THE CHALLENGES OF TUNNELLING WITH SLURRY SHIELD MACHINES IN MIXED GROUND

Russell Connors[1]

[1]*John Holland Pty Ltd, Singapore. Email: russell.connors@jhg.com.sg*

ABSRACT: The challenges encountered on the Thomson East Coast Line (TEL) contract T208, in the Bukit Timah Granite Formation, resulted from the underlying layers of hard rock with the presence of large boulders above the tunnel axis, surrounded by weathered soils.

The presence of large boulders in the excavation face can adversely affect the performance of the Tunnel Boring Machine (TBM) and Muck Reconciliation Systems, and may damage the cutterhead tooling requiring compressed air interventions in potentially unfavourable ground conditions.

Working in adverse ground conditions for prolonged periods of time increases the likelihood of face instability and air losses during compressed air interventions. These conditions can lead to volume losses resulting in ground failure and the development of sinkholes on the surface.

This paper will discuss the challenges of tunnelling with slurry shield TBMs in the mixed ground conditions of the Bukit Timah Granite Formation, and the mitigation measures used to limit volume losses.

KEYWORDS: Bukit Timah Granite; Slurry Shield TBM; Mixed Ground; Boulders; Muck Reconciliation; Volume Loss

1 INTRODUCTION

Tunnelling in mixed ground conditions including igneous rocks such as granites, quartz, clays and sands can pose several challenges during the construction of segmentally lined tunnels.

Slurry Shield TBMs are used in these ground conditions for maintaining positive face pressure, whilst supporting the ground through the application of a pressurised bentonite slurry suspension.

This paper outlines the challenges encountered whilst excavating through the mixed ground of the Bukit Timah Granite Formation using a Slurry Shield TBM for contract T208 in Singapore. It reviews the design and operation of the TBM and describes the controls and mitigation measures adopted to construct a conforming product with minimal disruption to the surrounding environment.

2 CASE STUDY: CONTRACT T208

The TEL is a joint line between the Thomson Line and the Eastern Region Line in Singapore. Once completed and in operation by 2024, the 43 km TEL will run fully underground through the north-south corridor of Singapore. It will extend from Woodlands Town to Marina Bay before terminating in the East Coast, as shown in Fig. 1.

Connections with the existing network will be made possible by 7 interchange stations, linking the TEL with the East-West Line (EWL), North-South Line (NSL), North-East Line (NEL), Circle Line and the Downtown Line.

Leighton Asia and John Holland, forming a Leighton John Holland Joint Venture (LJHJV), was appointed to deliver Contract T208 of the TEL in November 2013 by the Singapore Land Transport Authority (LTA). It involves the construction of Springleaf Station, Tagore Cut and Cover Tunnels, over 4.4 km of segmentally lined bored tunnels, six cross passages and two in-line sumps, as shown in Fig. 2.

Figure 1: TEL Alignment in Singapore

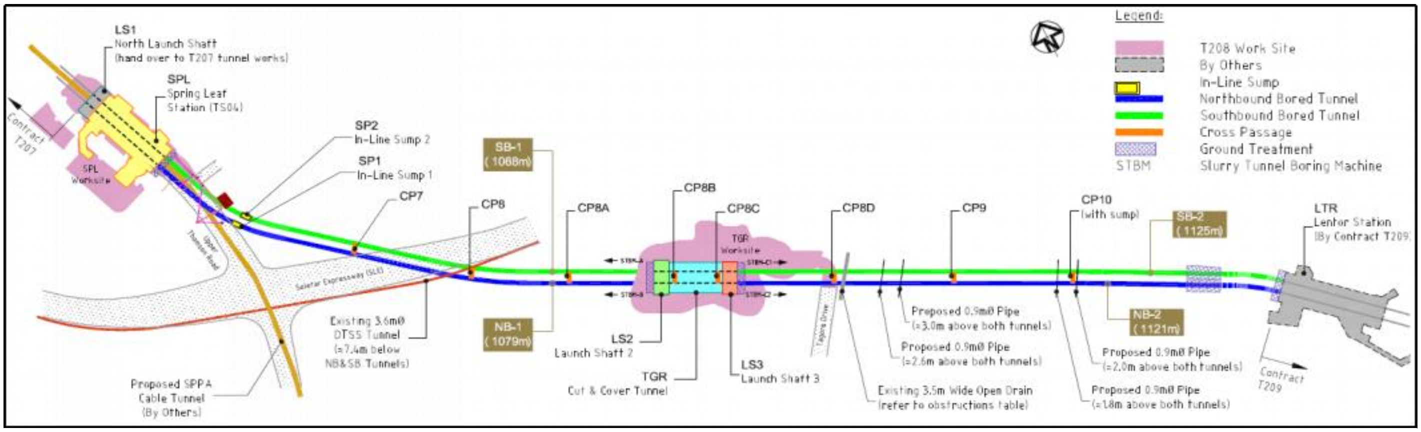

Figure 2: Contract T208

2.1 Northbound and Southbound Tunnels from the Tagore Cut and Cover to Springleaf Station Box

The twin bored tunnels from the Tagore Cut and Cover Tunnel to Springleaf Station consisted of 2 x 1.1km of segmentally lined tunnels. The tunnel depths range from 12m to 29m and consist of two right hand curves with a radius varying from 813m to 323m and gradients of +/- 3%. Both tunnels' alignments under-crossed critical infrastructure, such as the Seletar Expressway (SLE), Upper Thomson Road, Public Utilities Board (PUB) sewers, major watermains, and many other third party utilities.

Geotechnical conditions were similar along the two alignments, and consisted of weathered soil and rock derived from the Bukit Timah Granite Formation as shown in Fig. 3. This formation was located below a localised layer of the Kallang Formation which itself consisted of marine and alluvial clays.

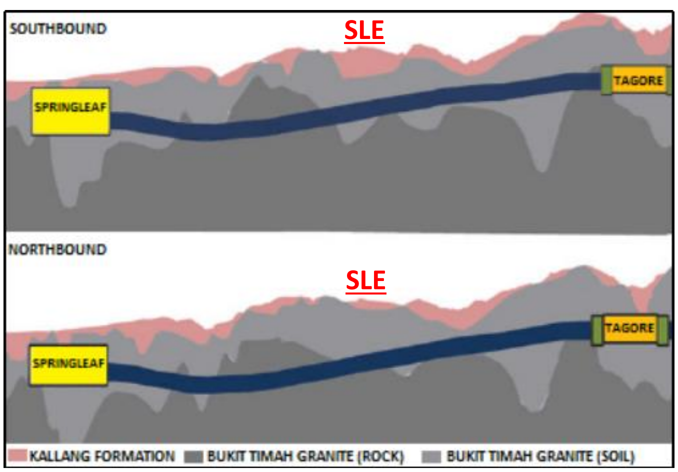

Figure 3: Geotechnical Conditions for the Northbound and Southbound Tunnels from Tagore to Springleaf

Commenced in April 2016, the 1.08km northbound tunnel alignment from the Tagore Cut and Cover Tunnels to Springleaf Station box was successfully completed in March 2017. The second 1.07km southbound tunnel alignment commenced in July 2016 and was completed in early July 2017.

Each tunnel drive was successfully excavated using a 6.66m diameter Slurry Shield TBM. The Slurry Shield type TBM was selected to allow for excavation through varying lengths of soil, rock and mixed ground as estimated in the Ground Based Geotechnical Baseline Report (GIBR) [1].

The actual encountered and estimated length of tunnelling in various ground conditions is repeated for convenience in Table 1.

Table 1: Anticipated and actual Geological Conditions encountered at the excavation face from Tagore to Springleaf

Geology	Northbound Tunnel		Southbound Tunnel	
	GIBR (m)	Actual (m)	GIBR (m)	Actual (m)
Soil	520	420	600	380
Mixed	500	240	400	390
Rock	380	420	350	300

Performance of the TBMs varied along the tunnel alignment. High production rates of up to 20m to 30m a day (50-60mm/min) were achieved in a full face of soil (GIV-GVI). For the more abrasive Bukit Timah Granite (GI-GIII), production rates were between 5 to 10m per day (5-10mm/min). In the more challenging conditions of mixed ground, production rates of 1-3m per day (2-4mm/min) were achieved.

2.2 Geotechnical Background

Bukit Timah Granite Formation is one of the oldest formations in Singapore and its intrusion some 200 to 250 million years ago, is well documented. The formation is widely distributed across the northern and central parts of the island and contains igneous rocks ranging from granite to granodiorite [2].

The weathering of the Bukit Timah Granite is gradational, with the upper parts generally more weathered and decomposed into residual soils. These upper parts consist of reddish to yellowish brown clayey soils with an air permeability estimated to be more than 70 times greater than the water permeability [3].

There is typically a sharp boundary between the more completely weathered layers (GIV to GVI) and the moderately weathered granite (GIII), as shown in Fig. 4. The highly abrasive granite (GI-GII) typically encountered along the tunnel drive had an Unconfined Compressive Strength (UCS) more than 150 to 170MPa.

The presence of boulders, often several metres in diameter, is a result of the weathering process. They are formed from the chemical process that took place between the ground water seeping into the granite fissures and the rock particles that were directly in contact with the water [1].

The mixed ground conditions encountered along the tunnel drives typically consisted of abrasive granite (GI-GII) below the tunnel axis, and the weathered granite (GIV-GVI) above the tunnel axis. Difficult to predict, boulders of various sizes from 3-6m were encountered in these mixed ground conditions, with their size and frequency more prevalent with the weathering of the Bukit Timah Granite.

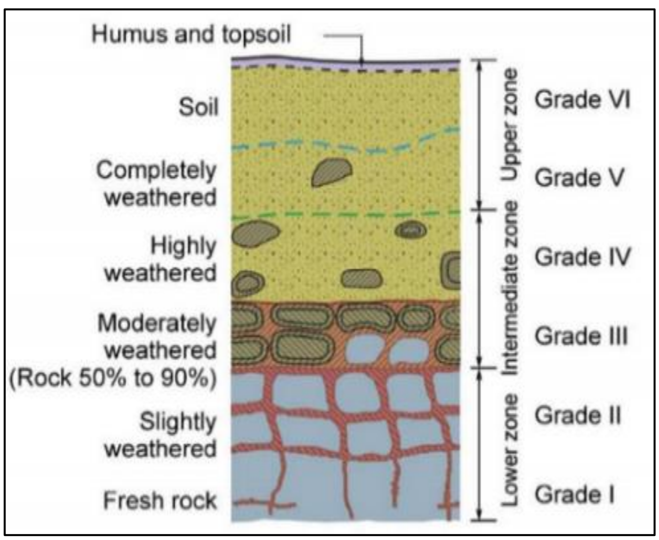

Figure 4: Weathering Profile of Bukit Timah Granite Formation

3 SLURRY SHIELD TBM FOR T208

Slurry Shield TBMs are widely used for non-cohesive soils, ranging from fine-grained sands to coarse-grained gravel, and use a pressurised bentonite slurry suited to counteract the prevailing groundwater and earth pressures. This bentonite slurry also acts as the carrier fluid for the excavated material [4].

3.1 Slurry Machine Principle

The characteristic design feature of the Slurry Shield TBM used on T208 is the submerged wall dividing the pressurised front section of the shield into two chambers. The chamber behind the cutterhead is called the excavation chamber, while the chamber between the submerged wall and the plenum is called the pressure chamber.

In Slurry Shield TBM operations, the bentonite slurry supplied from the feed line is pressurised by an air bubble and excavated material. The compressed air above the bentonite slurry layer in the pressure chamber is controlled by an automatic air regulation valve, which operates by either supplying or relieving compressed air. The pressure from this air bubble is transferred through the submerged wall to the bentonite slurry suspension in the excavation chamber, providing the required face support, as shown in Fig. 5.

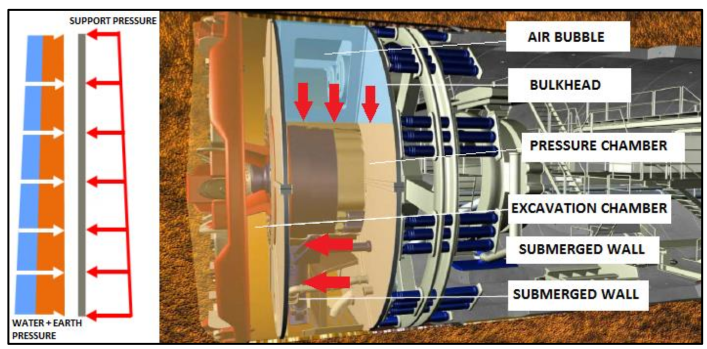

Figure 5: Slurry Shield TBM principal

Any fluctuations in the bentonite slurry level or the air bubble pressure when mining will be transferred to the excavation face [5]. Inadequate face pressures can lead to over-excavation, creating a large void in the excavation face. Increased face pressures can breach blow out limits causing slurry leakage to the surface.

To isolate the pressure chamber from the excavation chamber, a hydraulic gate is installed to allow for maintenance. Minor blockages at this ‘bubble’ gate is offset by communicating pipes that limit pressure fluctuations in the excavation chamber, by allowing injected bentonite to bypass the blockage.

When advancing, the excavated material falls through the cutterhead openings and is held in the pressurised slurry suspension. The slurry is then pumped to the Slurry Treatment Plant (STP) for treatment and re-use in the slurry circuit, as shown in Fig. 6.

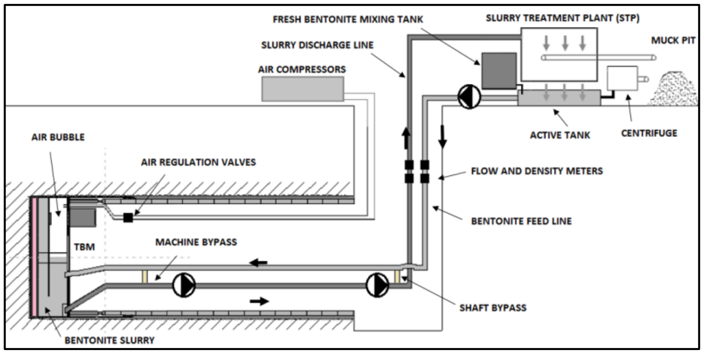

Figure 6: Slurry Circuit for T208

The Muck Reconciliation System calculates the volume of solids and dry mass by monitoring the flow and density meters in the slurry circuit. By plotting the cumulative volume of solids and dry mass against the theoretical limits that contain all solids and water, an indication of the amount of material excavated can be observed during an excavation cycle [6].

The bentonite injection and slurry extraction rates must be maintained and monitored when advancing. This ensures solids remain in suspension when conveyed, reduces wear along the slurry circuit, limits blockages in the excavation chamber, and enables the flow and density meters for the Muck Reconciliation System to operate efficiently.

Any increase in the slurry extraction flow rates in mixed ground conditions can indicate that the overlaying softer material is being conveyed too quickly, leading to over-excavation. Fluctuations in the slurry extraction rates can signal blockages in the excavation chamber, affecting performance of the TBM, and requiring either flushing from the slurry circuit or compressed air interventions to manually clear the blockage.

Flow reductions in the bentonite feed and slurry discharge lines can be made to isolate the TBM from the slurry circuit. This is achieved in bypass mode, and is performed either by the Operator or automatically for any planned or unplanned stoppages.

Where over-excavation occurs, the pressurised bentonite slurry will immediately fill the void above the excavation face until the void passes over the TBM tail shield where it will be grouted. Further targeted grouting may be required depending on the size and location of the void, either secondary grouting through the tunnel segments, or from the surface.

Voids in front of the machine will be supported by the bentonite slurry and the cutterhead as the TBM advances forward. This will be represented as under-excavation until excavating a full face of material again.

3.2 Bentonite Slurry Performance

When tunnelling in mixed ground it is important that bentonite slurry properties, both fresh and recycled, are within Key Performance Indicators (KPIs) as specified by a Mud Engineer. This is to support the required face pressures to prevent over-excavation, and provide a protective membrane to limit any air loss through the softer material during a compressed air cutterhead intervention [7]. Optimal bentonite slurry also acts to reduce wear on the slurry circuit, pumps, pipes cutterhead, and disc cutters from the more abrasive Bukit Timah Granite (GI-GII).

The clay minerals from the bentonite suspension penetrate the weathered soil (GIV-GVI) and seal any pores that may form. When pressurised, this bentonite suspension acts as a sealing membrane across the tunnel face, as shown in Fig. 7. This membrane restricts slurry and air losses through the ground that would otherwise reduce face supporting pressure during excavation and compressed air interventions [8].

The bentonite slurry suspension when mining in the mixed ground had a rapidly changing content of sand, silt and other aggregated materials, that altered the properties of the slurry. This reduced its effectiveness as a sealing membrane and increased the demand on the STP and centrifuges. Reducing their ability to separate the coarser materials and fines from the bentonite slurry. To overcome this, a high viscosity cellulose and biopolymer agent was added to improve the bentonite slurry properties in line with specified fluid KPI’s.

In principal, the bentonite slurry properties are adjusted based on an observation of actual material extracted from the TBM in the STP muck pit, performance of the TBM, observation of the actual bentonite slurry qualities as they encounter changing ground conditions, and the requirement for additional face support or the need to perform a compressed air intervention.

Figure 7: The application of a good bentonite face provides minimises slurry and air losses

3.3 Cutterhead and Tooling

The 6.66m cutterhead, as shown in Fig. 8, had a 26% opening ratio to allow excavation through all anticipated geology with minimum requirements for maintenance. Based on the cutting wheel design, solids were limited to a maximum size of 250mm from entering the excavation chamber by grizzly bars capable of 66kN of loading fitted between the openings.

Figure 8: The 6.66m cutterhead configuration

To protect the cutterhead from direct exposure to the ground, the cutterhead tooling consisted of 43 nos. of 19inch disc cutters whose tracks on the excavation face were spaced 89mm apart. In addition, there were 128 soft ground tools either side of the main arms which were removed in the mixed ground. There were 4 nos. of gauge cutters that provided the 25mm overcut to enable the 6.61 diameter TBM shield to advance without getting jammed.

The 19inch disc cutters supplied could withstand up to 320kN of loading, 35N.m of rotating resistance torque and work to a maximum external pressure of 4bar without the need for any pressure compensation. The disc cutters were held into place by a double wedge block system, as shown in Fig. 9. The system allowed for the bolts to hold the centre wedge into position, while loading was transferred through the adjacent wedges only.

A hydraulic rock crusher located in the pressure chamber in front of a grill reduces solid sizes from entering the slurry circuit. The maximum solid size is a critical parameter in reducing pump blockages, reducing wear along the slurry circuit, and minimising pressure fluctuations in the excavation and bubble chambers. For both TBMs, the maximum allowable solid size was 80x80mm.

Figure 9: Double wedge block system was used to secure the 19inch disc cutters in the housing

4 CHALLENGES ENCOUNTERED ON T208

There were four main challenges encountered in the mixed ground: minimising damage to the cutterhead and tooling; conducting compressed air interventions; minimising stoppages and advancing the TBM; and minimising volume loss.

The excavation profile of the machine is enlarged from the movement of boulders around the periphery of the shield and in front of the TBM cutterhead, as shown in Fig. 10. These boulders tended to displace the weathered soils creating voids above and in front of the tunnel axis. Until these boulders are either pushed outside of the excavation face or broken up, they continue to move around and damage the cutterhead tooling, requiring compressed air interventions in potentially unstable ground conditions.

4.1 Minimising Damage to the Cutterhead and Tooling

To minimise damage to the cutterhead in mixed ground conditions, the challenge was in identifying the onset of damage. If the damage was not realised immediately and mining excavation continued, the potential to further damage the cutterhead and tooling would increase exponentially. Knowing when to stop for an intervention became imperative and it was necessary to monitor the operational parameters of the TBM and monitor the STP muck pit while excavating.

Figure 10: Large boulder encountered in front of the excavation face

The source of most of the damage came from the boulders that were in the excavation face. As these boulders are not readily broken up into manageable fragments, they are moved around by the rotation of the cutterhead, pushed across the excavation face and accumulated as the TBM advances.

These boulders would routinely smash against the disc cutters and split the retaining rings, eventually destroying the disc cutter. Other issues included exposed disc cutters hubs that would crack the bearings if they were damaged, eventually leading to flatspotting on the disc cutter, as shown in Fig. 11.

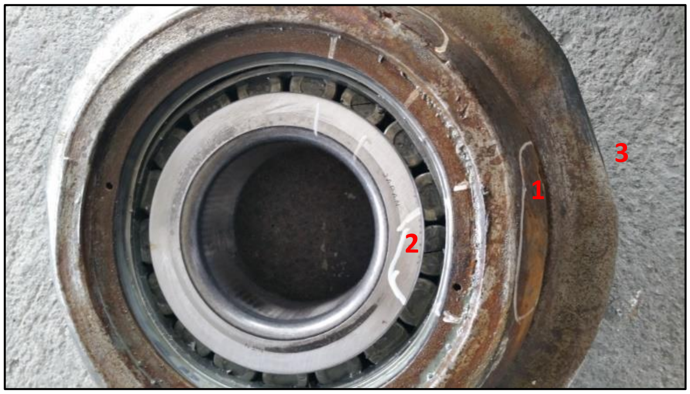

Figure 11: Damaged or worn hubs (1) can cause bearings to either seize or crack (2), resulting in flatspotting of the retaining ring (3)

These boulders would also cause the wedge locking system to loosen, or shear the retaining bolts, as shown in Fig. 12. These loose wedges would either then jam in the housing, or they would fall and circulate around the cutterhead. This would often cause further damage to tooling and the stone crusher, or cause blockages along the slurry circuit, until they were eventually discharged at the STP muck pit.

Figure 12: Loose and fallen wedges can further damage disc cutters

The disc cutter usage on the TBMs in the mixed ground was substantial. In total, 431 disc cutters were changed for the northbound tunnel. For the mixed ground encountered, a total of 108 disc cutters were changed. This includes 29 double cutters and 79 single cutter changes.

Comparatively, for the southbound tunnel a total 442 disc cutters were changed. For the mixed ground encountered, a total of 173 disc cutters were changed. This includes 53 double cutters and 122 single cutter changes.

The high replacement rate of disc cutters in the mixed ground was due to flatspotting and split retaining rings, and exceeded initial estimates.

Figure 13: Flatspotting of a double disc cutter in the mixed ground. Note the exposed hub, which is prone to damage and wear

Until the boulders are either pushed outside of the excavation face or broken up, they continue to move around and damage the tooling, block the excavation chamber and jam the cutterhead. This will cause the cutterhead rotation to experience sudden oscillations in measured torque values. Where the machine is operating too close to the nominal torque limit, the cutterhead will lock, stopping the TBM from advancing and isolating it from the slurry circuit. The ideal operating range of the cutterhead torque is below 60% of this nominal torque value. For abnormal oscillations in the cutterhead torque, or above nominal limits, the cutterhead will lock and stop the TBM. This will either require changes to TBM operating parameters or a compressed air intervention to inspect the cutterhead and perform any required repairs.

To minimise damage to the cutterhead and tooling, it was necessary to limit the rotation speed of the cutterhead and the thrust force. As the thrust forces are much higher in the bottom rock group than the overlying soil, the TBM penetration rates were kept to 3-4mm per each rotation of the cutterhead (mm/rot). This was to mitigate the effects of an unbalanced cutterhead contact force as it encountered the bottom layer of rock, minimising damage to cutterhead tooling.

Furthermore, it is essential to monitor the STP muck pit and stop the TBM when metal fragments are detected. This includes split retaining rings, bolts and wedges that have managed to clear the slurry circuit. Oil present in the STP active tank can be indicative of seized disc cutter bearings and must be acted upon accordingly.

4.2 Conducting Compressed Air Cutterhead Interventions in Mixed Ground

The challenges of conducting compressed air interventions in mixed ground arose from completing the required works in unstable ground, and the need to reduce air losses to acceptable levels to allow the compressed air interventions to proceed.

The purpose of interventions is to inspect the cutterhead tooling and perform repairs after a stoppage. During compressed air interventions, it is necessary to balance the compressed air pressure with the groundwater pressure. This would otherwise inundate the excavation chamber and unravel the soil, leading to possible settlement breaching alert levels.

Over 12,500 man hours were spent in compressed air for both tunnels from Tagore to Springleaf. Of the total 466 compressed air interventions conducted for the northbound tunnel, a total of 255 were performed in the mixed ground at pressures averaging 2.1bar.

Comparatively, for the total 584 compressed air interventions conducted for the southbound tunnel, a total of 536 were performed in the mixed ground at pressures averaging 1.9bar.

The compressed system was set up to cope with the high permeability of the ground. For each TBM, there were 2 nos. of

110kW compressors on the surface providing 38m3/min at 8 bar of breathable air. During a typical intervention in mixed ground with a stable face, the air loss was less than 10m3/min.

Settlement during a compressed air intervention was routinely monitored and compared to the design volume losses. Air pressures were adjusted based on performance of the compressed air system and prevalent ground conditions.

The nature of intervention works means that it is necessary to turn the cutterhead to complete any tool mapping, tool changes or repairs. This turning of the cutterhead can disrupt the excavation face and potentially dislodging any boulders that may be present. As boulders, cannot be held in place with compressed air, they will create a void when they are dislodged. The now exposed soil (typically GV-VI) that was behind the boulder is not supported by the bentonite cake. This soil will dry out over time and spall, enlarging the void with potential for it to propagate to the surface.

In the event of ground instability or unacceptable air loss, the compressed air intervention will be aborted. The excavation chamber is filled up with the bentonite slurry and is re-pressurised for several hours to re-apply the bentonite cake. The compressed air intervention can resume once it is observed that conditions in the excavation chamber are stable.

Compressed air pressures were calculated to compensate the entire effective soil pressure required to provide a stable face. Pressures were limited to avoid soil instability due to dried out soils (GV-GVI). The minimum compressed air pressures were designed to a minimum of 1.05 times the hydrostatic pressures and required no additional groundwater control measures. For the intervention, the air pressure was designed to compensate the hydrostatic pressure at a level of 1m above the invert. Due to the expected undrained behaviour of the ground, prolonged compressed air interventions in the mixed ground did not cause any ground water drawdown.

Minor voids that remain stable can be left untreated until they are supported by bentonite slurry on recommencement of mining. This minor void will be stabilised by primary and secondary grouting once the TBM shield passes. For larger voids, the objective is to either directly pressure grout from within the cutterhead, via the TBM shield, or perform grouting from the surface. Once the minimum volume targets of 120% are achieved, the grout is then allowed to cure before the TBM advances any further.

4.3 Advancing the TBM

The aim should be to advance the TBM by at least one shield length (11m) before the next intervention. This will help to minimise the enlargement of voids due to frequent stoppages and compressed air interventions.

Advance rates of up to 1 to 3m a day were achieved in ground conditions that transitioned from a full face of the rock, to soil. In this mixed ground, boulders were more easily pushed away from the excavation face. However, as the TBM approached the transition from soil to rock, advance rates were at best less than 1m per day, with frequent stoppages between interventions.

Damaged and bent grizzly bars, as experienced on both tunnel drives, would allow boulders from 500 to 700mm to rapidly converge into the excavation chamber, as shown in Fig. 14. These smaller boulders would overwhelm the mixing arms, blocking the bubble gate and the crusher, as shown in Fig. 15. These blockages would require frequent compressed air interventions to manually clear the boulders and repair the grizzly bars.

Figure 14: Damaged and bent grizzly bars allowing boulders larger than 250mm to enter the excavation chamber

Figure 15: Blocked excavation chamber and bubble gate from smaller boulders

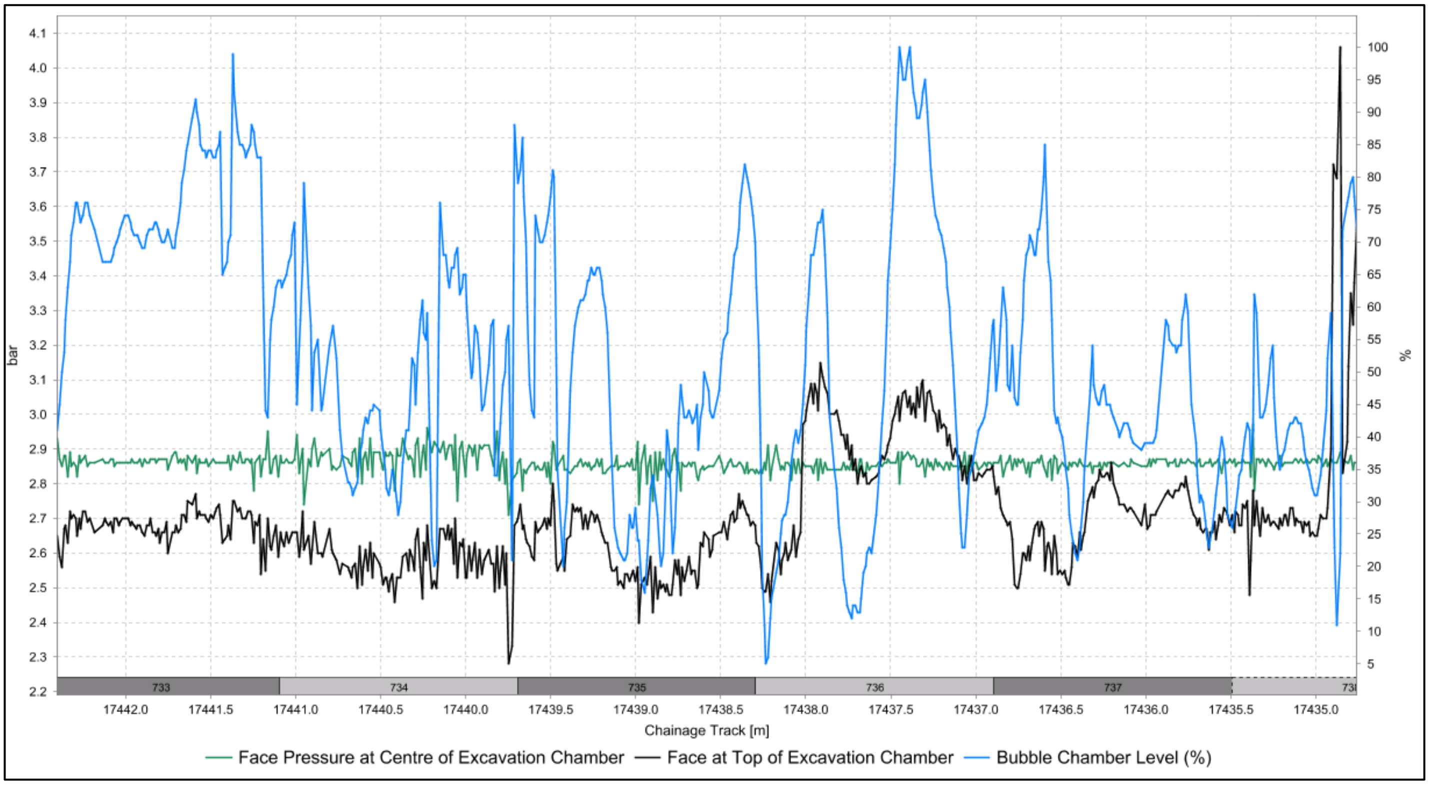

Figure 16: Fluctuations in the bentonite slurry level will be transferred to the excavation face. Inconsistent pressures can lead to over-excavation or blow outs as shown

As the bubble gate is severely blocked and the stone crusher unable to function as intended, the flow in the bentonite feed and slurry discharge lines is now restricted, causing pressure fluctuations and activating bypass mode, as shown in Fig. 16. This sudden stoppage and isolation of the TBM from the slurry circuit also causes a pressure wave (water hammer) to propagate down the slurry circuit. These pressure waves will continue until the blockage is cleared, delaying the advance of the TBM and causing problems from noise and vibrations to damaging inline extraction pumps.

It should be noted, frequent interventions in succession can cause successive voids that can enlarge and follow the TBM as it advances. This will further increase the likelihood of settlement on the surface.

The following will allow the operator to advance the TBM the required distance with minimal delays in mixed ground: adjust the bentonite injection and slurry extraction flow rates to limit materials building up in the excavation chamber; ensure the cutterhead is rotated only when advancing at reduced revolutions to minimise boulders spalling from the excavation face; adjust the thrust forces as necessary to achieve the optimal contact force; and monitor nominal cutterhead torque values.

At the onset of deterioration in the TBM performance in the mixed ground, a compressed air intervention is undertaken to inspect conditions in the cutterhead and perform the necessary repairs. Planned TBM maintenance regimes at regular intervals in the mixed ground should ensure unwarranted stoppages are minimal.

4.4 Minimising Volume Loss

Allowable volume losses for the tunnel drives from Tagore to Springleaf were between 0.5% to 1.5%, as shown in Table 2. This was due to the presence of critical infrastructure, such as the Seletar Expressway (SLE), Upper Thomson Road, Public Utilities Board (PUB) sewers, major watermains, and many other third party utilities including high voltage power mains.

Table 2: Volume Loss Comparisons (Tagore to Springleaf)

Chainage		Volume Loss			
		Design			Actual (Max)
From	To	Northbound	Southbound	Average	
Tagore	18+120	1.2%	1.2%	1.2%	0.15%
18+120	17+860	0.75%	0.75%	0.75%	0.34%
17+860	17+680	0.5%	0.5%	0.5%	0.34%
17+680	17+550	1.5%	1.5%	1.5%	0.25%
17+550	Springleaf Station	0.75%	0.75%	0.75%	0.08%

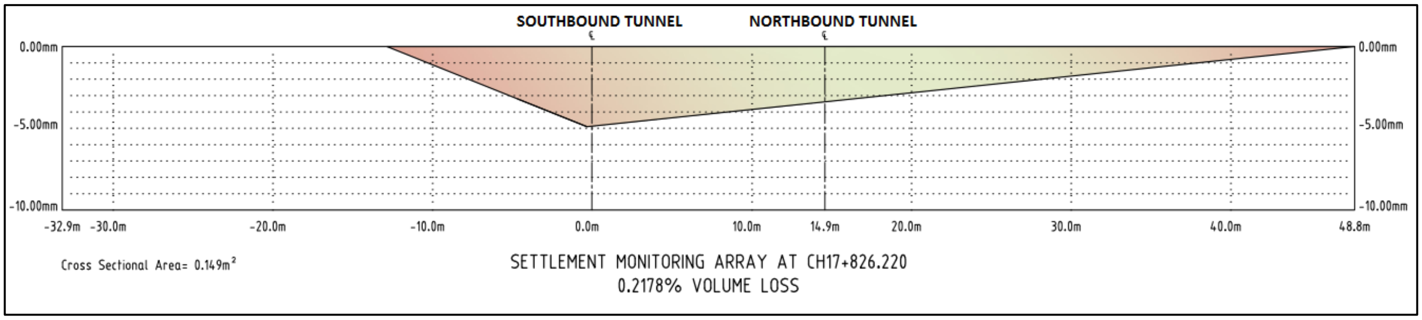

Figure 17: Volume Loss computation from Tagore to Springleaf. Note this settlement monitoring array was beneath the SLE, where both TBMs experienced challenging mixed ground conditions

To monitor actual muck volumes removed versus theoretical muck volumes, both a primary and secondary Muck Reconciliation System was used:

a. Primary Muck Reconciliation System – MRS
b. Secondary Muck Reconciliation System – STP muck pit volume measurements

a) Muck Reconciliation System:

Long excavation cycle times to cut the rock resulted in greater volumes of slurry passing the flow and density meters. This, coupled with frequent TBM stoppages in the mixed ground, magnified the errors in the Muck Reconciliation System.

Face pressures over these longer excavation cycles needed to be maintained by the careful operation of bentonite feed and slurry extraction rates, with close attention paid to the theoretical volume and weight limits. With the constantly changing properties of excavated material in the mixed ground, bentonite properties (KPIs) were frequently monitored and adjusted at the STP.

The Muck Reconciliation system became unreliable in the mixed ground due to the changing face conditions, frequent stoppages and blockages that caused fluctuations in the bentonite feed and slurry extraction rates. For the optimal performance of the flow and density meters, the slurry circuit needed to be running at 1000m3/hr during both excavation and bypass modes. As the percentage of rock, soil and the quantity of boulders is constantly varying, the density values used for the theoretical calculation limits cannot be accurately determined.

Due to the performance of the Muck Reconciliation system in the mixed ground, it was necessary to monitor for any fluctuations in the face pressures and slurry extraction rates to indicate over-excavation. As voids are created, they are quickly filled by the bentonite slurry and any indication of over-excavation can be difficult to determine.

b) STP Muck Pit Volume Measurement:

The STP muck pit is visually inspected 2 to 4 times per excavation cycle, as show in Fig. 18. Manual volume checks are performed measuring the coarse and sand material that is discharged at the STP.

Figure 18: Manual volume checks at the STP in regular intervals supports the MRS. Any inconsistencies between the two systems can be determined

Fines that are separated by the centrifuges on the STP are measured by calculating the difference in density between the bentonite feed and the slurry discharge lines into the active tank for each excavation cycle. With an increase in the active tank volume, the percentage of fines can be measured.

For areas where it was calculated that the quantity of material removed was greater than 115%, secondary grouting was performed within the tunnel.

As the volume checks for coarse material, sand and fines is manually performed 2-4 times per excavation cycle, any inconsistencies with muck excavation volumes can be determined. TBM operational parameters and bentonite slurry

KPIs can be changed to minimise volume losses at the excavation face.

Any areas where there was potential for surface anomalies, for example due to over-excavation or overbreak caused during interventions, remedial grouting was undertaken. Methods of remedial grouting for the surface included TAM grouting, auger drilling and grouting at targeted depths, and lance grouting. This combination allowed the project to achieve volume loss within allowable ranges.

CONCLUSIONS

Several factors contribute to the success of mixed ground tunnelling. For contract T208, surface settlements typically ranged from 0 up to 10mm. Volume losses of between 0.5% to 1.5% were achieved. Furthermore, settlement from mining in mixed ground was minimal underneath the critical infrastructure zones.

The design of the cutterhead is paramount if mixed ground conditions are expected. Disc cutters must be adequately protected and mounted effectively to minimise damage.

Close monitoring of TBM operational parameters and bentonite slurry performance allows for early identification of any damage to the cutterhead tooling. This allows for compressed air interventions to perform the necessary repairs and minimise delays to the advance of the TBM.

Monitoring of the muck pit volumes at the STP in regular intervals supports the MRS, which can be inaccurate in mixed ground. This minimises over-excavation from occurring, thus reducing volume losses.

Targeted grouting and the application of a pressurised bentonite cake can reduce air losses during compressed air interventions where the ground has become unstable. Voids that have passed the TBM shield are stabilised by primary and secondary grouting, re-pressurising any ground that may have relaxed.

Effective monitoring and intervention strategies, combined with the design of the cutterhead and tooling, mitigate the challenges encountered in mixed ground: minimising damage to the cutterhead and tooling; conducting compressed air interventions; minimising stoppages to the TBM; and minimising volume losses. This creates a conforming product with minimal impact on the surrounding environment.

REFERENCES

[1] LTA; Working Documents; *Geotechnical Interpretative Baseline Report* (GIBR) for T208

[2] V. Chepurthy. *Construction Challenges in Bukit Timah Formation*, Underground Singapore 2016

[3]. Schenck, *Air Consumption and Overburden for Tunnelling in Compressed Air*, Bautchnick, 1963, pp 41-47

[4] Golder Associates. *Ground Control for Slurry TBM Tunnelling*, Geo Report No. 249, February 2008

[5] Z. Zizka and M. Thewes. *Recommendations for Face Support Pressure Calculations for Shield Tunnelling in Soft Ground*, October 2016

[6] R. Duhme, R. Rasanavaneethan, L Pakianathan and A Herud. *Theoretical Basis of Slurry Shield Excavation Management Systems*, International Conference on Tunnel Boring Machines in Difficult Grounds (TBM DiGs) Singapore, 18-20 November 2015

[7] M. Marotta. *Singapore Bukit Timah Granite: Slurry Quality Control for TBM Tunnelling*, Proceedings of the World Urban Transit Conference 2010 (WUTC 2010)

[8] H. Bratlien, *KVU Oslo-Navet Tunnel Boring Machines*, Appendix 8 Technical-Economic Plan, September 2014