Figures 34 and 35 have been expanded so that the points are more distinct, the number of points still results in significant overlapping. The number of data points with a value for Specific Energy of less than 18.5 Mj/m$^3$ is:

Up-Track tunnel 84 out of 147 (57%)
Down-Track tunnel: 164 out of 296 (56%)

18.5 Mj/m$^3$ was selected as the value is the start of a limited overlap with data from the tunnelling in the rock (Figure 22). It is inferred that a value of Specific Energy of 18.5 Mj/m$^3$ approximately defines the boundary between completely decomposed and highly decomposed granite, although this remains to be proven and would be specific to the SCL 1103 TBM.

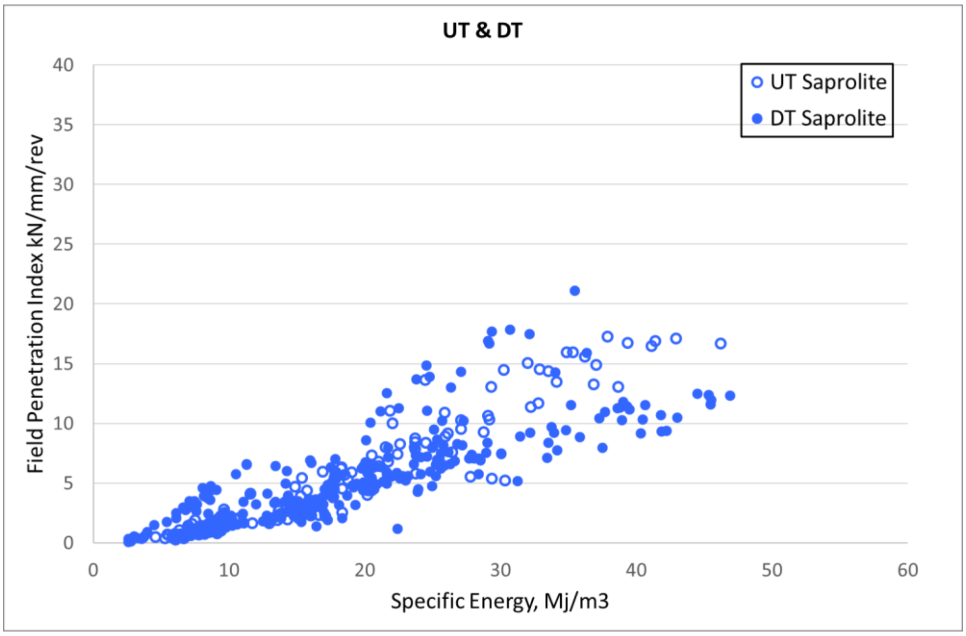


Figure 35. Specific Energy vs Field Penetration Index, saprolite, both drives combined

### *9.2 Clayey cdg*

The data from the Up-Track drive in the clayey cdg is presented in Figure 36a, and for the Down-Track in Figure 36b. The two sets of data are combined in Figure 37, with ellipses bounding the data for each drive superimposed on the figure.

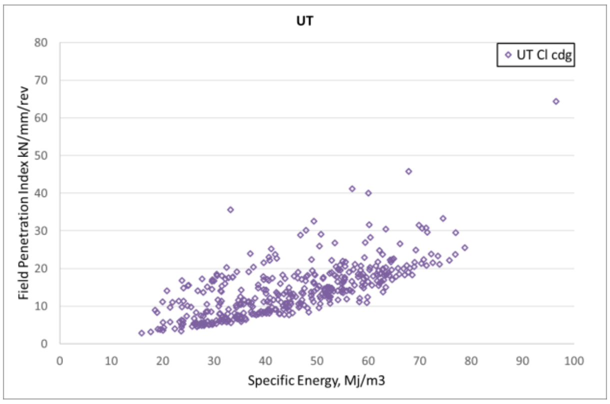


Figure 36a. Specific Energy vs Field Penetration Index, clayey cdg, Up-Track

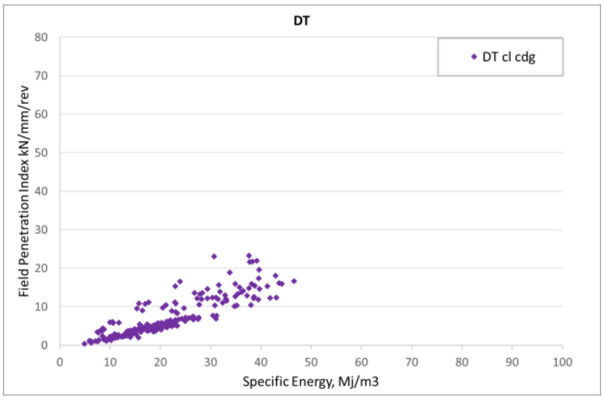


Figure 36b. Specific Energy vs Field Penetration Index, clayey cdg, Down-Track

The data for the clayey cdg from the two drives occupy different locations on the graphs, although with some overlap.

The high values of Specific Energy for the Up-Track tunnelling in the clayey cdg was identified while the tunnelling was in progress. Comparing Figures 36a and 34a, most of the values for Specific Energy in the clayey cdg during the Up-Track drive were over 20 Mj/m$^3$, whereas the majority of the data for the saprolite was less than 20 Mj/m$^3$. The high values of Specific Energy encountered during the Up-Track tunnelling were generally encountered in bands, as shown in Figure 38. The clayey cdg and saprolite were encountered from Ring 322. In Figure 38 four bands of high Specific Energy are shown as 'cl cdg' (clayey cdg) between Ring 322 and Ring 600, with the three bands of low Specific Energy between that were assessed as saprolite.

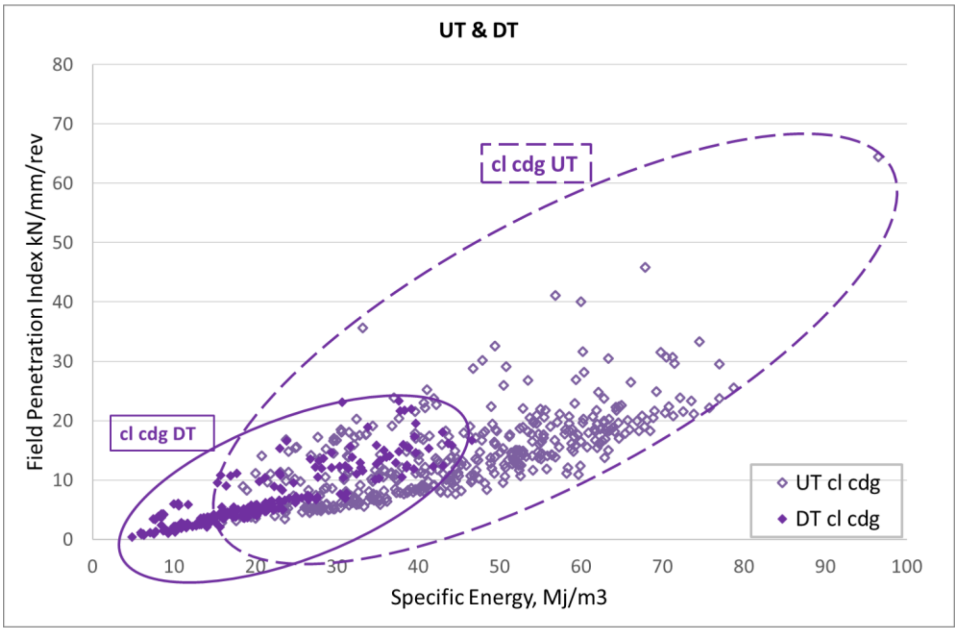


Figure 37. Specific Energy vs Field Penetration Index, clayey cdg, both drives combined

Figure 38 was prepared during the Up-Track tunnelling and was part of a study used to justify the alterations to the TBM and STP planned for the Down-Track tunnelling.

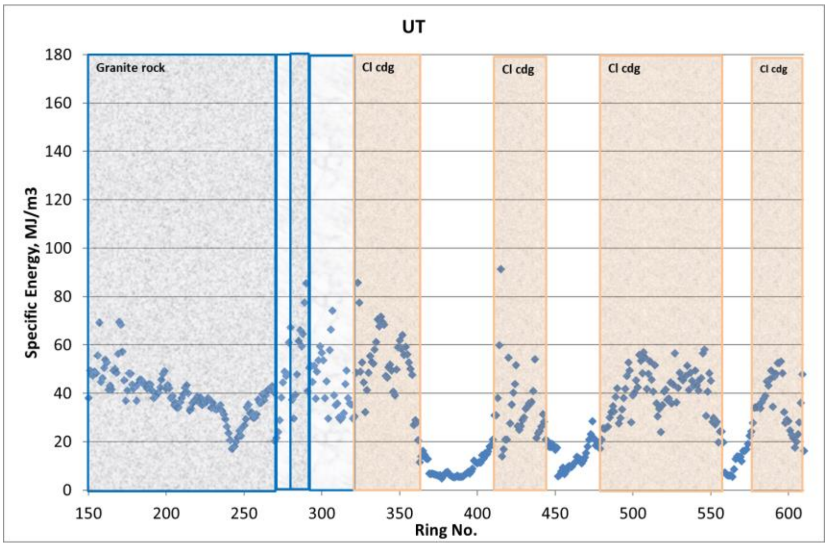

Figure 38. Specific Energy between Rings 150 and 600 of the Up-Track drive

### 9.3 *Mixed ground*

The data for the mixed ground encountered on the Up-Track drive is presented in Figure 39a, and on the Down-Track drive in Figure 39b.

The scatter in terms of both Specific Energy and Field Penetration Index that is apparent in Figure 39a for the Up-Track drive can be contrasted with the more concentrated data from the Down-Track drive in Figure 39b. The combined graph and the general locus of the data for each of the drives is shown in Figure 40, with ellipses bounding the data from each of the drives.

It is evident from Figure 40 that the changes made to the TBM for the Down-Track drive had a significant beneficial effect on the tunnelling in the mixed ground.

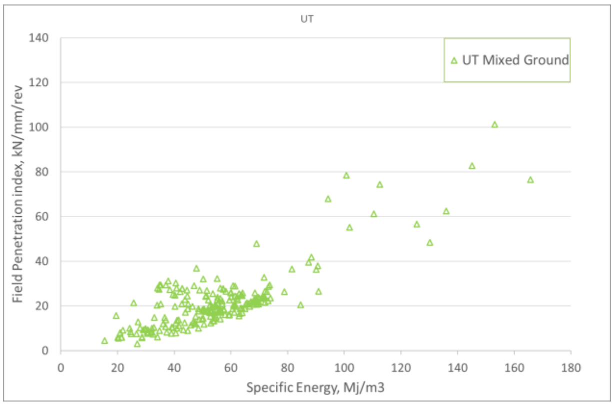


Figure 39a. Specific Energy vs Field Penetration Index, mixed ground, Up-Track

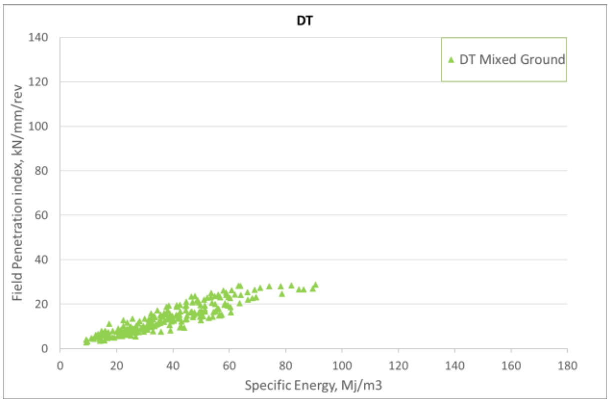


Figure 39a. Specific Energy vs Field Penetration Index, mixed ground, Down-Track

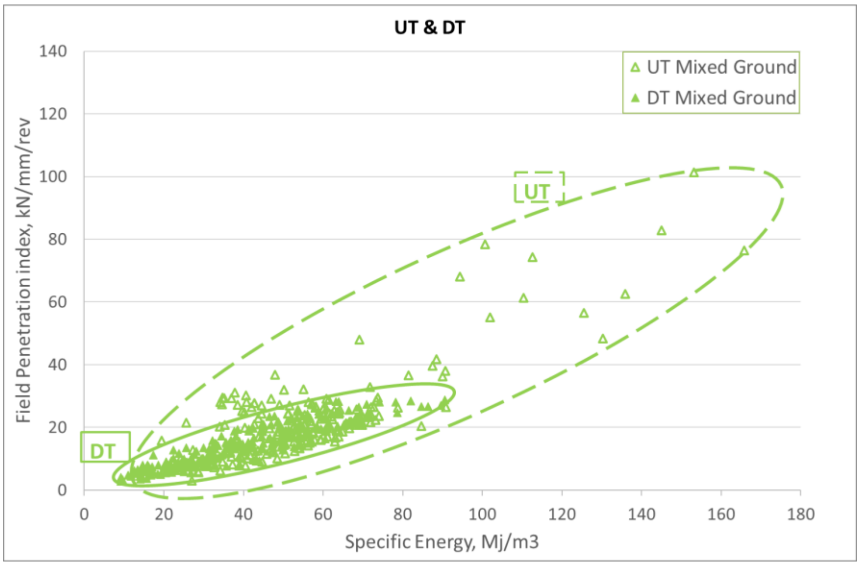


Figure 40. The data for mixed ground for both drives, with the general loci of each drive’s data set

## *9.4 Rock*

The data for the rock from the Up-Track drive is presented in Figure 41a, and the Down-Track data in Figure 41b. The two plots are similar. This confirmed by superimposing the two data sets in Figure 42.

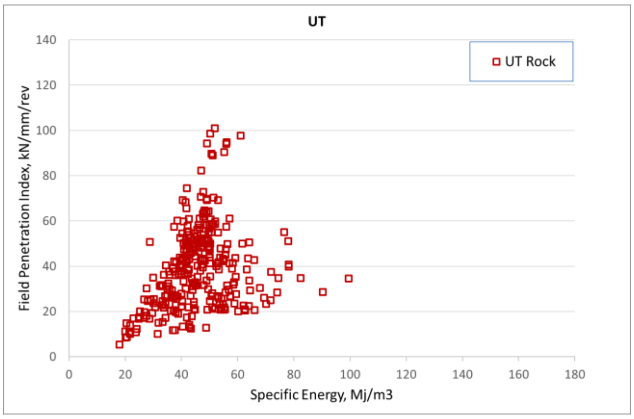


Figure 41a. Specific Energy vs Field Penetration Index, rock, Up-Track

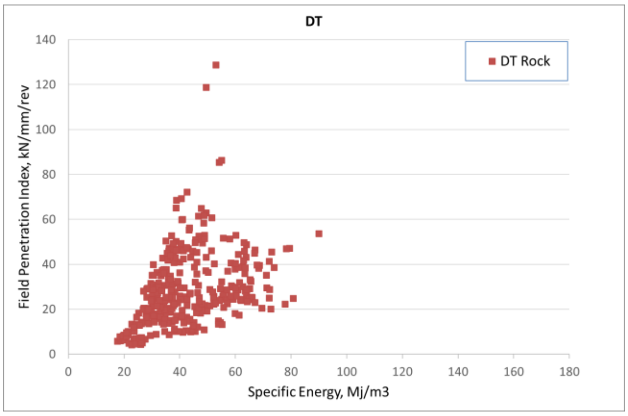


Figure 41a. Specific Energy vs Field Penetration Index, rock, Down-Track

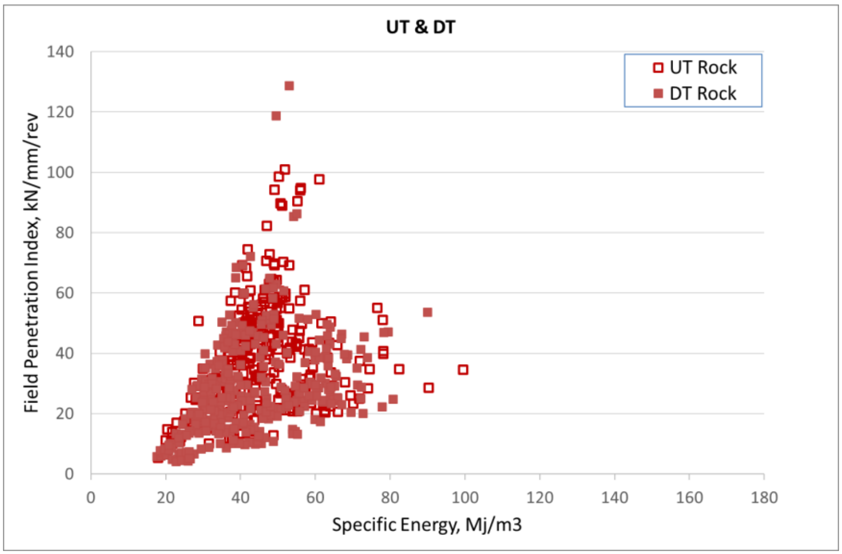


Figure 42. The data for rock for both drives

### *9.5 Analysis of the overlapping of data sets*

A target of the study is to establish whether the ground conditions in weathered granite can be determined from the TBM data. The results presented in Figure 31 show that the data from the tunnelling in the saprolite, clayey cdg and mixed ground follow approximately the same trajectory when plotted as Specific Energy vs Field Penetration Index. In general, the lowest values for Specific Energy are for saprolite and the highest for mixed ground, with clayey cdg in between. However, significant scatter in the data leads to overlapping of the data sets. The degree of overlapping on the Down-Track drive is presented in Table 13, for comparison with that on the Up-Track drive presented in Table 11. For the Up-Track drive the degree of overlap is also illustrated in Figures 25 and 26. Although most of the overlapping points were located close to the boundary, this was not consistent.

Table 13. Degree of overlapping of data sets for saprolite, mixed ground and rock, Down-Track drive

| **Ground category** | **Criterion** | **Number of points beyond criterion** | **Percentage of points beyond criterion** |
|---|---|---|---|
| Saprolite | SE<24.9 | 74 out of 296 | 24.3% |
| Mixed Ground | SE>24.9 | 57 out of 237 | 24.1% |
| Mixed Ground | FPI/SE<0.42 | 57 out of 237 | 24.1% |
| Rock | FPI/SE>0.42 | 83 out of 351 | 23.6% |

There are factors which are likely to contribute to the overlapping of the data sets between saprolite and mixed ground, and between mixed ground and rock. These include:

1. The distinction between saprolite and rock at a material scale is based on imprecise field identification tests
2. The basis for the actual ground conditions consists of occasional face logging, with the ground in between face logs assessed from interpolation and a qualitative assessment of the scalpings at the slurry treatment plant. The interpolation is unlikely to precisely identify the actual ground conditions
3. Even the highest quality records available, the face records prepared during the interventions, were of limited accuracy because part of the face was obscured by the cutterhead structure and incomplete emptying of the excavation chamber.
4. The face log represented a single 'snapshot' within a 1.5m advance.

The greater overlap observed in the data for the Down-Track drive, compared with the Up-Track, would have been partly a result of the effect of the altered flushing system, which reduced the average values, and concentrated the data sets, for clayey cdg and mixed ground, as shown in Figures 37 and 40. However, the number of interventions and face logs significantly reduced on the Down-Track drive, so the basis for the actual ground conditions is likely to have been of lower accuracy than on the Up-Track drive.

## 10.0 FRICTION ON THE TBM SKIN AND TAIL SEALS

The total force due to friction on the TBM skin and tail seals was not measured directly but calculated by subtracting the forces due to the face pressure, contact force and tail drag from the total thrust force. The total thrust force and the sum of the other forces were much larger than the calculated friction force, so the process involved subtracting one large value from another value that was almost as large. For some rings, particularly for the Up-Track drive, this resulted in a small negative value for the friction, which is not realistic. Where the calculated value was negative, the value was taken as zero.

The total force due to friction was converted into an average unit skin friction by dividing the force due to friction by the area of the shield skin. For this calculation the length of the shield skin was 11.67m and the average outside diameter was 7.40m. The length of the cutterhead structure was not allowed for, as any friction in this part of the TBM would be included in the contact force. There was a small difference in the outside diameter of the middle shield and tail skin, 7.41m and 7.39m respectively, but this was of no significance to the calculation. In this calculation the forces on the tail seals are not considered; in practice, the values for unit friction on the skin would be even lower than calculated as the friction at the tail seals is potentially significant. The results are presented as an average and a maximum value for each of the ground categories in Table 14.

Table 14. Average and maximum values for skin friction in the four ground categories for the two drives.

| **Drive** | **Value** | **Unit** | **Saprolite** | **cl cdg** | **Mixed Ground** | **Rock** |
|---|---|---|---|---|---|---|
| UT | Average | kPa | 18 | 22 | 13 | 5 |
| DT | Average | kPa | 15 | 15 | 11 | 7 |
| | | | | | | |
| UT | Maximum | kPa | 48 | 51 | 41 | 43 |
| DT | Maximum | kPa | 30 | 39 | 37 | 24 |

The average value of the skin friction was highest in the clayey cdg, and lowest in the rock for both drives. The average and maximum values reduced between the Up-Track and Down-Track drives in every case except for the average value in rock, which increased slightly.

## 11.0 DISCUSSION

The purpose of the study was to assess:

1. How does the TBM data change with different ground conditions?
2. What combination of measured parameters or derived parameters best reflect the changes in the ground conditions?
3. Can TBM data be used to interpret the ground conditions encountered during tunnelling, and, if so, on what basis should such an interpretation be made?
4. Can the effect of the changed TBM design be measured in the selected parameters?

A further area of study was the magnitude of the friction on the TBM skin. These issues are discussed below.

### *11.1 How the TBM data changes with changing ground categories in weathered Kowloon granite*

When the forces applied to the TBM and the rate of penetration are compared, as shown in Figures 18, 19, 21, 29 and 30, it is evident that:

1. The tunnelling in the saprolite was characterized by generally low values for: contact force, Specific Energy, Field Penetration Index and modified Field Penetration Index. The tunnelling

in the rock was characterized by generally low values for the rate of penetration, torque and skin friction, but high values for contact force, Field Penetration Index and modified Field Penetration Index

2. The data from the tunnelling in the clayey cdg and the mixed ground tends to fill the area on the graphs between the general loci for the saprolite and that for the rock; for the Up-Track data, there were some extreme values, particularly when tunnelling in the mixed ground. However, there is considerable scatter and overlapping of the data for the four ground categories. The data for the Down-Track tunnelling plotted on the same basis shows considerable change, particularly for the clayey cdg and mixed ground, although still with some degree of scatter.

3. The average values for skin friction were greatest in the clayey cdg, almost as high in the saprolite, and then progressively less in the mixed ground and the rock. Generally, there was some reduction in the both the average and maximum values for skin friction for the tunnelling for the Down-Track, when compared with the Up-Track.

4. The effect of encountering sticky clay minerals within the generally inert granitic saprolite is clear in the data. For the Up-Track drive, the result of encountering clayey cdg was a significant increase in the values for Field Penetration Index and Specific Energy. The altered flushing system for the Down-Track drive resulted in substantial reductions in both parameters, to the point where it was difficult to distinguish the clayey cdg from the normal saprolite. The effect of the changed flushing system was evident in reduced values for the average torque and contact force while achieving a higher average rate of penetration.

*11.2 What combination of measured parameters or derived parameters best be used to identify the changes in the ground conditions?*

The graphs for Specific Energy plotted against Field Penetration Index in Figure 31 show a common pattern with the data for the four ground categories occupying specific locations on the graphs. Of all the combinations of parameters plotted, these provide the clearest distinction between the tunnelling in the four ground categories and for both drives. The data for the saprolite, clayey cdg and mixed ground follow a similar trend of FPI/SE, but with generally increasing values of Specific Energy and Field Penetration Index as the face conditions changes from saprolite to clayey cdg to mixed ground. This distinct pattern is maintained for the Down-Track drive, although with a reduction in the average values and degree of scatter of data for the clayey cdg and mixed ground, as shown in Figures 37 and 40.

The data sets for the four ground categories overlap when plotted as Specific Energy vs Field Penetration Index. Some of this overlap must be due to the nature of the materials, which grade into each other, with no distinct boundaries as shown in Figure 6. There is also a lack of precision in the identification of the actual ground encountered during the tunnelling, with respect to:

- The simple field tests used to distinguish saprolite from rock and clayey cdg are of limited accuracy and are not precise
- The presence of the cutterhead and incomplete emptying of the cutterhead limit the inspection of the face during cutterhead interventions
- Between the interventions, the ground category was assessed from the scalpings at the slurry treatment plant, which is of limited accuracy

These factors could account for much of the overlap seen in Figures 31a and b.

*11.3 Can TBM data be used to interpret the ground conditions encountered during tunnelling, and, if so, on what basis should such an interpretation be made?*

Based on the results shown in Figures 31a and b, the location of the data on a plot of Specific Energy vs. Field Penetration Index can be used to identify the most likely ground conditions for each TBM advance, although not with absolute precision, in weathered granite. Part of the reason for the overlap in the TBM data is the nature of weathered rock, and how any classification scheme creates artificial conceptual boundaries where none exist in nature. It is likely that much clearer definition may be achieved in geological conditions that are more clearly distinct and differentiated.

The change in the loci of the data for the clayey cdg and the mixed ground between the Up- and Down-Track tunnelling shows that any interpretation must be specific to a particular TBM and ground category. Each interpretation should be calibrated against reliable data, such as that obtained during an intervention or from borehole data very close to the line of the tunnelling.

Identifying the ground conditions from the TBM parameters treats the TBM as a very large ground investigation tool, even though it is not designed for that purpose. The rate of penetration on the SCL 1103 drives in weathered rock varied greatly, from 2mm/rev to 25mm/rev. Because of this variation in the rate of penetration, simply comparing the measured values of the torque and the contact force does not show a consistent relationship with the ground encountered. However, if the unit values of torque and contact force are divided by the rate of penetration, which is what is done in deriving the values for Specific Energy and Field Penetration Index, a reasonably consistent relationship is shown between the data and the changes in the ground conditions.

In complex, weathered ground profiles some overlapping of data points is probably inevitable. However, it is considered that much of the overlapping is due to the limitations in the identification of the actual ground conditions, from interventions and the scalpings at the slurry treatment plant. A comparison is made between the data from the interventions and from the TBM in Table 15.

Table 15 Comparison of data obtained from a face intervention with that from the TBM parameters

| Item | Intervention | TBM data |
|---|---|---|
| Distinction between saprolite and rock | Depends on human hand strength, uncalibrated | Depends on measurement of TBM parameters using calibrated measurement devices |
| Extent of face assessed | Partial | Full |
| Coverage of full advance for one ring | Snapshot at one point during advance, often the end | Measurements throughout the advance |
| Continuity of information | For SCL 1103 interventions were conducted on between 9.5% (DT) and 13.3% (UT) of the ring advances | For SCL 1103 complete sets of data were available for 96.8 (UT) and 97.7% (DT) of the ring advances |

It is suggested that a more accurate identification of the ground conditions encountered can be obtained by using TBM data calibrated to the intervention records and boreholes very close to the tunnel alignment than from interpolation between intervention records together with the review of the information from the scalpings.

### *11.4 Can the effect of the changed TBM design be measured in the selected parameters?*

The effect of the changed slurry circulation system, particularly on the tunnelling in the clayey cdg and the mixed ground, is evident in the data and in the comparison plots produced. The clearest presentation of the effect of the changes is in the plots of Specific Energy vs. Field Penetration Index. The change in the slurry circulation system was made to improve tunnelling performance in the clayey cdg. The improved tunnelling performance in the mixed ground, which is evident from this study, was not anticipated.

### *11.5 Friction on the TBM shield*

The data presented above shows that:

1. Generally, the friction on the shield skin and tail seals was quite low during slurry TBM tunnelling
2. The average unit skin friction reduced as the TBM passed from clayey cdg to mixed ground to rock
3. The skin friction appeared to reduce as the strength of the rock increased
4. The change in the slurry circulation system between the Up- and Down-Track drives reduced the average unit skin friction in all ground categories except for the rock

To discuss the data for unit skin friction, it is necessary to consider the geometry and buoyant force on the TBM during tunnelling. The excavated diameter of the TBM was 7.46m. This was the diameter cut by the gauge cutters when they were new; as they wore with use, the cut diameter would tend to reduce. The cutterhead structure was 735mm in depth. The cutterhead weighed 105t. During TBM operation the cutterhead would be fully submerged in bentonite slurry, so after allowing for the buoyancy force from slurry with a typical operational unit weight of 1.15 t/m$^3$, the submerged weight would be approximately 90t. This weight would be carried back into the TBM structure through the main bearing.

The TBM skin had a total length of 11.67m, with 0.8m extending forward from the pressure bulkhead and 10.87m behind the bulkhead. The weight of the shield excluding the cutterhead structure was 490t. The submerged weight of the cutterhead would have to be supported by the main shield structure, giving a total of 580t. During operation the TBM should be fully submerged in bentonite slurry. Assuming an operating slurry density of 1.15t/m$^3$. The buoyancy force on the TBM, excluding the cutterhead, would be 537.6t. The submerged weight of the TBM, including the buoyant weight of the cutterhead, would therefore be 42.3t. This calculation is sensitive to the unit weight of the operational slurry, which does vary. For a slurry density of 1.25t/m$^3$, a value likely to be reached during an advance, the buoyancy force on the TBM would exceed the weight of the TBM.

During operation there would be varying additional loads from the lining segments for the next ring as it was being assembled, by slurry being pumped out of the excavation chamber to the slurry treatment plant and other temporary loads. The buoyancy of the TBM behind the main pressure bulkhead would also have been resisted at the tail skin by the vertical forces on the tail seals and excluder plate. Overall, the loads and the resistances to buoyancy are concentrated in the front and back of the TBM. This is likely to hold the TBM reasonably central within the excavated void. This would suggest that there is little or no direct contact between the shield skin and the ground, although there will be contact at the cutterhead and at the excluder plate.

The difference is diameter between the cut diameter and the outside diameter of the shield skin would result in a 25mm annulus around the middle shield and a 35mm annulus around the tail skin, assuming that the TBM is exactly central within the excavated void, as shown diagrammatically in Figure 43.

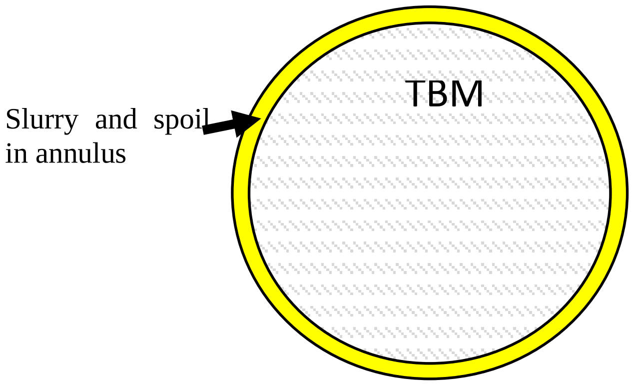


Figure 43. Annulus around the shield skin

The low maximum values for the friction in all ground conditions shows that the ground around the annulus was kept stable by the slurry pressure, as was also confirmed by the low values of volume loss measured over the tunnelling, as discussed in Shirlaw et al. (2017).

The data in Figures 16, 17 and 28 show that although the friction was generally low, there was significant variability in the magnitude. It is possible that pieces or lumps of excavated material become trapped in the annulus around the TBM skin. This would increase the skin friction, but in an irregular and variable manner. This could also explain the values of skin friction observed and how it varies with the ground category and with the change in flushing system on the Down-Track TBM.

Generally, little excavated material should enter the annulus around the shield skin, other than small particles suspended in the bentonite slurry. However, if there is clogging in the tool gap just in front of the cutterhead, the contact force applied to the cutterhead may result in lumps and pieces of excavated material being forced around the TBM skin. Figure 4 shows clayey cdg being extruded through an opening in the cutterhead. It is likely that the force required to extrude the excavated clayey cdg through the cutterhead openings also resulted in lumps of clayey cdg being extruded into the annulus around the shield skin, increasing the skin friction on the TBM. This could explain why there was a reduction in the average unit skin friction for the tunnelling in the clayey cdg and mixed ground for the Down-Track drive. There is good evidence in the measured TBM parameters that the revised flushing system incorporated into the Down-Track TBM significantly reduced the effects of clogging, particularly in the clayey cdg and mixed ground. The reduced unit skin friction seen the same two ground categories could thus be due to less material being extruded or pushed into the annulus around the TBM skin.

As summarized in Table 14, the average unit skin friction decreased on the Down-Track drive for all ground categories except the tunnelling in the rock. For the rock, the increase in numerical terms was from 5kPa to 7kPa, which is not significant.

## 12. FURTHER PLANNED STUDIES

This study has involved a review of the TBM parameters and how these changed in the various ground categories and with the change in the TBM design. This study has identified some further studies that could be carried out on the SCL 1103 TBM data. The further studies identified include:

- Evaluation of the strength of the rock, using the TBM data; how this varied in the weathered rock profile; and the effect of the strength and variation in the strength of the rock on the tunnelling. A particular issue of interest is why the average cutter load applied during the tunnelling in the rock was just 48.6% of the limiting contact force on the disc cutters for the Up-Track drive and 51.1% for the Down-Track.

- The effect of the magnitude of the slurry pressure on rates of penetration and other TBM parameters

- Disc consumption and how and why this changed between the drives, and the effect on the time for each drive.

- Effect on tunnelling of the sticky, clayey cdg and how this related to the clay content and the clay minerals present.

## 13. POTENTIAL USE IN FRAMEWORK FOR TUNNELLING CONTRACTS

Currently, for tunnelling projects in weathered rock in Hong Kong and Singapore the baseline (anticipated) ground conditions are defined in relation to the type of generalized face category discussed in this paper. The use of TBM parameters to help define the actual ground conditions encountered is potentially a contribution to the contractual process as well as to the understanding of how the TBM and the ground interact. However, it may be possible to further develop this so that the baseline is defined in terms of directly measurable TBM parameters, such as rate of penetration, contact force, torque, Specific Energy or Field Penetration Indexrather than in terms of geological condition. This would greatly simplify the evaluation of whether unanticipated ground conditions were encountered, and the effect on the tunnelling. Such an approach has been followed on some rock TBM tunnelling projects, with the baselining of 'boreability' classes, based on the rates of penetration achieved, rather than baselining the geology. For examples see Gomes (2020) and Ertl et al (2020). To develop an equivalent contractual basis for mixed ground TBMs in weathered rock requires improved understanding of the relative influence of the ground, the TBM design and TBM operation on rates of penetration and other TBM parameters. This study is intended to contribute to such an understanding.

## 14. CONCLUSIONS

A major factor in the magnitude of the forces and rates of advance for a slurry TBM is the nature of the ground conditions. The interaction of a slurry TBM and the ground was studied for two drives in weathered Kowloon Granite.

Excavating in granitic rock required relatively high contact force compared with the torque, whereas excavating in granitic saprolite required generally low values for contact force and torque. In mixed ground and clayey cdg relatively high values of both torque and contact force were required. These results were consistent with the nature of the ground and the action of the cutting tools. Comparing the data from the two drives, during the Up-Track drive the clayey cdg and the mixed ground resulted in clogging that caused additional torque and contact force. Implementing modifications to the TBM for the Down-Track drive, particularly the altered slurry circulation system, reduced the clogging and therefore the values for both the contact force and torque in the clayey cdg and the mixed ground.

Clogging in clayey cdg and mixed ground also affected the rate of penetration and Specific Energy. When plotted against Specific Energy, the data for the rate of penetration on the Up-Track drive showed wide scatter, with particularly high values of Specific Energy required in the clayey cdg and the mixed ground. With the modified circulation system reducing clogging, the data for the Down-Track showed a general trend of reducing rate of penetration with increasing Specific Energy as the ground varied from soil to rock and increased in resistance to penetration.

Although the nature and complexity of weathered rock profiles results in some overlapping of the data for the four general face categories used in the study, most of the ground encountered fell squarely into one of the four ground categories. As a result, the data from the tunnelling generally appeared in a distinct and different locus for each of the four categories, particularly when plotted as Specific Energy against Field Penetration Index. For both drives, the data for the saprolite, clayey cdg and mixed ground followed general trend lines for the ratio of Field Penetration Index (in kN/mm/rev) to Specific Energy (in $Mj/m^3$) between of between 0.29 and 0.41. The data for the rock generally had higher values for this ratio.

When plotted as Field Penetration Index against Specific Energy there was a clear difference in the performance of the Up-Track TBM and the Down-Track TBM in the clayey cdg, with a reduction in the average value and with the data becoming more concentrated. This showed that the revised slurry circulation system made the performance of the tunnelling in the clayey cdg almost indistinguishable from the normal saprolite, whereas there had been a clear distinction during the driving of the original TBM on the Up-Track tunnel. The revised system was almost as effective in improving performance in the mixed ground. The analysis provided a detailed rationale for what was already evident in the overall improvement in the tunnelling performance during the driving of the Down-Track tunnel, compared with the Up-Track.

The parameters recommended in this study, Specific Energy and Field Penetration Index, are effectively unit values for Torque and Contact Force, respectively, divided by the rate of penetration.

The friction on the TBM shield was generally low, and, on average, reduced as the TBM passed from saprolite to mixed ground to rock. Factors that would keep the friction low would include: the overcut of the TBM on the gauge, the buoyant forces on the TBM from the slurry in the overcut annulus around the TBM, the low friction of the slurry or any residual filter cake, and the stability of the ground under the slurry pressure. The average and maximum values for friction in all ground conditions except rock reduced between the Up-Track and Down-Track tunnel. It is postulated that a reduction in the clogging and the contact force required resulted in fewer lumps of excavated material being pushed into the annulus around the TBM.

The study illustrates several possible uses for the large amounts of data generated by a pressurized face TBM:

1. The data can be used to quantify the horizontal forces applied to the TBM in a range of ground conditions

2. The data can be used, as it was on SCL 1103, to assess the nature of any problems encountered during tunnelling and help to justify changes to the TBM design and/or operation
3. The data can be used to quantify the benefits (or otherwise) of design changes to the TBM
4. The data can be used, together with information from interventions and boreholes close to the tunnel alignment, to refine the understanding of the ground conditions as actually encountered during tunnelling

Currently, for tunnelling projects in weathered rock in Hong Kong and Singapore the baseline (anticipated) ground conditions are defined in relation to the type of generalized face category discussed in this paper. The use of TBM parameters to help define the actual ground conditions encountered is potentially a contribution to the contractual process as well as to the understanding of how the TBM and the ground interact. It may be possible to further develop this so that the baseline is defined in terms of directly measurable TBM parameters, such as rate of penetration or Specific Energy, rather than in terms of geological condition.

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