Analysis for operation of TBM encountered in five incidents

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ABSTRACT

This paper presents result of analysis for operation of TBM made from the monitoring records obtained during the excavation for the DTSS in Singapore. The long distance and deep tunnel excavation of 7.3km was carried out for this project. The subsoil at the excavation depth of TBM is generally Old Alluvium underlying a relatively thin fill layer for 85% of whole distance. There were some exceptions where relatively thick layer of Kallang formation is lying at 15% at last excavation area. Tunneling was done totally within the Old Alluvium. However TBM were encountered five incidents. Four cases are caused by abrasion and operation. One case was caused by the unforeseen geological condition. According to the result of analysis for TBM operation data, added soil investigations help the understanding of geological conditions in detail and reducing risks for tunneling collapse with ground settlement.

Keywords: TBM, incident, Old Alluvium, soil investigation, monitoring, abrasion

1 INTRODUCTION

The Deep Tunnel Sewerage System (DTSS) was conceived by PUB (Public Utilities Board) to meet Singapore’s long-term needs for used water collection, treatment, reclamation and disposal. According to PUB, the concept of the DTSS is to use deep tunnel sewers to convey used water by gravity to centralised water reclamation plants (WRPs) located at the coastal areas. Fig.1 shows this construction site in DTSS route map.

The long distance and deep excavation of 7.3km was carried out in Fig.3. This paper presents result of analysis for operation of TBM made from the monitoring records obtained during the excavation for the DTSS in Singapore.

Fig.1 DTSS route map. (retouched to PUB map)

Introduce site is located phase 1 construction. Phase 1 completed in 2008 of the DTSS comprises a 48km long deep sewer tunnel running from Kranji to Changi, a centralised water reclamation plant at Changi, two 5km long deep sea outfall pipes and 60km of link sewers. Diameter of tunnel excavated by TBM of Earth Pressure Balanced type is about 6 meter shows in Fig.2.

2 SUBSOIL CONDITION

Site investigation was carried out along 7.3 km before the detailed design in Fig.3. A total of twenty-five boreholes in planning stage were done along the proposed tunnels generally at about 300m spacing. In-situ testing including SPT, pressure meter and permeability and laboratory testing on undisturbed samples collected from the borehole investigation were carried out as well.

The geological structure of this site mainly consists of the Old Alluvium in Fig.4. As revealed by the boreholes, the site is generally topped with Fill layer overlying the Old Alluvium formation except for the final 1 km section where the Old Alluvium is existed below recent thick sediments of the Kallang Formation.

The Fill consists of the man-made deposits which
are encountered throughout most part of the entire site. This layer consists of sand and silty/clayey sand. The depths vary from 2m to 10m. Average SPT N-value was about 5 within this layer.

The Kallang Formation comprises estuarine, fluvial deposits and marine clay at this site. Thin layer of KF was noted at 85% of the whole distance and the remaining 15% was thick layer lying on the weathered OA. The estuarine is mainly peaty clay, or organic clay or organic silt. The thicknesses were from 1.5m to 7m, an average was about 4.5m. The fluvial deposits include two different soil types, namely, fluvial sand and fluvial clay. The thickness of fluvial layer was from 2m to 6m, an average was about 3m. The marine clay (MC) consists of generally more than 50% clay. Liquid limit of MC from the site was 60% to 100%. The thickness varies from 5m to 25m. Average SPT N-value was 0 within this layer. The upper MC contains the higher organic content among the marine clay members.

The Old Alluvium layer consists of three weathered conditions and mainly of slightly cemented silty sand with localized pockets of sandy or clayey silt. Heavily Weathered Old Alluvium (HWOA) is covered in shallow depths and their SPT N-values generally are found from 4 to 50 with increasing in depth. The Weathered OA (WOA) which has 50 to 100 of N-values exists below the HWOA. The particle size distribution from the laboratory testing indicates that the soil generally consists of 65% to 90% of coarse-grained material and least 60% is sand.

The water table is around 5m under the ground surface. The depth of tunnel excavation is mainly WOA layer.

3 DESIGN CONDITION OF TBM OPERATION

Main tunneling method should be determined by the normal area, and some additional works should be needed at the special area (if any) with main method in economy.

In tender Geological profile, all excavation area is in WOA.

The soil characteristic of WOA is in low permeable with some possibility of rare and limited high permeable zone. But this high permeable zone cannot be found by soil investigation exactly because the water flow is a waterway like a piping or a rock joint.

The fundamental and important item for excavation shows in Table 1. According to the tender investigations, design conditions of TBM were determined by the low permeable OA condition with careful operation.

<table>
<thead>
<tr>
<th>EP in Chamber of TBM</th>
<th>high</th>
<th>low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability of Ground</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Attitude of bulkhead</td>
<td>rough</td>
<td>Very rough</td>
</tr>
<tr>
<td>Stability of cut line</td>
<td>good</td>
<td>little</td>
</tr>
<tr>
<td>Excavation Speed</td>
<td>slow</td>
<td>good</td>
</tr>
<tr>
<td>Long distance excavation</td>
<td>difficult</td>
<td>possible</td>
</tr>
<tr>
<td>TBM damage</td>
<td>serious</td>
<td>small</td>
</tr>
</tbody>
</table>

Table 1. Choice of TBM Operation method

Fig.5 Earth pressure of TBM for low permeable ground
Fig. 5 and Fig. 6 show the determination of Earth pressure in the chamber of TBM in this site.

On the other hand, According to the tender report, abrasion of TBM is the most important issue for long distance excavation. Therefore, the try and error method was required during the first stage excavation, the ring number 0001(R001) to R1092, and the earth pressure condition of TBM face was determined as the method of excavation for the normal area.

4 INCIDENTS DURING EXCAVATION

Five incidents have occurred during excavation by TBM in Singapore DTSS construction.

This chapter shows estimated scenarios which happened in tunnel excavation based on TBM monitoring data, photos & investigations. Five incidents are as follows;

(1) Incident of Abrasion on the Cutter Head at the R1092.
(2) Outbreak of water inflow with soil from the TBM Screw Conveyer at the R3140
(3) Outbreak of water inflow with soil from the TBM Bulkhead Gate, ground surface had subsidence at the R4188
(4) Water inflow with soil from the TBM Screw Conveyer Settlement was occurred at the R4290
(5) Water inflow with soil from the lower punching hole on TBM bulkhead, settlement was occurred at the R4387

Fig. 7 shows locations of five incidents with subsoil conditions obtained additional boring. The changing of thrust jacking speed and earth pressure monitoring data were indicated in the same figure. This paper focuses two cases, settlement at R4290 and R4387

4.1 Settlement at R4290

Fig. 8 shows the location and records of TBM earth pressures at R4290.

Water inflow with soil broke out from the TBM Screw conveyer at R4291. Settlement was occurred on the ground surface at the same time. Maximum settlement was 400mm. Two cracks were found during the inspection of bulkhead at R4309. Original causes are as follows;

(1) High water level
(2) Insufficient water proof function of TBM Screw conveyer
(3) Unexpected valley of Kallang Formation reached to the tunneling excavation level
(4) Well-permeable quartz gravel & sand layer existed in the lowest part of Kallang Formation

Trigger causes are as follows;

(1) Insufficient earth pressure in the chamber against the unexpected water pressure in gravel seam
(2) Excessive abrasion in TBM bulkhead (Cause of cracks)

Water inflow with soil broke out from the TBM Screw conveyer. Settlement was occurred. Determined operation factor of TBM driving taken abrasion of the cutter head was not insufficient for the unexpected high water pressure of well-permeable quartz gravel or sand layer existed in the lowest part of KF.
Therefore, water with soil was flown inside TBM through the screw conveyer. In addition, KF could not take the arching in the soil, the loosening area developed to the ground surface. Maximum immediate settlement is 500mm. This gravel or sand layer is consisted of quartz. The bottom of the Bulkhead became thin for its grinding effect in 100 rings.

Fig.9 and Fig.10 show the boring investigation at tender stage, post award stage and after incident respectively. Until the incident happened, hidden valley was not in considering. Fig.11 is the sketch of settlement image and mechanism at R4290.

Measure methods were set in the following manner.
(1) Applied the ground freezing method for inspection and repairing in the chamber of TBM
(2) Welded the steel plate on the crack area from inside the TBM (R4309)
(3) Use of the conditioner
(4) Inspection from TBM inside
(5) Confirmation of the ground condition by Added Boring investigation

During R4309–R4387, TBM was drive carefully.

**4.2 Settlement at R4387**

Fig.15 shows two areas of punching holes found on TBM-bulkhead. Water inflow with soil broke out from lower area of punching hole. The settlement occurred on the ground surface at the same time. Maximum settlement was 500mm.

Original Causes are as follows;
(1) Unconfirmed H-Pile supported the EMAS (Expressway Monitoring and Advisory System) Sign Board at same level of tunnel excavation
(2) High water level
(3) Near the Kallan Formation valley.
(4) Well-permeable quartz gravel and sand layer existed in the lowest part of Kallan Formation

Trigger Causes are as follows;
(1) Excessive abrasion in TBM bulkhead
(2) Cut the H-Pile and Twisted H-Pile was struck the Bulkhead.
Unconfirmed H-Pile supported the EMAS sign board was cut by TBM driving and twisted H-Pile was struck the thin bulkhead which was grinded by the gravel and sand consisted of quartz materials at the bottom of Kallan Formation. Photo 2 shows debris. Two punching holes were found. The punching hole of lower part on bulkhead was the biggest one and the width is 120mm and height is 40mm. Water with soil from lower punching hole were flown too much. The ground surface had the 500mm settlement. Lesson is need of study of foundation of the structure near the TBM tunneling.

Emergency measures were set in the following manner.

(1) Confirmation of the TBM-bulkhead
(2) Repair the punching hole of the lower bulkhead from the inside with the steel plate and valve
(3) Inspection from TBM inside

Essential measures were set in the following manner.

(1) Detailed additional investigation of ground
(2) Excavate and move the TBM to the stable ground position at R4410
(3) Reinforce the cutting face ground with freezing method
(4) Remove the H-Pile
(5) Confirm the damage of the repaired cutter bit and bulkhead from the outside of TBM.
(6) Weld the damaged point of the lower bulkhead with Steel Plate

After break through, repaired bulkhead and abrasion were confirmed on the ground in Photo 3. The thickness of bulkhead was measured. Fig.12 is the abrasion sketch of bulkhead and Fig.13 and 14 are measured the bulkhead thicknesses in detail.

According to the additional investigation in Fig.10, there is no hidden valley of Kallan Formation as same as the R4290 until the arrival shaft. Therefore, the operation of TBM was performed by using the method of low permeability and cemented for the further excavation. The Operation of TBM driving was safety performed and the tunnel could break through the arrival shaft.
5 CONCLUSIONS

Based on the considerations, the following conclusions could be drawn.

(1) Main tunnel excavation method was determined in economy. At the geological profile in the plan, the soil characteristic of WOA is in low permeable with some possibility of rare and limited high permeable zone. Therefore this area was decided to design the TBM for the low permeable OA condition with careful operation.

(2) The design documents were showed taking care about the abrasion of TBM. Therefore, the try and error method was applied during the first stage excavation from the starting shaft to R1092.

(3) TBM encountered the special zone from R4290 in long distance. TBM encountered the hidden valley of Kallang Formation from R4290. Additional boring investigations were carried out. As a result, the hidden deep valley of Kallang Formation consisted of high permeable quartz coarse sand and gravel was found.

(4) Two cracks were found during the inspection of bulkhead at R4309 for the confirmation of the ground condition. Very serious abrasion occurred during this excavation due to high earth pressure and quartz coarse sand and gravel. Detailed additional investigation was carried out from here to the final shaft, and troublesome soil was reinforced by ground freezing method after incident.

(5) No Hidden Valley of Kallang Formation to the final shaft was confirmed by the additional soil investigations. Therefore, the operation factor of low permeability area was applied for the further excavation. The tunnel was broke through.

Finally, R4290 incident should be focused again. Fig.15 is the schematic profile of coastal deposit in the tender document and Fig.16 is the schematic profile in this site after incident. They indicate the significant suggestion. When the tunnel construction would be planned in the planes continued from hills in lands of tropical regions, Investigations should be required at the beginning stage for finding the hidden valley likely to be present under the ground surface.

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REFERENCES