Study on the optimum grouting materials and their performance in the TBM tunnel collapse reinforcement project

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Abstract: Considering the water inrush and collapse accident involving a tunnel boring machine (TBM) in a tunnel of the Qingdao Metro Line 1, the difficulties in grouting reinforcement in the collapse area were analyzed in order to avoid the adverse effects of grouting on the TBM equipment. The zoning governance method was chosen to solve these problems. The performance requirements of grouting materials for different areas were analyzed, after which the key properties of the materials were tested and the optimum was determined. For the water gushing area, polyurethane material was the common option, whereas for the shield area, a new high-expansion grouting material with low-strength was chosen. For the cutter head area, cement silicate grout modified by adding bentonite and quick-setting additives was tested, with the resulting material showing low strength and a quick-setting property. For the tunnel vault area, cement silicate grout and polymer-modified material were deemed suitable. After testing its viscosity change, we found that the polymer-modified material had a viscosity stabilization period. Thus, it was subsequently used at the key area. The selection of materials could reduce the consolidation risk of cutter disc and shield shell in the TBM. The research findings provide useful reference for similar projects.

1. Introduction
Tunnel boring machine (TBM) has the advantages of fast driving speed, safe and reliable construction, and high comprehensive benefits; thus, it is widely used in tunnel engineering projects[1-2]. Due to the complex geological conditions of tunnel engineering, TBM often encounters water gushing collapse and other accidents when passing through special strata, such as water-rich weak strata and fault fracture zones. These often lead to the formation stress directly acting on the TBM shield and cutter head, thus causing TBM jamming.
Recent studies have been carried out on the TBM relief technology. For example, Xu[3] addressed the problems of the collapse of the open TBM crossing fault structure fracture zone in a Xinjiang water diversion project, which caused the TBM cutter head to be struck by the surrounding rock of the tunnel face collapse and the shield to be suppressed by the broken body. The chemical grouting material with high fluidity, early strength, and high-strength performance was used to consolidate the grouting in front of the surrounding rock and above the shield. The subsequent removal of the scum around the cutter head and shield helped overcome the problem. Ma[4] investigated frequent jamming caused by unfavorable geological conditions, such as expansive mudstone, faults, and water-rich strata, during the TBM excavation of the Daban Tunnel in Xinjiang. Several measures were applied to successfully solve the problem of TBM removal, including the manual excavation of pilot tunnels,
cemment and chemical grouting, emergency water blocking and ground drainage in the tunnels, mortar or fine stone concrete filling, and the placement of a temporary steel support, among others. In another instance, Wang et al.\cite{5} addressed and accident in which the cutter head was buried during the excavation of a TBM construction tunnel, also in Daban, Xinjiang. In that case, the serious tunnel collapse was caused by the extremely large deformation of the surrounding rocks. Hence, LW water-soluble polyurethane grouting material was used to reinforce the tunnel rock collapse section and help the TBM pass smoothly. Zhang\cite{6} addressed the problem of a jammed machine in the Shaanxi Yinhong Jishi Water Transfer Project wherein the TBM passed through a fault fracture zone. The TBM was successfully started by injecting chemical grout into the loose rock, which collapsed outside the cutter head, and then manually cleaning the rock body near the cutter head. Shang et al.\cite{7} solved the problem of TBM shield jamming caused by the squeezing of the surrounding rock during the construction of the Shanggongshan diversion tunnel in Kunming. They helped the TBM to successfully pass the section of the weak surrounding rock by adopting measures, such as the adoption of manual expansion and steel arch support as well as pilot heading. Meng\cite{8} resolved an accident related to a jammed TBM in an unfavorable geological fault fracture zone in a diversion tunnel project in Xinjiang. The use of chemical grouting around the side shield and the cutter head was proposed, and the loose body outside the side roof shield and the cutter head was consolidated to the grouting. This allowed the soil near the cutter head to be removed, thereby successfully solving the problem at hand.

In the TBM relief treatment, grouting is an important method for the reinforcement of a loose collapse area. Many related studies on the grouting treatment plan have been conducted, but only a few investigated the selection of the appropriate grouting material, which is very important for the grouting effect. In choosing grouting materials, the most common criteria were based on engineering experience or similar engineering analogies. The material selection lacked pertinence, and the selection process has not been fully informed in the past years. This has led to inadequate grouting effects, wasted materials, and excessive costs. Based on the engineering background of the TBM relief project in the An-Xue section of the Qingdao Metro Line 1, this paper studies the situation of a TBM trapped due to water inflow and collapse during the excavation of a coastal accumulation area. According to the formation conditions and grout properties, we optimized the grouting materials, analyzed the suitability of different materials, and fully utilized the advantages of different materials in order to solve the problem of TBM release. Thus, the findings of this work have certain reference value for similar projects in the future.

2. Projection introduction

The construction of the 1st bid and one work area of the Qingdao Metro Line 1 is located in Huangdao District, Qingdao. The section between Anzi East Station and Xuejiadoa Station departs from Anzi East Station (excavation station), runs along Xingangshan Road through Beifu Road and Binhai Road, and then lays down to Nanfu Road to reach Xuejiadoa Station (undercutting arch cover method station). The total length of the section is 1757.950 m, which is close to the large mileage end of Anzi East Station. Open excavation (236,550 m) procedure was adopted in the section. A TBM starting well was set at the large mileage end of open excavation section, and the TBM starting hole (15,000 m) was constructed by mining method. The TBM receiving hole (5,000 m) was constructed by mining method near the small mileage end of Xuejiadoa Station. The remaining sections were constructed by TBM. According to the geological exploration data, the strata excavated from the TBM within a range of about 100 m were strongly weathered quartz monzonite, which had a granular structure and easily softened by water. The excavation of the foundation pit in the An-Xue section revealed that the mixed-fill soil layer contained a rock-fill layer (about 2–4 m in thickness), and the maximum particle size of the rock-fill was about 70 cm. When the right line of the An-Xue section was tunneled for 18.9 m, water burst above the cutter head, accompanied by ground collapse. The water inflow in the early stage was about 2400 m³/h, which gradually decreased to 500 m³/h in the later stage. The TBM tunnel was flooded, and the left line was forced to stop. The situation of the TBM water gushing and collapse trapped scene is shown in Figure 1.
3. Grouting reinforcement analysis

3.1. Analysis of difficulties in removing TBM

The TBM relief process faces several difficulties. First of all, the TBM shield and the cutter head are stuck at the same time, and only manual slag removal in front of the cutter head can be performed. Water inrush on the tunnel face led to the poor stability of the collapse body in front of the cutter head. During the slag cleaning process, the originally blocked water passage can be easily damaged. This can lead to the formation of another seepage channel, causing water inrush and threatening the safety of the operator.

Second, the collapsed body in front of the cutter head and around the shield was loose and had no grouting capacity. The grout diffusion range was also difficult to control. During grouting, the grout was likely to flow into the TBM and cause equipment damage. As the traditional grout solidified, the high strength of the stone body caused the consolidation of the shield, cutter head, and formation.

Finally, the project was located in a complex coastal accumulation area with weak water-rich strata and complex geological conditions. The vault of the tunnel was covered with strong weathered quartz monzonite, which had poor stability. These conditions can easily produce large deformation under the effect of grouting pressure, which in turn, can jam the shield or even destroy the shield structure.

3.2. Analysis of the grouting scheme

This project belongs to the stuck “shield + cutter head” category. Hence, to prevent collapse accidents during the cleaning of the cutter head and subsequent excavation, the TBM must be grouted and reinforced as it comes out of the trap. At the same time, to ensure the progress of the project and reduce the safety risks, the side pilot heading, expansion, and other support measures were selected, and the surface grouting reinforcement scheme was adopted. Therefore, it was also necessary to ensure that the grouting stones cannot affect the subsequent normal TBM excavation. In order to meet the above requirements, the principles adopted by this project were hierarchical grouting and zoning governance.

Water gushing area: A water inrush disaster occurred on the palm face. Before the grouting reinforcement, the water passage near the palm face and between the shield and the surrounding rock should be blocked to prevent the tunnel surrounding rock from softening and causing a larger collapse. Thus, the focus of this area is to block water gushing.

The area near the shield: The loose area of the collapse must be properly reinforced to ensure the stability of the area while cleaning the cutter head. The reinforcement strength should not be too high to prevent the grout stone body and shield from consolidating into a whole, thereby affecting the subsequent advancement of the TBM.

Cutter head area: Appropriate filling and grouting should be carried out in this area, and the loose body near the cutter head bearing should be reinforced with low strength. Reasonable filling can prevent the grout from spreading to the cutter area during grouting in other areas. Not following this procedure can lead to adverse effects on the TBM equipment and may affect the subsequent cleaning of the cutter head.
**Tunnel vault area:** The grouting and water-blocking reinforcement of the water-rich and strongly weathered strata and landslides within the tunnel vault area must be done, in order to prevent the surrounding rock instability or the excessive deformation caused by the start of TBM, which can lead to the squeezing impact on the shield.

### 4. Selection of grouting materials
The performance of a grouting material determines the grouting effect. A variety of materials can be selected for grouting reinforcement and water plugging. Hence, the option of grouting material should be determined in combination with the purpose of use and the performance of the material.

#### 4.1. Water gushing area
The focus of this treatment is the plugging of the gushing water. The conventional water-blocking materials include a mixture of cement and sodium silicate, acid water glass, and polyurethane. In view of the large amount of water inrush, the material must have good resistance against dynamic water dispersion. At the same time, the volume of the underground watercourse is relatively small, and the grouting volume is not expected to be large. Therefore, the polyurethane material is selected, because of its excellent water-blocking performance and low cost.

#### 4.2. Shield area
The traditional mixed cement and sodium silicate grouting or chemical materials can be used in the shield area. However, the strength of the grout's stone body is relatively high, and the grout can easily diffuse into the cutter head warehouse, thereby damaging the equipment and consolidating the cutter head and shield. Therefore, a low-strength material must be injected first near the shield for isolation. Based on the above considerations, a new high-expansion grouting material (developed by Shandong University) was selected in the shielding area for water blocking and reinforcement. The material has the characteristics of high expansion (150–300 times, as shown in Figure 2), high water retention (0.3 MPa pressurized water retention rate of more than 90%), and controlled expansion rate (100 times, 60 s–50 min). The water absorption data are shown in Table 1. The shear strength of the material is low, and the force on the cutter head and shield is small.

![Figure 2. Material swelling with water](image)

**Table 1** Change of water absorption quality of the polymer particles

| Water absorption time | The quality of groundwater absorbed by polymer particles greater than 100 mesh/(g) | 30–50 mesh polymer particles absorb groundwater quality/(g) |
|-----------------------|----------------------------------------------------------------------------------|----------------------------------------------------------|
| 0 s                   | 0 g                                                                               | 0 g                                                      |
| 10 s                  | 26.2 g                                                                           | 39.6 g                                                   |
| 20 s                  | 36.6 g                                                                           | 44.3 g                                                   |
| 30 s                  | 30.9 g                                                                           | 28.5 g                                                   |
| 40 s                  | 22.6 g                                                                           | 18.4 g                                                   |
| 50 s                  | 14.6 g                                                                           | 5.7 g                                                    |
In this project, the TBM had the problems of shield and knife disk, and it could not be lifted out by the “backward” movement. In order to solve this problem, the gravel in the cutter head silo needed to be cleaned first, and the staff must then enter the front of the cutter head through the manhole and the center knife part. However, manual slag removal may cause secondary collapse during the cleaning process. Thus, the surrounding rock must be reinforced. The surrounding rock and gravel near the cutter head and shield were loose, the diffusion range of the grouts and the grouting pressure were difficult to control, and the traditional cement-based materials may enter the TBM equipment, thus causing further damage to the equipment or the subsequent consolidation of the shield, cutter and stratum. Certainly, these would cause difficulties for subsequent construction. Thus, low-strength cement silicate grout was selected. Its setting time and strength was adjusted by adding modified materials to the cement silicate grout. The modified materials were made of bentonite and quick-setting additives. The initial setting time of the modified cement silicate grout was tested. The data are shown in Table 2. In this project, the second group was selected for the modified cement grout at a mixing volume ratio of 3:1.

Table 2. Initial setting time of the modified cement silicate grout

| Mixing volume ratio | Initial setting time (s) |
|---------------------|--------------------------|
| 1:1                 | 170                      |
| 3:1                 | 78                       |
| 1:2                 | 306                      |
| 1:1                 | 216                      |
| 3:1                 | 63                       |
| 1:3                 | 720                      |
| 1:1                 | 157                      |
| 3:1                 | 51                       |
| 1:2                 | 240                      |
| 1:1                 | 170>1000                 |
| 3:1                 | 168                      |
| 1:1                 | 63                       |
4.4. Tunnel vault area

The tunnel vault was covered with a large amount of water-rich and strongly weathered strata, which were easily softened and significantly affected by groundwater. When the TBM started up, the formation was greatly disturbed and collapse was imminent. Thus, the overlying strongly weathered formation had to be grouted and reinforced. Cement-based quick-setting grouting materials or chemical grouting materials can be used in this area, both of which can meet the demand. The cement-based quick-setting grouting materials mainly include cement silicate grout and polymer-modified cement grout. These include a wide range of materials, are low in cost, non-toxic, and environmentally friendly, thus making them popular choices in various grouting projects[9]. Therefore, for the above-mentioned project, priority may be given to cement-based quick-setting grouting materials.

In comparison, polymer-modified cement grout is a new type of grouting material, which has been independently developed based on the principle of polymer modification. The material has the advantages of adjustable initial and final setting times, good diffusion control, anti-dispersion of moving water, and high early strength. It is also non-toxic and environmentally friendly.

| Table 3. Basic performance parameters of polymer-modified grouting materials |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Initial setting time     | Final setting time       | Compressive strength/MPa | Curing rate/%            |
| time                     | 1 h                     | 3 h                      | 28 d                     | 71–95                    |
| 45 s–30 min              | 2–45 min                | 0.5–1.1                  | 4.1–6.2                  | 18.2–20                  |

Grout solidification is a process in which the viscosity of the grout develops over time[10]. This reflects the diffusion movement of the grout in the formation. The changes in viscosities of the cement silicate grout and the polymer-modified cement grout in time were then tested. The rules are shown in Figure 3.

The viscosity change of cement silicate grout can be divided into three stages: low viscosity period, rising period, and curing period. The viscosity of the grout increases slowly, and the viscosity value is low during the initial stage of mixing. Then, the viscosity growth rate suddenly increases. After the initial setting, it continues to thicken until finally reaching the curing period.

![Figure 3. Viscosity change with time](image-url)
The change in viscosity of cement silicate grout indicates rapid solidification, and the time interval of the viscosity rising period is short, thus making it suitable for water blocking and reinforcement in a small range. Under the influence of grouting pressure, the grout quickly squeezes away the pore water and imposes an instantaneous load on the target stratum. However, a large amount of grout injection is not conducive to stratum stability when the bearing capacity of the target stratum is poor.

In comparison, the polymer-modified material has a viscosity stabilization period relative to the cement silicate grout. In this stage, the grout takes on a toothpaste-like consistency and can continue to diffuse and flow. Cement silicate grout has the characteristics of instantaneous solidification, such that the pressure will increase rapidly during the injection process. Thus, it is not suitable for controlling grouting pressure in the stratum. For the current project, the grouting was divided into two small sub-areas. The polymer-modified material was used in the area within 2 m from the TBM to avoid the impact of grouting pressure on the TBM equipment. The other areas have low demand for material performance; hence, the cheaper cement silicate grout can be used for the purposes of filling and strengthening.

5. Grouting effect evaluation

After the grouting construction was completed, the drilling core method was used to evaluate the grouting reinforcement effect. The drilling core is shown in Figure 8. Before grouting, core drilling was difficult, as the stratum consisted mainly of gravel, mud, and sand. After grouting, the core underwent discontinuous solidification, and the core rate reached 75%–85%. Thus, its strength met the requirements of TBM tunneling.

![Drilling core situation](figure4.png)

(a) before grouting (b) after grouting

**Figure 4.** Drilling core situation

After the grouting was completed, the staff entered the front of the cutter head through the manhole and the center knife part. There was no secondary collapse during the cleaning process. Furthermore, there was no obvious seepage water in the work area, and the grouting area near the cutter head reached the expected results. After the clean-up work was completed, the TBM proceeded smoothly, and no further secondary collapse occurred, thereby proving that other areas have achieved better reinforcement and that the overall stability met the requirements of TMB driving.

6. Conclusion

(1) During grouting reinforcement in the collapse area, especially at the ground surface, there was a risk of consolidating the cutter head and shield; thus, avoiding the adverse effects of grouting on TMB equipment was the key issue that must be resolved. The idea of zoning governance is reasonable, and engineering practice has proven that the selection of optimum grouting materials according to different regional needs can effectively reduce risks.

(2) For the shield area, a new high-expansion grouting material with low-strength was chosen. It can easily diffuse into the cutter head warehouse, preventing damage on the equipment, and consolidating the cutter head and shield. This material can isolate the shield from the subsequent grouting stone body, thus providing good conditions for subsequent grouting work.
(3) Low-strength cement silicate grout was selected for the cutter head area. Its setting time and strength were adjusted by adding modified materials to the cement silicate grout. This material can play a role in consolidation, while ensuring that the grouting does not produce catastrophic consequences.

(4) For the tunnel vault area, cement silicate grout and polymer-modified material were deemed suitable. The polymer-modified material has a viscosity stabilization period. It takes on a toothpaste-like consistency and can continue to diffuse and flow. Thus, it can avoid the sudden change of grouting pressure in the stratum, which is very important for grouting applications.

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