DEVELOPMENT OF TECHNOLOGY TO CONTROL AND MANAGE MUCK FLOW INSIDE EPB SHIELD CHAMBER

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A new technology has been developed to establish a more reliable excavation control protocol than currently used to ensure face stability. The new technology comprises the development of a measuring device, such as flappers, for muck flow inside the chamber and numerical analysis to evaluate the status of plastic muck flow for earth pressure balance shield tunneling. Flappers were installed in the chamber of the shield machine and the torque on the flappers was measured. Then, a numerical analysis was conducted to satisfy the data obtained in the field. Once the numerical analysis had been obtained, the condition of the muck flow in the chamber could be evaluated. The result of the field application verified that this technology was useful to evaluate the status of and to control the muck flow inside the chamber.

Key Words: Earth Pressure Balance (EPB) tunneling method, face stability, flappers, plastic muck flow, numerical analysis

1. INTRODUCTION

The shield tunneling method is employed as a standard method in the construction of linear underground structures in urban areas, such as subway and road tunnel construction works. In recent years, the earth pressure balance (referred to as EPB) shield method has been extensively applied due to the advantages it offers the minimum job site facility area in the urban areas.

However, due to the issues of reliability in relation to face stability, EPB shield tunneling is rarely applied in shield tunneling work with a large cross-section, exceeding a tunnel diameter of 10 m.

Fig. 1 (a) shows an outline of the EPB shield method. In this method, a mud additive material is mixed with the excavated muck and a plastic muck flow is created to ensure the faces stability. In addition, it is necessary to smoothly remove the muck from a screw conveyor. Because of this, if the muck inside the chamber is not plastically fluidized, a blockade and adhesion of the muck in the chamber occur, resulting in a significant reduction in excavation speed or the suspension of excavation. On the other hand, if the muck in the chamber flows excessively, it blows from the screw conveyor and control over the earth pressure
will be lost, which induces an unstable face condition. Therefore, it is extremely important for the EPB shield method to appropriately control the state of plastic muck flow in the chamber.

Conventionally, the method has been used to control muck properties relying upon judgments based on engineers’ accumulated experience in the field, including visual observation of the properties of the excavated muck, slump tests, the efficiency of muck removal from the screw conveyor, and cutter and screw conveyor torque. In contrast to these conventional methods, Nishida, et al. proposed a method in which the state of plastic flow of the muck in the chamber could be determined in real time based on evaluations of fluctuations in pressure as observed by an earth pressure meter attached to the kneading blades, changes in the strain on the kneading blades, and the amount of excavated muck. However, evaluations based on Nishida et al.’s measurements focused on only part of the status in the chamber or relied on evaluations of excavated muck, and their research did not evaluate the status in the entire chamber. Narasaki, et al. focused on muck flow rate vectors and attempted to elucidate the state of flow of the muck in the chamber using fluid analysis, carrying out analyses of the agitating effect of agitators in relation to EPB shields with single-circular and twin circular faces. However, the researchers did not verify the results of their analyses in actual tunneling work. As this indicates, in previous research, measurement and analysis have been conducted separately, and there are virtually no examples of studies linking measurement results and analytic data.

With the background mentioned above, the authors developed a muck flow control and management technology that combines devices that measure the plasticity of muck flow in the chamber (referred to as “flappers”) and a method of evaluating the state of plastic flow of the muck using fluid analysis, in order to increase the face stability and the accuracy of work management for the EPB shield method. This paper describes measurements of torque acting on flappers installed on a shield machine during tunneling work, and discusses the state of plastic flow in the chamber based on data obtained from these measurements.

### 2. OUTLINE OF MUCK FLOW MANAGEMENT SYSTEM

Fig. 2 shows the muck flow management system in the chamber for the EPB shield tunneling method. The muck flow management system consists of 3 major technical components: 1) real-time measurement technology using flappers in the chamber, 2) muck flow analysis technology that formulates a three-dimensional model inside the chamber by making the measurements consistent with analysis values obtained by flapper torque, and 3) excavation management technology that evaluates the status of plastic flow of muck in the chamber and utilizes work management of shield tunneling.
(1) Real-time measurements in the chamber using flappers

Fig. 3 shows the dimensions of a flapper while Photo 1 shows the position of the flapper installed inside the chamber. The flappers are made up of a steel shaft that protrudes into the chamber from the bulkhead, and a flapper blade at the end. The flapper blade is a steel plate 9 mm in thickness, 190 mm in height and 125 mm in width. The dimensions and position of the flappers were determined with consideration of muck resistance and the relationship between the flapper position and the positions of the kneading blades, fixed blades and the agitator in the chamber. During excavation, an electric motor rotates the flapper blade twice a minute, and the torque acting on the blade is continuously measured. The measurement resolution for the flapper torque is 0.19 N•m, and measurement accuracy is ±2%.

As Fig. 1(b) shows, during tunneling work, four flappers were installed concentrically in the chamber, and the torque acting on the flapper blades was measured. The flapper blades were positioned 495 mm from the bulkhead.

(2) Analysis of muck flow in chamber

In order to evaluate the state of plastic flow of the muck in the chamber by means of fluid analysis, first the yield value and the viscosity were obtained by the Casson model from the flapper torque data. Next, fluid analysis was carried out using the obtained analytic constants and the flow rate and shear rate in the chamber were calculated. Here, the shear rate is the change with time in shear strain, and is also termed shear gradient.

Fig. 4 shows the analytical model employed in the flow analysis. The kneading blades and fixed blades in the chamber of the shield machine used in actual tunneling work were modeled in detail in three dimensions.

For the analysis, a three-dimensional fluid simulation analysis using the mixing tank was carried out, as in the case of Narasaki, et al., and the flapper torque value, muck flow rate and shear rate in the chamber were calculated. Narasaki et al.’s analytical method assumed a non-Newtonian fluid made up of muck and mud additive materials (foam and auxiliary materials), and they carried out fluid analyses with incompressible Navier-Stokes equations, which considered hypothetical density stratification, as the basic equations. In the analysis, they assumed that the excavated muck from the cutting face, whose volume is related to the speed of excavation, with mud additive materials in the chamber was removed from an outlet (at the entrance of the screw conveyor) located in the lower section of the bulkhead. The inflow and outflow amounts per unit time were assumed to be in equilibrium.

The constitutive equations of the Casson model used in the analysis are expressed as follows:

For \( \tau > \tau_c \),

\[ \sqrt{\tau} = \sqrt{\tau_c^*} + \mu_c \dot{\gamma} \]  \hspace{1cm} (1)

For \( \tau \leq \tau_c \),

\[ \tau = 0 \]  \hspace{1cm} (2)

where, \( \tau \) : Shear stress
\( \tau_c \) : Casson yield value
\( \mu_c \) : Casson viscosity
\( \dot{\gamma} \) : Shear rate
(3) Excavation management

In the shield excavation management process, the measured values of flapper torque were monitored in order to maintain an appropriate state of plastic flow of the muck in the chamber. In case extraordinary behavior would occur during excavation, such as a sudden fluctuation in the measured flapper torque value, the state of plastic flow in the chamber would be evaluated by fluid analysis and the state of the removed muck would be physically checked. Then, by changing the amount and location of injected mud additives, the state of plastic flow would be maintained in the chamber and the value of the flapper torque would be stabilized.

3. OVERVIEW OF TUNNELING WORK

Fig. 5 shows a geological profile at a section of the shield tunneling work for the Central Circular Shinjuku Route of the Tokyo Metropolitan Expressway, in which an EPB shield tunneling machine with flappers was used. The shield excavation diameter was φ12.02 m. The torques of the flappers were measured between the first 200 rings from the launching shaft and the arrival shaft at the end of the tunnel. The segment widths of a ring used in this tunnel work were 1.5 m and 1.2 m.

From the launching shaft to approximately 250 rings, the geological feature of the section was the multiple layers of the Musashino gravel layer (referred to as “Mg layer”), with N values from 12 to 50 or higher; the Tokyo gravel layer (“Tog layer”), with N values of 50 or higher; and the Tokyo gr avel layer (referred to as “Tog layer”), with N values of 11 to 50 or higher (referred to as “Ks1-c layer”) appeared at the bottom of the tunnel. From 850 rings to the end of the tunnel, a Kazusa Formation sand-silt layer ranging from medium to extremely dense (N value: 12 to 50 or higher) predominated (referred to as “Ks1 layer”), and from 1,200 rings a Kazusa Formation hard consolidated silt layer (termed the “Kc1 layer”) appeared below.

4. EVALUATION OF INFLUENCE OF FACTORS VIA MEASUREMENT RESULTS OF FLAPPER TORQUES AND MULTIPLE REGRESSION ANALYSIS

(1) Measurement results during tunneling

Fig. 6 shows the transition in the flapper torque value, the ratio of soil types (gravel, coarse sand, fine sand, silt-clay), the earth pressure on the cutting-face, the foam injection ratio, and the amount of injection of auxiliary materials from the 200th ring, at which flapper torque measurements were commenced. Figures for the earth pressure on the cutting-faces indicate averages for four earth pressure meters attached to the central section of the chamber. The foam injection ratio is the ratio between the amount of excavated muck and the amount of foam injected. Since significant variations occurred in the flapper torque values during measurements, the measured values were shown by using the average values and standard deviation for each ring.

a) Flapper torque values

Fig. 7 shows the measured flapper torque values for two individual rings. For the flapper torque close to the 1,290th ring, the average flapper torque value and standard deviation were both high. For the one close to the 810th ring, the average value and standard deviation were both low, as shown in Fig. 6. This figure indicates that, despite the fact that all flapper torque values fluctuated significantly close to the 1,290th ring, average values and amplitude showed the same tendency. In the case of the flapper torque close to the 810th ring, the measurements for the lower flapper were highest, followed by the middle (left) flapper and the upper flapper; however, the differences...
between the values were small. Based on these results, torque values measured by the upper flapper were taken as representative flapper torque values for this study, as discussed below. That the flapper torques took on negative values as shown in Fig. 7 is considered to be a result of the fact that the speed of motion of the muck was higher than the speed of motion of the flapper blades when the flapper blades and the cutter spokes were moving (rotating) in the same direction.

Fig. 6(a) and Fig. 6(b) show the average flapper torque value and standard deviation for the flapper attached to the upper section of the bulkhead, respectively. These figures indicate that the higher the torque value of the average flapper becomes, the higher the standard deviation tends to become. There were significant fluctuations in both the average value and standard deviation, however the actual tunneling work proceeded well through all sections with no clogging of muck in the chamber or blowing of mud from the excavated muck outlet. This indicates that a certain amount of fluctuation occurs in flapper torque values even when the muck maintains a good plastic flow.

**b) Factors affecting flapper torques**

- **Effect of geology**

Fig. 6(c) indicates that, in the section between 200 rings and 640 rings, the average value and standard deviation for flapper torques displayed a tendency to decline simultaneously with the reduction in gravel content. In the sections between 640 and 800 rings and 1,340 and 1,400 rings, the ratios of silt and clay almost agreed with the results for average value and standard deviation for flapper torques. However, between 800 and 1,200 rings, the average value and standard deviation for flapper torques fluctuated significantly despite the fact that the fluctuations in the ratio of gravel, coarse sand, fine sand, silt and clay were compara-
Effect of face pressure

Fig. 6(d) indicates that, in the section from 200 rings to 780 rings, while face pressure increased overall, the average values and standard deviation for flapper torques showed a tendency to decrease. In the section from 780 rings to 956 rings, open cut work above ground was performed so that a low overburden section from 780 rings to 956 rings, open cut work reduced from 0.34 MPa to 0.13 MPa. Despite this outcome, the average value and standard deviation for flapper torques did not show any major changes. From 956 rings onwards, flapper torques significantly fluctuated, while face pressure was almost constant.

Effect of foam injection ratio

Fig. 6(e) shows that the foam injection ratio became high from 200 rings to close to 800 rings, at a section with a high amount of gravel. In addition, since the average value of flapper torques suddenly increased during tunneling close to 740 rings, the excavation speed slowed and the foam injection ratio increased. As a result, the average value of flapper torques declined. From 800 rings, there existed an inversely proportional relationship between the foam injection ratio and the average value and standard deviation for flapper torques, with the latter two parameters declining when the former parameter increased.

Effect of injection amount of auxiliary material

During the tunneling work, a polymer mud additive material was injected as an auxiliary material to prevent muck from adhering to the cutters, agitator and other parts. The injection amount of this material was increased or reduced in response to the silt-clay ratio. Close to 1,200 and to 1,300 rings, both the average value and standard deviation for flapper torques showed a tendency to increase, and the injection amount of the auxiliary material therefore increased. As a result, the average values and standard deviation for flapper torques were observed to decrease.

(2) Evaluation of influence of factors using multiple regression analysis

Multiple regression analyses were carried out in order to evaluate the influence of different factors on measured values for flapper torques. Since the relationship between each of the factors and the flapper torque was unknown, the multiple regression analyses were carried out assuming that the relationships were treated as linear.

Table 1 shows the partial regression coefficients, variance ratio F and T values, statistical test results, partial correlation figures for the average values, and standard deviation for the flapper torques, as determined by the multiple regression analyses. Factors with high multicollinearity were excluded from the multiple regression analyses. Table 1 indicates that the foam expansion ratio, foam injection ratio, face pressure, excavation speed, cutter torque, shield thrust, ratio of silt-clay, ratio of fine sand, injection amount of auxiliary material and water content all show meaningful relationships with the average values and standard deviation for the flapper torque. Among the geological factors, the relationships between silt-clay ratio and the average value and standard deviation of the flapper torque are particularly significant and indicate that the silt-clay ratio has a significant influence on the state of plastic flow of the excavated muck.

Since there existed a significant relationship between the foam injection ratio and the foam expansion ratio and the average values and standard deviation for flapper torques, it was judged that torque measurements taken using the flappers would be effective in understanding the effect of the foam injection ratio into the excavated muck on the state of muck flow. In addition, given the significant relationship between flapper torque values and earth pressure, it was concluded that torque measurements would also be effective in evaluating the face stability. The significant relationships between excavation speed, cutter torque, and shield thrust and flapper torque indicated that experience-based and indirect methods of evaluating the state of plastic flow in the chamber were effective.
5. RESULTS OF FLUID ANALYSIS

(1) Simulation results in relation to measured values

Using analytical constants based on flapper torque values measured during the actual tunneling work, the state of plastic flow of the muck in the chamber was evaluated by means of fluid analyses.

a) Analytical constants

Since the excavation had proceeded well through all sections, it was expected that an adequate plastic flow had been achieved and maintained for the muck in the chamber. The fluid analysis accordingly focused on the sections close to the 1,290th ring and the 810th ring, where the average value and standard deviation for the flapper torque were at their maximum and minimum, respectively, as shown in Fig. 6(a) and (b). The yield values and viscosities for the Casson model were found using inverse calculations. Table 2 lists analytical case studies and analytical constants.

Table 2: List of cases for analysis.

<table>
<thead>
<tr>
<th>Case</th>
<th>Muck conditions</th>
<th>Analytic constant</th>
<th>Subject of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1C</td>
<td>High measured values for flapper torque</td>
<td>τ = 3000 N/m², μ = 6000 N/m²·s</td>
<td>Chamber</td>
</tr>
<tr>
<td>Case 2C</td>
<td>Low measured values for flapper torque</td>
<td>τ = 200 N/m², μ = 200 N/m²·s</td>
<td>Screw conveyor</td>
</tr>
<tr>
<td>Case 3C</td>
<td>Blowing conditions</td>
<td>τ = 20 N/m², μ = 50 N/m²·s</td>
<td></td>
</tr>
<tr>
<td>Case 1S</td>
<td>High measured values for flapper torque</td>
<td>τ = 3000 N/m², μ = 6000 N/m²·s</td>
<td></td>
</tr>
<tr>
<td>Case 2S</td>
<td>Low measured values for flapper torque</td>
<td>τ = 200 N/m², μ = 200 N/m²·s</td>
<td></td>
</tr>
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<td>Case 3S</td>
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<td>τ = 20 N/m², μ = 50 N/m²·s</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows periods of 60 seconds, corresponding to two rotations of the flapper. The fact that the measurement and analysis results in Fig. 8 basically correspond indicates that fluid analysis using the Casson model is able to roughly simulate the torque values for flappers installed in the chamber.

b) Relationship between flow rate and shear rate

Fig. 8 shows the relationship between shear stress and shear rate obtained by substituting the analytic constants τ and μ from Table 2 in Equation (1).

Fig. 9 shows the relationship between shear stress and shear rate for flappers installed in the chamber.

Fig. 10 shows the relationship between shear rate and shear stress.
the relationship between distance from the center of the cutter and flow rate for three cross-sections (close to the cutter face, the center of a cross-section of the chamber, and close to the bulkhead) in addition to the cutter speed distribution. These figures indicate that muck speed almost agreed with cutter speed at the cutter support section for all three cross-sections, i.e. the muck rotated at the same speed as the cutter. On the other hand, at the outer circumference of the cutter, the difference between muck speed and cutter speed increased with proximity to the bulkhead. It is estimated that the muck had been fluidized. In addition, the figures indicate that complex changes occurred in the flow rate around the agitator.

Focusing on the analysis results for Case 2C, Fig. 11 plots the flow rate and shear rate at the agitator, the cutter support section, and the outer circumference of the cutter for cross-sections. These figures show that, despite the fact that the flow rate indicated a tendency to increase in the radial direction close to the cutter face, no difference was observed in the shear rate in the radial direction, and the shear rate maintained a uniform low value overall. However, (c) Close to bulkhead on Fig. 11 indicates that the flow rate close to the outer circumference of the cutter decreases, while the flow rate at agitator increases slightly.

In the case of the shear rate, while there had been virtually no effect on the positions of the chamber at the cutter support section, the shear rate indicates a tendency to increase at the agitator and the outer circumference of the cutter.

From these results it is considered that the muck in the chamber was gradually plastically fluidized as it moved from the cutter face and approached the bulkhead. However, this tendency was weak at the cutter support section, indicating difficulty in achieving plastic fluidization.

c) Distribution of flow rate and shear rate in the chamber

Fig. 12 and Fig. 13 show the distribution of flow rate and shear rate at the three cross-sections shown in Fig. 1(b) from the analysis results for Cases 1C and 2C, respectively. These figures indicate that flow rate and shear rate showed similar distribution patterns irrespective of the magnitude of the flapper torque. The muck flow rate showed a complex non-uniform distribution as it approaches the bulkhead from close to the cutter face, and the flow rate in the chamber changed significantly due to the effect of the fixed blades, kneading blades, and agitator. On the other hand, the shear rate was low across the entire cutter face cross-section, and close to the cutter support section in the center of the chamber cross-section and the cross-section close to the bulkhead. It is estimated that the muck was almost entirely unfluidized in these sections. However, the area in which the shear rate was high increased in size with proximity to the bulkhead as the muck moved toward the bulkhead from the cutter face, so that it was found that the range of fluidization of the muck was increasing.

Since the tunneling work proceeded well through all sections, it is considered that the muck in the chamber was adequately plastically fluidized irrespective of the magnitude of the flapper torque. Taking into consideration the fact that the measured values and the analysis results for flapper torques almost corresponded, the flow rates and shear rates shown in Fig. 12 and Fig. 13 are considered to express adequate states of plastic fluidization.

(2) Simulation analysis assuming conditions for muck blowing

Blowing is a phenomenon in which muck spurts from the outlet because the pressure of the muck in the screw conveyor does not decrease sufficiently due to the excessive fluidization of the muck in the chamber. When blowing occurs, it becomes impossible to regulate the amount of muck discharge by means of the rotation speed of the screw conveyor. On the other hand, under good muck discharge conditions, resistance in the screw conveyor reduces the pressure of the pressurized excavated muck in the chamber to atmospheric pressure by the time it
reaches the outlet, and the amount of muck discharge
can be regulated using the speed of rotation of the
screw conveyor.

During the actual tunneling work, it was possible to
proceed with good muck discharge while ensuring
face stability through the entire tunnel line. Therefore,
no measurements were taken of the flapper torque in
the chamber under conditions in which blowing of
excavated muck from the screw conveyor occurred.
A detailed three-dimensional model of the screw
conveyor section (shown in Fig. 14) was therefore
formulated and used in a fluid analysis of the state of
pressurization from the interior of the chamber to the
screw conveyor outlet, and analytical constants for
muck blowing were determined by comparing the
earth pressure at the muck inlet and the pressure at
the discharge outlet. Table 2 shows the cases for
analysis of the screw conveyor section (Case 1S,
Case 2S, and Case 3S) and the analytical constants.

Fig. 12 Distribution of flow rate and shear rate in chamber cross-sections (When flapper torque is high (Case 1C)).

Fig. 13 Distribution of flow rate and shear rate in chamber cross-sections (When flapper torque is low (Case 2C)).

Fig. 15 shows the state of pressure in the screw
conveyor, formulated from the analysis results for
Cases 1S, 2S and 3S. In Case 1S, the pressure in the
chamber rapidly decreased close to the screw con-
veyor inlet, and this is considered to express a state of
low plastic fluidization. In Case 2S, pressure in the
screw conveyor gradually decreased until it reached
zero close to the discharge outlet, and this is consi-
dered to express a state of high plastic fluidization.
From these results, the analysis results for the
chamber and for the screw conveyor can be consi-
dered to almost correspond. In Case 3S, no reduction
in pressure occurred even at the screw conveyor
discharge outlet, and the conditions of a state of muck
blowing were able to be simulated.

Next, in Case 3C a fluid analysis of the interior of
the chamber when blowing occurred was carried out
using the analytical constants from Case 3S. Fig. 16
shows the changes with time in flapper torque ob-
tained from the analysis. The figure shows that the value of the flapper torque reached close to zero, and it is assumed that this expresses a state in which viscosity in the chamber is extremely low and the muck is excessively fluidized. Fig. 17 shows the flow rate and shear rate in the chamber for Case 3C. A comparison of Fig. 17 with Fig. 12 and Fig. 13 demonstrates that when blowing occurs, the area in which the flow rate is low expands, and the shear rate becomes high in comparison with good discharge conditions over the cross-section of the cutter face. This simulation well expresses that the level of fluidization of the muck was extremely high.

This is considered to indicate that the control and management of muck flow based on flapper torque values would be effective in preventing blowing. The use of fluid analyses based on flapper torque values enables a quantitative evaluation of muck flow conditions in the chamber to some extent when blowing occurs.

6. EVALUATION OF PLASTIC FLOW

Fig. 18 shows average values for flow rate and shear rate at the agitator, the cutter support section, the outer circumference of the cutter for the cross-sections close to the cutter face, at the center of the chamber cross-section, and close to the bulkhead. This figure shows that the plots for Case 1C and Case 2C tend to shift from Zone I to Zone II as the muck flow approaches from close to the cutter face to the bulkhead. Since the muck was immediately taken into the chamber after excavation, it is considered that the muck did not reach a state of plastic fluidization. Since there was insufficient agitation mixing and the muck did not become plastically fluidized, as is also clear from the fact that the excavated muck close to the cutter face rotated in a mass at the same speed as the cutter shown in Fig. 10, it is considered that the muck was close to a solid state. Considering...
that the actual tunneling work proceeded well, with no clogging or blowing, it could be estimated that the muck in the chamber maintained an adequate state of plastic fluidization. In other words, the area shown as Zone II in the figure can be considered as indicating a state of adequate plastic fluidization of the muck. In comparison with the results from good excavation conditions, the results for Case 3C both close to the cutter face and close to the bulkhead are distributed in Zone III, where the flow rate is low and the shear rate is high. This zone indicates a state of excessive fluidization.

Based on the above results, the states of the muck in the chamber could be divided into the three zones shown in Fig. 19.

Zone I: The flow rate is high and the shear rate is low in this zone. The muck is not in a state of plastic fluidization, or there is less agitation effect; e.g., the muck in the chamber and the cutter rotate simultaneously, and this might lead to clogging.

Zone II: Adequate flow rates and shear rates are obtained in this zone. The muck maintains an adequate state of plastic fluidization.

Zone III: Flow rate is low and shear rate is high in this zone. The level of fluidization is extremely high, and there is a possibility of blowing.

Therefore, it is considered that the relationship between flow rate and shear rate, obtained from fluid analyses based on the results of the flapper torque, can be used to perform the quantitative evaluation of the state of fluidization of the muck in the chamber.

In addition, it is considered that the use of measurements of torque taken by flappers during excavation and the accumulation of analyses taking these measurement results and excavation conditions into consideration would enable the implementation of efficient excavation management by identifying the zone for the flow rate and shear rate of muck in a state of plastic flow during actual tunneling, and the application of management methods to prevent deviation from this zone.

7. CONCLUSION

This paper has discussed the development of a muck flow control and management technology using flappers to measure the plastic fluidization of the muck in the chamber and fluid analyses to evaluate the state of plastic flow of the muck, and has discussed the application and verification of this method in actual tunneling work.

Based on the results of this study, the following conclusions can be drawn.

(1) Values of flapper torque vary significantly under the influence of various factors such as the ratio of different soil types (gravel, coarse sand, fine sand, or silt-clay), the foam injection ratio, and the injection amount of auxiliary material. Since flapper torque measurements reflect the state of the muck in the chamber, they enable that state to be known in real time, and can therefore be considered to be extremely effective in controlling and managing muck properties.

(2) The results of multiple regression analyses indicated that values of flapper torque were closely related to the foam expansion ratio, foam injection ratio, face pressure, excavation speed, cutter torque, shield thrust, silt-clay ratio, fine sand ratio, and the injection amount and water content of auxiliary materials. Since the foam injection ratio and foam expansion ratio show a particularly
significant relationship with average values and standard deviation of the flapper torque, torque measurements obtained from flappers can be utilized effectively to judge the state of flow of the excavated muck with the known amount of auxiliary material injected.

(3) Fluid analyses using Casson models are able to accurately reproduce the flow rates and shear rates of the muck with a gravel content of around 20% in the chamber, and the flapper torque values for conditions of good plastic flow and muck blowing.

(4) The calculation of flow rate and shear rate by means of fluid analyses enables quantitative evaluation of the state of plastic flow of the muck in the chamber. From the relationship between the flow rate and the shear rate, the flow state of the muck can be divided into a zone of clogging, a zone of good flow, and a zone of blowing. The classification of flow states into zones can provide effective indicators for the evaluation of the state of plastic flow of the muck.

(5) The application of the developed muck flow control and management technology, combining measurements taken by flappers and fluid analyses based on those measurements in an actual excavation, verified the technology’s effectiveness in enabling a quantitative understanding of the state of plastic flow of muck in the chamber in the earth pressure balance shield method.

It is expected that the issues of tunneling work in large cities like the Tokyo metropolitan area – characterized by large cross-section shields, lack of space for work, construction in the vicinity of important structures, increasing depth of tunnels, and the need for reductions of construction cost – will increase the demand for the earth pressure balance shield method.

The developed muck flow control and management technology combining measurement and analysis of flapper torque proposes a method of quantitative evaluation of the state of plastic flow of muck, and the effectiveness of this technology has been verified in actual tunneling work. In particular, since changes in flapper torque occur before changes in the properties of excavated muck discharged from the screw conveyor, the rapid recognition of extraordinary flapper torque values is effective in ensuring face stability in shield tunneling work. However, since the developed muck flow control and management technology was applied and tested in just one tunneling project, it will be necessary to resolve the following problems and increase the practical applicability of the system:

- Since a 5-minute time lag is necessary between the implementation of a work procedure and analysis in the current muck flow control and management technology, it will be necessary to reduce this time lag and increase the speed of analysis towards the realization of real-time analysis.
- It will be necessary to collect data concerning the various factors that affect the flapper torque value and the plastic flow of the muck during EPB shield tunneling work, and to realize increased accuracy in the system.
- It will be necessary to research the relationships between the analytic constants for the Casson model and the factors that affect the plastic flow of the muck. In particular, it will be necessary to study the relationship between the properties of the discharged muck and the yield values and viscosity values used in analyses by means of laboratory tests and other methods, to enable the setting of analytic constants in response to the various state of the muck.

REFERENCES


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