The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Slurry TBM management for evaluating over-excavation

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ABSTRACT

In recent years, the slurry-type Tunnel Boring Machine (TBM) method has been increasingly employed for tunnel construction in urban areas under high water pressure, beneath rivers and seabeds. However, TBM operations pose potential risks such as ground settlement and collapse, often resulting from over-excavation. Slurry serves multiple functions, the primary of which is to form a pressurized membrane at the tunnel face to maintain face stability and prevent groundwater inflow. As the condition of the slurry can influence both over-excavation and groundwater ingress, it is essential to manage these factors in an integrated manner. Accurate evaluation of over-excavation is critical to preventing ground settlement. However, excavation management is inherently challenging in slurry TBM operations due to the closed-circuit system in which excavated materials are circulated. To estimate the volume of excavated material, sensor data such as flow meters and density meters are commonly used within a theoretical framework. While conventional methods based on in-situ or dry density measurements are available, they are limited in their ability to account for conditions where excess groundwater infiltrates from the surrounding ground.

In this study, a modified formula has been proposed to separate the amount of excavated wet soil from the excess groundwater inflow. Also the over-excavation was evaluated by the modified formula with sensor values from a field site. The revised method was validated through field measurements to investigate the causes of over-excavation.

1. INTRODUCTION

Slurry performance have various functions divided by primary functions related to stabilization of tunnel face with controlling the ground water and secondary functions for seamless TBM operation (Massimo 2010). The problem can be occurred by insufficient strength in poor ground condition or drain condition due to high water discharge (Prakash et al. 2020). The volume of additional muck discharge as illustrated in Fig.1

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was largest factor to induce the ground settlement among the various variables (An et al. 2022). Current practices rely on sensors such as density meters and flow meters to calculate excavated volume and mass in-situ and dry conditions as shown in Fig.2 (Duhme et al. 2016, Tang et al. 2021). These indirect methods, while widely used, are sensitive to the quality of sensor data as well as proper calculation theory. Dry condition method can evaluate the accurate value, but it is insufficient to verify the actual measurement in site. (Jung et al, 2024) have suggested a revised method with modified formula which can calculate the over-excavated dry soil amount apart from water ingress. However, the modified formula has limited applicability in the field, as it requires either an assumption or tested value for the density of over-excavated soil. Therefore, further refinement is necessary to enhance its practical applicability in field conditions.

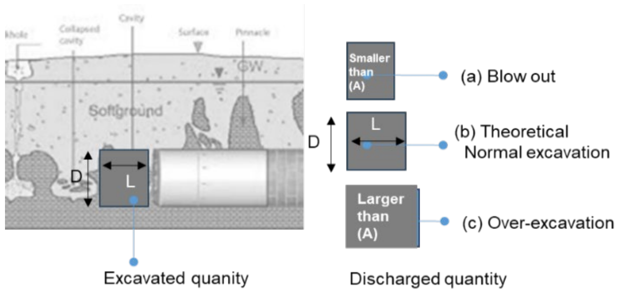


Fig. 1 Explanation of excavation condition

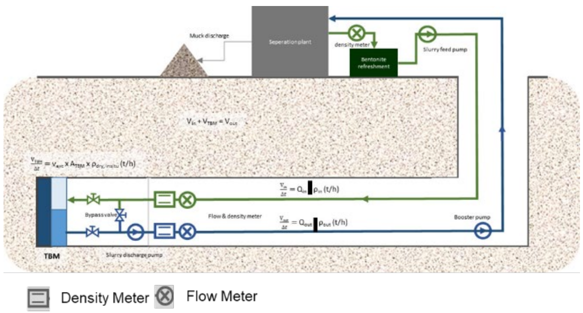


Fig. 2 Slurry TBM circuit and sensors

2. EVALUATION OF OVER-EXCAVATION FOR SLURRY TBM

Theoretically, the excavation can be computed considering sensor data from density meters and flow meters installed in the feed and discharge lines in the slurry circuit.

The difference between theoretical excavated amount and discharged amount by sensors indicate the over-excavated amount of volume unit or mass unit by density meter. Practically, two methods including saturated condition with water content and dry condition have been employed to evaluate the over-excavation by the formulas as following paragraph.

2.1 CONVENTIONAL FORMULA

The in-situ approach uses real-time measurement of slurry density and flow rates. The excavated volume is determined by taking the difference flow rates between discharge and feed line. The difference reflects the material removed from the excavation face. The excavated volume and mass are then calculated by multiplying the density and volume as following Eqs. (1) and (2) (Duhme et al. 2018, Marotta 2018). If the no volume change within the excavation chamber is assumed, the over-excavation between the start and the end of one ring advancement can be computed by Eqs. (3) and (4).

$$V_{(Ex)\ in-situ} = A_{section} l_{advance} = \frac{\pi D^2}{4} l_{advance} \tag{1}$$

$$M_{(Ex)\ in-situ} = V_{ex.(insitu)} \rho_{ex.(insitu)} \tag{2}$$

Where, $V_{(Ex)\ in-situ}$ is the theoretical excavation volume and $M_{(Ex)\ in-situ}$ is the theoretical excavation mass. $A_{section}$ is the tunnel section and $l_{advance}$ is the advance length. $\rho_{(Ex)\ in-situ}$ is the in-situ density of the excavated material.

$$V_{(Dis)\ in-situ} = \dot{Q}_{discahrge} - \dot{Q}_{feed} \tag{3}$$

$$M_{(Dis)\ in-situ} = \dot{Q}_{discahrge} \rho_{discharge} - \dot{Q}_{feed} \rho_{feed} \tag{4}$$

Where, $V_{(Dis)\ in-situ}$ is the discharged soil volume in the slurry circuit and $M_{(Dis)\ in-situ}$ is the discharged soil mass in the slurry circuit. And $\dot{Q}_{discahrge}$, $\dot{Q}_{feed}$ are the flow rates of discharge line and feed line. $\rho_{discharge}$, ρ_{feed} are the density of discharge line and feed line. The volume and mass of the over-excavation are calculated by Eqs. (5) and (6).

$$V_{(O.E) in-situ} = \dot{Q}_{discahrge} - \dot{Q}_{feed} - V_{ex.(insitu)} - \Delta V_{chamber} \tag{5}$$

$$M_{(O.E) in-situ} = \dot{Q}_{discahrge} \rho_{discharge} - \dot{Q}_{feed} \rho_{feed} - V_{(Ex)\ in-situ} \rho_{(Ex)\ in-situ} - \Delta V_{chamber} \rho_{discharge} \tag{6}$$

Where, $V_{(O.E) in-situ}$ is the volume of over-excavation. $M_{(O.E) in-situ}$ is the mass of over-excavation. $\Delta V_{chamber}$ is volume change of the chamber. The total volume and mass of over-excavation per ring can be accumulated using integral if it is assumed that the change of the $\Delta V_{chamber}$ remains same as seen in Eqs.(7) and (8).

$$V_{(O.E) in-situ} = \int_{Ring\ start}^{Ring\ end} \dot{Q}_{discharge} dt - \int_{Ring\ start}^{Ring\ end} \dot{Q}_{feed} dt - \int_{Ring\ start}^{Ring\ end} V_{(Ex)\ in-situ} dt \tag{7}$$

$$M_{(O.E) in-situ} = \int_{Ring\ start}^{Ring\ end} \dot{Q}_{discharge} \rho_{discharge} dt - \int_{Ring\ start}^{Ring\ end} \dot{Q}_{feed} \rho_{feed} dt - \int_{Ring\ start}^{Ring\ end} V_{(Ex)\ in-situ} \rho_{(Ex)\ in-situ} dt \tag{8}$$

This method is straightforward and easy to understand but it carries the risk of errors due to excessive water inflow. Therefore, another method using dry condition method was suggested, which removes the water content as following Eqs. (9) ~ (12). (Yamazaki et al.1976, Duhme et al. 2016).

$$V_{feed,dry} = \dot{Q}_{feed}\left(\frac{\rho_{feed} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right) \tag{9}$$

$$M_{feed,dry} = \dot{Q}_{feed}\left(\frac{\rho_{feed} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right)\rho_{bentonite} \tag{10}$$

$$V_{discharge,dry} = \dot{Q}_{discharge}\left(\frac{\rho_{discharge} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \tag{11}$$

$$M_{discharge,dry} = \dot{Q}_{discharge}\left(\frac{\rho_{discharge} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{soild} \tag{12}$$

Where, $V_{feed,dry}$,$V_{discharge\ dry}$ are the dry volume of feed line and discharge lines. $M_{feed,dry}$, $M_{discharge,dry}$ are the dry mass of feed line and discharge lines. $\rho_{bentonite}$ is solid density of bentonite and ρ_{solid} is solid density of ground. $V_{(Ex)dry}$, $M_{(Ex)dry}$ are the dry volume and mass of excavation which can be calculated from flow meter and density meter as shown in Eqs. (13) and (14). The dry volume and mass of over-excavation can be accumulated using integral as seen in Eq. (15) and (16).

$$V_{(Ex)dry} = \int_{Ring\ start}^{Ring\ end} [\dot{Q}_{discharge}\left(\frac{\rho_{discharge} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) - \dot{Q}_{feed}\left(\frac{\rho_{feed} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right)]dt \tag{13}$$

$$M_{(Ex)dry} = \int_{Ring\ start}^{Ring\ end} [\dot{Q}_{discharge}\left(\frac{\rho_{discharge} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{soild} - \dot{Q}_{feed}\left(\frac{\rho_{feed} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right)\rho_{bentonite}]dt \tag{14}$$

$$V_{(O.E)dry} = \int_{Ring\ start}^{Ring\ end} [\dot{Q}_{discharge}\left(\frac{\rho_{discharge} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) - \dot{Q}_{feed}\left(\frac{\rho_{feed} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right) - V_{(Ex)in-situ}\left(\frac{\rho_{(Ex)in-situ)} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)]dt \tag{15}$$

$$M_{(O.E)dry} = \int_{Ring\ start}^{Ring\ end} [\dot{Q}_{discharge}\left(\frac{\rho_{discharge} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{soild} - \dot{Q}_{feed}\left(\frac{\rho_{feed} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right)\rho_{bentonite} \tag{16}$$

$$-V_{(Ex)in-situ}\left(\frac{\rho_{(Ex)in-situ}-\rho_{water}}{\rho_{soild}-\rho_{water}}\right)\rho_{soild}]dt$$

Where, $V_{(O.E)dry}$, $M_{(O.E)dry}$ are dry volume and dry mass of the over-excavation. While this method can provide more precise results than the in-situ approach, it does not account for the scenario where excess water infiltrates from the surrounding ground, such as when the membrane at the tunnel face is partly or entirely damaged, leaving the face unsealed. The ground loss at the tunnel face can be affected by water seepage forces generated by the water inflow (Cao 2018, Jebelli et al. 2010). But the dry method cannot consider excessive water flow for the over-excavation, even though the water inflow is important factor (Zhou et al. 2020). Hence, the water inflow in over-excavation has to be considered. In such cases it is theoretically appropriate to separately evaluate over-excavated solid, void water as well as inflowing water in the context of underwater tunnelling. Moreover, (Jung et al. 2024) proposed a method to distinguish between water inflow and over-excavated soil volume using a modified formula of Eq. (17).

$$m_{(over\ ex.dry)}=v_{over\ ex\ in\ situ}\left(\frac{\rho_{over\ ex\ insitu}-\rho_{water}}{\rho_{soil\ solid}-\rho_{water}}\right)\rho_{soil\ solid} \tag{17}$$

Where, $m_{(over\ ex.dry)}$ is mass of the dry soil and $v_{over\ ex\ in\ situ}$ is volume of over excavated soil in place. $\rho_{over\ ex\ in\ situ}$ is density of the over excavated soil and $\rho_{soil\ solid}$ is density of the soil solid. The $\rho_{over\ ex\ in\ situ}$ can be assumed or obtained by field test.

2.2 MODIFIED FORMULA

In this research, a new formula is proposed to enable the calculation of over-excavated soil mass and groundwater volume with over-excavated soil density calculated by modifying the existing method of (Jung et al. 2024). Eq. (15) can be rewritten as Eq. (18). Using Eqs. (19) and (20), Eq. (18) can be simplified to Eq. (21) to calculate the dry volume of over-excavation using the total volume of over-excavation and the density of total over-excavation provided in Eqs. (20) and (21), which indicates the summation of in-situ and inflow water. Furthermore, the dry volume of over-excavation can be rewritten using in-situ volume of over-excavation as shown in Eqs. (22) and (23). Then, the in-situ mass of the over-excavation can be calculated by multiplying the in-situ density and the total volume of over-excavation as seen in Eq. (24).

$$\begin{aligned}&\int V_{(O.E)dry}\,dt\\&=\frac{\int Q_{discharge}(\rho_{discharge}-\rho_{water})dt}{\rho_{solid}-\rho_{water}}-\frac{\int Q_{feed}(\rho_{feed}-\rho_{water})dt}{\rho_{solid}-\rho_{water}}\\&\quad-\frac{\int V_{(Ex)in-situ}(\rho_{(Ex)in-situ}-\rho_{water})dt}{\rho_{solid}-\rho_{water}}=\int(Q_{discharge}-Q_{Feed}-V_{(Ex)in-situ})dt\end{aligned} \tag{18}$$

$$\times\left(\frac{\frac{\int(Q_{Discharge}\rho_{discharge}-Q_{Feed}\rho_{Feed}-V_{(Ex)in-situ}\rho_{(Ex)in-situ})dt}{\int(Q_{Discharge}-Q_{Feed}-V_{(Ex)in-situ})dt}-\rho_{water}}{\rho_{solid}-\rho_{water}}\right)$$

$$\rho_{(O.E)total}=\frac{M_{(O.E)total}}{V_{(O.E)total}}=\frac{\int(Q_{Discharge}\rho_{Discharge}-Q_{Feed}\rho_{Feed}-V_{(Ex)in-situ}\rho_{(Ex)in-situ})dt}{\int(Q_{Discharge}-Q_{Feed}-V_{(Ex)in-situ})\,dt} \tag{19}$$

$$\int V_{(O.E)total}\,dt=\int(Q_{Discharge}-Q_{Feed}-V_{(Ex)in-situ})\,dt \tag{20}$$

$$\int V_{(O.E)dry}\,dt=\int V_{(O.E)total}\left(\frac{\rho_{(O.E)total}-\rho_{water}}{\rho_{solid}-\rho_{water}}\right)dt \tag{21}$$

Where, $\rho_{(O.E)total}$ is the density of the total over-excavation. $M_{(O.E)total}$, $V_{(O.E)total}$ are the mass and volume of the total over-excavation.

$$V_{(O.E)dry}=V_{(O.E)total}\left(\frac{\rho_{(O.E)total}-\rho_{water}}{\rho_{solid}-\rho_{water}}\right)=V_{(O.E)in-situ}\left(\frac{\rho_{(O.E)in-situ}-\rho_{water}}{\rho_{solid}-\rho_{water}}\right) \tag{22}$$

$$V_{(O.E)in-situ}=V_{(O.E)total}\left(\frac{\rho_{(O.E)total}-\rho_{water}}{\rho_{(O.E)in-situ}-\rho_{water}}\right) \tag{23}$$

$$M_{(O.E)in-situ}=V_{(O.E)total}\left(\frac{\rho_{(O.E)total}-\rho_{water}}{\rho_{(O.E)in-situ}-\rho_{water}}\right)\rho_{(O.E)in-situ} \tag{24}$$

Where, $V_{(O.E)in-situ}$, $M_{(O.E)in-situ}$ are volume and mass of the over-excavated soil in place . $\rho_{(O.E)in-situ}$ is density of the over-excavated soil in place.

3. FIELD APPLICATION

3.1 SITE OVERVIEW

The OO line is an express road project which stretches a 6.7 km section, out of which 2.98 km tunnel lies beneath the XX River, as illustrated in Fig. 3. A slurry Tunnel Boring Machine (TBM) with a diameter of 14.01 m was employed for the underwater tunnel excavation. The geological profile along the tunnel alignment features hard rock at the launching point, transitioning to various ground types near the receiving point as illustrated in Fig. 4. Hard rock was encountered in the river-side section close to the launching point, while soft rock predominated beneath the river. The Uniaxial Compressive Strength (UCS) of the rock ranged from 60 to 155 MPa, with 18 fracture zones identified along the tunnel route. The slurry TBM was chosen for its ability to handle these diverse ground conditions and manage high groundwater pressure effectively. The in-situ ground density ranged from 1.8 to 2.4 t/m³, as summarized in Table 1.

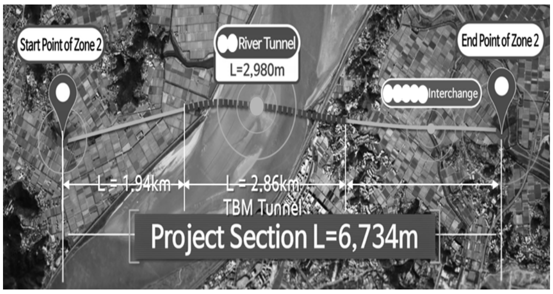


Fig. 3 Explanation of excavation condition

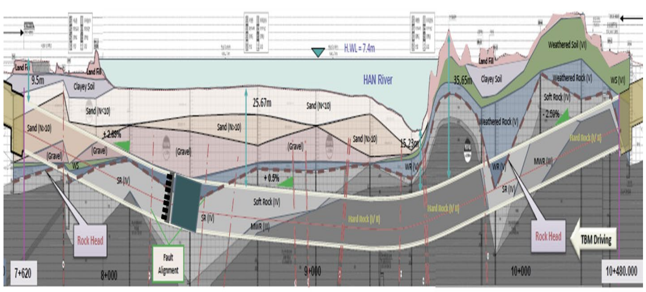


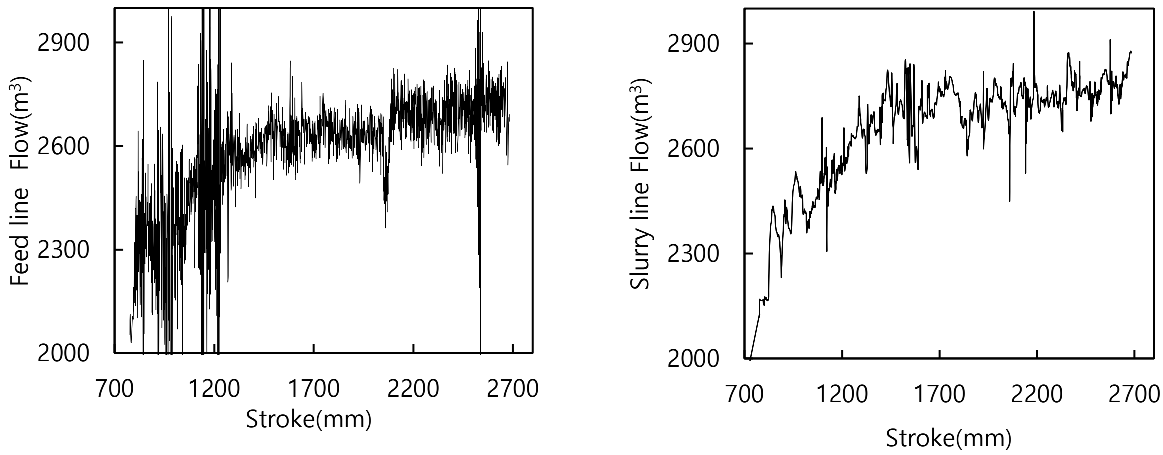
Fig. 4 Explanation of excavation condition

Table 1. In-situ density for ground type

Type	In-situ Density (tonf/m^3)	Type	In-situ Density (tonf/m^3)
Sand/clay	1.80	Soft rock	2.30
Weathered soil	1.85	Hard rock	2.40

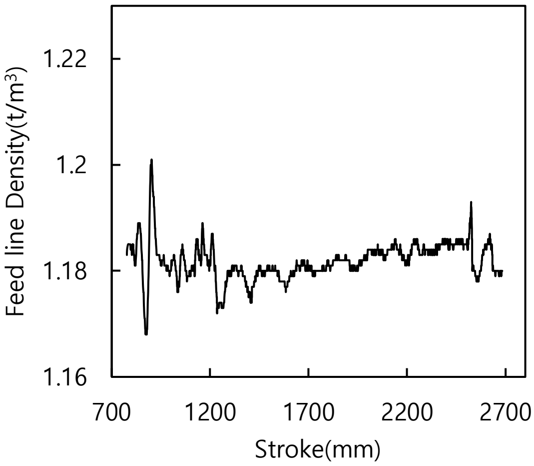
3.2 CALCULATION OF OVER-EXCAVATION

The modified formula was applied to evaluate over-excavation for Ring 1189 located in composite ground condition under river section. The Fig. 5 and Fig.6 indicate the sensor values of density meters and flow meters for the section. The excavated and discharged total soil amount are calculated by Eqs. 1 and 2 as shown Fig. 7 which indicate the accumulated soil volume. The gap between excavated and discharged soil amount means the over-excavation of total amount including soil and water inflow.

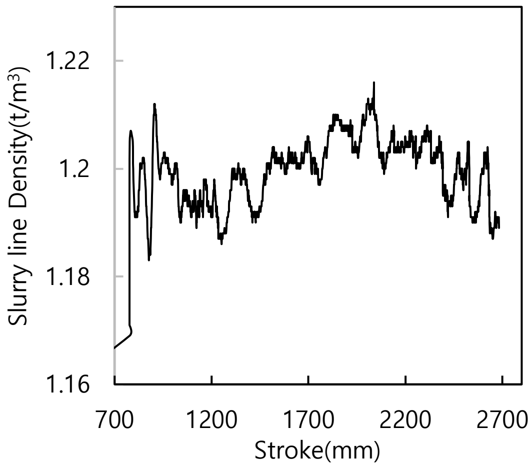


(a) Feed line (In let) (b) Slurry line (Out let)

Fig. 5 Flow rate values



(a) Feed line (In let)



(b) Slurry line (Out let)

Fig. 6 Density meter values

The theoretical excavation volume and discharged volume per ring were 285 m³ and 430 m³. The total over-excavation volumes, calculated from real-time sensor data, were 145 m³ for Ring 1189. Since these values represent the over-excavation relative to the ring excavation amount, it is necessary to distinguish between the actual soil amount and the amount of groundwater inflow. The over-excavated soil density was calculated by Eq.19 in the modified method as shown in Fig. 8. The accumulated soil density of over excavation indicated 1.26 as similar value of slurry that can be affected by large water inflow. The modified method by Eq. 22 was applied to calculate the in-situ soil over excavated among total over-excavation. Over-excavated soil was 34m^3 The volume of over-excavated soil amounted was significantly smaller compared to the groundwater inflow volume of 140m^3.

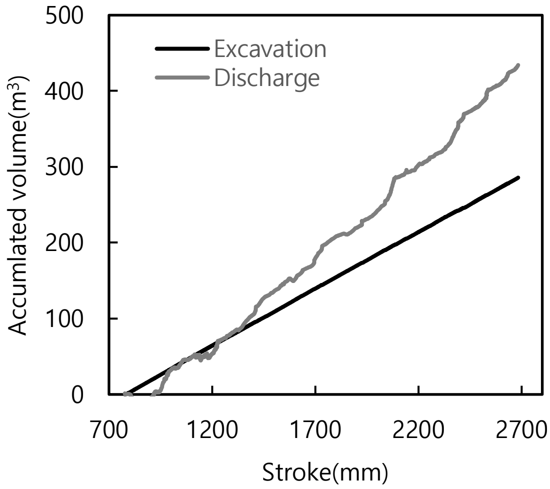


Fig. 7 Accumulated volume for Ring 1189

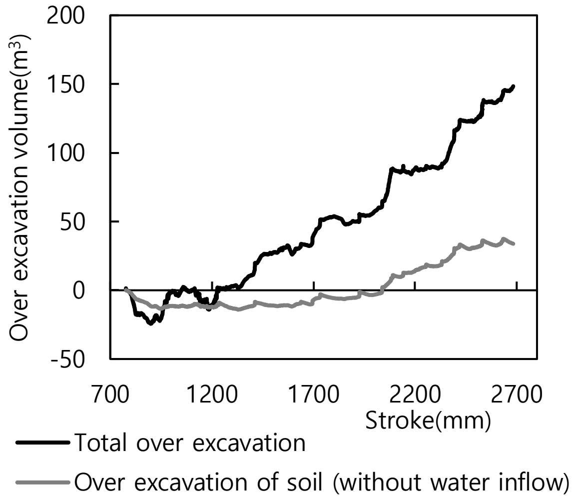


Fig. 8 Over-excavated volume

Therefore, the majority of the total over-excavation volume can be attributed to groundwater inflow, and the over-excavation volume due solely to soil was confirmed to be approximately 11% relative to the ring excavation volume. According to the modified formula, the actual over-excavation volume attributable solely to the soil was not substantial, and the majority of the over-excavation was attributed to groundwater inflow for Ring 1189.

4. CONCLUSIONS

This study proposes a formula for evaluating over-excavation in slurry-type TBMs. The modified formula provides the advantage of distinguishing between groundwater inflow and excavated soil, thereby enabling a more accurate assessment of over-excavation through direct comparison between measured values and those calculated using the modified formula. This discrepancy is presumed to result from limitations in sensor accuracy and the loss of soil during actual measurement. Nevertheless, by excluding groundwater inflow, the modified approach prevented overestimation of the over-excavation volume and allowed for a more rational and accurate evaluation of the actual over-excavation. Notably, the use of the modified formula enables identification of the respective contributions to over-excavation, thereby facilitating the determination of its underlying causes. Furthermore, when combined with performance evaluations based on slurry key performance indicators (KPIs), this approach may allow for adjustments to the slurry mixture, ultimately enhancing field operation efficiency. It is anticipated that this method will contribute to more effective evaluation and mitigation of over-excavation in slurry TBM tunneling.

ACKNOWLEDGEMENT
This work was supported by the Institute for Korea Spent Nuclear Fuel (iKSNF) AND Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (Ministry of Trade, Industry and Energy, MOTIE) (No. RS-2023-KP002657)

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