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Performance of a muck pumping system for EPB TBMs in soft ground condition

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ABSTRACT

In Earth Pressure Balance (EPB) TBM tunneling, the face is supported by pressurized excavated soil in the chamber. This support pressure is controlled by the rotation of screw conveyor and its pressure controllability is dependent on its water tightness. If the water tightness is not enough to control the support pressure, it can be enhanced by applying the secondary muck discharge equipment. This paper presents a case study of the application of a muck pumping system (MPS) for an EPB TBM in the construction of a tunnel in soft ground with permeable layer in form of lenses. The MPS was effective in controlling the face support pressure and minimizing ground settlements, even in the presence of permeable sand lenses. Moreover, the discharge efficiency of MPS was found to depend on the injected air volume during foam generation. To maintain the efficiency of MPS, it is necessary to quickly recognize the occurrence of muck pump damage or screw conveyor clogging.

1. INTRODUCTION

Tunneling in soft ground is challenging due to the complex and unpredictable nature of the soil. Hence, the selection of tunneling methods and equipment is crucial for achieving successful and safe excavation in soft ground. In recent years, closed-type tunnel boring machines (TBMs) have emerged as a viable solution for soft ground tunneling. These machines incorporate active support systems to effectively control ground movement induced by tunneling activities. Face support pressure is used to maintain the stability of the tunnel face, while a stiff shield skin plate and backfill grouting are used to prevent ground movement around the tunnel. This approach aims to minimize potential impacts on nearby structures and facilities.

Among closed-type TBMs, two main types are commonly utilized: Earth Pressure Balance (EPB) TBMs and Slurry TBMs. EPB TBMs rely on the excavated soil as a medium for providing support. The soil within the excavation chamber is pressurized to activate the face support pressure. The face support pressure is controlled by the rotation of a screw conveyor. The water tightness of the conveyor determines how well the pressure can be controlled. If the screw conveyor is not watertight, the face support

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pressure will not be able to be controlled effectively. This may require the use of secondary muck discharge equipment to improve the pressure control.

This paper presents a case study of the application of an EPB TBM in the construction of the Mass Rapid Transit (MRT) line in Singapore. The tunnel was constructed in a vulnerable soft ground, which posed significant challenges in the past years (Kumarasamy 2017, Lai et al. 2021). The tunnel passes through a predominant stratum of clay, with some sections containing permeable sand lenses. These lenses have posed challenges in controlling face stability and ground movement, which have required the use of special measures to mitigate these risks. Such measures include extensive pre-grouting or adaptations to the screw conveyor to increase screw length, screw resistance, or screw pressure. In this case, a close-type muck pumping system was deployed effectively in terms of face stability and ground settlements.

2. DETAILS OF SHIELD TBM TUNNELING

2.1 Tunnel Alignment and Geological Condition

The project, which is introduced in this paper, took place in a congested urban area in Singapore and included a total of four bored tunnels, one station, and one underground space for shopping centers (Fig. 1). The four tunnels were located on either the east or west side of the station and underground space. The tunnels on the east side were constructed as horizontally parallel twin tunnel using a single tunnel boring machine (TBM). The up-track tunnel was constructed first, and the machine was then disassembled and reassembled to construct the down-track tunnel. The alignment of the tunnels on the west side started as horizontally parallel twin tunnel but changed to vertically stacked twin tunnel from the middle part of the tunnel.

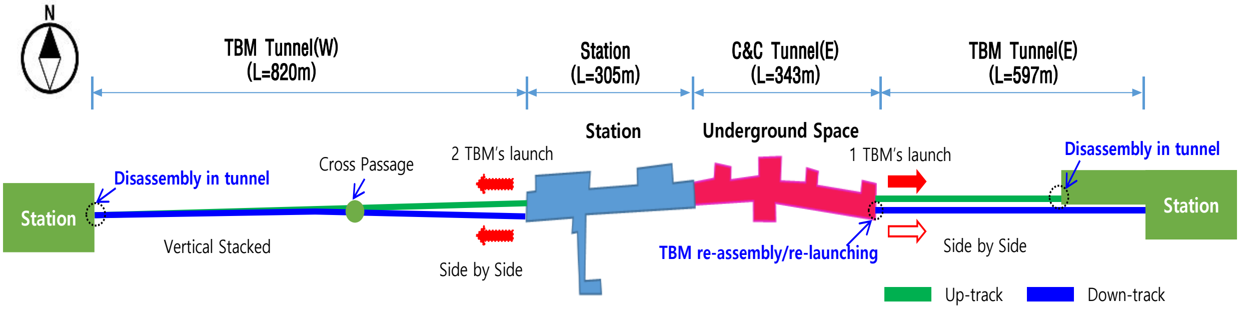
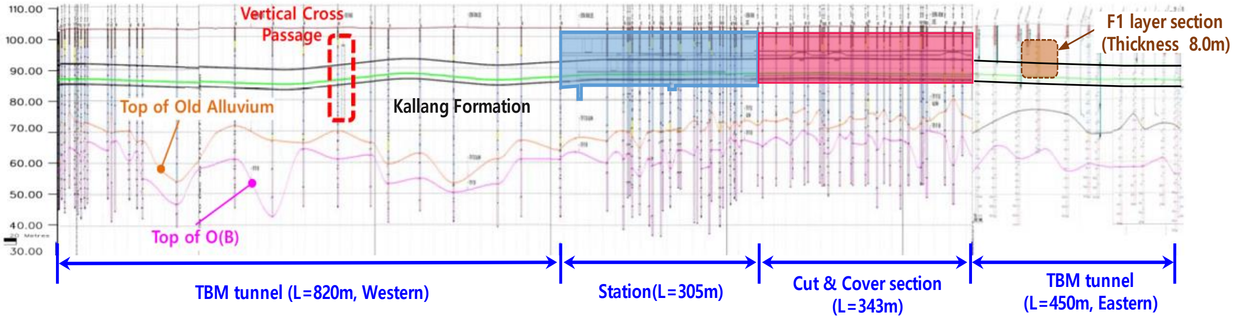
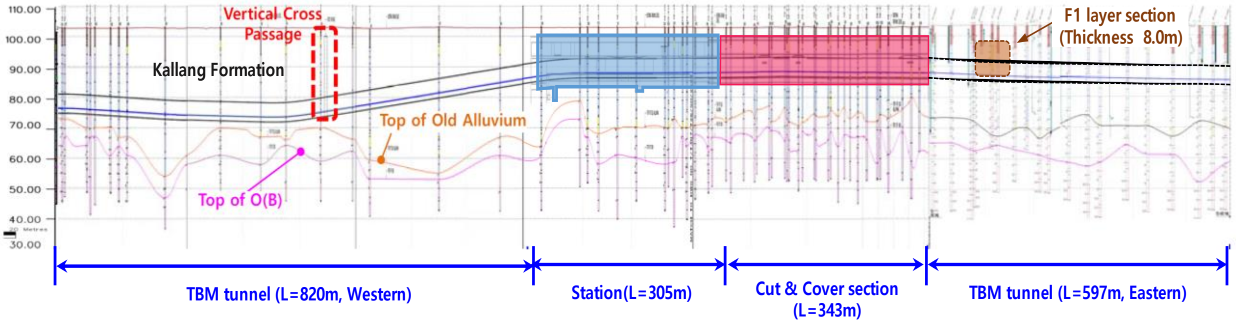


Fig. 1 Tunnel alignment

The tunnels were constructed in the Kallang Formation geology in Singapore as presented in Fig. 2. Table 1 summarizes the geotechnical parameters of the ground at tunnel depth. The tunnels are situated above the interface to Old Alluvium and fully in Upper Marine Clay (UMC) and Lower Marine Clay (LMC). Several lenses containing Fluvial Sand (F1) and Fluvial Clay (F2), as well as Estuarine Clay (E) have been identified. The Marine Clay is known to be very soft and mainly normally consolidated. As a result, stress relaxation due to tunneling could cause immediate squeezing, and large consolidation settlement could be expected due to additional loads or water drawdown. Moreover, because it is sticky, it has a high clogging risk. On the other hand, the F1 is highly permeable and immediately gushes out. Furthermore, F2 has also a high clogging risk. Ground water level locates approximately 2 m below ground level, so a maximum ground water pressure of 3.5 bar was expected at tunnel face.



(a) Up-track



(b) Down-track
Fig. 2 Geological profile

Table 1. Geotechnical design parameter of the ground

Ground type	F1	F2	E	UMC	LMC
γ [kN/m^3]	20	19	16.5	16	17
ϕ' [°]	30	24	22	22	22
c' [kPa]	0	0	0	0	0
S_u [kPa]	-	1.25(120-z)	0.75(126.67-z)	0.33(161.67-z)	0.67(120-z)
E_u [kPa]	-	375(120-z)	187.5(126.67-z)	99(161.67-z)	201(120-z)
E' [kPa]	560(113.5-z)	E_u/1.2	E_u/1.2	E_u/1.2	E_u/1.2
k [m/s]	1x10^{-5}	1x10^{-8}	1x10^{-8}	1x10^{-8}	1x10^{-9}

2.2 TBM Specification and Muck Pumping System (MPS)

The anticipated geological conditions along the tunnel alignment and the tunneling work in a congested urban area necessitated the selection of an EPB TBM. To secure the controllability of face stability and ground movement, when TBM encounters F1 layer, a muck pumping system was deployed for muck transportation (Fig. 3). Moreover, the overall ground conditions were suitable for the application of muck pumping system (Fig. 4).

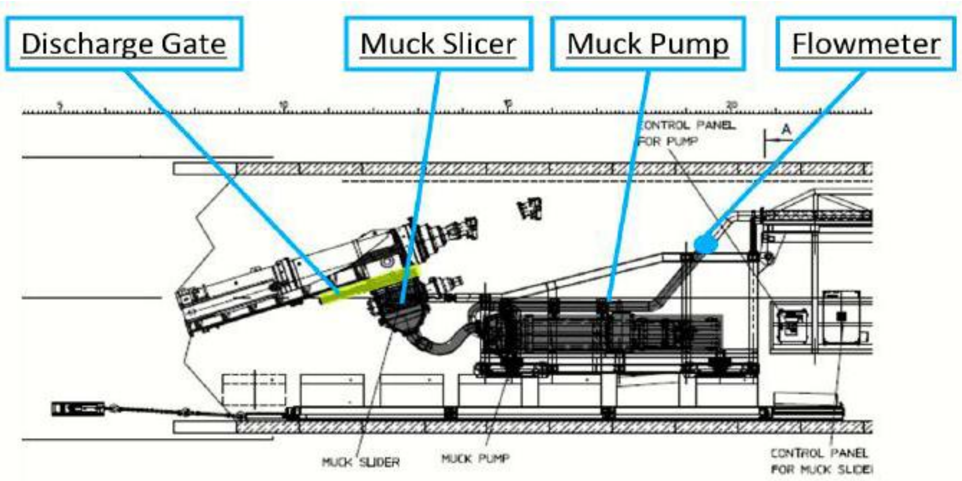
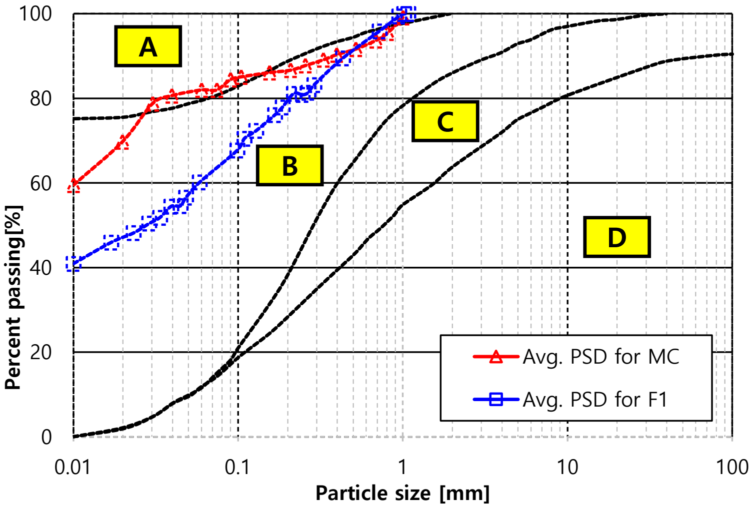


Fig. 3. Close-type muck pumping system applied for the corresponding project



Zone A : Applicable with water injection
Zone B : Applicable with normal additive injection
Zone C : Conditionally applicable with special additive injection
Zone D: Unsuitable

Fig. 4 Particle size distribution for muck pumping conformity (Japan Society of Civil Engineers 2016)

The muck pumping system that was applied was a close-type system. The muck pump with double piston was installed directly behind the muck slicer at the discharge gate of screw conveyor. The muck pump was connected to the muck slicer at the outlet of screw conveyor, and the system was pressure-sealed (Fig. 5). This ensured that the existing earth pressure at the discharge gate was maintained throughout the pump, minimizing the risk of blow out and spillage into the tunnel. Additionally, a muck pumping system has advantages such as noise reduction, continuous muck transportation without TBM drive break, direct muck discharge to muck pit on the surface and so on.

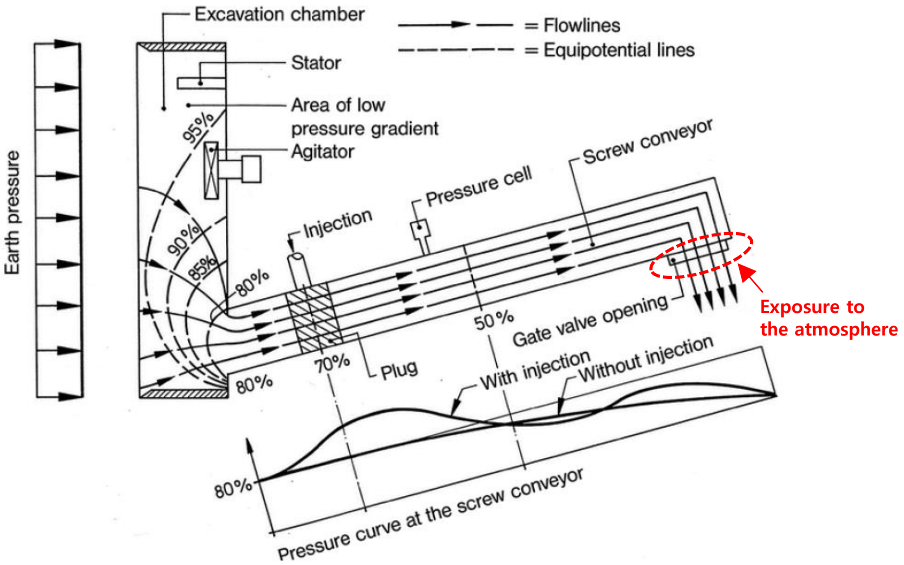


Fig. 5 Earth pressure distribution diagram (Maidl et al. 2012)

3. Effect of Muck Pump on Face Support Pressure and Surface Settlement

As previously mentioned, the applied close-type muck pumping system established the press-sealed system between the screw conveyor and muck pump. Fig. 6 presents the pressures in the chamber and screw conveyor that were measured in up-track tunnel on the east side. Excluding the pressures in the section between Ring no.1 and Ring no. 41, in which the fine tuning of muck volume measurement was carried out, the pressures were stable, even though the TBM encountered F1 layer.

In EPB TBMs, the muck discharge from the chamber is commonly controlled by the screw rotation. However, the use of a muck pumping system in EPB TBMs facilitates muck volume management, as the muck discharge rate can be controlled primarily by the piston reciprocating speed of the muck pump, in addition to the screw rotation. Fig. 7 shows that muck volumes were managed under their upper limit stably in the overall section excluding the section between Ring no. 1 and Ring no. 41.

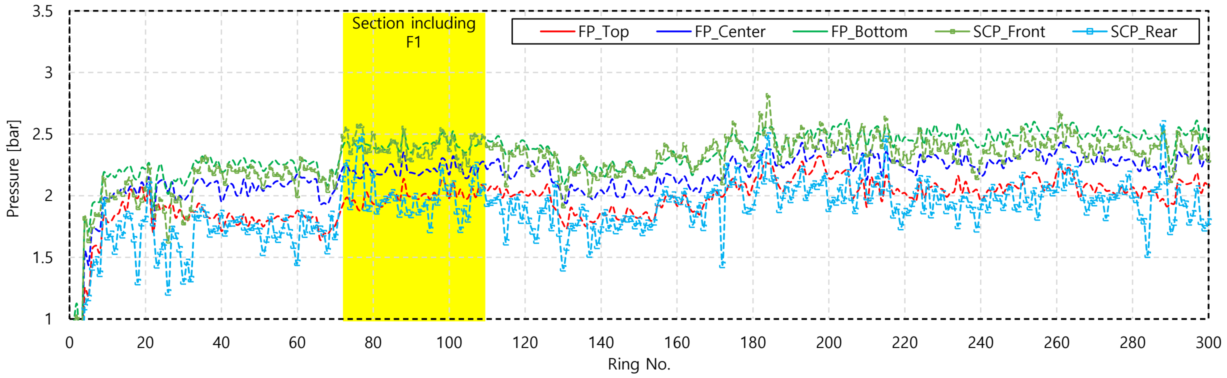


Fig. 6 Pressures in the chamber and screw conveyor measured in up-track tunneling on the east side

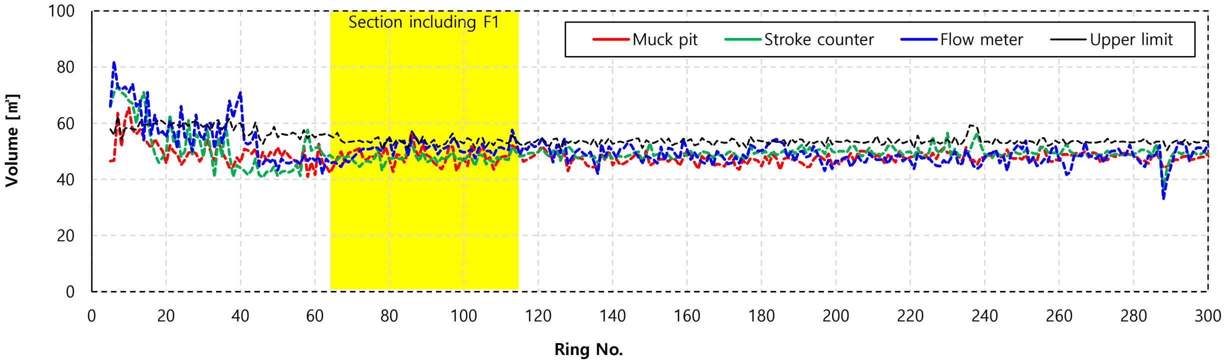


Fig. 7 Muck volumes for 1 ring measured in up-track tunneling on the east side

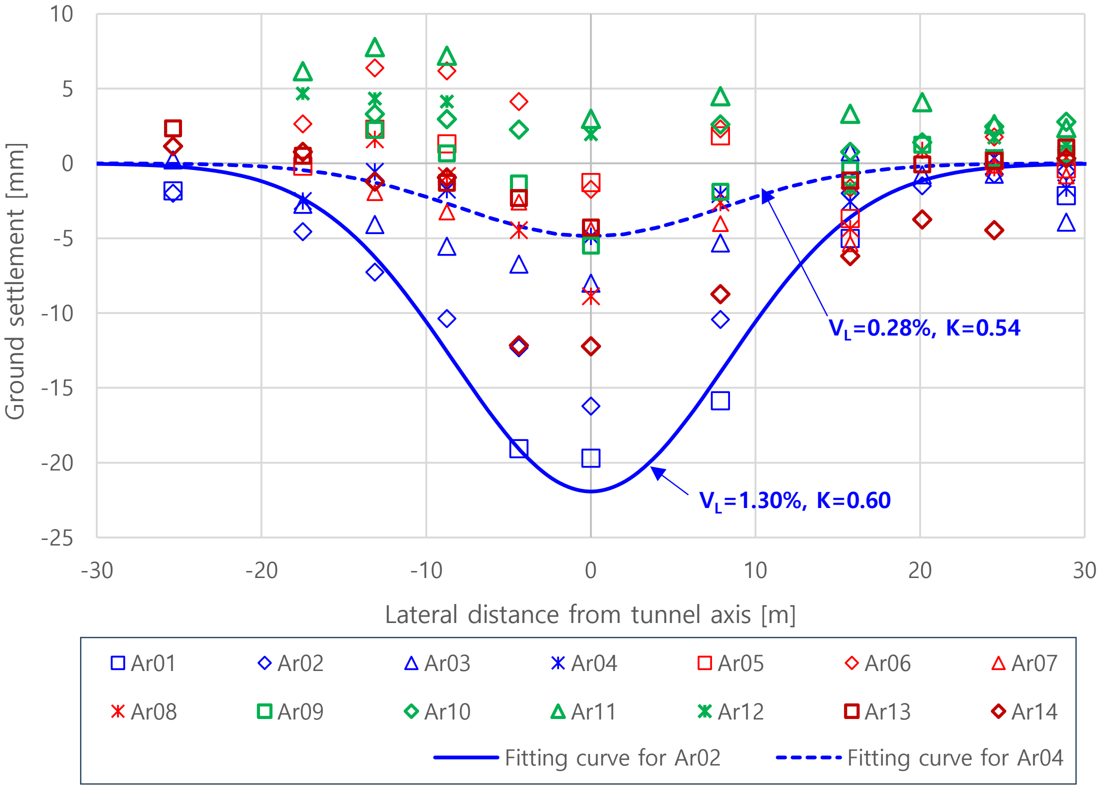
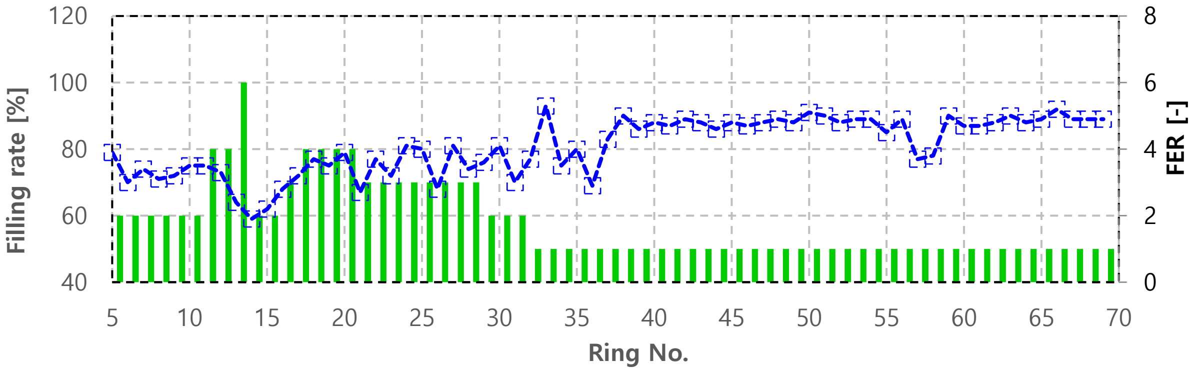


Fig. 8 Transversal surface settlement troughs measured in up-track tunneling on the east side

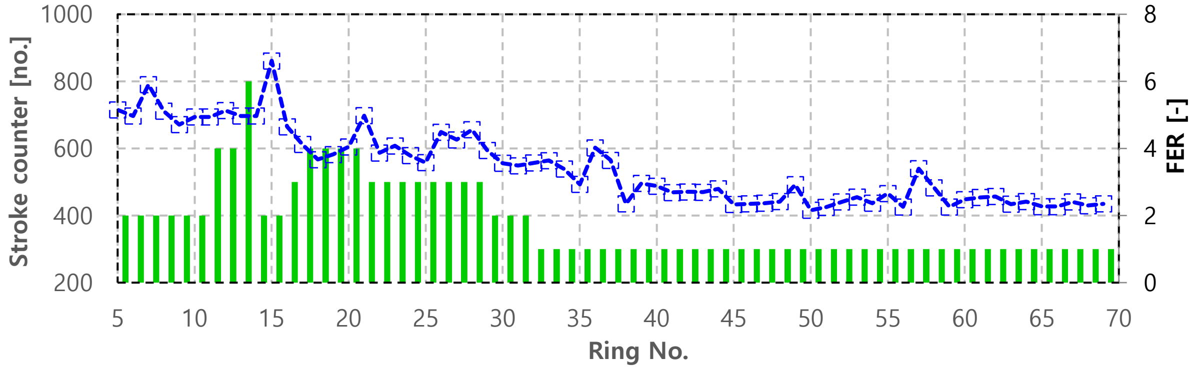
Fig. 8 shows the transversal surface settlement troughs measured from the settlement point arrays installed along the up-track tunnel. The evaluation which is based on the Gaussian curve fitting of the monitored transverse settlement troughs (Peck 1969) shows that the maximum volume loss (V_L) was 1.3%, which is lower than the 2% value required by the Client. Furthermore, the settlements were well-controlled in the section including F1 layer. The maximum settlement was 4.9mm, and the volume loss was 0.23%, which is about 12% of required control value. However, there is a limitation to analysis using in-situ instrument data. Correlation analysis between TBM operation conditions such as face support pressure, position, backfill grouting, etc. and settlement is difficult, as the time of settlement measurement is not generally recorded.

4. Influence of Foam Additive on Muck Discharge Efficiency

The soil conditioning is the process of improving the properties of the excavated soil in an EPB TBM. This can help to improve the safety and efficiency of tunneling by improving controllability of face support pressure and of muck transportation.



(a) Filling rate



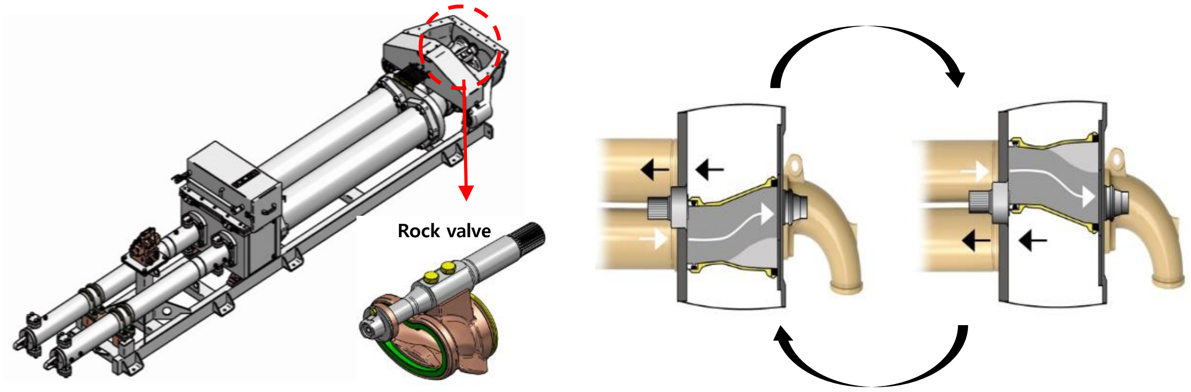
(b) Stroke counter

Fig. 9 Filling rate and stroke counter measured in up-track tunneling on the east side

In this project, foam and water were utilized as additives for soil conditioning. It was discovered that the pump discharge efficiency varies depending on the volume of air injected during foam generation. Fig. 9 shows the cylinder filling rate and the stroke counter per ring for the up-track tunnel on the east side. Filling rate is defined as the discharge rate per one cycle of piston reciprocation, while the stroke counter represents the number of piston reciprocations during the excavation for one ring. The filling rate tended to decrease when the foam expansion ratio (FER) was high, resulting in an increase in stroke counter. This phenomenon can be attributed to the pressure changes in the muck pump cylinder during the reciprocating motion of the piston. When the muck inflows in the cylinder, the piston retracts, creating the negative pressure (suction pressure) within the cylinder. On the other hand, when the muck flows out of the cylinder, the piston extends, generating the positive pressure within the cylinder. Since air volume is sensitive to pressure changes, an increase in air volume can decrease the filling rate. Therefore, it may be advantageous to use foam with reduced air injection or liquid additives.

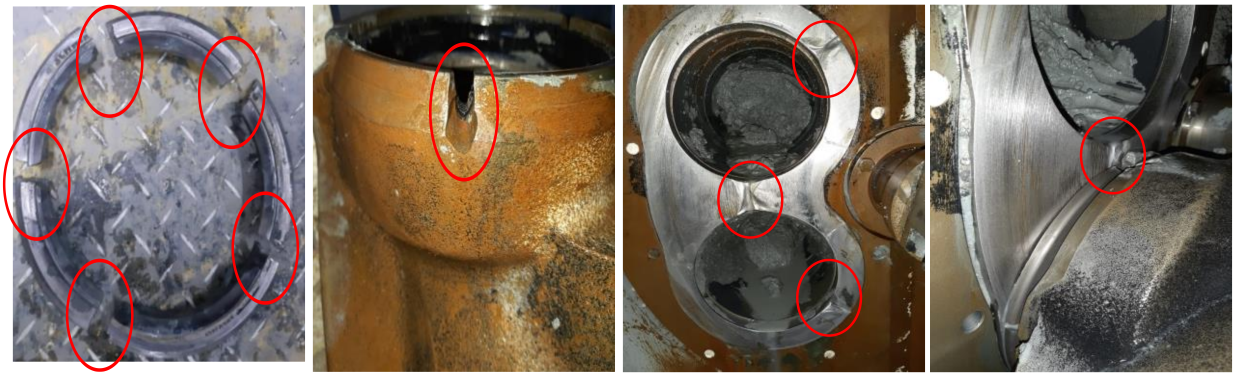
5. Troubles Related to Muck Pump

TBM productivity can be significantly affected by troubles such as damage of the rock valve of muck pump and clogging of the screw conveyor.



(a) Rock valve (b) working mechanism

Fig. 10 Rock valve of muck pump and its working mechanism



(a) Cutting ring (b) Seal (c) Insert ring (d) Housing lining

Fig. 11 Damage of cutting ring and seal of rock valve

Fig. 10 illustrates rock valve of muck pump and its working mechanism. The rock valve is one of the most important components of a two-piston pump. Under high pressure, it switches between the two delivery cylinders and ensures that the flow of muck from the delivery cylinders into the outlet is seamless.

In this project, damage to the sealing part of the rock valve was observed, as shown in Fig. 11. Possible causes of damage include impact from metal debris that entered the muck pump during ground improvement passage and impact load on the rock valve when the rock valve swings around the rotating shaft. This damage to the seal prevented the formation of a pressure-sealed system, which resulted in a simultaneous decrease in the amount of muck inflowing into and outflowing from the cylinder. Consequently, the filling rate significantly decreased, reducing the discharge efficiency of the muck pump and causing an overestimation of the muck volume from the stroke counter (Fig. 12).

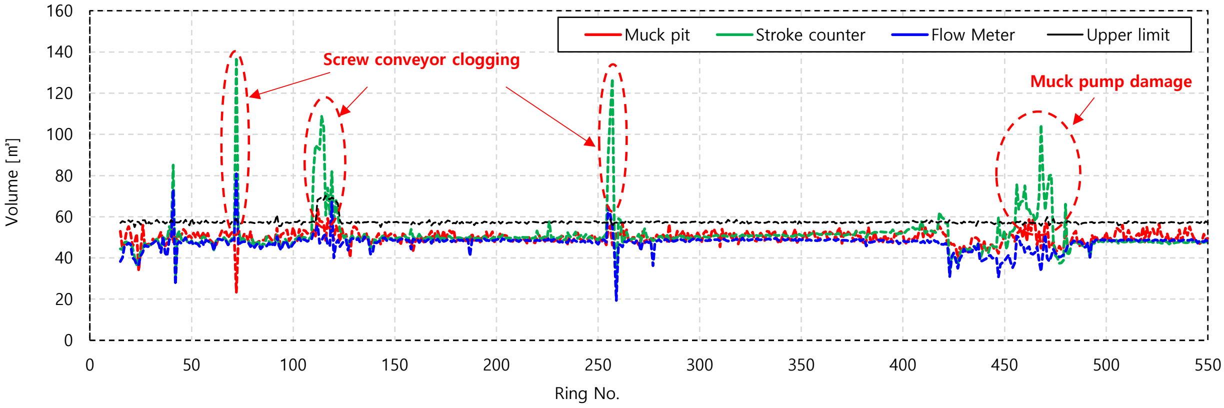
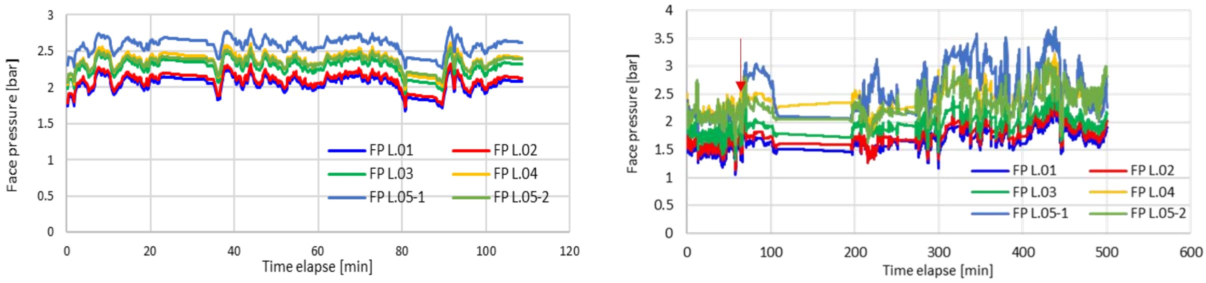


Fig. 12 Muck volumes for 1 Ring measured in up-track tunneling on the west side

Fig. 13 shows the internal of the clogged screw conveyor. Clogging in the screw conveyor resulted in a decrease in the amount of muck flowing into the muck pump cylinder. Consequently, the filling rate is decreased and the muck volume from the stroke counter was also overestimated (Fig. 12).

Fig. 13 Clogging of screw conveyor due to stickiness of clay



(a) Influence of muck pump damage (b) Influence of crew conveyor clogging

Fig. 14 Influence of muck pump damage and screw conveyor clogging on the muck volume measurement during excavation

As previously mentioned, the trends of muck volume due to rock valve damage and screw conveyor clogging were found to be similar. In both cases, the muck volume from stroke counter was overestimated due to a decrease in filling rate. However, the difference between these two troubles could be observed from the pressure in the chamber. As shown in Fig. 14, in the case of rock valve damage, the pressure in the chamber remained stable, while it increased when the clogging occurred in the screw conveyor.

6. CONCLUSIONS

This paper presented a case study on the application of an EPB TBM with muck pumping system for soft ground tunneling. The muck pumping system demonstrated good performance in terms of face stability and ground surface, providing advantages in maintaining stable face pressure and minimizing surface settlement. The discharge efficiency of MPS was found to depend on the injected air volume during foam generation. Therefore, it may be advantageous to use foam with reduced air injection or liquid additives. Two significant troubles related to the MPS were damage to the rock valve and clogging of the screw conveyor. Although both cases exhibit similar tendencies in terms of muck volume, making it difficult to distinguish between them, the difference could be observed from the pressure in the chamber. In the case of rock valve damage, the pressure in the chamber remained stable, while it increased when the clogging occurred in the screw conveyor.

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