From Runways to Tunnels: Navigating the Challenges of Tunnelling Underneath Singapore's Changi Airport

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ABSTRACT: Thomson-East Coast Line extension (TELe) Contract T316 involves the construction of twin-bored tunnels between Changi Airport's future Terminal 5 (T5) and the existing Changi Airport Station at Terminal 2 (T2). Both bounds of tunnelling works were carried out concurrently using two Earth Pressure Balance Tunnel Boring Machines (EPB TBMs), driven from the launch shaft in the T5 development area towards T2 aircraft stand E5. Hence, critical airport infrastructure had to be undercrossed by the TBMs during tunnelling. The undercrossing of live aircraft movement areas, such as Tango Taxiway, posed additional operational constraints on top of the technical difficulties involved. This paper will discuss how these operational and technical challenges were addressed and assess the effectiveness of implemented measures.

1 INTRODUCTION

The Land Transport Authority (LTA) awarded Contract T316 to Shanghai Tunnelling Engineering Singapore (STECS) to construct twin-bored tunnels from Changi Airport's future Terminal 5 (T5) to the existing Changi Airport Station at Terminal 2 (T2). The two bounds are named 'Changi Bound' and 'Woodlands Bound', following the nomenclature of the overall Thomson-East Coast Line (TEL). Tunnel construction was split into two phases – the first phase was carried out in 2022 from April to December. Contract T316 also included the construction of an Underground Infrastructure Building (UIB) but will not be elaborated upon in this paper. The discussion will focus on the challenges encountered during the first phase of tunnelling, paying particular attention to the airport environment and the ground underlying the airport.

Changi Airport has consistently been ranked as one of the world's busiest airports and is a vital economic link for Singapore. Hence, the importance of ensuring that tunnelling was carried out safely and without any disruption to airport operations.

2 BACKGROUND INFORMATION

2.1 Tunnel Alignment

The tunnel alignment is shown in Figure 1. Tunnelling started at the launch shaft within the T5 development area and progressed towards T2. Enroute, the TBMs would undercross Runway 02, Tango Taxiway, a 3-cell box culvert and other ancillary aerodrome infrastructure. T2 is inclusive of all the parking aprons and the terminal buildings which can be seen in the top of Figure 1. The first phase of tunnelling runs northwards from the launch shaft and ends at aircraft stand E5.

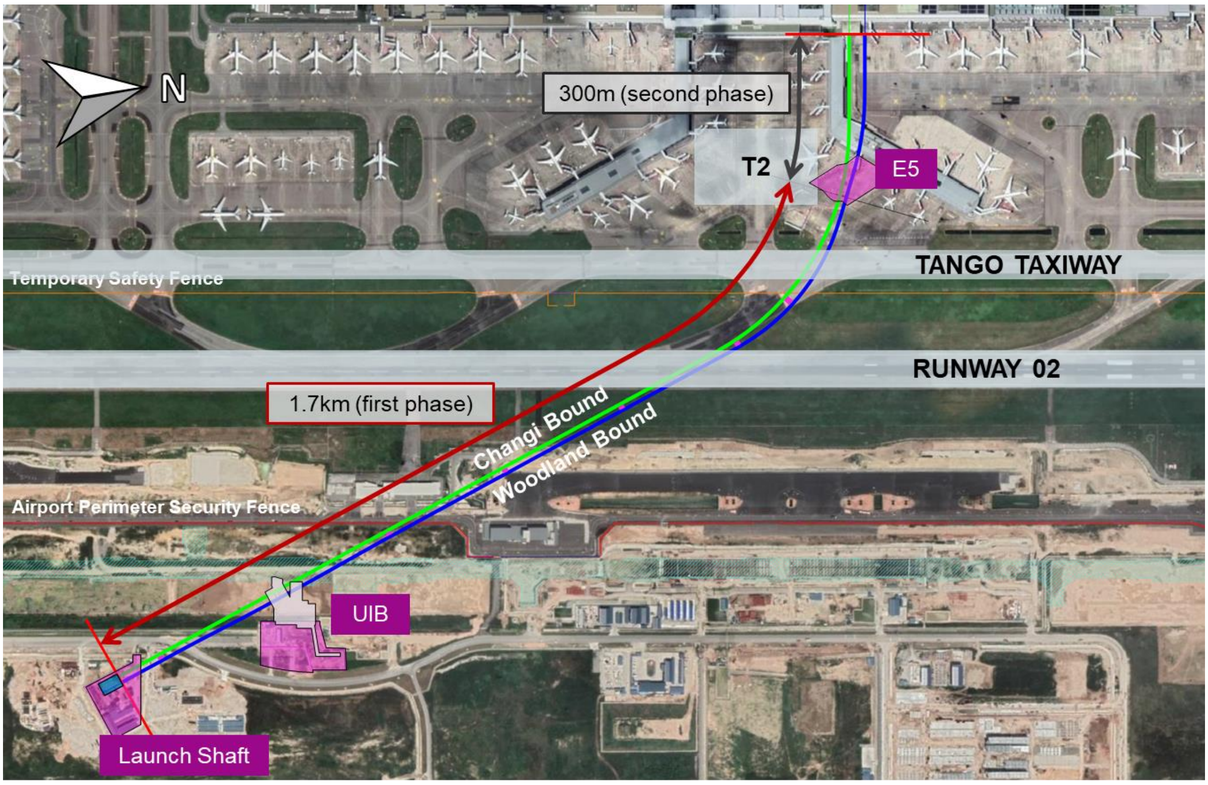

Figure 1. Tunnel alignment in airport.

2.2 *Topography and Geology*

The topography of the project site is relatively flat at an approximate elevation of 4m Singapore Height Datum (SHD). The site is located entirely within reclaimed land, hence its ‘flatness’. Based on available records, the reclamation was carried out in varying stages over the 1970s to early 2000s for the development of Changi Airport and relevant supporting infrastructure (Bo et al. 2011). The subsurface conditions generally consist of ‘Fill’ of varying thickness. Underlying this material is Bedok Formation Old Alluvium (OA) which is the predominant geology encountered at tunnel depth. The OA consists of soil of varying weathering grades. The soil investigation and subsequent construction affirmed OA(A) and OA(B) as the encountered types of OA. Deposits of Kallang Formation, specifically Fluvial Clays (F2) and Fluvial Sand (F1), were identified underneath Tango Taxiway and its vicinity. Figure 2 gives an overview of the geological profile along the alignment.

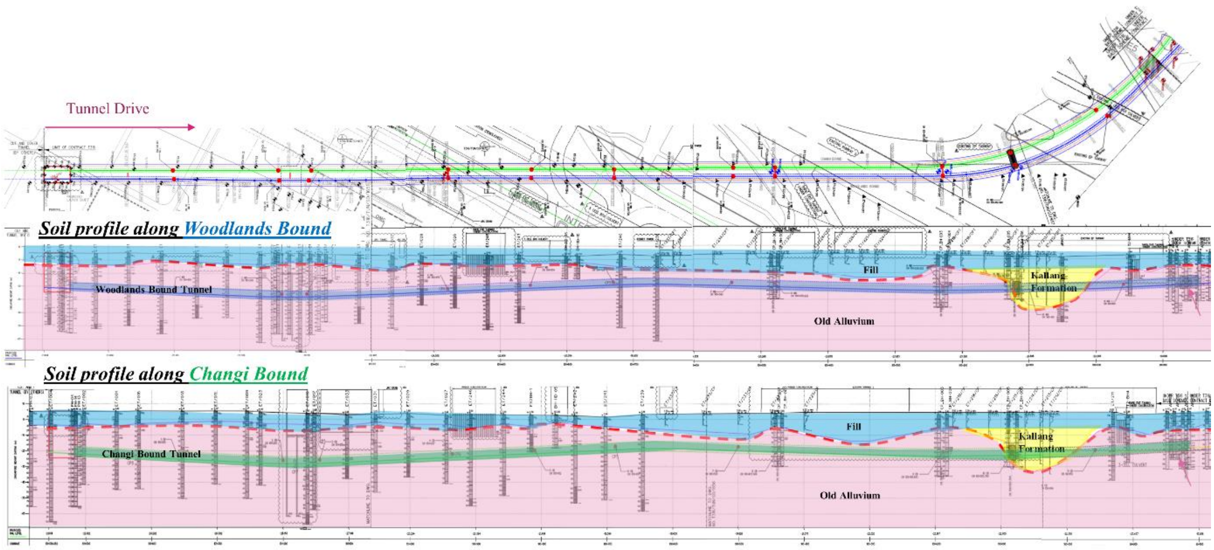

Figure 2. Geological profile along Woodlands Bound (top) and Changi Bound (bottom).

2.3 Tunnel Boring Machines

The two EPB TBMs used for this project were manufactured by Shanghai Tunnelling Engineering Co. Ltd. and were designed to construct the tunnels with an external diameter of 6.35m. EPB-type machines were chosen because of the general clayey nature of the geology predicted along the alignment.

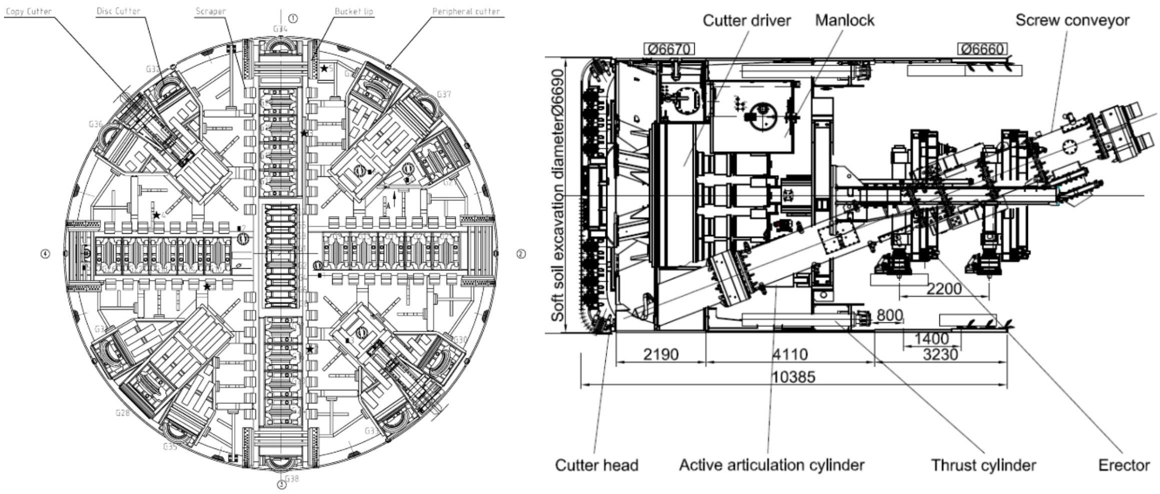

Figure 3. EPB TBM used in T316.

Table 1 below presents a summary of the key specifications of the TBM used in Contract T316.

Table 1. EPBM data.

Component	Key Specification
Type	Earth Pressure Balance (EPB)
Segment Outer Diameter	6350 mm
Segment Inner Diameter	5800 mm
Segment Length	1400 mm
Ring Distribution	7+1
Major TBM Shield Components	Cutterhead, front shield, middle shield & tail shield
Overall Shield Length	10.40 m
Excavation Diameter	6690 mm
No. of Back-up Gantries	7
Total Length (Full Config.)	98.67 m
Main Drive Unit	1 no., electric type
Maximum Excavation Speed	80 mm/min

3 CHALLENGES, OPPORTUNITIES AND SOLUTIONS

In this section of the paper, the main challenges encountered during the first phase of tunnelling are discussed. Meanwhile, some situations presented unique opportunities in terms of tunnelling operations. For instance, Runway 02 was closed in October 2020 and was scheduled to reopen only at the end of 2023. Hence, there was a window for the undercrossing of Runway 02 to be completed during this closure period to minimise any impact to airport operations.

3.1 Undercrossing Runway 02

Runway 02 is located at the eastern side of Changi Airport Terminal 2, as indicated in Figure 1, and was commissioned in 1984 (Singapore Monitor, 1984). It is a type of flexible pavement, measuring 60m x

4000m, along with 7.5m of shoulder on both sides of the runway (Koh et al. 2005). Figure 4 shows the cross section of the Runway 02 flexible pavement.

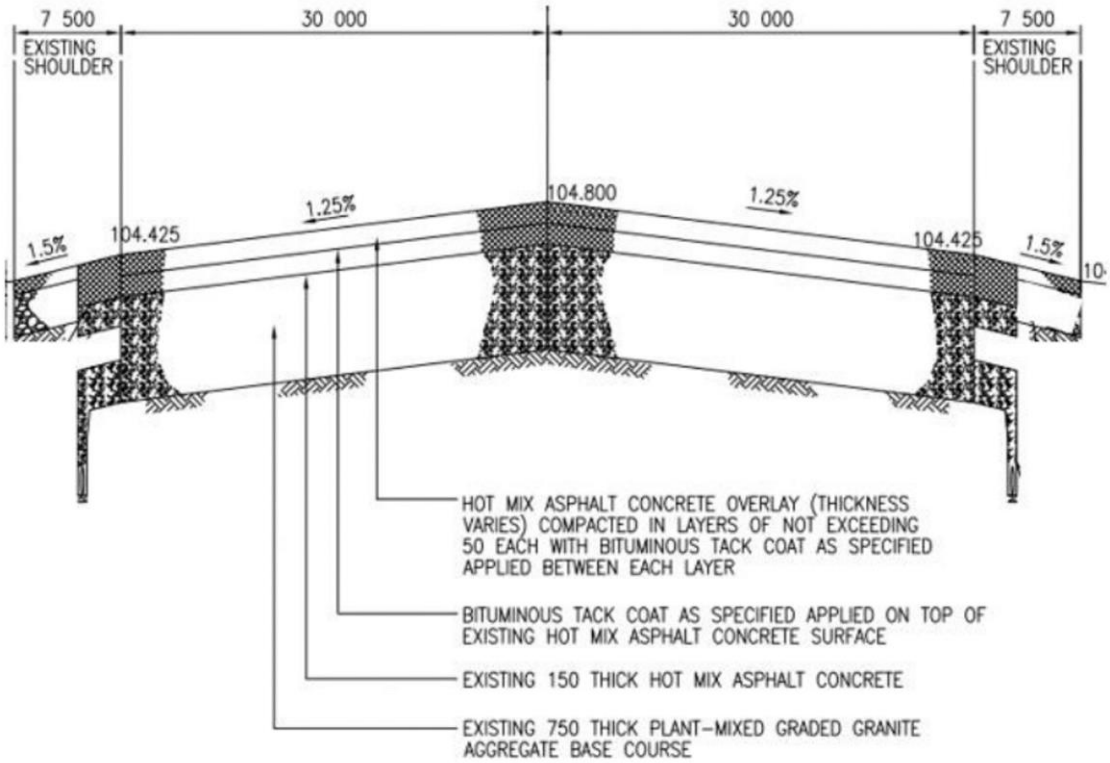

Figure 4. Typical cross section of Runway 02 (not to scale).

Runway 02 was undercrossed successfully by the Changi Bound and Woodlands Bound TBMs in October 2022 and November 2022, respectively. Table 2 gives a summary of the TBM parameters applied during the undercrossing.

Table 2. TBM parameters applied at Runway 02 and 3-cell box culvert.

Parameters	Values at Runway 02
Face pressure (bars)	2.65 - 2.85
Primary Grout volume (m^3)	5.4 -5.5 (per ring)
Grout Pressure (bars)	3.2 - 3.3
Cutterhead Rotation Speed (rpm)	2 – 2.2
Thrust force (kN)	18000 - 20000
Cutterhead Torque (kNm)	2100- 2460
Average Advance Speed (mm/min)	52

Due to the consistent nature of the geology underneath Runway 02, the parameters remained stable during this stretch of tunnelling works.

3.2 Tango Taxiway: Micro-Tremor Survey

Tango Taxiway and connected taxilanes remained operational before and during tunnelling works, presenting a set of unique operational challenges – the first of which was the inability to carry out conventional soil investigation works in the area, especially boreholes. Hence, a micro-tremor survey was conducted by using vehicles equipped with special equipment to 'sweep' the areas of Tango Taxiway and connected taxilanes within the influence zone of tunnelling works. The area over which the micro-tremor survey was conducted is depicted in Figure 5.

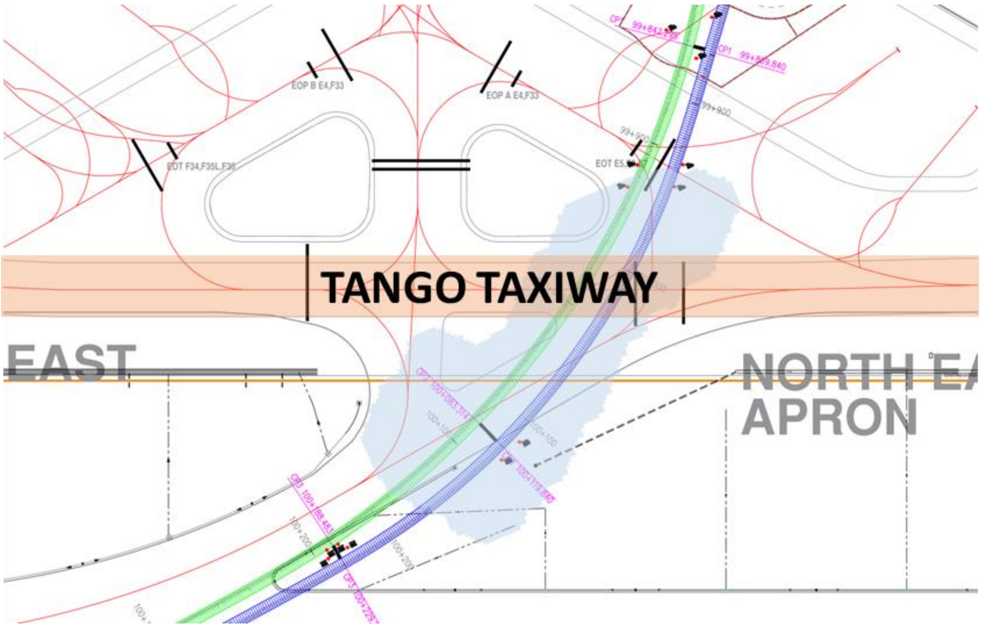

Figure 5: Plan view of micro-tremor survey (shaded in blue).

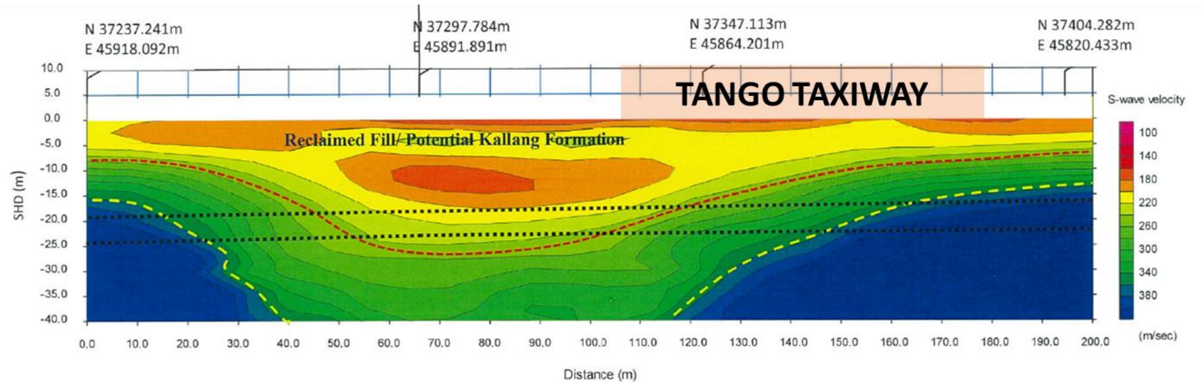

Figure 6: Sample of results from the micro-tremor survey.

The micro-tremor survey's objective was to map out the boundary between soft and hard soil, i.e., the boundary between Kallang Formation and OA(B), as shown in Figure 6. The results indicated that the Kallang Formation was distributed in a valley-like manner vis-à-vis the surrounding OA. However, the micro-tremor investigation was unable to distinguish between the various components of Kallang Formation (e.g., Marine Clay vs. F1). Hence, to be conservative, a layer of F1 fluvial sand was interpolated between the two closest boreholes on either side of the taxiway, giving the predicted geology presented in Figure 7.

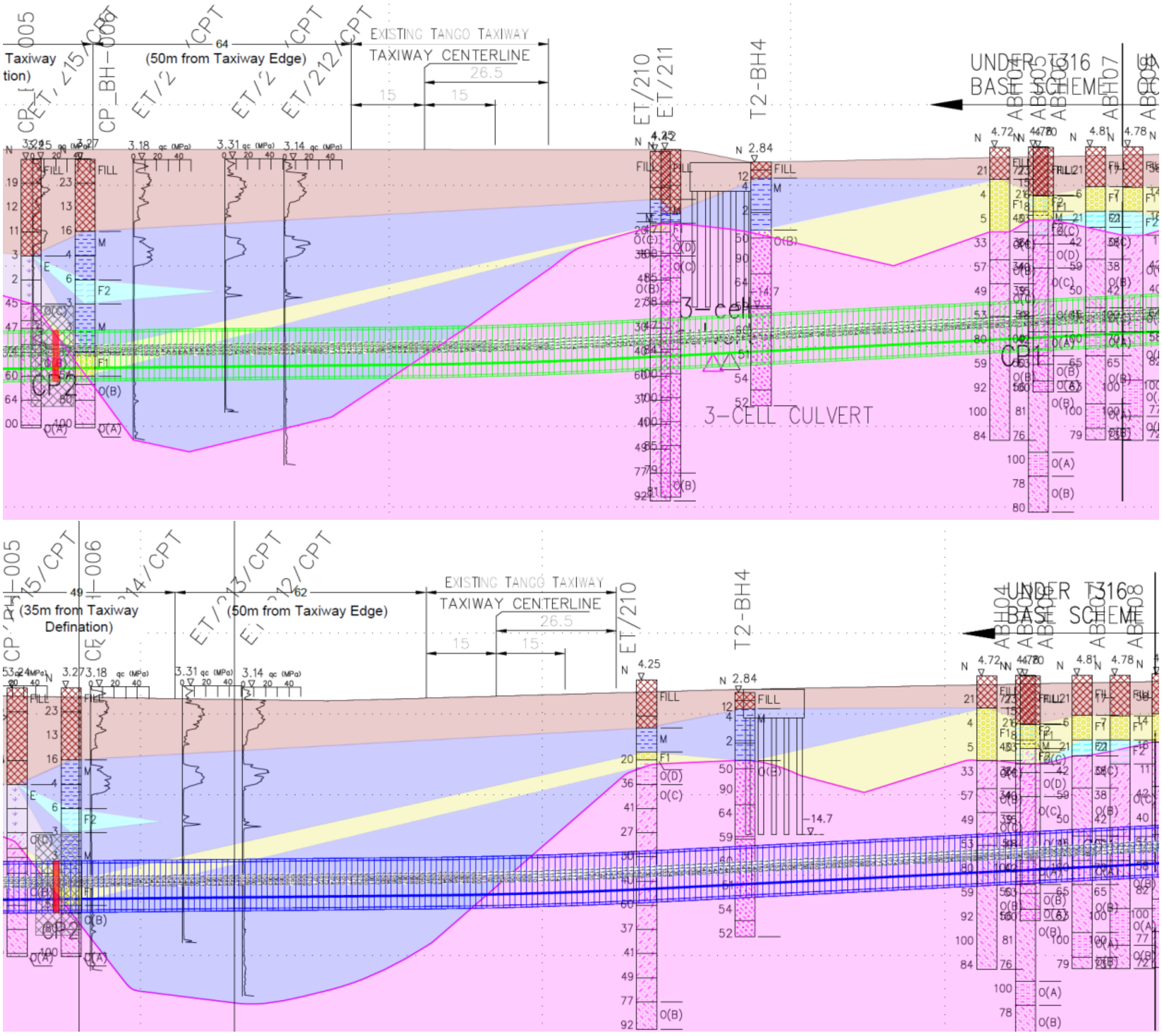

Figure 7: Geology underneath Tango Taxiway; Changi Bound (top) and Woodlands Bound (bottom).

3.3 Prefabricated Vertical Drains (PVDs)

The ground underneath Tango Taxiway was treated in the 1970s using Prefabricated Vertical Drains (PVDs) and surcharge to increase the rate of consolidation of the soft compressible marine clay layers. Records revealed that these PVDs generally consist of a synthetic plastic-like core wrapped by a geotextile-like material (Yang et al. 1999). They were left-in after the completion of the ground improvement works. The PVDs were generally installed towards the eastern side of Taxiway where F2 marine clays were expected and were installed in square-grid with spacings of 2.5m and 3.2m. The TBMs were expected to encounter PVDs at the locations shown in Figure 8.

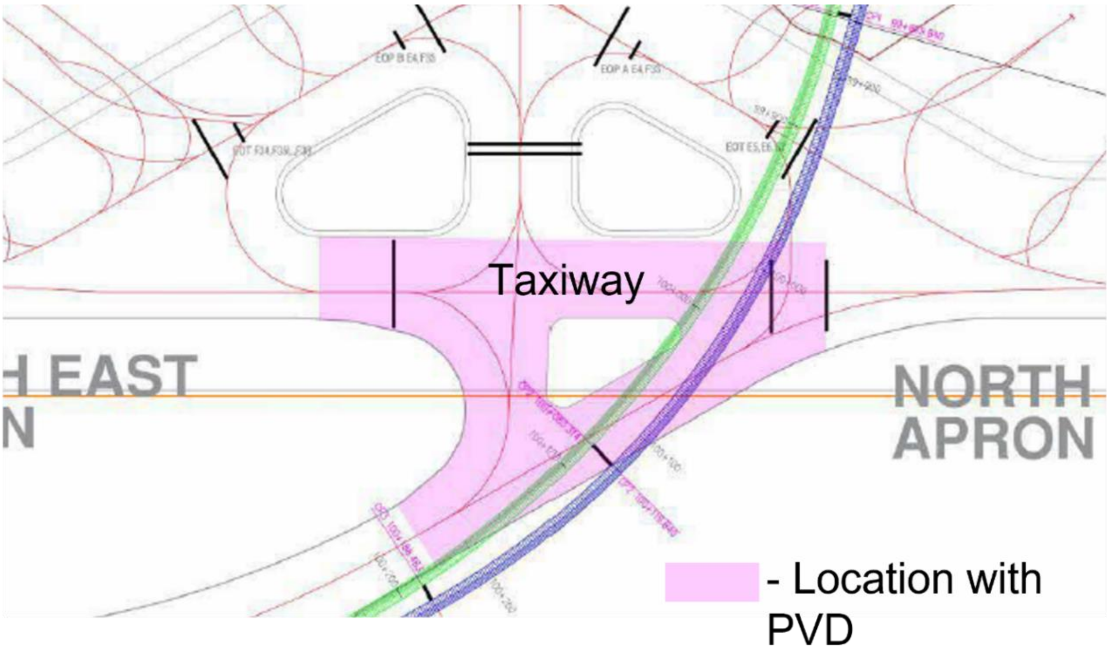

Figure 8. Location of PVDs at Tango Taxiway in relation to the tunnel alignment.

Given that the PVDs could not be removed from the surface prior to tunnelling, the chosen approach was to have the TBMs designed to tunnel through them. The main objective here was to allow the TBMs to be able to tunnel and cut these PVDs without any adverse effects such as excessive ground movement or a disturbance leading to long term consolidation of the marine clay. Additionally, the PVDs should be cut into smaller sizes for seamless transportation within the excavated muck and through the TBM.

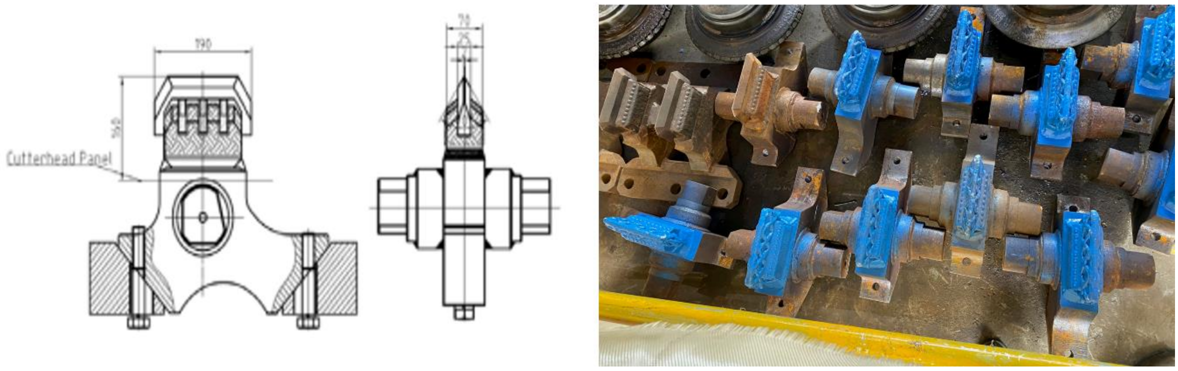

Figure 9. PVD cutters.

The solution was to replace some of the disc cutters with specialized cutting tools for the PVDs. These tools had a steep angled edge profile which were hardened to allow for a smooth cut as much as possible when the cutterhead rotates. Trials were carried out off site and under a simulated environment to determine the suitable TBM parameters.

These tools were replaced during a cutterhead intervention before entering the stretch of tunnel alignment predicted to have PVDs. 15 disc-cutters were swapped (Figure 10), with the remainder unchanged, to achieve a balance between cutting the PVDs and ensuring that the TBMs could still tunnel through the relatively stiff and abrasive OA geology that would be encountered after passing the area of known marine clay.

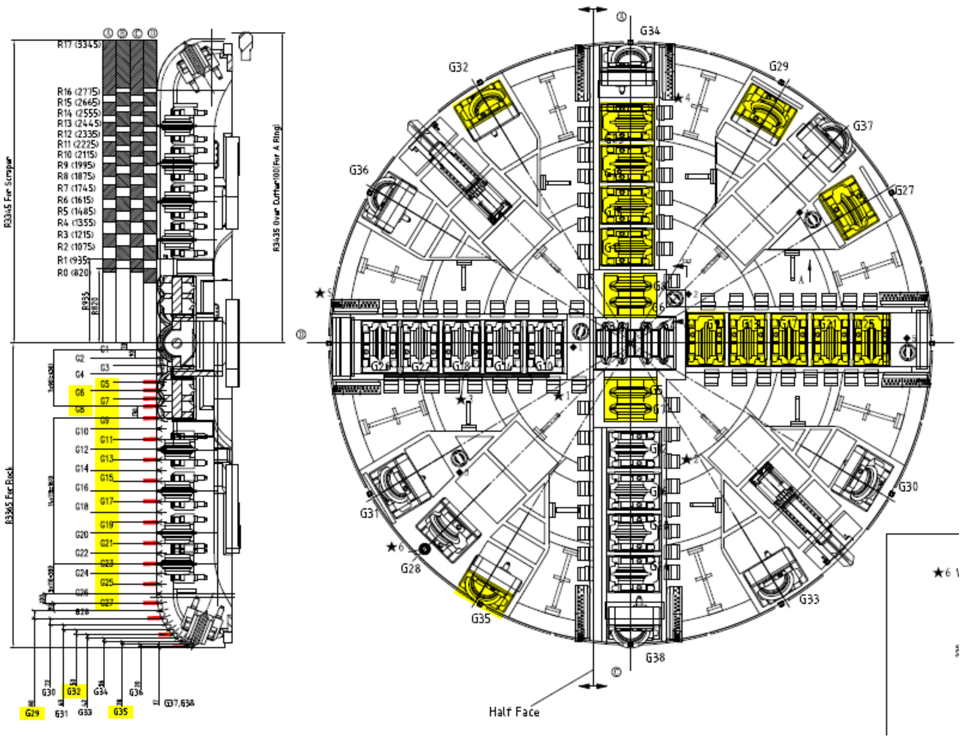

Figure 10. Position on cutterhead where PVD cutters were installed.

Figure 11: PVDs encountered during tunnelling.

Examples of the PVDs that were encountered and cut during tunnelling are shown in Figure 11. The PVD cutters were effective and enabled the TBMs to excavate the soil without any complications caused by the presence of PVDs.

3.4 Undercrossing Tango Taxiway

During the undercrossing of Tango Taxiway, one of the main concerns was the potential loss of ground support and excessive ground movement as a result of tunnelling in Kallang Formation and especially F1 fluvial sand.

To prevent the loss of ground support, appropriate soil conditioning was used to manage the envisaged F1 fluvial sand at this location. The highly fluvial nature of the F1 layer would pose a challenge to the TBMs' ability to maintain the pressure built up by the excavated soil in the chamber and screw conveyor. Hence, water-absorbing polymer was added to the usual soil conditioning foam to improve the plug-forming characteristic of the F1 fluvial sand. This soil conditioning mixture was dispersed at the soil conditioning ports at the TBM cutterhead and screw conveyor to ensure that the soil plug could be achieved.

In addition, the TBMs operated closer to the maximum allowed FP values (e.g., Changi Bound operated at an average FP of about 3.8 bar, i.e., ~90% of overburden pressure). This was another precautionary measure to safeguard against the possibility of encountering a layer or pocket of F1 fluvial sand and to generally keep any surface ground movement to a minimum, especially since Marine Clay's response would be relatively quick. Of course, there was also the concern of heaving as Kallang Formation is sensitive to the face pressure applied, hence the face pressure was only raised or lowered in small (0.2 bar) increments between the mining of each ring to monitor and control the ground's response. The design face pressures used for the undercrossing have been summarised in Table 3.

Table 3: Design face pressures for the undercrossing of Tango Taxiway

	Changi Bound	Woodlands Bound
Max. FP (bar)	3.3 – 4.0	2.9 – 3.7
Target. FP (bar)	2.7 – 3.4	2.5 – 3.3
Min. FP (bar)	2.5 – 3.2	2.3 – 3.1

Other measures include an 'Automatic Face Control' system that would automatically pump bentonite into the chamber if the face pressure were to suddenly drop below a pre-determined safety threshold, providing immediate face support, as well as additional grouting equipment that was on standby to perform grouting from the surface or within the tunnel when necessary.

3.5 MOAS Monitoring Grid

During the undercrossing of any airport infrastructure, inclusive of the operational Tango Taxiway, it was imperative to ensure that the ground movements were monitored closely to ensure safety and to meet aerodrome requirements. The taxiway is required under section 7.2 of the Manual of Aerodrome Standards (MOAS, 2021) to meet specific physical requirements in terms of slopes in order to be deemed operationally ready.

The taxiway slope is basically the vertical height difference between 2 points along the taxiway divided by the distance between these 2 points. There are specific requirements for slopes measured along the longitudinal and transverse alignments of the taxiway (MOAS, 2021). Hence, to determine if tunnelling operations had breached relevant aerodrome requirements, the monitoring layout at the taxiway was modified. Essentially, the surface monitoring points were arranged in a grid-like format, as shown in Figure 12, in order to compute the required pavement slopes as mentioned above.

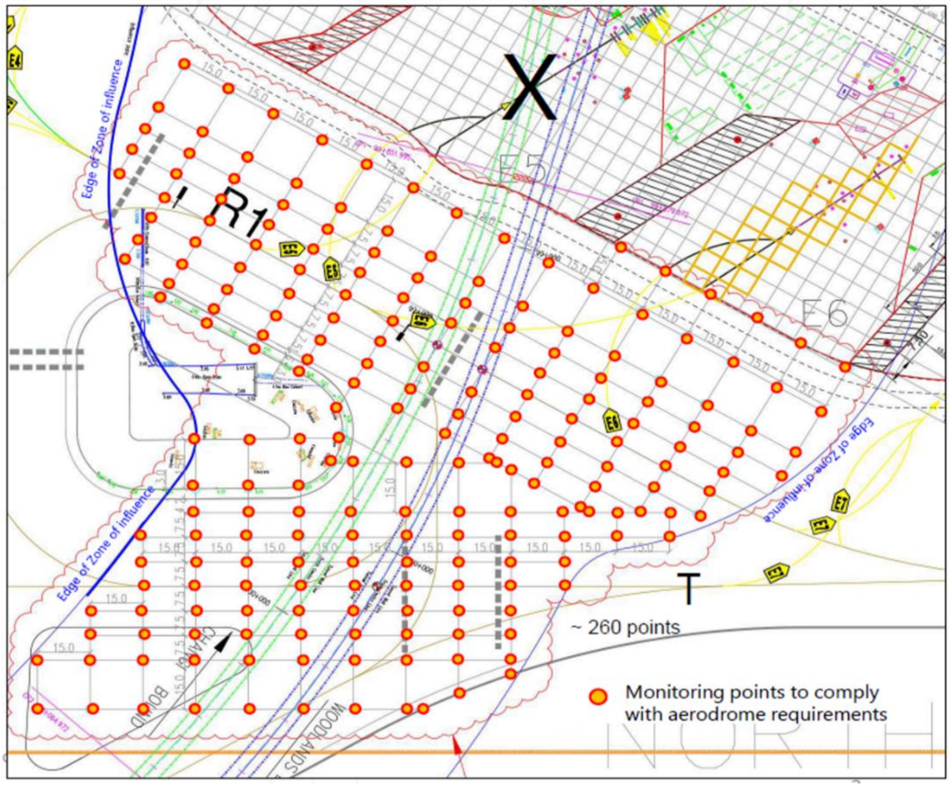

Figure 12. Monitoring points at affected taxiways and taxilanes, arranged in a format suitable for MOAS slopes.

In addition, as these were operational aircraft manoeuvring areas, monitoring prisms could not be installed on the pavements. Hence, 'reflectorless' monitoring was adopted, whereby an Automatic Total Station (ATS) was used to shoot directly onto the pavements at coordinates determined by the MOAS monitoring grid. An example of the ATS used is shown below.

Figure 13: ATS used for reflectorless MOAS grid monitoring.

As demonstrated by the graph in Figure 14, the settlement values at the taxiway remained relatively stable throughout tunnelling. Ground movement was effectively kept within a magnitude of 10mm, well within the alert limits. The post-tunnelling ground movement values remained within the same range.

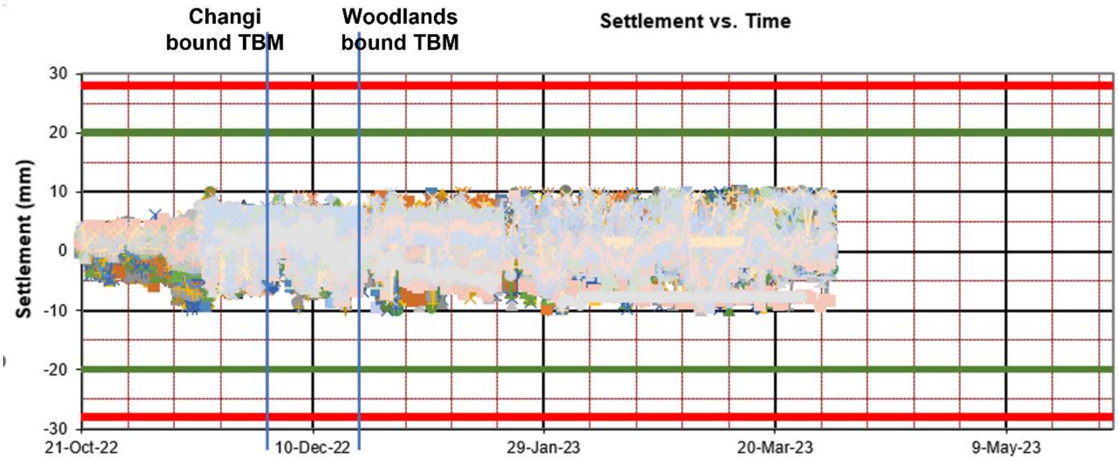

Figure 14. Settlement values at Tango Taxiway.

3.6 Free-Air Cutterhead Interventions

Finally, as the ground at tunnel depth was predominantly of hard cemented Old Alluvium soils, it was possible to carry out cutterhead interventions (CHIs) under free-air conditions. This was an opportunity capitalised upon to reduce the time spent performing CHIs in order to minimise any risk to overlying airport infrastructure during these stoppages. The suitability to perform free-air CHIs was verified through design checks using methods described by Anagnostou and Kovari (1996) as well as Kimura and Mair (1981). Three-dimensional finite element analysis was also carried out for sensitivity studies, providing additional confidence that the face stability could be maintained.

Overall, the following criteria were crafted to determine feasible locations for free-air CHIs:

- In full face OA and a minimum cover of one tunnel diameter of OA with an average SPT N> 30, or full face in a ground improvement block.
- Away from sensitive interfaces or utilities.

Meanwhile, an observational approach was adopted when carrying out step-downs of the supporting pressure from the initial CHI pressure. The following conditions had to be verified at each step-down until free air was reached:

- The water ingress is not excessive to ensure that the exposed face remains undrained.
- Face is stable and verified by face mapping.
- Ground settlement does not exceed the allowable range so that the SLS condition is met.
- Face pressure shall be increased immediately of above conditions cannot be met.

In addition, the designer would have to reassess the face condition and all relevant instruments at every 72-hour interval of CHI works to check if the free-air CHI can be continued.

In summary, 20 counts of CHI were executed on site, of which 14 were at the planned locations while 6 numbers were at unplanned locations. All 20 CHIs were carried out under free air conditions, following the gradual step-down procedure from the target face pressure. 16 counts of CHI works were carried out in competent Old Alluvium, while the remaining 4 were performed in ground improvement blocks due to the presence of Kallang formation or at the locations of cross passages. All CHIs were completed successfully with negligible water inflow observed or induced ground movement.

Table 4. Summary of free-air CHIs performed in competent Old Alluvium (16 counts).

Reference	Depth below ground (m)	Expected soil condition at tunnel face from nearest borehole	Competent soil cover above tunnel crown (m)	Total duration of CHI under free air (hrs)	Observed water inflow (L/min)
1 CB	23.9	OA(B) - 100%	18.4	129.5	0
2 CB	27.7	OA(B) - 100%	20.5	89.5	0
1 WB	24.1	OA(B) - 100%	15.3	63.5	0

3 CB	27.3	OA(B) - 100%	20.1	55.0	0
4 CB	23.2	OA(B) - 100%	16.0	68.0	0
2 WB	30.3	OA(B) - 100%	21.5	69.5	Initial Seepage 4.5L/min but flow rate reduces to 1.25L/min
3 WB	28.0	OA(B) - 100%	21.7	35.0	0
5 CB	17.1	OA(B) - 100%	9.0	45.5	0
4 WB	23.3	OA(B) - 100%	16.6	78.5	0
6 CB	19.9	OA(B) - 100%	10.5	43.0	0
5 WB	17.8	OA(B) - 100%	9.3	67.5	0
7 CB	22.9	OA(B) - 100%	12.7	52.5	0
6 WB	19.7	OA(B) - 100%	6.6	48.5	0
*8 CB	22.6	OA(C) - 100%	5.8	53.5	0
7 WB	21.2	OA(B) - 100%	12.4	45.5	0
*8 WB	20.4	OA(C) - 100%	2.9	44.5	0

*8CB and 8WB were located at greenfield locations and were unplanned CHIs which were not selected for free-air CHI during the design stage. The free air CHIs were carried out adhering to the observation approach. During face pressure step-down, it was observed that the excavation face was stable with no signs of erosion or distress, and water inflow and ground movement were all within the allowable range.

Figure 15. Photos from free-air CHI; (left) Changi Bound and (right) Woodlands Bound.

4 CONCLUSION

In conclusion, tunnelling underneath Singapore Changi Airport was a challenging yet exciting endeavour. Comprehensive measures were taken to ensure that there would be no adverse impact to airport operations during tunnelling works and the undercrossing of airport infrastructure. This paper demonstrates that when the difficulties of working in such an environment are managed proficiently, and the opportunities to optimise operations are promptly taken advantage of, tunnelling can be executed safely and timely.

ACKNOWLEDGEMENT

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REFERENCES

Anagnostou, G. & Kovari, K. (1996). Face Stability in Slurry and EPB Shield Tunnelling. *Tunnels and Tunnelling*, December 1996, pp. 27-29.

Bo, M. W., Chang, M. F., Choa, V., Arulrajah, A. 2011. Ground investigations for Changi east reclamation projects.

Kimura, T. & Mair, R. J. (1981). Centrifuge Testing of Model Tunnels in Soft Clay. *Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, 15-19 June 1981. Rotterdam: Balkema, pp. 319-22.

Koh, M. S., Lim, B. C., Wu, D. Q. 2005. Chemical-Soil Stabilization for Runway Shoulder Widening at Singapore Changi Airport. *The 4th APTE Conference, Xi'An, China.*

Singapore Monitor. 12 March 1984. Accessed via: https://eresources.nlb.gov.sg/newspapers/Digitised/Page/singmonitor19840312-2.1.3?ST=1&AT=search&k=changi%20runway&QT=changi,runway&oref=article

Yang, K. S., Chiam, S. L. 1999. Geotechnical Engineering for Transportation Infrastructures in Singapore. Part B: Airport Developments.

Civil Aviation Authority of Singapore. 15 June 2021. Manual of Aerodrome Standards (MOAS) version 2.6.