

Technology to reduce water ingress for TBM cutterhead intervention

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Abstract. Tunnel site where high water pressure is applied, such as subsea tunnel, generally selects the shield TBM (Tunnel Boring Machine) to maintain the tunnel excavation face. The shield TBM has cutters installed, and the cutters wear out during the process of excavation, so it should be checked and replaced regularly. This is called CHI (Cutterhead Intervention). The conventional CHI under high water pressure is very disadvantageous in terms of safety and economics because humans perform work in response to high water pressure and huge water inflow in the chamber. To overcome this disadvantage, this study proposes a new method to dramatically reduce water pressure and water ingress by injecting an appropriate grout solution into the front of the tunnel face through the shield TBM chamber, called New Face Grouting Method (NFGM). The tunnel model tests were performed to determine the characteristics, injection volume, and curing time of grout solution to be applied to the NFGM. Model test apparatus was composed of a pressure soil tank, a model shield TBM, a grout tank, and an air compressor to measure the amount of water inflow into the chamber. The model tests were conducted by changing the injection amount of the grout solution, the curing time after the grout injection, and the water/cement ratio of grout solution. From an economic point of view, the results showed that the injection volume of 1.0 L, curing time of 6 hours, and water/cement ratio of the grout solution between 1.5 and 2.0 are the most economical. It can be concluded that this study has presented a method to economically perform the CHI under the high water pressure.

Keywords: cutter head intervention; face pressure; grouting; high water pressure; tunnel boring machine

1. Introduction

The development and utilization of underground space is continuously increasing due to the saturation of available ground space due to the growth of modern society. Among the underground structures, the demand for tunnels is steadily increasing because of their excellent environmental benefits and social cost reduction effects compared to other underground structures (Jeon *et al.* 2020, Lee and Ng 2005, Rezaei *et al.* 2019). If a tunnel is to be built in a place where the excavation depth is deep, such as the subsea tunnel or the riverbed tunnel, and therefore the external pressure such as water pressure is large, the slurry shield TBM (Tunnel Boring Machine) is generally applied to maintain the tunnel excavation face (Anagnostou 1995, Duhme and Tatzki 2015). The shield TBM has a cutterhead, to which various excavation tools such as disc cutter and cutter bit are attached. The excavation tools cut the contacted soil/rock face while the cutterhead rotates. Since tools are fixed to the cutterhead, slippage between the cutter and the rock face is induced while rotating. This slippage causes a resisting force against the cutter, resulting the wear of excavation tools.

The cutter of the shield TBM wears out for various

reasons such as continuous excavation and complex ground excavation, which decreases the excavation efficiency of shield TBM. In particular, the excavation of composite ground condition frequently causes the one-sided wear of disc cutter. Therefore, it is important to inspect the cutter condition and replace the cutter, if necessary to maintain the excavation efficiency. The CHI (Cutterhead Intervention) is a series of processes of checking and replacing the excavation tools installed in the cutterhead of the shield TBM (Farrokh and kim 2018). In general, for the CHI, the workers directly enter the chamber to replace the cutter, while being directly exposed to earth and water pressure acting on the chamber. In particular, the CHI in subsea tunnel or riverbed tunnel where earth pressure and water pressure are very high, is very disadvantageous in terms of safety and economics because humans perform work in response to high water pressure and huge water inflow in the chamber (Kim and Moon 2020). The conventional CHI methods include the compressed air method using the compressed air to perform the CHI in response to the earth pressure and water pressure acting on the tunnel face, the mixed gas method in which workers perform the CHI using the mixed gas, and the saturation driving method in which workers use a separate pressurized facility to perform the CHI (Chan *et al.* 2021, Kindwall 1990, The International Tunnelling Association Working Group 2018). Such conventional CHI methods have disadvantages in that they may cause workers' health problems through pressurization and decompression, or that they require an additional accessory facility and professional manpower.

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In the conventional CHI methods, the high water pressure acting on the chamber and the large amount of influent water into the chamber are the biggest reasons that make it very difficult to check and replace the cutter. Therefore, if the water pressure and the amount of water ingress are reduced, the CHI can be easily performed. Based on this thought, this study proposes a new method to dramatically reduce water pressure and water ingress by injecting an appropriate grout solution into the front of the tunnel face through the shield TBM chamber to fill soil voids or rock joints in the ground (hereinafter, New Face Grouting Method, NFGM) (Jin *et al.* 2018, Kim *et al.* 2018). In the past, to grout in front of the tunnel face, the additional facility such as a pre-excavation equipment was separately installed on the TBM or the grouting was performed on the ground (Lee *et al.* 2021). This requires a complicated process and a lot of manpower and construction cost. However, the method proposed in this study is to inject grout material in front of the tunnel face using a feed pipe and discharge pipe without additional equipment, securing the economic efficiency and constructability. To finalize the NFGM, it is necessary to determine the characteristics of grout solution, injection amount, curing time, and other influential factors such as injection pressure and chamber rotation speed in TBM (Au *et al.* 2003, Bezuijen *et al.* 2004, Celik 2019, Dias and Bezuijen 2017, Kasper and Meschke 2006).

In this study, the concept and construction process of NFGM are proposed. For this, the characteristics of grout solution, its injection amount and curing time of the grout material were first determined among the above-mentioned influential factors. After making a model tunnel in the soil tank and experimentally modeling it in the same way as the NFGM, the factors such as amount of grout solution injection, curing time after grout injection, and water/cement ratio of the grout solution were determined. The CHI frequently occurs in the places unexpected during the design stage due to uneven wear of the disk cutter. If the water pressure is large, the construction period is delayed and the construction cost is increased, which leads to a very difficult situation. Therefore, it can be said that this study has presented a method to economically perform the CHI under the high water pressure.

2. New face grouting method, NFGM

To grout in front of the tunnel face of shield TBM, the pilot horizontal boring grouting (Brian *et al.* 2008, Yoon *et al.* 2018) and/or the ground vertical boring grouting has conventionally been performed (Ahn *et al.* 2018, Masini *et al.* 2014). However, these methods require additional equipment and a lot of construction cost. Therefore, this study proposes the NFGM that can economically grout in front of the tunnel face without additional equipment. The main application target of this study is a slurry type shield TBM that already has two outlets in the chamber to fill the chamber with slurry. The basic concept of NFGM is as follows.

If it is determined that the TBM disc cutter needs to be

replaced due to its wear, the miscellaneous substances and slurry present in the chamber are first discharged. Two injection tubes are then connected to the chamber so that grout solution and/or water can be filled respectively in the chamber. To inject the grout solution into the front of the tunnel face, the grout solution is filled in the chamber and an appropriate constant pressure is applied to allow the grout solution in the chamber to inject into the front of the tunnel face. At this time, the cutterhead is rotated at a constant speed to prevent the grout material from solidifying in the chamber. When the target amount of grout solution is injected, the injection is stopped and then water is injected to respond to the face pressure. While the chamber is filled with water in order to respond to the face pressure, the injected grout material is cured, and the water ingress gradually decreases. When performing NFGM, the chamber is slightly pulled back from the tunnel face and rotated to prevent damage to the cutterhead. When the grout bulb is formed with sufficient strength to reduce the water ingress through proper curing time, the water in the chamber is discharged and the decompression process is started after filling it with air. While continuously measuring the water inflow amount during the decompression process, if the water ingress is too large before reaching the target pressure at which the workers can change the cutter, the decompression process is stopped, and it goes back to the beginning of NFGM sequence and starts again from the grout material injection process. If the water ingress is small enough even though the operator has decompressed to the target pressure, the CHI is now carried out.

NFGM uses only the suspension-type cement grouting without using accelerator by applying the 1-shot mixing system. If the accelerator is used, the hardening time of grout material is so shortened that it can be solidified in the chamber. This causes damage to TBM equipment or components, which can greatly affect excavation schedule and, in severe cases, can stop the excavation. The grout material is composed of cement, water, and bentonite. Water and cement are basic materials for grout solution that develops the strength due to hydration reaction, while the bentonite acts as a barrier to water ingress. According to the construction site situation, a stabilizer to prevent the material separation and/or a foaming agent to secure the fluidity of grout solution can be used together.

Since the NFGM injects the grout solution forward through the shield TBM chamber, an appropriate grout injection pressure must be selected. The higher the injection pressure, the easier it is to inject the grout solution. But, if it is higher than the maximum design pressure of the TBM equipment, the bearings in the cutterhead can be damaged. On the contrary, if the injection pressure is too low, the grout solution cannot extend to ahead of the tunnel face but hardens in the chamber, causing damages to the TBM equipment. Theoretically, the grout injection pressure can be obtained by adding the additional injection pressure to the hydrostatic (water) pressure acting on the tunnel face. The additional injection pressure varies according to the situation of the tunnel construction site.

To finalize the NFGM, it needs to determine the

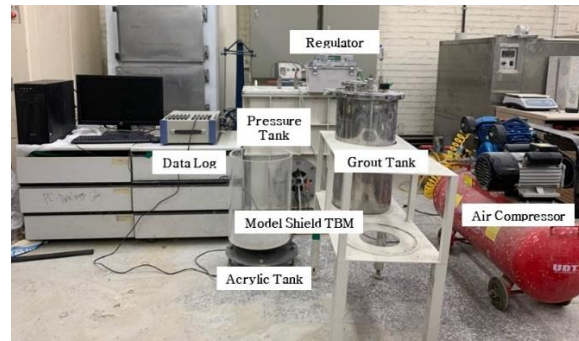
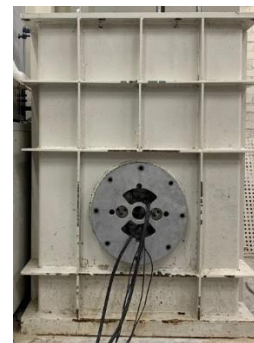


Fig. 1 Tunnel model test apparatus



(a) Before installing the model shield TBM



(b) After installing the model shield TBM

Fig. 2 Pressure soil tank with model shield TBM



(a) Side view



(b) Back side view

Fig. 3 Model shield TBM

grouting factors such as grout material properties, injection amount, and curing time, and the TBM operation factors such as grout material injection pressure and chamber rotation speed. In this study, the grout material properties, injection amount, and curing time related to grouting factors are first determined and presented. Currently, TBM operation factors such as grout material injection pressure and chamber rotation speed are under study.

3. Tunnel model test for water ingress reduction

3.1 Tunnel model test apparatus

To determine the grout material properties, injection amount, and curing time suitable for the NFGM, the tunnel

model test apparatus was manufactured as shown in Fig. 1. It was composed of a pressure soil tank to install the model ground, a model shield TBM to represent the TBM, a grout tank to inject the grout solution, an air compressor to apply the air pressure on the top of the pressure soil tank simulating the overburden pressure as well as the grout injection pressure, a regulator, an acrylic water tank and a data logger to measure the amount of water inflow into the chamber.

The pressure soil tank that forms the model ground for TBM excavation is 60 cm long, 40 cm wide, and 85 cm high, and the model shield TBM is in its center as shown in Fig. 2. To prevent the transfiguration of the soil tank due to internal/external pressure, it was made of 3cm thick steel and welded with the grid-type steel on its outer surface. To apply the overburden pressure to the model ground, a

pressurizer device using air pressure was installed on the upper part of the soil tank.

The model shield TBM that injects grout material in front of the tunnel face consists of, as shown in Fig. 3, a cylindrical chamber with the diameter of 20 cm and the width of 10 cm and a cutterhead. The grout injection hole was installed in the center of the front side and connected to the grout tank with a hose so that the grout solution could be injected into the model ground using a 1-shot system. The cutterhead simulated a spoke-type configuration that is mainly used for the soil ground. Its opening ratio was set to 14%.

The grout tank, which can control the pressure to inject the grout solution forward under the overburden pressure acting on the model ground, was manufactured to accommodate a pressure resistance of 0.5 MPa and a capacity of 10 L. The water flowing into the model shield TBM was directed to the acrylic tank with the load cell attached, so that the water ingress amount over time could be measured through the data logger.

3.2 Tunnel model test conditions and procedures

The experiment using a model soil tank to measure the amount of water inflow into the chamber after injecting the grout material in front of tunnel face is carried out in the following order: forming a model ground in the soil tank; applying an overburden pressure on the top of the soil tank; injecting the grout solution in front of the tunnel face by applying injection pressure; measuring the water ingress over time.

Jumunjin sand was used for the model ground formation. Table 1 shows the physical properties of the sand used. The model ground was compacted by 15 cm to keep the relative density constant until it reached a total height of 75 cm. To simulate the subsea tunnel, the water was filled into the soil tank so that the groundwater table reached 5 cm higher than the height of the filled model ground. By connecting the regulator jointed to the air compressor and the top plate of the soil tank, the overburden pressure was applied by the air pressure. The maximum overburden pressure applied in this study was 0.3 MPa, and tests were performed by taking 0.1 MPa, 0.2 MPa, and 0.3 MPa, respectively.

The grout solution was consisted of water, cement, and bentonite. Generally, accelerator is used for grouting for fast hardening. However, NFGM uses a chamber to inject the grout solution into the front of the tunnel face, so if we use an accelerator, it will harden easily in the chamber, causing damage to the TBM equipment and no penetration into the front. Therefore, this study chose a 1-shot system without an accelerator. The cement used was SuperCem 6000-E, a micro cement, and the bentonite was Tixoton Standard, which is mainly used for water curtain construction.

By applying air pressure to the grout tank containing the grout solution, it reaches the chamber through the hose. On reaching the chamber, the grout solution is injected forward to the tunnel face through the opening of the cutterhead. At this time, the injection pressure of the grout solution was selected to be 0.15 MPa in order to be advantageous for

Table 1 Physical properties of sand

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

ground penetration and to prevent hardening. If the overburden pressure existed, the actual injection pressure for the grout solution was estimated by adding the overburden pressure to the 0.15 MPa selected above.

After waiting a while until the strength of the grout material injected into the model ground was developed, the valve attached to the hose on the back-side of the model shield TBM was opened while the overburden pressure was being applied, and the amount of water ingress from the model ground was measured. The end of the valve was connected to the acrylic water tank so that the water flowed into the water tank. The inflow water amount was measured with a load cell installed under the water tank.

3.3 Tunnel model test program

The experimental test program carried out to determine the grout material conditions (characteristics of grout solution, injection amount, and curing time) suitable for the NFGM is as follows. First, in order to determine the injection amount of the grout solution, the inflow water amount from the model ground without grouting and the model ground with grouting by varying the injection amount of the grout solution was measured, respectively. Second, in order to determine the curing time of the grout solution, the amount of water ingress was measured according to the curing time after the grout solution was injected. Prior to the water ingress measurement test, the uniaxial compression test by varying curing time was first performed to select the test conditions. Third, in order to determine the water/cement ratio of the grout solution, an experiment for measuring the total injection amount according to the change in the water/cement ratio of the grout solution was first performed. Based on this result, the change in the inflow water amount according to the water/cement ratio was measured.

4. Results of tunnel model test for water ingress measurement

4.1 Water ingress amount from the model ground without grouting

In the model ground condition where no grout solution was injected, the amount of water ingress from the model ground into the TBM chamber was measured. To investigate the change in the amount of water ingress according to the overburden pressure, the experiments were performed under the overburden pressure conditions of 0.1 MPa, 0.2 MPa, 0.3 MPa, 0.4 MPa, and 0.5 MPa. The experimental results are shown in Fig. 4. It shows that the

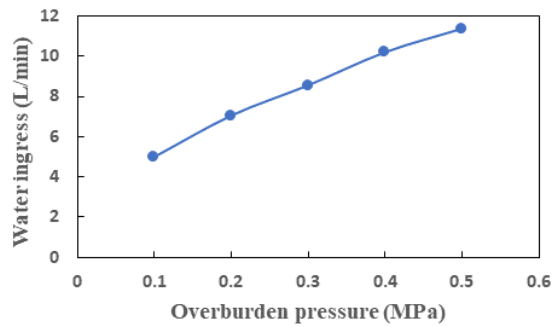
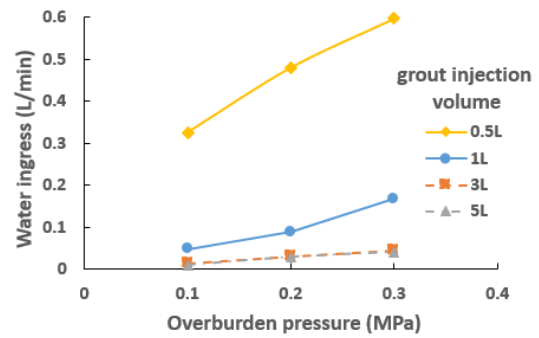


Fig. 4 Water ingress from model ground without grouting

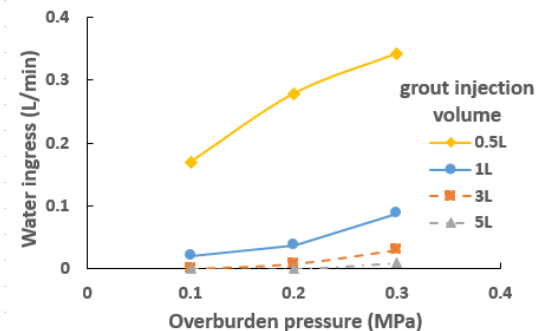
amount of water ingress increases as the overburden pressure increases.

4.2 Water ingress amount according to the injection volume

To determine the appropriate injection amount of the grout solution, the change in the water ingress amount was measured while changing the grout injection amount. The grout injection volume was set to 0.5 L, 1.0 L, 3.0 L, and 5.0 L, and was injected through the chamber, while the water ingress amount for each injection volume was measured. At this time, the water/cement (w/c) ratio of the grout solution used was 1.5, the overburden pressure was set to 0.1 MPa, 0.2 MPa, and 0.3 MPa, and the grout curing time was set to 6 hours and 24 hours, respectively. The results of the water ingress amount according to the overburden pressure and the injection volume of grout solution are shown in Figs. 5 and 6, respectively. We can see that, as the injection volume of the grout solution increases, the water ingress amount decreases. When the grout injection volume was 0.5 L, the amount of water ingress was the highest because the time was first performed to select the experimental parameter. As a result of uniaxial compression tests, 6 hours and 24 hours were selected as the curing time parameters. After 6 hours, the grout solution was not completely solidified but showed a slightly hardened gel form, however after 24 hours, the grout solution was completely solidified and showed sufficient compressive strength. The water/cement ratio of the grout solution used in the curing time decision was fixed as 1.5, and the injection amounts of the grout solution were set as 0.5 L, 1.0 L, 3.0 L, and 5.0 L, respectively. The experimental results of water ingress injection amount was too small to form the hardened grouting bulb of sufficient size ahead of tunnel face of the model shield TBM. In the cases of 3L and 5L of grout solution injection, there was little difference in the amount of water ingress, because both conditions formed the grouting bulbs larger than the diameter of the model shield TBM, decreasing the water ingress significantly. It was also found that the water ingress was sufficiently controlled for NFGM even when 1L of grout injection volume was used. Therefore, when considering the constructability and economic feasibility, it was judged to be effective to inject about 1L of grout solution.

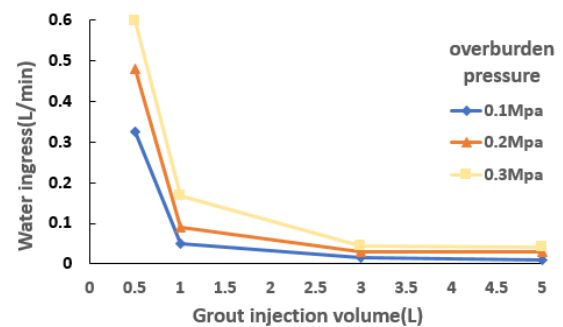


(a) 6 hours after injection

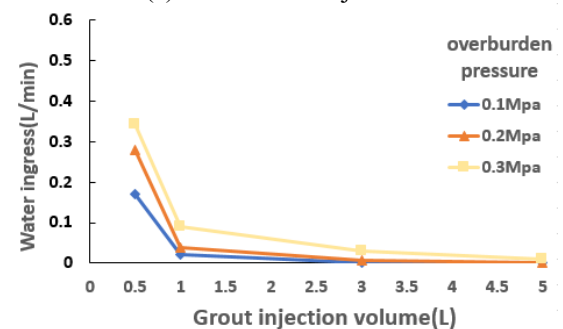


(b) 24 hours after injection

Fig. 5 Water ingress according to overburden pressure



(a) 6 hours after injection



(b) 24 hours after injection

Fig. 6 Water ingress according to grout injection volume

4.3 Water ingress amount according to the curing time of grout solution

To determine the appropriate curing time of grout solution for NFGM, the amount of water ingress was measured according to the change in curing time after grouting. Prior to the water ingress measurement test, the uniaxial compression test of grout solution by varying

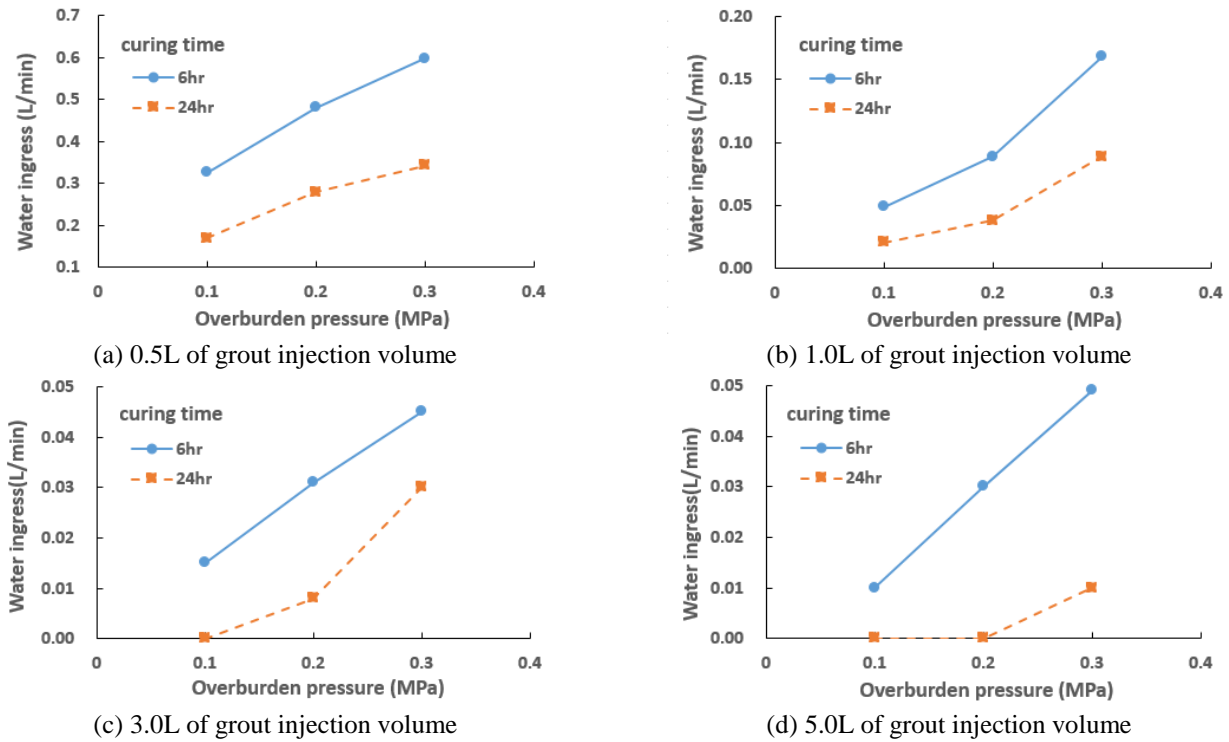


Fig. 7 Water ingress according to curing time

curing time was first performed to select the experimental parameter. As a result of uniaxial compression tests, 6 hours and 24 hours were selected as the curing time parameters. After 6 hours, the grout solution was not completely solidified but showed a slightly hardened gel form, however after 24 hours, the grout solution was completely solidified and showed sufficient compressive strength. The water/cement ratio of the grout solution used in the curing time decision was fixed as 1.5, and the injection amounts of the grout solution were set as 0.5L, 1.0L, 3.0L, and 5.0L, respectively. The experimental results of water ingress according to the curing time are shown in Fig. 7. As a result of the experimental tests, the water ingress after 24 hours of curing, when the strength was sufficiently appeared, was slightly smaller than that after 6 hours of curing, when the gel form was appeared.

4.4 Water ingress amount according to the water/cement ratio of grout solution

Before performing the experiment to measure the amount of water ingress according to the change in the water/cement (w/c) ratio of the grout solution, the amount of penetration of grout solution with time was first measured to understand the infiltration capacity of grout solution into the model ground according to the w/c ratio. As shown in Fig. 8, the grout solution was injected through the inlet at the bottom of the circular acrylic cylinder and, at the same time, the amount of effluent water from the outlet at the top of the cylinder was measured to determine the grout infiltration volume. At this time, the w/c ratio of the grout solution was set to 1.0, 1.5, 2.0, and 2.5, respectively.

The test results of the grout infiltration volume of the

grout solution are shown in Fig. 9. When the w/c ratio was 1.0, the injection was performed only for the first 15 seconds, then the infiltration rate was significantly reduced due to blockage of the grout material, and the infiltration volume was significantly smaller than other w/c ratio conditions. When the w/c ratios were 1.5 and 2.0, the infiltration rate was fast for the first, but also gradually decreased after 25 seconds due to the blockage of the grout material. When the w/c ratio was 2.5, the infiltration volume of the grout solution was the largest. As like the cases of other w/c ratio conditions, the infiltration rate decreased over time, but the grout solution was injected for the longest time because the blockage of the grout material least occurred.

The amount of water ingress was measured according to the change in the w/c ratio of the grout solution. Water/cement ratio was set to 1.0, 1.5, 2.0, and 2.5, respectively. At this time, the injection volume of the grout solution was set to 1.0 L, and the curing time after the grout injection was set to 6 hours. The water ingress from the model ground into the chamber according to the change in the w/c ratio of the grout solution is shown in Fig. 10. When w/c ratio was 1.0, the grout solution did not extend out of the tunnel face in the radial direction but rose upwards, thus maximizing the water ingress. This is thought to be because the cement content was so high compared to other conditions that the flow resistance increased during infiltration to retard the penetration into the model ground. When w/c ratios were 1.5 and 2.0, the grout solution rose slightly above the tunnel but less when compared to the w/c ratio of 1.0 and mostly extend forward. Therefore, the amount of water ingress was also the smallest. When w/c ratio was 2.5, it extends farthest in front of the tunnel face



Fig. 8 Injection volume measurement

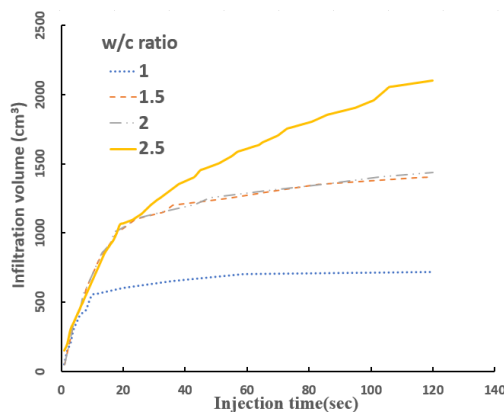


Fig. 9 Infiltration volume with time

compared to other conditions. However, the water ingress was rather high because the hardened bulb formation was not dense.

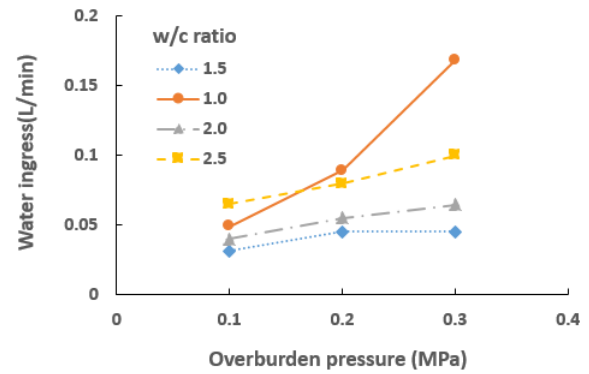
5. Determination of grout material characteristics for NFGM

5.1 Determination of the injection volume of grout solution

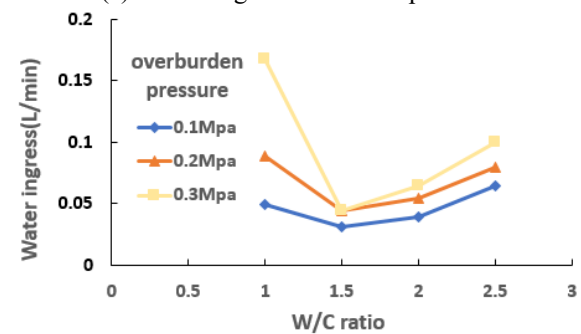
To determine the proper injection volume of the grout solution, the changes in the water ingress according to the injection volume were shown in Figs. 5 and 6. And Fig. 11 shows how much the water ingress of the model ground injected with diverse injection volumes of the grout solution (results of Figs. 5 and 6) was reduced compared to that of the model ground without the grout solution injection (results of Fig. 4). At this time, the tests were performed low as 1.0L. Since the capacity of the model shield TBM chamber used in this study is 1.8 L, it can be concluded that it is most appropriate to inject the grout solution about 60% of the chamber capacity of the on-site shield TBM during the NFGM construction.

5.2 Determination of the curing time of grout solution

To determine the proper curing time of the grout solution, the change in the water ingress according to the



(a) According to overburden pressure



(b) According to w/c/ ratio

Fig. 10 Water ingress according to w/c ratio

curing time after grouting was measured and the results were shown in Fig. 7. Along with these results, the reduction ratio of water ingress after 6 hours and 24 hours of grouting as shown in Fig. 11 was also analysed to find out the appropriate grout while changing the overburden pressure to 0.1 MPa, 0.2 MPa, and 0.3 MPa. Figs. 11(a) and 11(b) show the reduction ratio of the water ingress compared to the model ground without grouting according to each injection volume after the curing time of 6 hours and 24 hours, respectively.

When the injection volume was 1.0 L, 3.0 L, and 5.0 L, the water ingress decreased by 98% or more compared to the model ground without grouting. When the injection volume was 0.5 L, the reduction ratio was low compared to other conditions because the hardened bulb zone was not sufficient. As a result of the experimental tests with the grout injection volume of 0.5 L, 1.0 L, 3.0 L, and 5.0 L, it was considered that the injection volume of 1.0 L or more can sufficiently control the water ingress so that the CHI can be well performed. From the viewpoint of construction efficiency, it is economical to set the injection volume to as curing time. The average reduction ratio of water ingress after 6 and 24 hours of grout injection was 97.8% and 98.9%, respectively. In particular, except for 0.5 L, which is not suitable for the injection volume of the grout solution as mentioned earlier, the average reduction ratio of water ingress after 6 and 24 hours of grout injection was 99.3% and 99.7%, respectively, showing a high reduction ratio under both curing time conditions. It was considered that, if the curing time is more than 6 hours after grout injection, it can sufficiently control the water ingress from the ground for the CHI. From the viewpoint of construction efficiency,

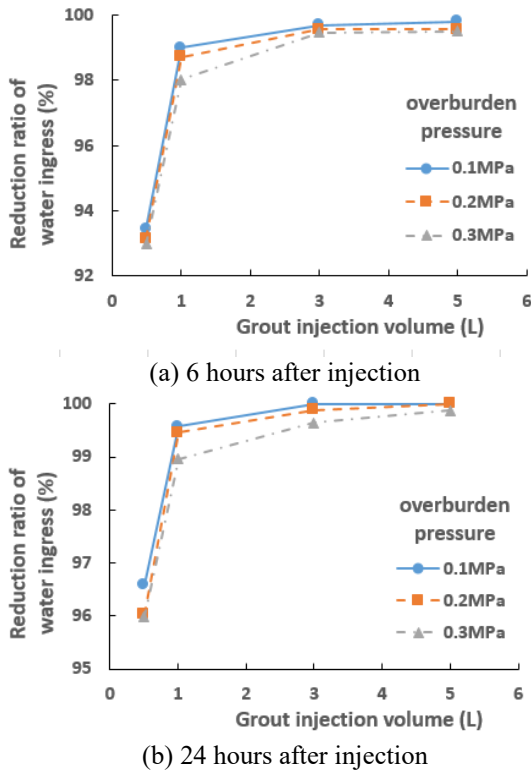


Fig. 11 Water ingress reduction ratio according to grout injection volume

it can be concluded that it is economical to set the curing time for grouting to 6 hours during the NFGM construction.

5.3 Determination of the water/cement ratio of grout solution

To determine the proper water/cement (w/c) ratio of the grout solution, the change in the water ingress according to the w/c ratio of the grout solution was measured and the results were shown in Fig. 10. Fig. 12 shows how much the water ingress of the model ground injected with diverse w/c ratio of the grout solution was reduced compared to that of the model ground without the grout injection. At this time, the tests were performed while changing the overburden pressure to 0.1 MPa, 0.2 MPa, and 0.3 MPa. As a result, all the w/c ratio conditions showed a reduction ratio of 98% or more compared to the model ground without the grout injection. In particular, the w/c ratio of 1.5 at the overburden pressure of 0.3 MPa showed the excellent reduction ratio of 99% or more. When the w/c ratio was 1.0, the compressive strength was the highest because of the high cement content, but the injection was not smooth, lowering the reduction ratio compared to the w/c ratios of 1.5 and 2.0. When the w/c ratio was 2.5, the cement content was so low that the injection was smooth, but the compressive strength was poor, lowering the reduction ratio compared to the w/c ratios of 1.5 and 2.0. Therefore, the w/c ratios of 1.5 and 2.0 were considered best due to smooth injection and appropriate strength, showing a sufficient reduction ratio of water ingress as shown in Fig. 12.

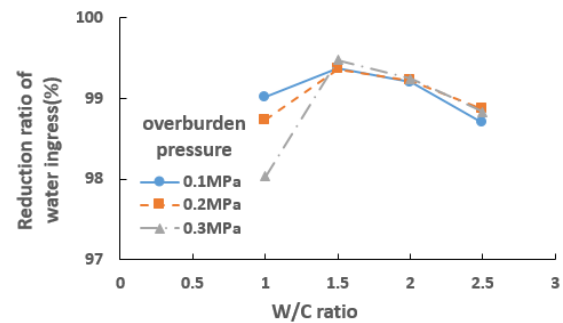


Fig. 12 Reduction ratio of water ingress according to w/c ratio

In conclusion, all the w/c ratio conditions performed in this study showed a high reduction ratio of 98% or more compared to the model ground without the grout injection. As described earlier, in the experiments for measuring the infiltration volume according to the w/c ratio (results of Fig. 9), the grout solution with the w/c ratio of 1.0 was quickly occluded from the beginning of the injection, so injection was not smooth. In this case, as the grout solution cannot be injected to the front of the tunnel face and can be hardened in the chamber, it may damage the TBM equipment. On the other hand, if the cement content is too low, as in the case of 2.5 w/c ratio, the injection can be smooth, but hardened bulb zone is so difficult to be formed that the effect of reducing the water ingress is relatively low. Therefore, it is concluded appropriate to use a water/cement ratio between 1.5 and 2.0 of the grout solution for the NFGM construction.

6. Conclusions

In this study, the concept and construction sequence of New Face Grouting Method (NFGM) were proposed to facilitate the economical cutterhead intervention (CHI) under a high water pressure. The tunnel model tests were performed to determine the characteristics, injection volume, and curing time of grout solution to be applied to the NFGM. The conclusions obtained in this study are as follows:

- (1) The NFGM uses a 1-shot system and the suspension-type cement grouting. The basic materials for the grout solution are water, cement, and bentonite. To improve the workability during construction, foaming agents and stabilizers can be also added.
- (2) As a result of experiment on the injection volume of grout solution, the reduction ratio of water ingress compared to the model ground without grouting was 98% or more at the injection volume of 1.0L or more. From a construction point of view, it is possible to select a grout solution injection volume of 1.0L or more, but from an economic point of view, it is considered that the injection volume 1.0 L is the most economical. Therefore, it is recommended to inject about 60% of the chamber volume with the grout solution during grout injection.
- (3) As a result of experiment on the curing time after grouting, the reduction ratios of water ingress compared to

the model ground without grouting after 6 and 24 hours after grouting were 98% and 99%, respectively. Therefore, considering both constructability and economic feasibility, it is considered that the curing time of about 6 hours is appropriate.

(4) As a result of experiment on the water/cement (w/c) ratio of the grout solution, the reduction ratio of water ingress was more than 98.5% compared to the model ground without grouting under all the experimental w/c ratio conditions. However, as shown in the test results, when the w/c ratio is too low, the viscosity of the grout solution increases, making the injection difficult. On the contrary, when the w/c ratio is too high, the hardened grout bulb zone is not dense. Therefore, it is recommended to set the w/c ratio of the grout solution between 1.5 and 2.0.

(5) The conclusions obtained in this paper are the results obtained under laboratory conditions by applying relatively low overburden pressure and water pressure compared to the actual construction sites. Therefore, it is recommended that a full-scale experiment should be performed in order to apply it to the actual construction sites.

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