

TBM mechanical characteristics for NFGM in mechanized tunnelling

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(Received November 22, 2023, Revised January 19, 2024, Accepted January 27, 2024)

Abstract. The process of inspecting and replacing cutting tools in a shield tunnel boring machine (TBM) is called cutterhead intervention (CHI) (Farrokh and Kim 2018). Since CHI is performed by a worker who enters the chamber in TBM, the worker is directly exposed to high water pressure and huge water inflow, especially in areas with high ground water levels, causing health problems for the worker and shortening of available working hours (Kindwall 1990). Ham et al. (2022) proposed a method of reducing the water pressure and water inflow by injecting a grout solution into the ground through the shield TBM chamber, and named it the new face grouting method (NFGM). In this study, the TBM mechanical characteristics including the injection pressure of the grout solution and the cutterhead rotation speed were determined for the best performance of the NFGM. To find the appropriate injection pressure, the water inflow volume according to the injection pressure change was measured by using a water inflow test apparatus. A model torque test apparatus was manufactured to find the appropriate cutterhead rotation speed by investigating the change in the status of the grout solution according to the rotation speed change. In addition, to prove the validity of this study, comprehensive water inflow tests were carried out. The results of the tests showed that the injection pressure equal to overburden pressure + (0.10 ~ 0.15) MPa and the cutterhead rotation speed of 0.8 to 1.0 RPM are the most appropriate. In the actual construction site, it is recommended to select an appropriate value within the proposed range while considering the economic feasibility and workability.

Keywords: cutterhead intervention; grouting; new face grouting method; TBM; water pressure

1. Introduction

The concentration to big cities in today's modern society has caused the saturation of usable ground space and, accordingly, underground space development is in the limelight. Tunneling is the most efficient way to develop the underground space (Jeon et al. 2020, Lee and Ng 2005, Rezaei et al. 2019). The tunnel excavation method using blasting in urban areas can generate noise and vibration, which can affect the stability of existing old structures. To solve these problems, a mechanized tunneling method using a TBM with less noise, vibration, and ground subsidence is being adopted mainly in developed countries. Especially, for a soft ground where the ground settlement is a concern and/or when water pressure is high, the slurry shield TBM is mainly used. The slurry shield TBM is also used when a tunnel is constructed under a riverbed or seabed.

The shield TBM excavates the ground by press-fitting the cutterhead with the cutting tools into the ground and rotating it. The cutting tools attached to the cutterhead are worn out due to various reasons (Liu et al. 2022). This leads to a decrease in excavation efficiency, which increases the construction period and cost. So, periodic inspection and replacement of cutting tools are required. Notably, there

may be cases where CHI is impossible due to a large volume of water inflow (Kim and Moon 2020). In the past, to reduce high water pressure and water inflow, grouting was performed into the ground by drilling and grouting from the ground surface to the tunnel excavation depth (Ahn et al. 2018, Masini et al. 2014), or by installing a special grouting facility inside the TBM (Brian et al. 2008, Lee et al. 2021, Yoon et al. 2018). However, such grouting from the ground surface and advanced boring grouting can be limited due to the installation of ground plants and grouting facilities, respectively, and in both cases, the ground reinforcement effect may be degraded.

To solve this problem, Ham et al. (2022) proposed a method of reducing water pressure and water inflow, without installing additional grouting facilities in the shield TBM, by injecting an appropriate grout solution into the voids or joints in the ground in front of the tunnel face through the shield TBM chamber, and named it the NFGM (Jin et al. 2018, Kim et al. 2018). Since NFGM can inject the grout materials to the front of the tunnel face by using the two injection tubes already installed in the shield TBM, it can be safe and can shorten the construction period compared to the existing grouting method. For the detailed NFGM, please refer to Ham et al. (2022). Further, to successfully perform the NFGM, it is necessary to determine material properties such as the mixing ratio, injection volume, and curing time of the grout solution used as well as the TBM mechanical operation characteristics such as injection pressure of grout solution and rotation speed of cutterhead (Au et al. 2003, Bezuijen et al. 2004,

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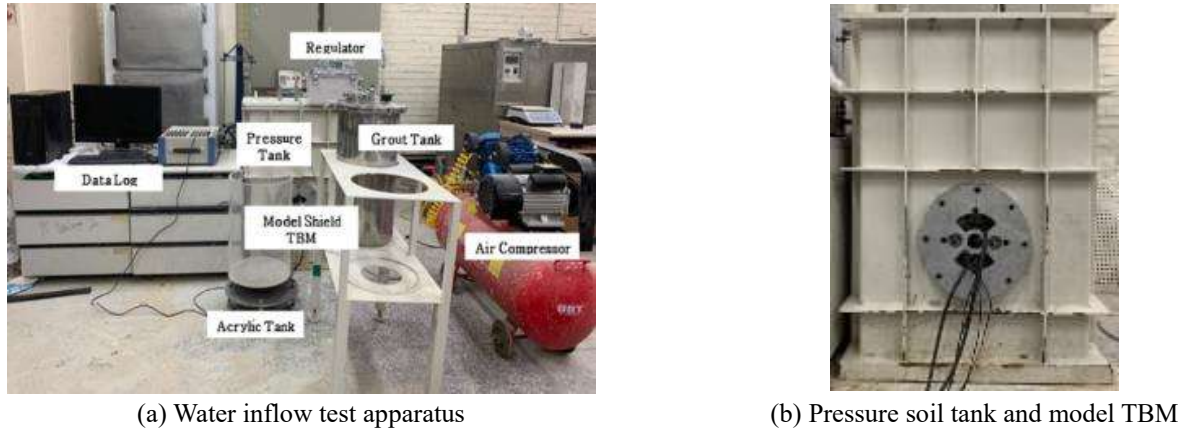


Fig. 1 Water inflow test apparatus (after Ham *et al.* 2022)

Celik 2019, Dias and Bezuijen 2017, Kasper and Meschke 2006). Among these characteristics for NFGM, Ham *et al.* (2022) first determined and proposed material characteristics such as the mixing ratio, the volume of injection, and the curing time of the grout solution.

In this study, to develop the research of Ham *et al.* (2022) and finally complete NFGM, the TBM mechanical characteristics including the injection pressure of the grout solution and the cutterhead rotation speed are determined and suggested for the NFGM. Further, to prove the validity of this study, comprehensive water inflow tests are carried out by applying the material property values presented by Ham *et al.* (2022) and the TBM mechanical characteristic values obtained in this study.

Accurately planning the CHI at the design stage is very difficult due to the uncertainty of ground conditions. If the CHI has to be performed in areas with high water pressure or large water inflow, the conventional ground surface grouting and the advanced boring grouting have many spatial and economical constraints. Therefore, this study suggests a new ground improvement method that can efficiently perform the CHI even when the water pressure is high, and/or a large volume of water inflow is generated.

2. Determination of injection pressure of grout solution

2.1 Water inflow test apparatus

To determine the appropriate injection pressure of grout solution for NFGM, an apparatus for measuring the water inflow into the chamber, as shown in Fig. 1, was manufactured by improving the model shield TBM and pressure soil tank used by Ham *et al.* (2022). It consists of a model shield TBM that simulates the slurry shield TBM, a pressure soil tank that forms the model ground, a grout tank, a regulator and air compressor that control the pressure of the soil and grout tanks, and an acrylic water tank that measures the volume of water inflow entering the chamber. The pressure soil tank (Fig. 1(b)) is 60 cm long, 40 cm wide, and 85 cm high. The cutterhead simulated a spoke-type shape that is mainly used for the soil ground. Its

Table 1 Physical properties of Jumunjin sand

Uniformity coefficient, Cu	Coefficient of gradation, Cc	Specific gravity, Gs	USCS*
1.53	0.87	2.63	SP

* Unified Soil Classification System

opening ratio was set to 14%. For detailed test apparatus specifications and test methods, please refer to Ham *et al.* (2022). This study is conducted with the opening ratio limited to 14%. Therefore, it is recommended that additional research on face grouting using opening ratio as a variable is necessary.

2.2 Experimental conditions and procedures for measuring water inflow

For the model ground in front of the shield TBM, the Jumunjin sands were used. Table 1 shows the physical properties of the Jumunjin sands. For the mechanical properties of Jumunjin sand, please refer to Jeong (2018) and Song (2013). Since the model ground had to maintain the same relative density in the repeated tests, the sand ground was divided into 5 layers and compacted, and piled up to a final height of 75 cm. To simulate the shield TBM construction site with high water pressure, water was filled so that the groundwater level was 5 cm above the model ground level. After then, the pressure soil tank was sealed, and the overburden pressure was applied with a regulator connected to the air compressor. In this study, an overburden pressure of 0.1 MPa was applied.

The material properties of the grout solution to be used in this study were selected according to the study results of Ham *et al.* (2022). That is, the mixing ratio (Water/Cement) was 2.0, the injection volume was 1.0 L, which is about 60% of the chamber capacity, and curing time was 6 hours. The grout solution consisted of water, cement, and bentonite. Micro-cement Supersem 6000-E was used as the cement, and Tixoton Standard, which is mainly used in water barrier wall construction, was used as the bentonite.

In grouting, strength in the injected area is usually accelerated by adding an accelerator, but in NFGM, an

Table 2 Water inflow volume according to injection pressure

Injection pressure (MPa)	0.10	0.11	0.13	0.15	0.20	0.25	0.30
Water inflow volume (L/min)	-	5.04	0.01	0.12	0.06	0.07	1.11
Reduction ratio of water inflow (%)	-	16.7	99.8	98.0	99.0	98.8	81.7

accelerator cannot be used because it can harden in the chamber as the grout solution is filled in the chamber first and then injected forward after a certain amount of time. Therefore, a 1-shot system without using accelerator was used. For more detailed material properties of the grout solution, please refer to Ham *et al.* (2022).

The water inflow test procedure is as follows: First, a model ground is formed in the pressure soil tank. After filling the model ground with water to form the groundwater level, the overburden pressure is applied using air pressure from the upper part of the soil tank. Then, the injection pressure is applied to the grout solution in the grout tank to inject it into the model ground in front of the tunnel face through the model shield TBM chamber. After 6 hours of curing time, the volume of water inflow into the TBM chamber from the model ground is measured. When the measurement of water inflow is completed, the shape of the grout bulb formed in the soil tank is observed and dismantled to end the test.

Likewise, the water inflow test program is as follows: First, while the overburden pressure of 0.1 MPa is applied to the model ground, the volume of water inflow in the undisturbed model ground with no injected grout solution is measured. If the injection pressure is too weak, the grout solution cannot penetrate into the model ground in front of the tunnel face; if the injection pressure is too strong, the tunnel face may be damaged and/or uplift may occur on the ground surface. Considering this, in the experiment, the injection pressure is changed from the same pressure as the overburden pressure (0.1 MPa) to 0.3 MPa. Experiments were conducted at seven different injection pressures. The reduction ratio of water inflow is calculated by comparing the water inflow volume of undisturbed model ground and that after injection at each injection pressure. Then, the appropriate range of injection pressure is determined by comprehensively judging the formation of the grout bulb along with the results of reduction ratio of water inflow.

2.3 Experimental results and determination of injection pressure

First, the water inflow volume was measured in the undisturbed ground in which the grout solution was not injected into the model ground. With the overburden pressure fixed at 0.1 MPa, the outlet on the back of the model shield TBM was opened to measure the water inflow volume. To derive accurate results, the test was conducted three times and the average value of the water inflow volume was calculated. The average water inflow volume in the undisturbed ground was 6.05 L/min.

Next, the water inflow volume was measured after

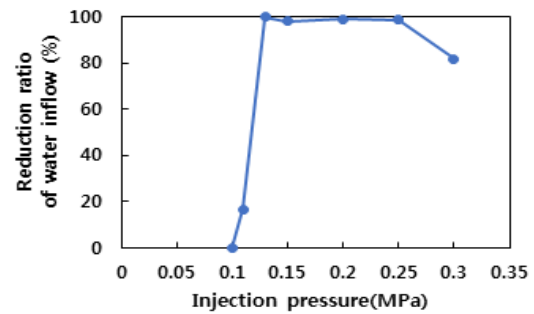


Fig. 2 Reduction ratio according to injection pressure



(a) Front of TBM tunnel face



(b) Inside TBM chamber

Fig. 3 Test results at the injection pressure of 0.13 MPa

injecting the grout solution by changing the injection pressure. Table 2 and Fig. 2 show the water inflow volume and its reduction ratio according to the change in injection pressure. Here, the reduction ratio of water inflow means the rate of decrease compared to the water inflow volume of undisturbed ground. When the injection pressure was 0.13 MPa or higher, the reduction ratio of water inflow was at least 98.0 %, however when the injection pressure went up so high as to 0.3 MPa, the reduction ratio decreased to 81.7 %.

When the injection pressure was 0.10 MPa, which is the same as the overburden pressure, even the grout solution couldn't be injected from the grout tank into the TBM chamber. In the case of injection pressures of 0.11 and 0.13 MPa, the conclusion was that the injection pressure was not high enough compared to the overburden pressure, so the grout solution failed to penetrate the ground in front of the tunnel face. Fig. 3 shows the injection failure of grout solution at the injection pressure of 0.13 MPa. In Table 2, unlike at the pressure of 0.11 MPa, the reduction ratio at the



(a) Front of TBM tunnel face



(b) Inside TBM chamber

Fig. 4 Test results at the injection pressure of 0.15 MPa



Fig. 5 At an injection pressure of 0.20 MPa



Fig. 6 At an injection pressure of 0.25 MPa



Fig. 7 At injection pressure of 0.30 MPa

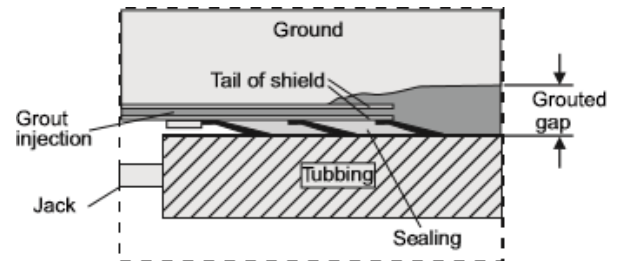


Fig. 8 Tail void in shield TBM (Moeller 2006)

injection pressure of 0.13 MPa was measured so high as 99.8% so it could be considered as an appropriate injection pressure. However, this reduction was not due to the phenomenon of injecting the grout solution well into the ground in front of the tunnel face and forming proper grout bulbs there. As a result of observing the grout bulbs after curing for 6 hours, as shown in Fig. 3 (b), it was confirmed that the grout solution gelled inside the TBM chamber and reduced the water inflow.

At the injection pressure of 0.15 MPa, similar to 0.13 MPa, if only the reduction ratio of water inflow is considered, it seems that the grout solution has penetrated well into the ground in front of the tunnel face, and it seems that most of the water inflow was blocked as high as 98.0%. However, when the inside of the soil tank and chamber were checked after the experiment, the grout bulb was not completely formed in the front of the tunnel face and some volume of grout solution remained inside the chamber, as

shown in Fig. 4. According to these results, it is considered that the grout solution is not well injected into the ground when the injection pressure is less than 0.15 MPa, causing the grout solution to harden inside the chamber and the breakdown of the TBM.

The grout solution penetrations (grout bulb formations) at the injection pressures of 0.20 MPa and 0.25 MPa are shown in Figs. 5 and 6, respectively. For these pressures, the grout solution was successfully injected into the ground, greatly reducing the water inflow volume.

At the injection pressure of 0.30 MPa, the injection pressure was so strong compared to the overburden pressure that the grout solution rose vertically, as shown in Fig. 7. In addition, bubbling sound was heard when the grout solution was injected, probably due to the strong injection pressure. The grout bulb shape of the rising grout solution could not sufficiently block the water inflow from the ground, lowering the reduction ratio to 81.7%. It turned out that the injection pressure of 0.3 MPa or higher, is not appropriate

for NFGM because the water inflow is not properly blocked.

In summary, the injection pressure of the grout solution for NFGM should be determined within a range that allows smooth injection and is not too strong at the same time. According to the experimental results conducted in this study, when the overburden pressure is 0.1 MPa, the appropriate injection pressure range turned out to be 0.20 ~ 0.25 MPa.

When constructing a tunnel with shield TBM, as shown in Fig. 8, the grout solution is injected at the calculated pressure (backfill pressure) to fill the gap (tail void) between the excavation surface and the segment. This shows a situation similar to this study in which the grout solution is injected into the void under the overburden pressure.

Many researchers have studied the theory of estimating the shield TBM backfill pressure. Analyzing these, many theories have been proposed to calculate the grout backfill pressure by adding a certain amount of pressure to the overburden pressure (Ahn and Lee 2020). Similar to the backfill pressure calculation theory, this study proposes to apply the “overburden pressure + (0.10 ~ 0.15) MPa” as the injection pressure of the grout solution. However, since this proposal is the result obtained by analyzing only the experimental results performed with the overburden pressure of 0.1 MPa, additional experiments would be needed by changing the overburden pressure to determine a more accurate injection pressure.

3. Determination of cutterhead rotation speed

As described above, NFGM is a technology that reduces the water inflow volume by reducing the permeability coefficient of the ground by filling the inside of the TBM chamber with a grout solution and injecting it into the ground in front of the tunnel face at an injection pressure. First, it is necessary to fill the TBM chamber with the grout solution, but in the actual construction site, it takes about 240 minutes to fill the chamber due to the limited capacity of the grout injection pipe. Therefore, the grout solution filled earlier can suffer from material separation or gelation. To prevent these issues, the cutterhead must be rotated at an appropriate speed. A slower rotation may cause material separation or gelation; meanwhile, a faster rotation may cause collapse of the tunnel face or ground subsidence due to over-excavation (Ahn *et al.* 2022, Chen *et al.* 2023).

To determine the appropriate rotation speed of cutterhead, three different types of experiments were performed as follows: First, a model chamber torque test was performed, and the torque value according to the change in rotation speed was measured to find the appropriate rotation speed range. Second, a mortar flow test was conducted. In this test, after 260 minutes of rotation, the grout solution was poured into the slump cylinder and the slump cylinder was lifted to measure how far the grout solution spreads. Finally, the water inflow test, which was previously performed as shown in Fig. 1, was performed again. After rotating the grout solution for 260 minutes, it

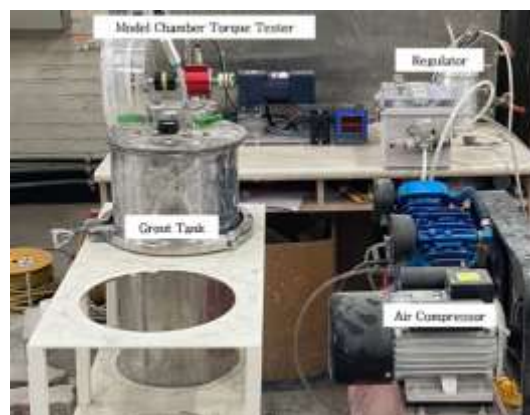


Fig. 9 Model chamber torque test apparatus



(a) Chamber and cutterhead (b) Power and control unit

Fig. 10 Model chamber torque tester

was injected into the model ground in front of the tunnel face, and the reduction ratio of water inflow compared to the undisturbed ground was investigated. The results of these three experiments were comprehensively analyzed to propose an appropriate rotation speed range.

3.1 Model chamber torque test

3.1.1 Apparatus

An apparatus manufactured for the model chamber torque test is shown in Fig. 9. It consists of a model chamber torque tester embodying the chamber of the shield TBM and the rotating cutterhead, a grout tank that injects the grout solution into the chamber, and an air compressor and regulator that control the pressure of the grout tank.

Fig. 10 shows in detail the model chamber torque tester including chamber and cutterhead. The model chamber was manufactured by reducing the diameter of the 4.6 m slurry shield TBM used in the construction site by 20:1, and was made of transparent acrylic so that the condition of the grout solution could be observed in real time. The torque tester consisted of a power unit that rotates the cutterhead and a mixing bar, and a control unit that measures torque value and controls the rotation speed. Like the actual TBM equipment, a mixing bar was installed on the model cutterhead to help maintain workability without hardening of the grout solution.

3.1.2 Experimental conditions and procedures

The grout solution used in the experiment was a mixture



Fig. 11 Mortar flow test

of water, cement, and bentonite as in the water inflow test, and the mixing ratio (water/cement) was 2.0. The order of model chamber torque test is as follows: The mixed grout solution is poured into the grout tank and then injected into the model chamber using an air compressor and regulator. The cutterhead is rotated after the grout solution is completely injected into the model chamber. When the cutterhead is rotated at the target speed, the installed mixing bar also rotates to prevent material separation and gelation of the grout solution. Considering the 240 minutes required to fill the chamber with the grout solution and the 20 minutes required for injection in the actual construction site, the cutterhead is rotated at the target speed for 260 minutes in the model test.

The model chamber torque test program is as follows: After setting the rotation speed of the cutterhead to 0.3, 0.5, 0.8, 1.0, 1.2, and 1.5 RPM, respectively, the state of the grout solution and the torque value were observed while rotating the cutterhead for 260 minutes. The torque is proportional to the force required to rotate the cutterhead, and a large torque value means that a lot of energy is required to rotate the cutterhead.

3.2 Mortar flow test

After rotating the cutterhead with a mixing bar for 260 minutes, the grout solution inside the chamber was collected, with which a mortar flow test (KS F 2594, standard test method for slump flow of fresh concrete) was conducted as shown in Fig. 11. The relative spread of the grout solution was analyzed to determine whether the grout solution retained or lost its workability. Through the mortar flow test, the minimum value of cutterhead rotation speed at which the grout solution does not lose workability was determined.

After completing the model chamber torque test and mortar flow test described above, the following additional experiments were conducted. By analyzing the results of the two experiments, a range of rotation speed was tentatively determined. While arbitrarily changing the rotation speed within the tentatively determined rotation speed range, the condition of the grout solution was observed in real time. If there is a sign of material separation or gelation, the rotation speed was increased; conversely, if a large torque occurs, the rotation speed was decreased within the tentatively determined range. By observing the change of the grout solution while controlling the rotation speed, it was judged whether the tentatively determined range of rotation speed was appropriate. At the same time, a mortar flow test was

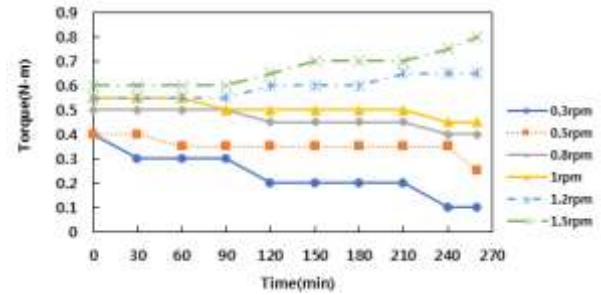


Fig. 12 Change in torque over time

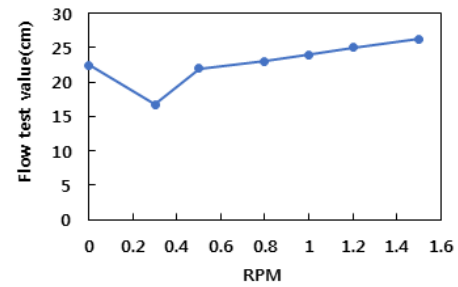


Fig. 13 Mortar flow test results

also conducted to determine whether the mortar had lost its workability.

3.3 Experimental results and analysis

3.3.1 Selection of rotation speed through model chamber torque test results

After setting the rotation speed of the cutterhead as 0.3, 0.5, 0.8, 1.0, 1.2, and 1.5 RPM, respectively, and operating it for 260 minutes, the torque changes were measured and are shown in Fig. 12. At the rotation speeds of 0.3 to 1.0 RPM, the torque value tended to decrease from the starting value over time. On the other hand, at 1.2 and 1.5 RPM, the torque tended to increase over time. The increase of torque means that the rotation force of the cutterhead becomes greater. If the torque is too large, not only the TBM is overburdened, but there is also a risk of ground subsidence due to over-excavation. Therefore, it is considered that the rotation speed of 1.2 RPM or more is not appropriate for NFGM.

3.3.2 Selection of rotation speed through mortar flow test results

After rotating for 260 minutes at each rotation speed, the grout solution was collected, and a mortar flow test was conducted. In the mortar flow test, it is possible to judge whether the grout solution has lost or maintained its workability by comparing the spreading condition of the grout solutions. The results of the mortar flow test are shown in Fig. 13. Here, the flow test value means the average value of the horizontal and vertical lengths of the grout solution spread when the slump cylinder is lifted.

The result of the experiment shows that, especially at 0.3 RPM, the flow test value decreased by 5.75 cm compared to that when the grout solution was not rotated (0 RPM). This means that the rotation at 0.3 RPM can cause

Table 3 Rotation speed and torque over time

Time (min)	0.0	30	60	90	120	150	180	210	240	260
RPM	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8	0.8
Torque (N-m)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

problems during NFGM as the workability of the grout solution decreases. On the other hand, when it was 0.5 RPM or more, the results of the mortar flow test showed a similar or increased aspect compared to 0 RPM. Therefore, it is considered that NFGM can be performed normally in this speed range because the workability of the grout solution does not decrease when the rotation speed of the cutterhead is 0.5 RPM or more.

Through the two experiments, the tentatively determined rotation speed is 0.5 ~ 1.0 RPM. To check whether this rotation speed range is appropriate, the following modified torque test was additionally performed. Instead of keeping the rotation speed constant, the torque value generated while adjusting the rotation speed within the tentatively determined range of 0.5 to 1.0 RPM was measured. At this time, adjustment of rotation speed was executed according to the condition of the grout solution while observing the changes of the grout solution in real time for 260 minutes of the rotation. That is, while keeping the rotation speed as low as possible, the speed was increased only when material separation and/or gelation of the grout solution were suspected, within a range where the torque value did not increase significantly. In addition, after the experiment was completed, the grout solution was collected, and a mortar flow test was performed to check whether the workability of the grout solution was well maintained. The experiment started from 0.5 RPM and proceeded by increasing the rotation speed when signs of material separation and/or gelation were observed. Table 3 shows the rotation speed of the cutterhead applied over time and torque value measured at that time during the experiment.

Around 30 minutes after starting the experiment at 0.5 RPM, the signs of material separation were observed, as shown in Fig. 14(a). Therefore, the rotation speed was increased at that time to 1.0 RPM, however the torque value did not change. After then, while observing the condition of the grout solution, the rotation speed was reduced to 0.8 RPM and maintained from the time of 210 minutes. The condition of the grout solution after the final 260 minutes is shown in Fig. 14 (b).

After the end of the test, the grout solution was collected, and a mortar flow test was performed. The results showed that the flow test value increased to 23.5 cm, compared to the flow test value of 22.5 cm at 0 RPM, indicating that the workability of the grout solution was secured.

3.3.3 Selection of rotation speed through water inflow test results

In order to additionally investigate whether the rotation speed range tentatively determined through the torque test and the mortar flow test (0.5 to 1.0 RPM) is suitable for



(a) Grout solution after 30 minutes



(b) Grout solution after 260 minutes

Fig. 14 Variation of grout solution condition over time

Table 4 Water inflow according to rotation speed

Rotation speed (RPM)	0.0	0.3	0.5	0.8	1.0	1.5
Water inflow volume (L/min)	-	1.522	1.045	0.123	0.045	0.059
Reduction ratio (%)	-	74.84	82.73	97.96	99.26	99.02

NFGM, water inflow test, as shown in Fig. 1, to measure the water inflow volume according to the rotation speed change was performed. The rotation speed was set as 0.0, 0.3, 0.5, 0.8, 1.0, and 1.5 RPM, respectively, and the grout solution was rotated for 260 minutes and then injected into the ground in front of the tunnel face. At this time, the injection volume of the grout solution was set as 1.0 L and the curing time was set as 6 hours according to the results of Ham *et al.* (2022). Table 4 shows the water inflow volume and the reduction ratio of water inflow according to the rotation speed change. As described above, the average water inflow of the undisturbed ground before grouting was 6.05 L/min. At 0.0 RPM, the grout solution hardened and the injection itself did not work. At 0.3 RPM and 0.5 RPM, the grout solution did not extend forward and formed unstable grout bulbs, resulting in relatively large water inflow volume. It is considered that this is because the material separation occurred during the rotation for 260 minutes, and penetration into the model ground was not smooth during the injection. At 0.8 and 1.0 RPM, no material separation occurred during 260 minutes of rotation, and grout bulbs were well formed in the front of the tunnel face, showing over 97% of water inflow blocking effect. Therefore, from the result of the water inflow test, it is considered that the range of rotation speed appropriate for NFGM is 0.8 RPM or more.

Finally, the appropriate rotation speed of cutterhead is determined as follows: According to the torque test, the rotation speed should be 1.0 RPM or less; according to the mortar flow test, the rotation speed should be 0.5 RPM or more; furthermore, the appropriate rotation speed obtained through the water inflow test was 0.8 RPM or more. Consequently, the optimum rotation speed of cutterhead for NFGM is considered to be from 0.8 to 1.0 RPM. In practice, since there is no need to rotate the cutterhead while inducing a large torque, it is recommended to maintain a low rotation speed such as 0.8 RPM, but increase the rotation speed up to 1.0 RPM if material separation is expected.

4. Comprehensive experiments for the verification of research results

The validity of the research results of this study and Ham *et al.* (2022) was verified through the water inflow test by applying the material properties proposed by Ham *et al.* (2022) (injection volume of grout solution, water/cement ratio, and curing time) and the TBM mechanical operation characteristics (injection pressure of grout solution and cutterhead rotation speed) determined in this study. Table 5 summarizes the optimal construction conditions for NFGM obtained from this study and Ham *et al.* (2022).

The experiment was conducted three times using the water inflow test apparatus shown in Fig. 1. The “Best case”, which is thought to have the highest water inflow blocking capacity, the “Worst case”, which is estimated to be corresponding to the lowest water inflow blocking capacity, and the “Mean case” between the two extremes were selected. The characteristic values selected for the three cases are shown in Table 6.

After injecting the grout solution into the model ground and having a curing time of 6 hours, the water inflow volume and reduction ratio of water inflow were measured and calculated. The results for the three cases are shown in Table 7. For the “Best case” and the “Worst case”, the calculated reduction ratios were as high as 99.02% and 98.82%, respectively. The “Mean case”, which is the middle of the two conditions, also showed a high reduction ratio of 98.84%. Considering that the three construction conditions performed were already within the range of optimal conditions suggested in previous studies and this study, the results of this experiment were fully expected. Therefore, if NFGM is constructed within the range of construction conditions in Table 5, it is considered that a high reduction ratio of water inflow will be obtained. Through this verification of research results, it is recommended to select an appropriate value for NFGM in consideration of economic feasibility and workability within the suggested range in the actual construction site.

In conclusion, the briefly summarized NFGM manual obtained through this study and Ham *et al.* (2022) is as follows. The optimum mixing ratio (water/cement), injection volume, curing time, injection pressure, and cutterhead rotation speed for NFGM are 2.0, 60% of chamber capacity, 6 hours, overburden

Table 5 Optimal construction conditions for NFGM

Construction condition	Optimal range
Injection volume	About 60% of the chamber capacity
Curing time	6 hours
Water/cement ratio	1.5 ~ 2.0
Injection pressure	Overburden pressure + (0.10 ~ 0.15 MPa)
Rotation speed	0.8 ~ 1.0 RPM

Table 6 Three test conditions for verification

Construction condition	Best case	Mean case	Worst case
Injection volume	1.0 L	1.0 L	1.0 L
Curing time	6 hours	6 hours	6 hours
Water/cement ratio	1.5	1.75	2.0
Injection pressure	0.2 MPa	0.225 MPa	0.25 MPa
Rotation speed	1.0 RPM	0.9 RPM	0.8 RPM

Table 7 Test results for three conditions

Test condition	Water inflow volume (L/min)	Reduction ratio (%)
Best case	0.0593	99.02
Mean case	0.0702	98.84
Worst case	0.0714	98.82

pressure+(0.10~0.15) MPa, and 0.8 to 1.0 RPM, respectively. For other variables such as applicable ground type, standard procedure, quality control, etc., please refer to Ham *et al.* (2022).

5. Conclusions

In this study, the TBM mechanical operation characteristics were determined and proposed to complete the NFGM, in which the cutters installed on the TBM cutterhead can be economically and safely replaced in areas with large water inflow volume and/or high water pressure. An appropriate injection pressure of grout solution was determined through a water inflow test. A model chamber torque test, a mortar flow test, and a water inflow test were performed to determine the appropriate rotation speed of the cutterhead. Finally, it was experimentally verified whether the optimal construction conditions obtained from previous studies (Ham *et al.* 2022) and this study were appropriate. The conclusions obtained from this study are as follows:

- During the NFGM construction, the injection pressure of the grout solution should be determined within a range that is not too strong while making the grout injection smooth. As a result of the experiments, it is recommended to apply an “overburden pressure + (0.10 ~ 0.15) MPa” as the injection pressure, similar to the theory of calculating the backfill pressure of the shield TBM.

- As a result of the experiments, it is recommended that the optimum cutterhead rotation speed for the NFGM be 0.8 RPM to 1.0 RPM. In the actual construction site, since there is no need to rotate the cutterhead while inducing a large torque, it is recommended to maintain a low rotation speed such as 0.8 RPM, but increase the rotation speed up to 1.0 RPM if material separation is expected.
- As a result of performing verification experiments under three construction conditions to verify the research results, it is concluded that a high reduction ratio of water inflow can be obtained if the NFGM is executed within the range of optimal material and mechanical properties proposed in this study. In the actual construction site, it is recommended to select an appropriate value within the proposed range while considering the economic feasibility and workability.
- The conclusions obtained in this paper are validated through laboratory-scale experiments under limited overburden pressure and water pressure compared to the actual construction sites. Therefore, it is recommended that a full-scale experiment or field test should be performed in order to apply it to the actual construction sites.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (RS-2023-0020866820682073250001)

References

- Ahn, C.K. and Lee, S.W. (2020), "Ground subsidence due to the backfill pressure in tunnel boring machine", *Proceedings of the 10th International Symposium on Land Subsidence (TISOLS)*, The Netherlands. <https://doi.org/10.5194/piahs-382-19-2020>.
- Ahn, C.K., Yu, J.S. and Lee, S.W. (2018), "Evaluation of the backfill injection pressure and its effect on ground settlement for shield TBM using numerical analysis", *J. Kor. Tunn. Undergr. Sp. Assoc.*, **20**(2), 269-286. <https://doi.org/10.9711/KTAJ.2018.20.2.269>.
- Ahn, C.Y., Park, D. and Moon, S.W. (2022), "Analysis of surface settlement troughs induced by twin shield tunnels in soil: A case study", *Geomech. Eng.*, **30**(4), 325-336. <https://doi.org/10.12989/gae.2022.30.4.325>.
- Au, S.K.A., Soga, K., Jafari, M.R., Bolton, M.D. and Komiya, K. (2003), "Factors affecting longterm efficiency of compensation grouting in clays", *J. Geotech. Geoenviron. Eng.*, **129**(3), 254-262. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2003\)129:3\(254\)](https://doi.org/10.1061/(ASCE)1090-0241(2003)129:3(254)).
- Bezuijen, A., Talmon, A.M., Kaalberg, F.J. and Plugge, R. (2004), "Field measurements of grout pressures during tunnelling of the Sophia Rail Tunnel", *Soils Found.*, **44**(1), 39-48. <https://doi.org/10.3208/sandf.44.39>.
- Brian, F., Michael, B. and Knut, G. (2008), "Pre-excavation drilling and grouting for water control and ground improvement in highly variable ground conditions at the Arrowhead Tunnels Project", *Proceedings of North American Tunneling Society for Mining, Metallurgy & Exploration*, San Francisco, USA.
- Celik, F. (2019), "The observation of permeation grouting method as soil improvement technique with different grout flow models", *Geomech. Eng.*, **17**(4), 367-374. <https://doi.org/10.12989/gae.2019.17.4.367>.
- Chen, W., Tang, L., Zhao, H., Yin, Q., Dong, S., Liu, J., Zhu, Z. and Ni, X. (2023), "Investigation of three-dimensional deformation mechanisms of existing tunnels due to nearby basement excavation in soft clay", *Geomech. Eng.*, **34**(2), 115-124. <https://doi.org/10.12989/gae.2023.34.2.115>.
- Dias, T. and Bezuijen, A. (2017), "Grout pressure distribution during TBM tunnelling", *Geotechnical Aspects of Underground Construction in Soft Ground, Proceedings of the 9th International Symposium (IS-São Paulo)*, Brazil.
- Farrokh, E. and Kim, D.Y. (2018), "A discussion on hard rock TBM cutter wear and cutterhead intervention interval length evaluation", *Tunn. Undergr. Sp. Tech.*, **81**, 336-357. <https://doi.org/10.1016/j.tust.2018.07.017>.
- Ham, S.K., Kim, B.J. and Lee, S.W. (2022), "Technology to reduce water ingress for TBM cutterhead intervention", *Geomech. Eng.*, **29**(3), 321-329. <https://doi.org/10.12989/gae.2022.29.3.321>.
- Jeon, Y.J., Jeon, S.C., Jeon, S.J. and Lee, C.J. (2020), "Study on the behaviour of pre-existing single piles to adjacent shield tunnelling by considering the changes in the tunnel face pressures and the locations of the pile tips", *Geomech. Eng.*, **21**(2), 187-200. <https://doi.org/10.12989/gae.2020.21.2.187>.
- Jeong, G.C. (2018), "Assessment of groundwater contamination vulnerability by geological characteristics of unsaturated zone", *Eng. Geol.*, **28**(4), 727-740. <https://doi.org/10.9720/kseg.2018.4.727>.
- Jin, Y., Han, L., Meng, Q., Meng, Ma, D., Wen, S. and Wang, S. (2018), "Experimental investigation of the mechanical behaviors of grouted crushed coal rocks under uniaxial compression", *Geomech. Eng.*, **16**(3), 273-284. <https://doi.org/10.12989/gae.2018.16.3.273>.
- Kasper, T. and Meschke, G. (2006), "On the influence of face pressure, grouting pressure and TBM design in soft ground tunneling", *Tunn. Undergr. Sp. Tech.*, **21**(2), 160-171. <https://doi.org/10.1016/j.tust.2005.06.006>.
- Kim, K.S., Oh, J.Y., Lee, H.B., Kim, D.K. and Choi, H.S. (2018), "Critical face pressure and backfill pressure in shield TBM tunneling on soft ground", *Geomech. Eng.*, **15**(3), 823-831. <https://doi.org/10.12989/gae.2018.15.3.823>.
- Kim, Y.S. and Moon, J.S. (2020), "Change of groundwater inflow by cutoff grouting thickness and permeability coefficient", *Geomech. Eng.*, **21**(2), 165-170. <https://doi.org/10.12989/gae.2020.21.2.165>.
- Kindwall, E.P. (1990), "A short history of diving and diving medicine" (Eds., Bove, A.A. and Jefferson, C.D.) *Diving medicine* (2nd Ed.), WB Saunders Company.
- Lee, G.T.K. and Ng, C.W.W. (2005), "The effects of advancing open face tunnelling on an existing loaded pile", *J. Geotech. Geoenviron. Eng.*, **131**(2), 193-201. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2005\)131:2\(193\)](https://doi.org/10.1061/(ASCE)1090-0241(2005)131:2(193)).
- Lee, H.B., Oh, T.M. and Lee, J.W. (2021), "Evaluation of grout penetration in single rock fracture using electrical resistivity", *Geomech. Eng.*, **24**(1), 1-14. <https://doi.org/10.12989/gae.2021.24.1.001>.
- Liu, W., Yang, F., Zhu, X., Zhang, Y. and Gong, S. (2022), "Rock cutting behavior of worn specially-shaped PDC cutter in crystalline rock", *Geomech. Eng.*, **31**(3), 249-263. <https://doi.org/10.12989/gae.2022.31.3.249>.
- Masini, L., Rampello, S. and Soga, K. (2014), "An approach to evaluate the efficiency of compensation grouting", *J. Geotech. Geoenviron. Eng.*, **140**(12), 04014073-1-04014073-12. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001180](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001180).
- Moeller, S.C. (2006), "Tunnel induced settlements and structural forces in linings, PhD Thesis, Institute for Geotechnical Engineering of the University of Stuttgart, Berlin.
- Rezaei, A.H., Shirzehagh, M. and Golpasand, M.R.B. (2019), "EPB tunneling in cohesionless soils: A study on Tabriz Metro settlements", *Geomech. Eng.*, **19**(2), 153-165.

<https://doi.org/10.12989/gae.2019.19.2.153>.

Song, Y.S. (2013), "Estimation of unsaturated hydraulic conductivity function of Jumoonjin sand for various relative densities", *J. Korean Soc. Civil Engineers*, **33**(6), 2369-2379. <https://doi.org/10.12652/KSCE.2013.33.6.2369>.

Yoon, Y.M., Jeong, H.Y. and Jeon, S.W. (2018), "Review of pre-grouting methods for shield TBM tunneling in difficult grounds", *Tunn. Undergr. Sp. Tech.*, **28**(6), 528-546. <https://doi.org/10.7474/TUS.2018.28.6.528>.