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Characteristics of grout materials for the face grouting in mechanized tunnelling

Soo-Kwon Ham[1)], Beom-Ju Kim[1)], and *Seok-Won Lee[2)]

[1), 2)] *Department of Civil and Environmental Engineering, Konkuk University, Seoul 05029, Korea*
[2)] *swlee@konkuk.ac.kr*

ABSTRACT

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 earth pressure and water pressure are large, the shield TBM (Tunnel Boring Machine) is generally applied to maintain the tunnel excavation face. The shield TBM has a cutterhead, to which various excavation tools such as disc cutter and cutter bit are attached. The slippage between cutter and rock surface causes a resisting force against the cutter, resulting the wear of excavation tools. Especially, the excavation of composite ground condition frequently causes the one-sided wear of disc cutter. The CHI (Cutterhead Intervention) is a series of processes of checking and replacing the disk cutter. 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 water pressure is 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. 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 to fill soil voids or rock joints in the ground, called New Face Grouting Method (NFGM). The concept and construction sequence of NFGM are proposed to facilitate the economical 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. From an economic point of view, the results showed that the injection volume of 1.0L, curing time of 6 hours, and water/cement ratio of the grout solution between 1.5 and 2.0 are the most economical.

[1)] Graduate Student
[2)] Professor

1. INTRODUCTION

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; Rezaei et al. 2019). The shield TBM has a cutterhead, to which various excavation tools such as disc cutter and cutter bit are attached. 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. Especially, the excavation of composite ground condition frequently causes the one-sided wear of disc cutter. The CHI (Cutterhead Intervention) is a series of processes of checking and replacing the excavation tools (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 water pressure is 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). 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) (Celik 2019; Jin et al. 2018; Kim et al. 2018). The concept and construction process of NFGM are proposed in this study. 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. TUNNEL MODEL TEST FOR WATER INGRESS MEASUREMENT

2.1 Tunnel Model Test Apparatus

The tunnel model test apparatus was made as shown in Fig. 1. It was composed of a pressure soil tank, a model shield TBM, a grout tank, an air compressor, a regulator, an acrylic water tank, and a data logger. The pressure soil tank that forms the model ground is 60cm long, 40cm wide, and 85cm high, and the model shield TBM is in its center. 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 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. 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.

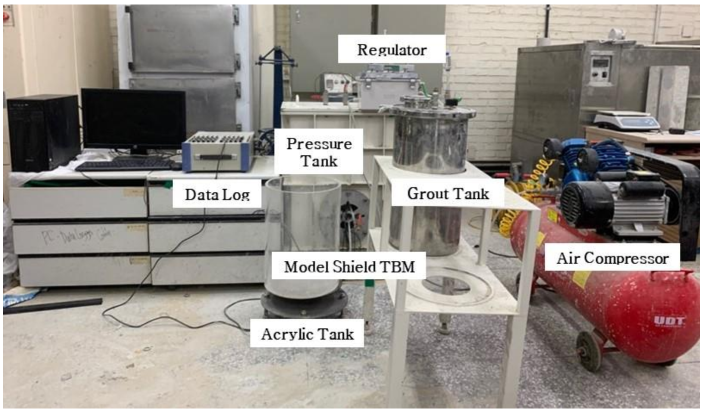

Fig. 1 Tunnel model test apparatus

2.2 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. The model ground was compacted by 15cm to keep the relative density constant until it reached a total height of 75cm. 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. The grout solution consisted of water, cement, and bentonite. 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. 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 to be advantageous for ground penetration and to prevent hardening (Bezuijen et al. 2004). After waiting a while until the strength of the grout material injected into the model ground was developed, 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.

2.3 Tunnel Model Test Program

The experimental test program carried out to determine the grout material conditions suitable for the NFGM is as follows. First, 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, 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. Third, in order to determine the water/cement ratio of the grout solution, the change in the inflow water amount according to the water/cement ratio was measured.

3. RESULTS OF TUNNEL MODEL TEST FOR WATER INGRESS MEASUREMENT

3.1 Water Ingress Amount according to Injection Volume

The change in the water ingress amount was measured while changing the grout injection volume. The grout injection volume was set to 0.5L, 1.0L, 3.0L, and 5.0L, while the water ingress amount for each injection volume was measured. At this time, 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. The results of the water ingress amount according to the injection volume of grout solution are shown in Fig. 2. We can see that, as the injection volume of the grout solution increases, the water ingress amount decreases. When the grout injection volume was 0.5L, the amount of water ingress was the highest. In the cases of 3L and 5L of grout solution injection, there was little difference in the amount of water ingress. It was also found that the water ingress was sufficiently controlled for NFGM even when 1L of grout injection volume was used.

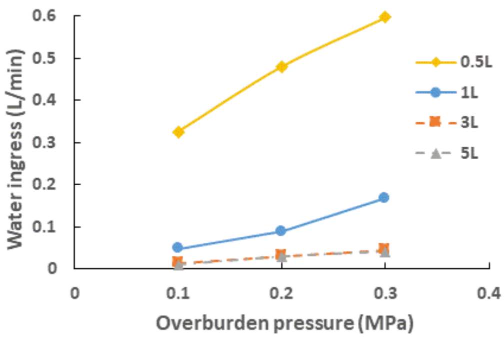

Fig. 2 According to injection volume

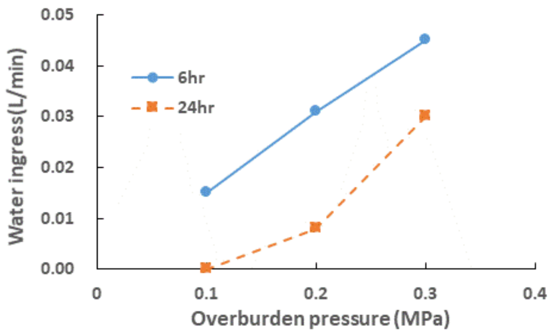

Fig. 3 According to curing time

3.2 Water Ingress Amount according to Curing Time of Grout Solution

The amount of water ingress was measured according to the change in curing time after grouting. The grout curing time was set to 6 hours and 24hours, respectively. Experiments were carried out by changing injection amounts of the grout solution to 0.5L, 1.0L, 3.0L, and 5.0L, respectively, but only the results for 3.0L are typically presented in this paper as shown in Fig. 3. The results showed that 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.

3.3 Water Ingress Amount according to Water/Cement Ratio of Grout Solution

The amount of water ingress was measured according to the change in the water/cement ratio (w/c) ratio of the grout solution. Water/cement ratio was set to 1.0, 1.5, 2.0, and 2.5, respectively. 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. 4. 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. 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 compared to other conditions. However, the amount of water ingress was large compared to those of 1.5 and 2.0.

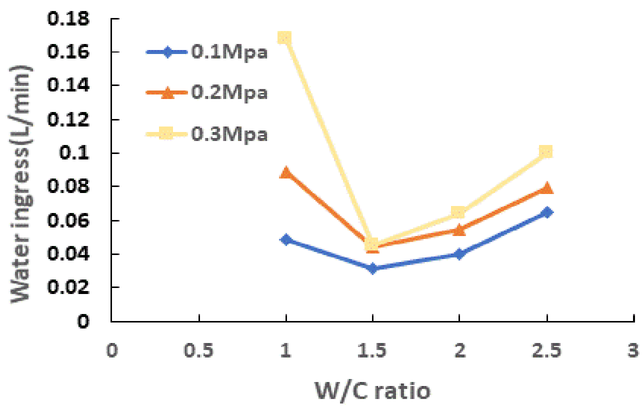

Fig. 4 Water ingress according to w/c ratio

4. CONCLUSIONS

The conclusions obtained in this study are as follows:

(1) 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 an economic point of view, it was considered that the injection volume of 1.0L is the most economical.

(2) The reduction ratios of water ingress for the curing time of 6 and 24 hours after grouting, compared to the model ground without grouting, were 98% and 99%, respectively. From an economic point of view, it was considered that the curing time of about 6 hours is the most economical.

(4) The reduction ratio of water ingress was more than 98.5% compared to the model ground without the grouting under all the experimental w/c ratio conditions. Therefore, from an economic point of view, it is recommended to set the w/c ratio of the grout solution between 1.5 and 2.0.

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