A case study of twin bored tunnelling under mixed-face soil - Bendemeer MRT station project 
(Downtown Line 3), Singapore

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ABSTRACT

The Bendemeer Station project is part of the construction of MRT Downtown Line 3 (DTL-3) in Singapore, under Contract C933. High variation in geological condition along the alignment was encountered during the tunnelling works in this project. The transitions from Old Alluvium soil towards the soft soils of Kallang Formation create the challenging mixed-face soil condition at the tunnel face. This sudden change of tunnelling medium creates the difficulties to control face pressure and over excavation which can cause substantial ground loss and movements. This paper mainly focuses on the ground responses caused by twin bored tunnelling under mixed-face soil condition and the implementation of building protection measures to the existing late 19th & early 20th centuries shophouses which the tunnelhead undercrossed in mixed-face soil condition.

Keywords: kallang formation, old alluvium, mixed face, bored tunnels

1 INTRODUCTION

The Downtown Line Stage 3 (DTL3) will be an underground Mass Rapid Transit (MRT) System extending from Downtown Line Stage 1 (DTL1) Chinatown Station and run through MacPherson, Bedok Reservoir, Tampines and ending at the East West Line (EWL) Expo Station. It consists of 16 stations and a total route length of about 21 km.

Contract C933 comprises the construction and completion of Bendemeer Station, cut-and-cover Cross-over box, and twin bored tunnels between Bendemeer and Geylang Bahru Station, and also between Bendemeer and Jalan Besar Station which undercrossed several shophouses and existing structures at some stretches. A total of four Earth Pressure Balanced (EPB) Tunnel Boring Machines (TBM) were used to mine the 4km of tunnel drives. The contract also includes the construction and completion of two escape shafts connecting to the main bored tunnels at Allenby Road and by the Kallang River. Figure 1 shows the C933 Overall Project Site Plan. Contract C933 has also been highlighted as a case study project by Ong et al (2014) and Poea et al (2014).

2 BORED TUNNELS FROM BENDEMEER TO JALAN BESAR STATION

The 6.35m external diameter twin bored tunnels were launched from a launch shaft, formed at the west end of the Bendemeer Station, to the east end of Jalan Besar Station. Along the tunnels route, the twin tunnels undercrossed or were in close proximity to existing shophouses, many of these shophouses are of two to four storey that were built in the late 19th & early 20th centuries. These old shophouses coupled with the soft soil or mixed-faced soil condition at the Old Alluvium (OA) and Marine Clay (MC) transition poses several construction challenges during the tunnelling operations.

The tunnels were constructed using 1.4m wide, 275mm thick precast steel fibre reinforced concrete (SFRC) lining segments. 7 segments and 1 key formed each ring. The segments were connected using straight bolts of 25mm diameter. The adoption of SFRC segmental tunnel lining in a MRT tunnel is a first in Southeast Asia and it was also awarded the Singapore Concrete Institute (SCI) Excellence Award 2013 as it improved productivity in segment production of up to 25%.

For the Tunnel alignment, the Bukit Panjang and Expo Bound tunnels were launched parallel to each other. After approximately 220m, the Expo Bound
tunnel was positioned at an elevation higher than Bukit Panjang Bound tunnel, both tunnels were unstacked into parallel position approximately 200m before docking into Jalan Besar Station. Figure 2 shows the location plan of C933 bored tunnel alignment from Bendemeer to Jalan Besar Station.

Figure 1. C933 Overall Project Site Plan

Figure 2. Location plan of C933 Bored Tunnel alignment from Bendemeer to Jalan Besar Station

2.1 Ground condition and geological profile

Figure 3 shows the assessed Geological profile along the C933 tunnel drives from Bendemeer to Jalan Besar Station. The Bukit Panjang Bound Tunnel axis levels typically varies between 27m to 39m below the existing ground level while the Expo Bound Tunnel axis levels typically falls between 22m to 28m below the existing ground level.

Both the Bukit Panjang Bound and Expo Bound TBMs were launched into good Old Alluvium (OA) soil with Standard Penetration Test (SPT) ‘N’ greater than 100 blow counts for a distance of approximately 730m before encountering Kallang Formation (Marine Clay) with thickness of up to 42m, for the remaining 320m. Challenging mixed-face soil condition exists at the OA to Kallang Formation (Marine Clay) transition.

Figure 3. Geological profile along C933 tunnel drives from Bendemeer to Jalan Besar Station

3 BORED TUNNELLING IN MIXED-FACE SOIL CONDITION AT THE OLD ALLUVIUM TO KALLANG FORMATION TRANSITION WITH STACKED TUNNELS

The first transition of Old Alluvium to Kallang Formation (Marine Clay) was located approximately at 730m away from Bendemeer station west launching shaft. Tunnel alignment layout plan and the geological profile of mixed-face soil area are shown in Figure 4 and Figure 5 respectively.

Figure 4. Plan of Stacked Twin Tunnels located in proximity to existing Shophouses
Generally, tunnelling in mixed-face soil can trigger a relatively higher amount of settlement when compared with uniform Old Alluvium even with a proper control of TBM operating parameters. The total settlement after combined twin tunnelling in pure OA condition is approximately about 5mm with the recorded volume loss less than 0.5%. Settlement tends to increase when the tunnel approaches the mixed face area. Despite the tunnel face still in OA, total settlement of 10mm and volume loss of 1.1% were recorded during twin tunnel driving under available OA cover above tunnel crown getting thinner due to thicker Kallang Formation (Marine Clay). Nevertheless, the recorded volume loss recorded during the twin tunnel driving inside OA is still within the LTA Civil design criteria (LTA, 2010) of 2%. The expected soil conditions encountered at tunnel face is also shown in Figure 6.

The development of settlement over time when the TBMs passed through the mixed-face soil condition is assessed in Figure 7. The monitoring results of ground settlement marker located above tunnel vertical axis and the rod extensometer at depths 5m and 17m are plotted together for review and study. As can be seen, the settlement results show similar trends between surface and subsurface settlements. When the tunnel entered the transition zone, settlement increased from 5mm to 14mm although the face pressure was maintained at 30% higher than hydrostatic pressure. As shown in Figure 15, additional settlement of 6mm and total of 20mm settlement are recorded after advancing both tunnels. The occurrence of a sharp drop is likely due to the contribution of Fluvial Sand (F1) layer in mixed-face, which usually shows drained behaviour giving a quick response to settlements. It is, therefore, worth to note that the F1 soil content plays an important role on the effect of settlement behaviour due to tunnelling.

It can also be seen that the immediate settlement tends to stabilize after 34m (5D, where D is diameter of tunnel) away from the tunnel for this case. This shows that the settlement in mixed face tunnelling takes longer time to stabilize as compared to that reported 20m in Cham (2009).

The measured transverse surface settlement troughs, plotted together with Gaussian distribution curves is shown in Figure 8. 2% volume loss calculated based on fitted Gaussian curve is recorded when the Bukit Panjang bound tunnel (BP) passed through the mixed soil location. Approximate volume loss of 0.6% is recorded when the Expo tunnel bound (EX) was driven under the Marine Clay and Fluvial Clay (F2) location. Since the tunnel alignments are located at highly built-up area, it is expected that the surface settlement trends are affected by the presence of adjacent foundations and structures as compared to Gaussian trough under green field condition. Larger settlements are observed below the shallow foundations whereas the presence of pile foundation resulted in shallower settlement points. Increase in settlements under shallow foundations can be due to the surcharge loading coming from the building. On the other hand, decrease in settlement shows the stiffening effect of the presence of pile foundation under the existing building.
When driving the TBM from competent OA soil into mixed-face soil condition at the OA and Kallang Formation (Marine Clay) transition, several engineering measures were implemented to mitigate the risk of excessive settlement especially due to the presence of thick Fluvial Sand layer (F1) which may caused the TBM screw conveyor to lose the soil plug and therefore failed to maintain the required Face Pressure. Usage of proper soil conditioning in terms of foam and polymer through Trials Test is therefore essential to ensure that the discharge of F1 sand from the TBM screw conveyor is well controlled. The TBMs in C933 are also equipped with an air purge port installed at the bulkhead near to the TBM crown. This safety feature allows possible pressurised air bubble accumulated at the top of the TBM Muck chamber to be released and subsequently the space is filled back with Bentonite/Muck. This is to prevent any potential sudden ingress of F1 sand into the TBM Muck Chamber as the TBM exits from the competent OA soil into MC. A Summary List of the TBM Key Operating Parameters at Mixed-Face of OA/MC(F1) is shown in Table 1.

Equally of importance is the Emergency preparedness in terms of standby resources eg. Grouting rigs, traffic diversion equipments which were ready to handle various envisage emergency scenarios eg. Suspected subsurface cavity, slurry/foam leaks to surface, excessive settlement and sinkholes etc. During the actual tunnelling in mixed-face, surface watchman was also deployed to closely monitor for any abnormality on the surface and will report to the TBM central control so that immediate action can be taken to address any incident.

Tunnelling in Mixed-Face Condition at the transition between OA to MC poses a challenging task, with the presence of Fluvial Sand (F1) content leading an important role on the rate and magnitude of settlement behaviour due to tunnelling. Proper site investigations should be carried out to locate the mixed-face and to determine the engineering properties of the various soil layers. TBM Key Operating Parameters needs to be well designed and most importantly properly executed so as to ensure the volume loss due to tunnelling is controlled to the minimum.

4 TUNNELLING UNDER 18 UNITS OF SHOPHOUSES WITH MIXED-FACE SOIL CONDITION

Along the Bukit Panjang Tunnel Route, it is required to undercoss 18 units of shophouses with mixed-soil condition as shown in Figure 9. Many of these Shophouses are of two to four storey that were built in the late 19th & early 20th centuries, special attention was therefore given to the assessment of the pre-existing condition of these Buildings, the impact

![Figure 8. Transverse Surface Settlement Trough at Mixed-Face Soil Area](image)

Table 1. TBM Key Operating Parameters in Mixed-face Soil Condition

<table>
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<th>S/No.</th>
<th>TBM Key Operating Parameters at Mixed Face of OA/MC(F1)</th>
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<td>01</td>
<td>Adequate Face Pressure</td>
<td>Minimum Face Pressure to be above Hydrostatic Water Pressure</td>
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| 02    | Proper Soil conditioning                              | i) Foam :  
FIR: 25-40%  
FER: 6  
CF: 2.5%  
ii) Diluted Polymer :  
PIR : 5-10%  |

Abbreviations : F1R – Foam Injection Ratio; Foam Expansion Ratio; CF – Concentration of Foam; PIR – Polymer Injection Ratio; CP – Concentration of Polymer
to the buildings due to bored tunneling works and the implementation of building protection as required prior to tunneling works (Poea et al., 2014).

This section will address some of the Building Protection measures implemented as part of the risk mitigation measures for tunneling under the shophouses.

As shown in Figure 9, the Bukit Panjang Tunnel entered the row of 18 units of shophouses at an oblique angle and undercrossed the shophouses adjacent to the five-footway façade. In order to allow settlement to occur more uniformly along the five-footway façade and to minimise the differential settlement between the façade column and the main building column, vertical props with spreader beams were installed to support the beam along the five footway façade as shown in Figure 10 and Figure 11.

In addition, 3 façade columns with pre-existing quality issues were wrapped with steel jacket and were connected to the main building using a steel frame as shown in Figure 10 so as to mitigate the risk of excessive settlement of the façade column during tunneling.

Lastly, at the location where the tunnel emerged out of the shophouses, raker struts were installed to support the Gable Wall as shown in Figure 12.

With the various Building Protection measures installed coupled with proper TBM Key Operating Parameters during tunneling in mixed face as mentioned in Section 3, the Bukit Panjang TBM Face Pressure was maintained at 53% higher than hydrostatic pressure and the Building settlement registered a range of 11mm to 24mm after the TBM undercrossed the row of 18 units of shophouses which majority are founded on shallow foundation.
5 CONCLUSIONS

Tunnelling in Mixed Face Condition at the transition between Old Alluvium to Marine Clay poses a challenging task, with the presence of Fluvial Sand content leading an important role on the rate and magnitude of settlement behaviour due to tunnelling. Proper site investigations should be carried out to locate the mixed-face and to determine the engineering properties of the various soil layers. TBM Key Operating Parameters needs to be well designed and most important is properly executed so as to ensure the volume loss due to tunnelling is controlled to the minimum.

Excavation for the Bored Tunnels between Bendemeer MRT Station to Jalan Besar MRT Station was successfully completed without causing significant impact to the surrounding structures. The successful completion was due to the detailed and prudent planning, design and execution of the Bored tunnelling works by the various project parties members.

REFERENCES

