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Experimental study on visualisation technology around shield machines and evaluation of plastic flowability of excavated soil using new sensing technology

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ABSTRACT: In recent years, TBM (Tunnel Boring Machine) machines have become more extensive in cross-section, and the sediment properties of the excavated soil can vary significantly in the vertical direction within the chamber of TBMs. In addition, the ground is heterogeneous, and the soil layer composition often changes rapidly as the excavation progresses. Evaluating the plastic flowability of excavated soil is qualitative, which has been a problem in the past. However, we have developed an innovative visualisation test apparatus to simulate the area around the cutter face and inside the chamber of an EPB (Earth Pressure Balance) TBM machine. This apparatus, along with a comb-type plastic flowability evaluation test apparatus, has revolutionised the field. The newly developed cutter bit strain sensor and stirring blade sensor were attached to the visualisation test apparatus to enable quantitative evaluation of the soil layer composition in front of the cutter face and the plastic flowability of excavated soil and sand, and the excavated soil can be quantitatively evaluated for its plastic flowability by the evaluation test apparatus. The results and actual field applications are reported.

1 INTRODUCTION

The demand for shield tunnel construction projects in complex and soft ground fields has recently increased (Kawano et al., 2019). The construction condition of EPB (Earth Pressure Balance) TBM (Tunnel Boring Machine) shield tunnelling has become challenging, especially when the boring data and ground information scoped in projects are insufficient. Meanwhile, in some cases, the TBM machines are becoming very large in cross-section, where the plastic flow of excavated soil inside the shield chamber may differ significantly due to insufficient degree of mixture (Naqi et al., 2023). To improve the plastic flow of excavated soils, soil conditioning, such as a foaming agent, polymer agent or bentonite slurry, is widely used in EPB TBM shield tunnelling. However, the formulation of soil conditioning can remain the same when the soil type or particle size of excavated soil changes. Hence, a rapid detection of soil type/layer information and formulation change is not just a necessity, but a crucial aspect of shield tunnel construction projects.

To cope with these problems, we have developed a prototype sensor (Kawano et al., 2021). It is essential to make sensors more sophisticated and to build up a monitoring system which can detect the changing of layers ahead of the cutter face and rapidly change the conditioning formulation while monitoring and evaluating the soil condition (plastic flowability) inside the chamber of TBMs.

Several attempts have been made to develop suitable soil conditioners (Liu et al., 2022). Wei et al. (2020) showed the performance of soil conditioners, and Wu et al. (2018) gave reasons why foam agents were widely adopted for soil conditioning. In this study, to evaluate the performance of the soil conditioner, a series of laboratory tests were conducted to compare the essential characteristics of different prototypes.

A series of laboratory experiments with the newly developed sensing technology, such as a stirring blade sensor, cutter bit strain sensor and comb-type plastic flowability evaluation test apparatus, were implemented on a device that can simulate both ahead of the cutter face and inside the chamber of a TBM. Then, the parameters mainly affected the sensor's performance and how they could be utilised in real TBM as a real-time visualisation system.

2 METHODOLOGY ADOPTED

The performance of soil conditioners, especially for foaming agents, as shown in Figure 1, needs to be evaluated quantitatively. We, therefore, made a foam diameter observation system with a digital camera and devised a foam remaining rate test.

New sensing technology is needed for visualisation inside a chamber and ahead of a cutter head of EPB TBM tunnelling. Hence, we have made two sensors: a cutter bit strain sensor and a stirring blade sensor. These sensors are now installed on actual EPB TBM shield machines with a diameter of approximately 15 m.

In addition to these sensors, a comb-type plastic flowability evaluation test apparatus has also been developed to evaluate the flowability of excavated soils quantitatively. This apparatus is a breakthrough, as plastic flowability could only be assessed qualitatively in the past.

Figure 1. Foam appearance.

2.1 Foam diameter observation system

A foam diameter observation system was built to investigate the soil conditioners' performance, as shown in Figure 2. This system includes a high-resolution digital camera with 24.2 million pixels, a foam chamber, an LED light, and a blackout curtain. The foam chamber was designed to resist the pressure of 500 kPa, which allows observation under different pressure conditions. The fine bubbles in the foam can be captured, as shown in Figure 2, and image analysis is implemented to calculate each bubble's diameter and count the number of bubbles by using photos.

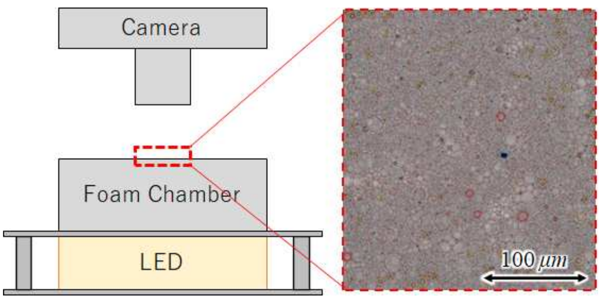


Figure 2. Foam diameter observation system.

2.2 Foam remaining rate test

A new foam agent has been continuously improved to strengthen the performance of each bubble. To check the performance of the newly developed foam agent, several attempts are made to compare the foam's lasting ability, viscosity, dynamic surface tension, and the interfacial viscoelasticity of the old/new foam agents, in addition to investigating the bubble‘s diameter and the number. Two different foam agents were foamed at the specific FER (Foam Expansion Rate) using the diluents of the particular concentration to evaluate the stability of the foam. Then, the foam was injected into an acrylic cylindrical container, as shown in Figure 3, and put into a thermostatic chamber for 24 hours, which can keep the atmosphere temperature at 20 degrees Celsius. With the foam dissipated and liquefied, the volume of the diluent can be measured from the bottom of the cylinder, which allows us to calculate the remaining foam volume.

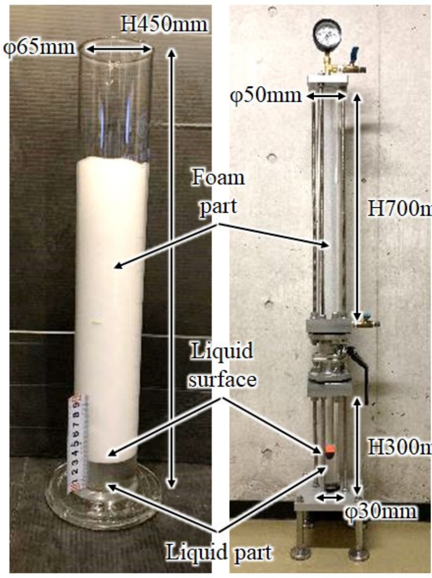


Figure 3. Acrylic cylindrical container.

2.3 TBM visualisation apparatus

A TBM visualisation apparatus was manufactured to simulate the behaviour inside a TBM chamber and test new sensing technologies, as shown in Figure 4. This apparatus consists of a soil chamber, a cutter head, and a motor system which can simulate propulsion and torque. The soil chamber has an inner size of W500 mm×H500 mm×D500 mm and is designed to keep a maximum air pressure of 500 kPa, equivalent to a water head of 50 m, to simulate the shield tunnelling construction condition at great depth.

The cutter head has a diameter of 395 mm and is equipped with sensors of different sizes: earth pressure gauge and water pressure gauge. The motor system consists of the pushing part and the rotation part. The pushing part has a maximum stroke of 100 mm and a minimum/maximum advance rate of 0.1 mm/min and 60 mm/min. The rotation part is designed with a maximum torque of 530 N·m and a maximum of 12.5 rpm at most.

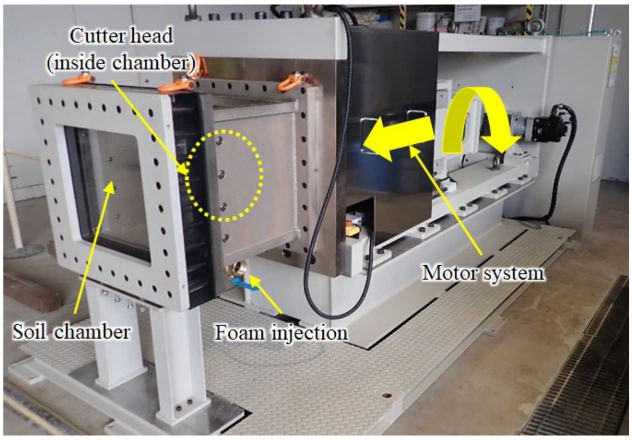


Figure 4. TBM visualisation apparatus.

2.4 Cutter bit strain sensor

The cutter bit strain sensor is developed, as shown in Figure 5, to visualise the soil layer ahead of the TBM cutter face. This sensor is made of steel, and the strain gauges are placed inside the base part of the sensor. The apex of the sensor is designed to have the same shape as the actual TBM cutter bit. Still, the body is much longer to increase sensitivity because the strain levels obtained in model tests are less significant than those obtained during excavation.

Figure 5. Cutter bit strain sensor.

2.5 Stirring blade sensor

The stirring blade sensor, as shown in Figure 6, is developed to monitor the soil condition inside a TBM chamber. Generally, several stirring blades are placed on a spoke inside a chamber to mix the excavated soil with water and soil conditioners. With the strain gauges placed inside the blade, the soil condition inside the chamber can be quantitatively evaluated since the sensor will show higher strain values when the soil is hard to stir. In contrast, the value will decrease when the soil is well-conditioned and mixed. Moreover, the effect of strain rate was negligibly small in the experiments implemented.

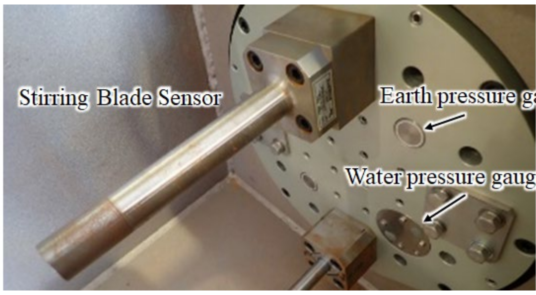


Figure 6. Stirring blade sensor inside soil chamber.

2.6 Comb-type plastic flowability evaluation test apparatus

Laboratory soil tests are popular for evaluating the plastic flowability of excavated soil mixed with foam. However, it is generally known that the type of soil and the type and amount of additives affect the plastic flowability of excavated soil. Therefore, the final judgment of plastic flowability is often made visually and by touch, and a more objective quantitative evaluation is needed. The problem is that we need to be able to make objective quantitative evaluations. Hence, a comb-type plastic flowability evaluation test apparatus, as shown in Figure 7, was developed to objectively and quantitatively evaluate the plastic flowability of excavated soil mixed with foam.

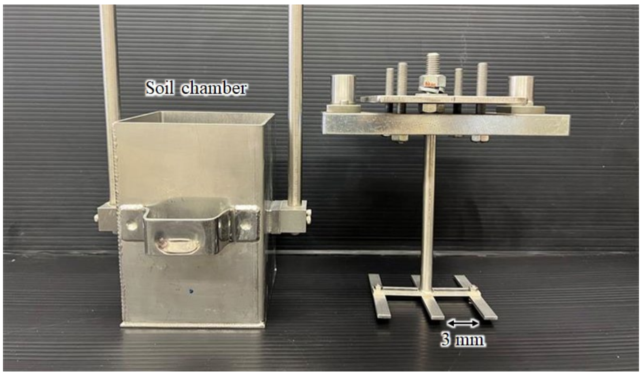
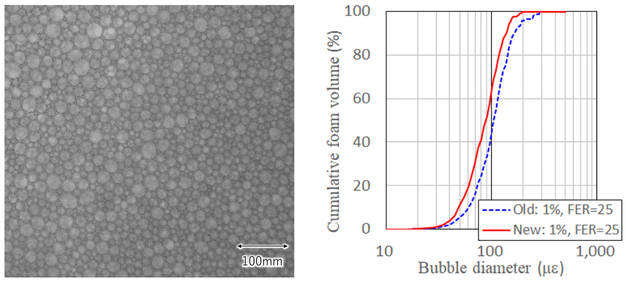


Figure 7. Comb-type plastic flowability evaluation test apparatus.

3 LABORATORY TEST RESULTS

3.1 Performance of foam agents

The foam diameter observation system observed the bubble's diameter; the results are shown in Figure 8. As can be seen in Figure 8, the new foam agent made more bubbles than the old one at the same foam expansion rate, and the percentage of fine bubbles was higher. Therefore, using high-performance bubbles can increase the bearing effect of excavated soil with foam. A high bearing effect ensures high plastic flowability.



(a) Image analysis result (b) Diameter distribution

Figure 8. Results of foam diameter observation system.

The time series of changes in the remaining foam volume of the old/new foam agents at some foaming specifications (diluent concentration, FER) are shown in Figure 9. The figure indicates that the newly developed foam agent offers better lasting ability at any concentration with any FER.

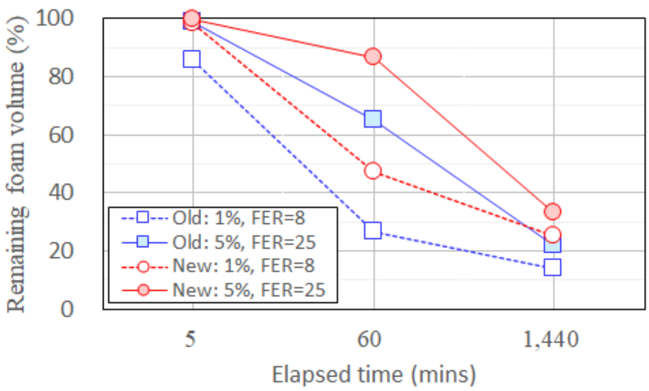


Figure 9. Change over time in remaining foam volume with different concentrations and foam agents.

3.2 Evaluation of plastic flowability with stirring blade sensor

As shown in Figure 10, the soil chamber of the TBM visualisation apparatus was set up to simulate inside the chamber of TBM, while the stirring blade sensors were equipped on the cutter face. Soil samples were prepared at lower flowability at the beginning of the test. After cutter face revolutions, the foam was injected into the chamber through an injection system installed at the bottom of the soil chamber, as shown in Figure 4. In addition, the flow table and slump tests were executed using the soil before/after the test to evaluate the flowability intuitively.

(a) Before experiment (b) During foam mixing

Figure 10. Experiment situation with stirring blade sensor.

The time history of the strain obtained from the stirring blade is shown in Figure 11. The relationship between the stirring blade strain and the results of flow table tests and slump tests are shown in Figure 12.

As shown in Figure 11, the stirring blade strain value peak was around 100 με and gradually dropped to 40 με after the foam injection. The result shows an apparent effect of foam injection.

As shown in Figure 12, the slump and flow table tests showed similar linear relationships with the stirring blade strain, which indicated that the stirring blade was quite reliable in evaluating the plastic flowability of excavated soil inside a TBM chamber. It is important to note that the stirring blade strain showed cyclic behaviour as the chamber was not 100% filled.

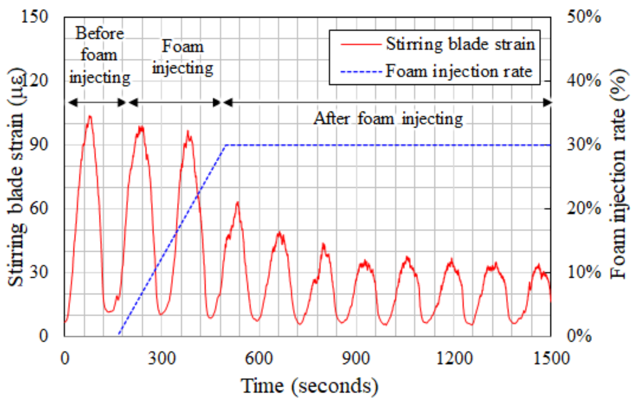
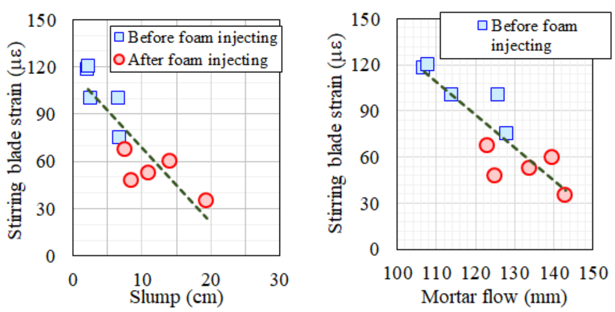


Figure 11. Change in stirring blade strain values before and after foam injection.



(a) Slump (b) Mortar flow

Figure 12. Relationship with stirring blade strain.

3.3 Assessing soil layer in front of cutter face with cutter bit strain sensor

The cutter bit sensor is developed to detect the ground information ahead of the cutter face of a TBM. The excavation operations can be adjusted according to the ground information. As shown in Figure 13, the soil chamber of the TBM visualisation apparatus was used to assess the soil layers ahead of a TBM's cutter face. The stabilised soil with different strengths, a cemented soil, was prepared to simulate actual soil models of varying strength levels.

(a) Before excavating (b) During excavating

Figure 13. Experiment situation with cutter bit strain sensor.

During the experiments, the rotation rate of the cutter face was always fixed at 0.55 rpm for a start, which is the same rate at a real construction site, while the advance rate of the cutter head was changed in steps, as shown in Figure 14. The experimental results indicate that the cutter bit strain is related to the advance rate of the cutter head.

The load acting on the cutter bit strain sensor increased as the advance rate increased. At an advance rate of 0.2 mm/min, the load was about 200 N, and it increased to about 1,400 N at an advance rate of 2.0 mm/min. In addition, as the advance rate increased, the cutter bit strain increased and the torque tended to increase.

Moreover, further analysis of the results reveals the relationships of the average cutter bit strain and the advance speed, as shown in Figure 15. This result means the advance rate should normalise the cutter bit strain because of the proportional relationship between the advance rate and average cutter bit strain when used to evaluate the actual soil during excavating. After the advance rate normalised the cutter bit strain, it was found to be related to the compression strength of the stabilised soil.

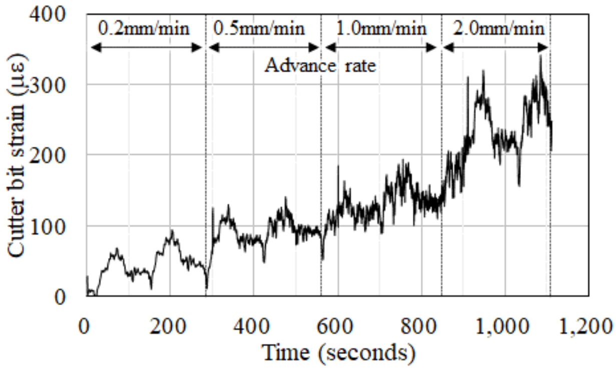


Figure 14. Cutter bit strain values at different advance rates.

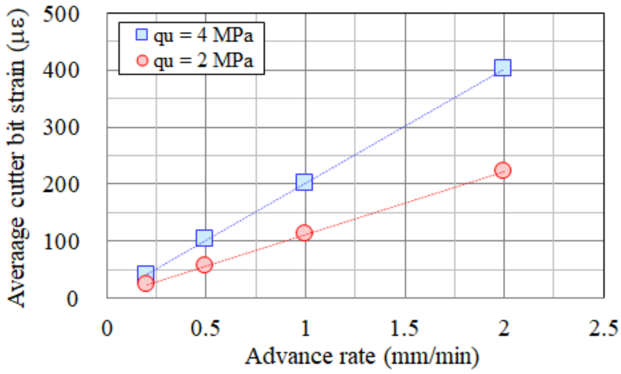


Figure 15. Relationship between average cutter bit strain and advance rate.

3.4 Tests for comb-type plastic flowability evaluation test apparatus

The comparison results of the amount of penetration gained by the comb-type plastic flowability evaluation test apparatus for both clay and sand are shown in Figure 16, and typical test situations are also shown in Figure 17. This device is capable of quantifying the situation in which soil with high plastic flowability emerges from between the combs. The device is designed to be simple to perform tests in the construction sites. Soil with high plastic flowability is placed in a soil container, and a heavy comb-shaped plate is placed on top of the soil container to measure the amount of settlement. Previously, plastic flowability was determined qualitatively by the feel of the soil when a human gripped it, but this device enables quantitative evaluation of plastic flowability by measuring the amount of settlement obtained.

The amount of penetration by the comb-type apparatus showed a similar trend to the mortar flow results regardless of the soil types, with sand having higher mortar flow values than clay when compared at the same amount of penetration. Even when the plastic flowability of clay and sand was evaluated by human visual and tactile evaluation of their plastic flowability, the mortar flow test showed that the clay tended to stick to the bottom plate due to adhesion, making it challenging to obtain flow values and causing underestimation as shown in Figure 17.

On the other hand, Figure 16 shows that the penetration was generally the same for both clay and sand with the comb-type testing apparatus, and the evaluation was quantified to be equivalent to visual and tactile assessment, as shown in Figure 17.

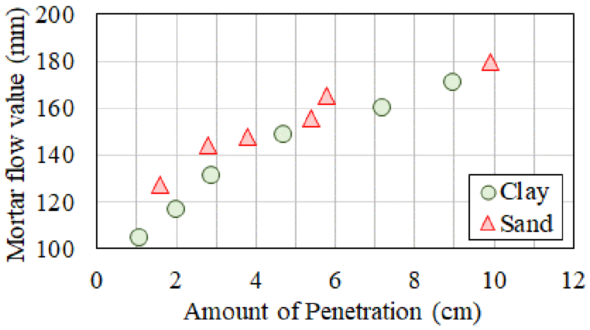


Figure 16. Comparison of mortar flow between clay and sand.

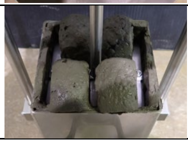
	Clay	Sand
Checked Visually & Tactilely		
Mortar Flow		
Evaluation with Comb-type apparatus		

Figure 17. Test situations of specimens having close tactile sensations.

4 CONCLUSIONS

Several attempts have been made to compare the old/new foam agent and the experiments for developing a TBM visualisation system and assessing plastic flowability evaluation. The following conclusions are obtained from the results:

1. The newly developed foam agent has shown better foam performance. Foam with FER = 50 can be achieved when the concentration is appropriate. The foam generated by the new foam agent will have more fine bubbles, so a better bearing effect in soil conditioning is expected.
2. The stirring blade sensor shows different values before/after conditioning the excavated soil inside the chamber. Laboratory tests for evaluating plastic flowabilities, such as slump and mortar flow tests, show a good relationship with the stirring blade strain, meaning that the new sensor can be utilised to evaluate the soil condition inside the chamber in real time.
3. The cutter bit strain sensor shows a higher strain level when the advance rate of the cutter head increases. Meanwhile, the experiment results also indicate that the strain of the cutter bit sensor is related to the unconfined compression strength of the stabilised soil. With information like boring data from the ground, the sensor can detect the changing of the soil layer ahead of the TBM during the excavation.
4. The developed innovative sensors can monitor the soil condition inside the TBM chamber and detect the changing of the soil layer ahead of the cutter head, which allows rapid response during the excavation.
5. With the comb-type plastic flowability evaluation test apparatus, the plastic flowability of excavated soil mixed with foam can be evaluated quantitatively without individual differences. In addition, it can also help engineers assess the plastic flowability of soil even though the excavated soil has low flowability. The evaluation results can be quantified visually and tactilely, regardless of the type of soil sample.

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