UNDERCROSSING LIVE TUNNELS IN PARALLEL BELOW THE WATER TABLE IN AN URBAN ENVIRONMENT

Diwakar Velu[1], Amsyar Tamami[2], Ramesh Nair[3]

[1]*Land Transport Authority, Singapore, Email: Diwakar_VELU@lta.gov.sg*

[2]*Land Transport Authority, Singapore, Email: Amsyar_Tamami_MOHAMAD_TAMAMI@lta.gov.sg*

[3]*Land Transport Authority, Singapore, Email: Ramesh_NAIR@lta.gov.sg*

ABSTRACT: Singapore Metro system has been developing in recent years to enhance the connectivity of existing network Mass Rapid Transit (MRT) system. Currently, there are 5 lines across the island in operation – North South Line (NSL), East West Line (EWL), Circle Line (CCL), North East Line (NEL) and Downtown Line (DTL). In addition, Thomson-East Coast Line (TEL) is under construction and 2 more lines – Jurong Region Line (JRL) and Cross Island Line (CRL) – are under planning. This increased connectivity has resulted in a more complex train network, which in turn poses greater construction risk of tunneling under or above existing lines. Contract T222 involves the construction of Outram Station and the TEL tunnels. The Outram Station will become an interchange connecting 2 existing lines in the Central Business District (CBD) located between Havelock Station (HVL) and Maxwell Station (MAX), overcrossing the existing NEL and undercrossing the EWL tunnels. One unique aspect of T222 is that the tunneling works undercrossing the EWL tunnels are in parallel for about 365m for both the tunnel drives with a clear distance ranging from 1.8m to about 8m.This is the first time such a tunnel drive is planned in a urban district with some complex geology under the ground water table.

Being within the urban district, there were numerous challenges to be encountered. One key challenge was to manage the stakeholders and to control the excavation to ensure that there was no over/under excavation that would impact the live tunnels. One another key challenge was to mine under the water table which was the sensitive criteria as drawdown could also cause movements to the tunnels and in addition managing the same water during the interventions was another concern.

This paper discusses the approach of tunneling for the undercrossing of the EWL tunnels, key tunnelling parameters used, stakeholder management and coordination, instrumentation arrangement, monitoring as well as the challenges faced and opportunities for future application.

1 INTRODUCTION

The Thomson-East Coast Line (TEL) is a Mass Rapid Transit line that is currently under construction in Singapore. The 43km long TEL consists of 31 new stations connecting Woodlands in the north to Marina Bay in the south which is the Central Business District (CBD) zone, and along the east coast of Singapore. The scope of work for contract T222 entails the construction of the Outram Park station and twin bored tunnels towards Havelock and Maxwell stations. The TEL involves 6 interchanges with about 5 contracts tunneling within the Railway protection zone (RPZ).

With reference to Figure 1, there are 2 launching shafts (LS1 & LS2) located within Outram Park Station. Starting from LS2, the 360m-long twin bored tunnels 1 and 2 towards Maxwell station were constructed using two Earth Pressure Balance Tunnel Boring Machines (EPB TBM). Subsequently, the TBMs were reassembled at LS1 to complete the 840m-long twin bored tunnels 3 and 4 towards Havelock station. For LS1, there was undercrossing of several infrastructure, namely the EWL tunnels, Wangz Hotel, Link Hotel, Cape Inn, SANA building and the PUB canal.

Figure 1. Tunnel drives from Outram Park Station to Havelock Station and Maxwell Station

The primary focus of this paper is on the undercrossing of the EWL tunnels, which differs from previous works such as the C937 of Downtown Line Stage 3 (DTL3) under Fort Canning Hill. C937 had the alignment overcrossing the existing North East Line (NEL) rail tunnel, undercrossing North South Line (NSL) and Circle Line (CCL) for a short length and perpendicular to these existing lines (Sze et al., 2015). T222 is different because it is situated in a sensitive location, hence the alignment had to be chosen such that the new tunnels had to be built parallel to the existing live tunnels. With reference to Figure 2, the undercrossing spans over 365m, with 260 rings built within this section.

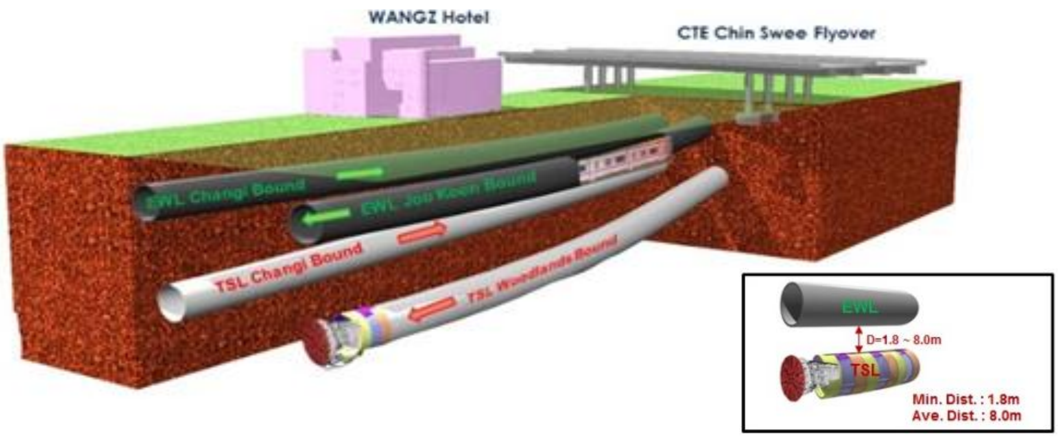


Figure 2. T222 Tunnel drives undercrossing beneath EWL Tunnels

As the tunneling works of T222 were located within the RPZ, the works were required to be in compliance with the Code of Practice for Railway Protection and Development of Building Control Rail (DBC Rail). It is noted that the EWL line was the first MRT line to be in operation and is the oldest, hence there is little existing data available about the project.

2 GEOLOGICAL CONDITIONS

Data on geological conditions was obtained from Geotechnical Interpretative Baseline Report (GIBR) and soil investigation report by the main contractor. Figure 3 below shows the geological profile of the section where undercrossing occurs.

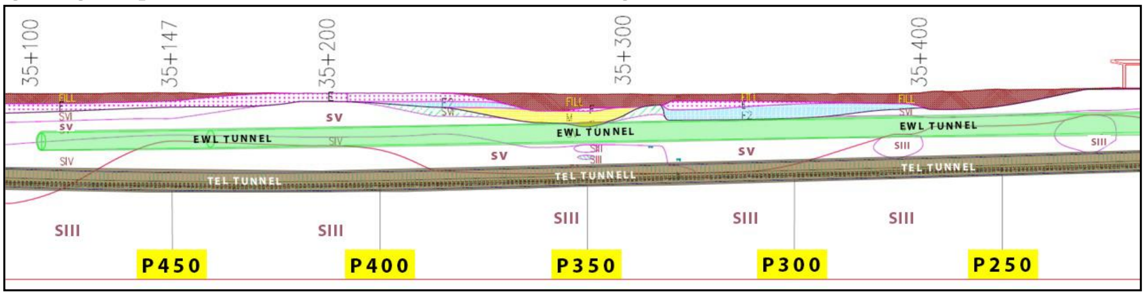


Figure 3. Geological profile of T222 Tunnel - North Bound under the EWL (green)

Grade	Characteristics
S(VI)	Bedding destroyed
S(V)	Rock weathered down to soil-like material, but bedding intact. Material slakes in water.
S(IV)	Core can be broken by hand or consists of gravel size pieces. Generally highly to very highly fractured, but majority of sample consists of lithorelics. Rock-quality designation (RQD) generally = 0, but RQD should not be used as the major guide for assessment. For siltstone, shale, sandstone, quartzite and conglomerate, the slake test can be used to differentiate between Grade V (slakes) and Grade IV (does not slake).
S(III)	Considerably weakened and discoloured, but larger pieces cannot be broken by hand. RQD is generally >0, but RQD should not be used as the major criterion for assessment.
S(II)	Slightly weakened, slight discolouration, particularly along joints.
S(I)	Intact strength, unaffected by weathering.

Figure 4. Rock Classification (taken from Singapore Standard Codes of Practice 4: 2003)

The geological conditions were categorized as Jurong Formation S(III) and S(IV). The Jurong Formation comprises a combination of sedimentary rocks of different strengths, ranging from stronger rocks such as cemented sandstone and siltstone, to relatively weaker rocks such as shale. The rock characteristics for S(III) and S(IV) are described in Figure 4. Groundwater was approximately 10-15m below ground level. The constructed twin bored tunnels have an overburden of more than 20m, and the vertical clearance between the tunnels and EWL tunnels is 6m.

3 PRE TUNNELING WORKS

3.1 Stakeholders

Stakeholder management was one of the important component which ensured the successful delivery of the project. The key stakeholder for the project was Singapore Mass Rapid Transit (SMRT), the train operator owning the concession for the EWL. This was because daily train commuters might be affected if there were any disruption to the train services as a result of the construction. The risk of train service disruption was rather high due to close proximity of the tunneling works to the existing EWL tunnels. Hence, proper and timely coordination with SMRT was crucial during the undercrossing of the EWL to ensure that this risk was properly managed.

In this case, the tunnels also run beneath some of the surface structures within the Tiong Bahru and Zion Road, hence affecting the CTE (express way), Wangz Hotel, Link Hotel and SANA Building. LTA Project team had to develop a Decanting Procedure in case of emergency as both TBMs were mining between the hotel piles as seen in the below figure.

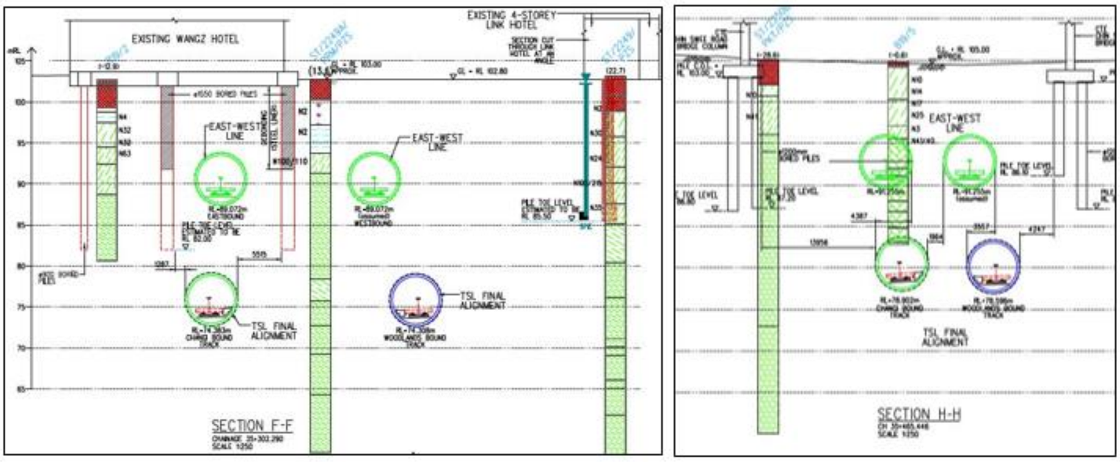


Figure 5. Undercrossing CTE viaduct (left) and Wangz Hotel (right)

As for the EWL, an Emergency Circular (OPS) was agreed between the regulator and detailed down. This had the information pertaining to the key contact person, emergency track access slots, flow chart detailing the steps to be followed in case of any breach of levels and instance when speed restriction needs to be imposed. As for the CTE (expressway) an in depth analysis of the bearing condition and assessments were made for the CTE viaduct, as the piles toe was within 5m of the influence of the TBM (Figure 5). This was to ensure there are no structural concerns arising from the tunneling works.

3.2 Instrumentation and Coordination

Another aspect of pre-tunneling works was the installation of the instruments within the two EWL bound tunnels covering a length of 800m consisting of Prism, EL beams, Tilt and Vibration meters apart from the surface instruments. Real-time monitoring was employed so that the movement of the track bed and the structural integrity of the tunnel were monitored closely at all times (Figure 6). The key challenges during this phase was getting the approval and clearance from the authorities and operator (LTA DBC and SMRT) , which took more than 4 months as the alignment was within the RPZ and had to be carefully assessed by prior to approval.

Another challenge faced was the short engineering hours when accessing the EWL tunnels. The duration of the engineering hours was only 4 hours (12am-4am), and getting the track access was subject to availability given that SMRT has their own track maintenance regime. As the tunneling works need to adhere to the CPRP. A breach of the Code can entail a train speed restriction being imposed on affected train services, or even a suspension of the train services. This was one of the key risks to be managed which involved a proper and systematic coordination during the parallel undercrossing as exposure of this particular risk was high .A detailed damage assessment was needed and it required a pre-condition survey to understand the current state of the tracks and structure. This also acted as separated document to protect the interests of the relevant authorities, contractor and operator.

The assessment showed that existing track operational levels was on the lower side as a slight movement could breach the work suspension levels for the train operation and also suspending the tunneling works. Considering this to be high risk, both LTA and SMRT had met up to come up with track replacement programme. This replacement works on completion was helpful to increase the tolerance margin for the TBM to underpass.

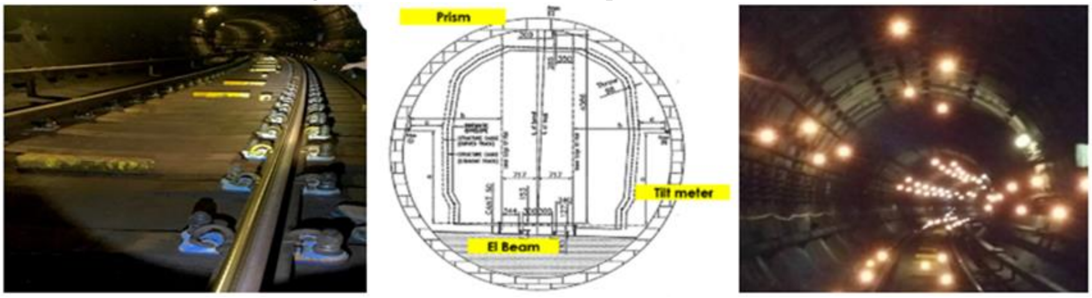


Figure 6. From left to right: Reinstated track bed, instrumentation details of live tunnel and prism layout

Close coordination between the LTA Project team, LTA DBC and SMRT was very critical during tunneling works as the procedures for track access application and safety measures had to be finalised and approved before any construction could commence. Various coordination meeting were held during the undercrossing phase. Some of the key agreements was to share the instrumentation results with SMRT on a daily basis throughout the undercrossing of the EWL tunnels. As part of a joint effort with SMRT additional track surveys were conducted on weekly basis to ensure that the EWL tunnels were structurally sound.

By maintaining a healthy professional relationship with SMRT through regular coordination meetings and site visits, the undercrossing of the EWL tunnels was executed smoothly and safely

4 TUNNELLING WORKS

This section will discuss the actual tunneling operations with reference to the TBM parameters when undercrossing the parallel sections. The first drive, TBM 3, took 158 days and the second drive, TBM 4, took 89 days. Mitigation measures and lessons learnt from the first tunnel drive had helped to understand the geology that led to reduction in time thus reducing the risk exposure under the live tunnels.

4.1 Mining Sequence and Lessons learnt

Two EPB TBM were deployed for tunneling throughout Contract T222. Due to the technical complexity of operating the EPB TBM, one key was to get familiarize with them, so as to ensure no major operating issues will arise during undercrossing. The undercrossing was in close proximity to the existing line, hence it was susceptible to major stoppages. In order to familiarise with the machines at little risk, the EPB TBM were first launched to drive towards the Maxwell Station, a relatively shorter tunnel drive. Subsequently, the EPB TBM were dismantled and reassembled at LS1 to complete the longer drive towards Havelock Station as shown in Figure 1. Some of the key specifications put in place for the cutter head was fitting them with grizzly bars to prevent damage or blockage from boulders.

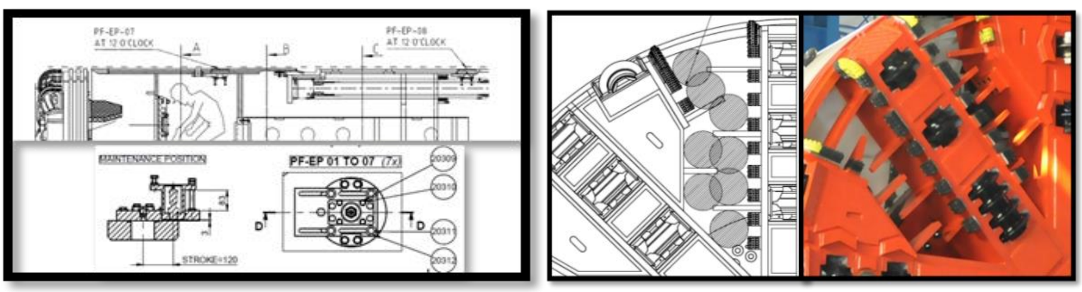


Figure 7. Diagram of 2 soil collapse sensors (left) and grizzly bars between the cutter arms (right)

The EPB TBM were also equipped with 2 pressure sensors at the crown along the front and middle shield to measure the soil collapse as shown in Figure 7. In addition, automatic face control was equipped to the TBM and shield bentonite was being injected to minimize the ground loss due to the overcut of the shield under the EWL. Two $5m^3$ bentonite tanks were installed within backup as a contingency to fill the chamber if CHI had to be abandoned. As a result of these retrofitting, the risk of downtime was greatly reduced.

This had helped the team understand the mechanical issues and as well the working crew to get familiarised with the machine. There was reduction of about 50% of the total downtime by this approach which in turn was one of the key to minimize the Mechanical TBM risk under the EWL.

4.2 Cutter Head Interventions (CHI) under the EWL line

One other major challenge was the cutter intervention under the EWL line. As mentioned, the geological conditions were categorized as Jurong Formation S(III) and S(IV). This formation - a combination of sandstone and siltstone – posed a challenge due to the high density.

Another challenge was managing the tunneling works where groundwater was approximately 10m below ground level. Caution had to be taken to ensure that there was no drawdown of water. Recharge wells were installed at regular intervals along the alignment as a contingency measure, and an additional set of cutter tools were stocked in place as a backup.

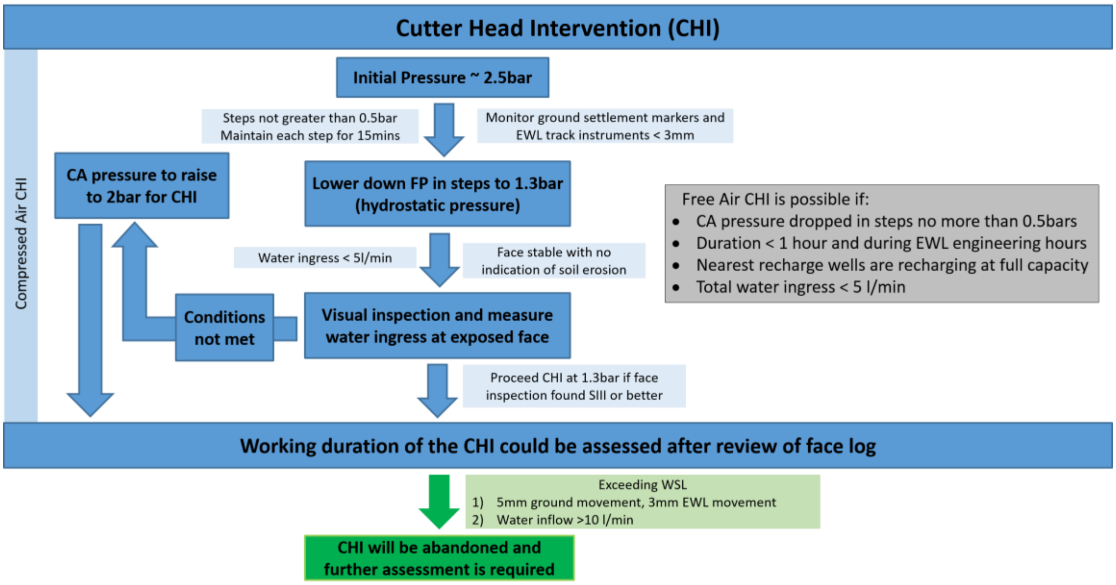
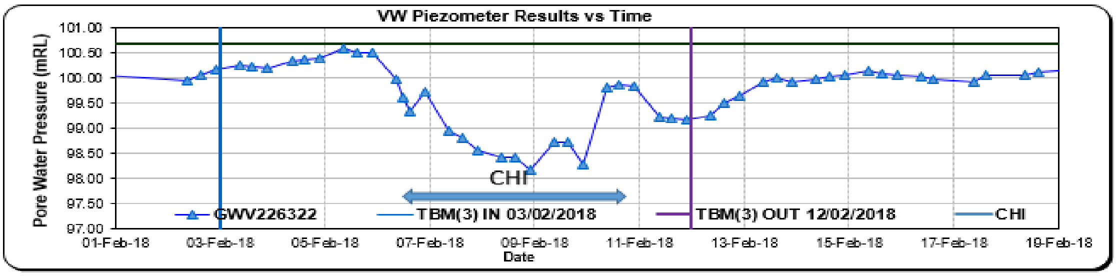


Figure 8. Flow Chart for CHI in compressed air

The flowchart above illustrates the step-by-step procedure for any unplanned CHI to mitigate the risk of settlement and water ingress, the CHIs were performed under compressed air. The initial pressure of the compressed air dive was targeted to be approximately 2.5 bar and gradually reduced after assessing the condition. The CHI duration was relatively longer, as it was completed in 6 days with a total of 25 dives. In order to reduce the duration, free air intervention was planned

during non-operating hours of the live line under strict criteria. If water ingress was detected, the face pressure would be raised to 2 bar. Reducing the duration of the CHI also meant reducing the exposure time of the operation to potential risks.

The piezometers were found to be very reactive and sensitive under the EWL (Figure 9).This was of concern for the structures resting on the soft ground along the alignment. The recharge



wells, installed during pre-tunneling stage as contingency measure, ensured the stability of the ground conditions to minimize the settlements.

Figure 9. Piezometer movement for TBM 3 during CHI at Ring 350

With reference to Figure 10, it was evident that the impact on prism movement and settlement was minimal despite reactive pore pressure trends. This implied the structural stability of the tunnel. In addition, the maximum dip allowed was 0.5mm and the corresponding twist was kept below the alert level of 1:500. For straight alignment, the versine was kept below 3mm, whereas for curved alignment, the versine was kept below 4mm.

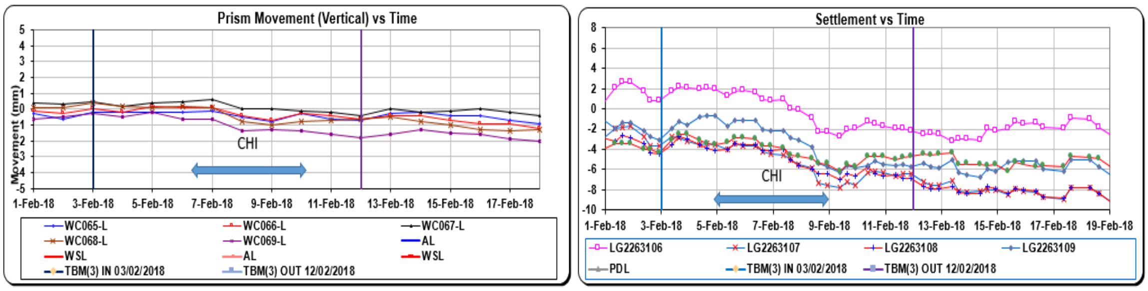


Figure 10. Prism movement (left) and settlement markers (right) for TBM 3

One other key observation from the tunnel drive was the tool wear trend. TBM 3 has 13 CHIs whereas TBM 4 has 8 CHIs during the undercrossing of the EWL Tunnels. The reason being a conservative approach followed for the first tunnel drive. Quick Intervention resulted in changing less % tools. This resulted in overloading of disc cutters while mining in sandstone and thus having more stoppages.

Figure 11. Worn-out disc cutters TBM 3

The observations of the cutter face and the EWL movements from the frequent CHI in return had proven to be advantageous for TBM 4. It is evident from the parameters were relatively more varied during TBM 3 - the first.as a result of extensive calibration to determine the appropriate ground conditions. Samples taken during the intervention were assessed and adjusted to get the right conditioning. Foam concentration was increased to have a thick concentrated bubbles reduce wear and tear of the disc cutters. Below trend plot shows CHI comparison In relation to the % tool wear, Ring interval and the numbers while undercrossing the EWL.

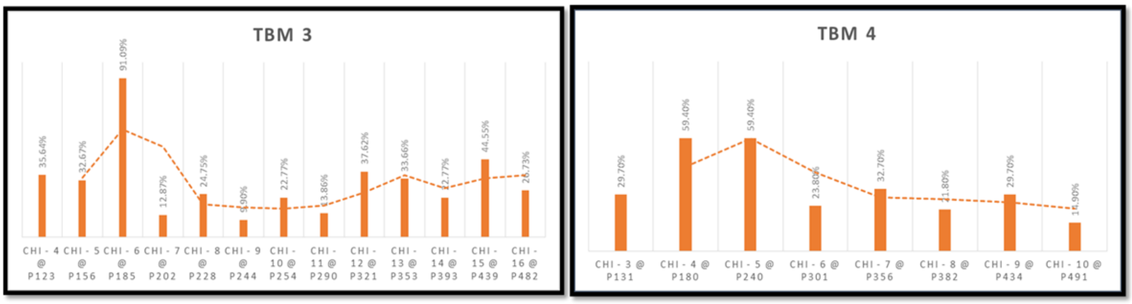


Figure 12. Comparison between TBM 3 and TBM 4 on the percentage change for tools replaced during each intervention with the ring interval.

4.3 Tunneling parameters

The following section discuss the parameters at which the two tunnel drives were operated under the EWL and they indicate the comparison between the cutter head speed and torque exerted, versus the actual penetration and rounds per minute completed. In this case the torque was limited at about 4000kNm so as to avoid overheating of the cutter head motors. The rpm was adjusted between 1.5 and 2rpm to get a better penetration. These parameter was helpful to achieve better results under the TBM 4 condition and led to an increase in the penetration from 6-12mm which can be seen from the below comparison plots of the 2 drives.

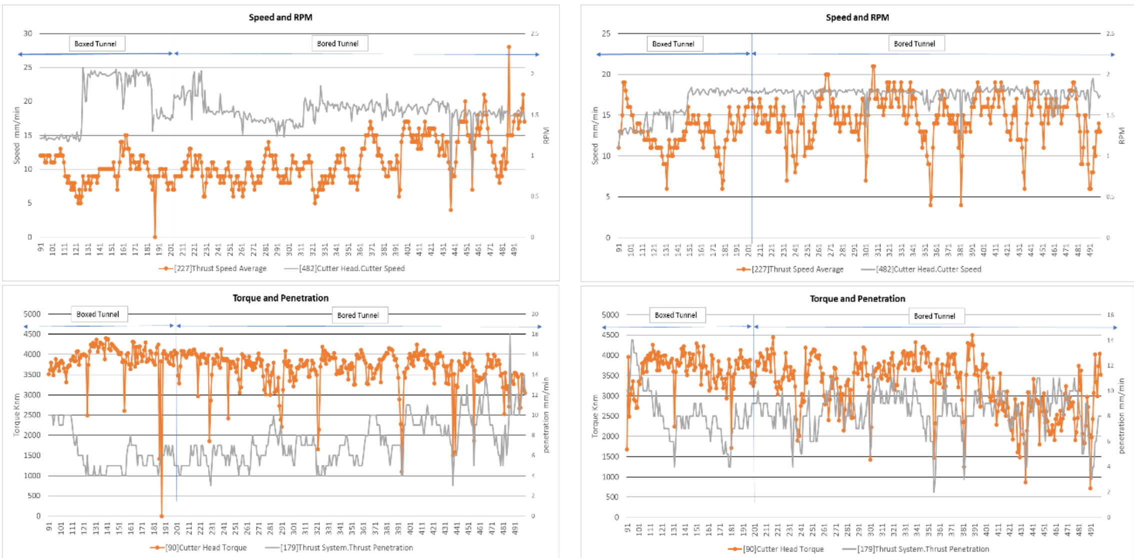


Figure 13. Parameters for TBM 3 (left column) and TBM 4 (right column)

It is evident that the parameters were relatively more varied during TBM 3 - the first drive compared to the other drive which was more consistent in operating the later part the torque was dropped due to a small interface of weathered silt stone. The face pressure was very well maintained within the range set and approved by the designers. An impact assessment was prepared to assess all the critical factors before arriving at the design face pressure. The challenge was to come up with the design limits considering the EWL and the surface structures sitting on soft strata

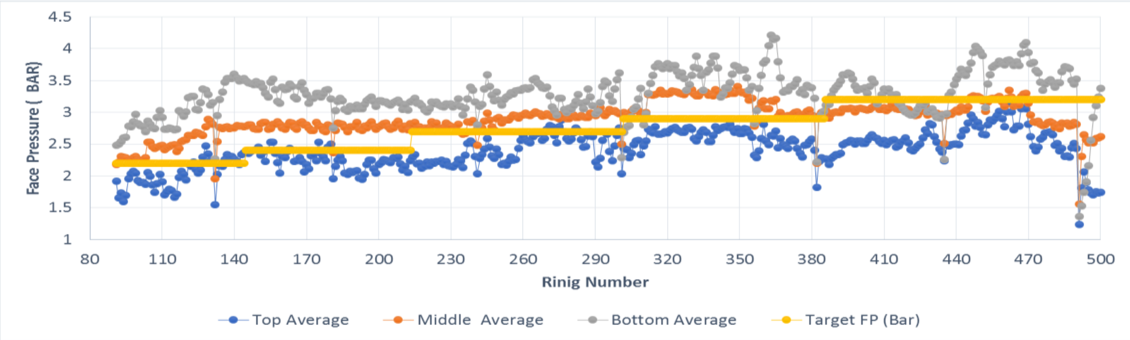


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Figure 14. Sample face pressure trend plot for TBM 4

Due to the shallow cover of the EWL at the initial section the face pressure was maintained slightly higher than the target/design face pressure. In addition any over/under excavation was maintained within 10% limit and anything beyond this limit was carefully assessed in terms of density and volume (Figure 15).

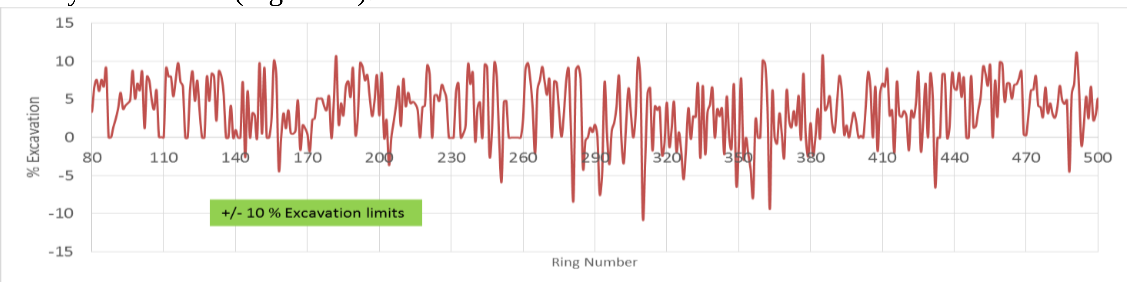

Figure 15. Graph of Percentage (%) Excavation against Ring Number for TBM 4

Due to the close cover of the EWL line, it was ensured that the required volume of primary grout was closely monitored. Additional quantity slightly more than the theoretically required volume was injected to ensure that there were no voids. Figure 18 shows the volume intake for TBM 4.

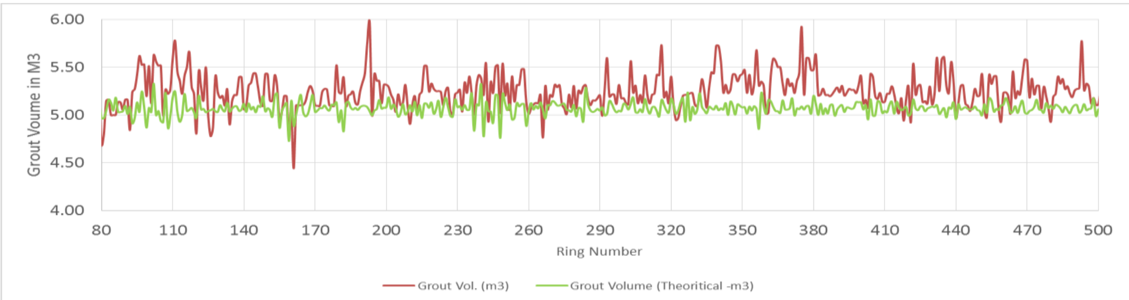

Figure 16. Theoretical vs actual grout volume used

All the above tunneling parameters was the key to control the EWL movements within the tolerance levels and complete the tunnels successfully.

5 CONCLUSION

The undercrossing of the EWL tunnels posed many unique challenges. Firstly, the undercrossing, stretching over 365m, was in a parallel alignment under existing live tunnels. Secondly, the construction was in close proximity to several infrastructures. Thirdly, the geology of the ground and ground water conditions were difficult. These challenges added to the complexity of the undercrossing, and presented practical implications which required effective project management throughout the entire project. The above has been elaborated in the detail in this paper.

Several key factors contributed to the successful completion of the undercrossing:

- A systematic approach was taken with regards to risk management. This entailed effective communication and close cooperation with the stakeholders- the regulators, contractor and the affected community; the earlier coordination was helpful to minimize some of the key risk due to the life of the EWL tunnel.
- Maintenance of the TBM was properly planned. This involved accurate face support pressures and ground conditioning agents from the lessons learnt from the earlier drives. The combination of the knowledge, experience and communication between the team and operators was crucial to the project
- The construction team was highly effective in analysing problems, learning from mistakes and implementing mitigation measures such as the CHI procedure which helped to manage the risk during the stoppage under the EWL. The setting up recharge wells and additional piezometer proved to be useful to assess and control the ground water table. A recommendation for future monitoring of ground water would be the inclusion of water standpipe within the zone around the piezometer, as this could help to better understand and assess the ground movements in relation to the level of water table.

The end result is an underground tunnel successfully built in difficult ground and ground water conditions. There were no major disruption to the live line, and zero loss of ground during excavation was achieved. Risks were assessed and actively managed. As a result of this project, the range of EPB TBM -related operations was effectively expanded, opening up greater opportunities for planning future tunneling projects under such conditions.

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