Numerical Analysis of Synchronous Grouting Pressure for a Large Diameter Subsea Shield Tunnel in Rock Stratum

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Abstract. Synchronous grouting can reduce the disturbance to the stratum and protect the tunnel structure to a certain extent. In this paper, we focus on how to determine the appropriate synchronous grouting pressure, based on a large diameter subsea shield tunnel in rock stratum in Shenzhen, China. The buoyancy of shield segment caused by synchronous grouting, the pressure distribution in grouting area, and the leakage of grouting slurry are analysed by numerical method. The results show that with the increase of synchronous grouting pressure, the leakage of slurry increases, but the buoyancy of segment decreases.

1. Introduction
The synchronous grouting layer, as the main filling material of shield tail gap (Huang, Li et al. 2017) and a barrier between the tunnel lining structure and the external water and soil environment (Ye, He et al. 2011), can reduce the impact of tunnel construction on the environment (Ye, ChangFei et al. 2014) and reduce the risk of tunnel leakage (Shi 2020). However, it is difficult to directly observe and monitor the synchronous grouting (Bezuijen, Talmon et al. 2008), which greatly increases the difficulty of research.

Based on the actual engineering applications, scholars study the composition, typical properties and application scope of grouting materials (He, Lai et al. 2020). Some scholars have carried out relevant research through experiments (W.Q, Chao et al. 2019). It is also a common analysis method used by scholars to establish theoretical model by simplifying conditions (Ye 2007, Fei, Huawei et al. 2019). Numerical method can analyse complex slurry flow behaviour, so it is favoured by scholars (Kasper and Meschke 2006, Michael, Dimitris et al. 2017, Chen, Meng et al. 2018, Liang, Zhaung et al. 2020)

However, most of the current studies are focused on the disturbance of synchronous grouting to surrounding rock (Li, Huang et al. 2017), while there are few studies on the diffusion and leakage of synchronous grouting slurry itself (Li, Ding et al. 2018, Shi 2020). And grouting pressure is a very important parameter and should be paid attention to (Ma, Peng et al. 2018, Zhou, Liu et al. 2020). In this paper, numerical analysis method is used to analyse the slurry diffusion mode, slurry leakage and the buoyancy of shield segments under different synchronous grouting pressure.

2. Project overview
Yueliangwan Avenue to Yanjiang Expressway Project is located in the west of Shenzhen, China. The project includes a large diameter shield tunnel with a length of 2063m. The shield excavation starts from the south bank (Mawan area) and ends at the north bank (Dachawan area), crossing a bay. The outer diameter of tunnel is 15m and the inner diameter is 13.7m. The thickness of the segment is 0.65m, the ring width is 2m, the concrete’s strength grade of the segment is C60, and the impermeability grade is P12. Figure 1 shows the engineering plan and cross section of the shield tunnel.

Figure 1. The project plan and the cross section of the shield tunnel.

Figure 2 shows the shield tunnel’s geological profile. The geomorphic units of the seabed where the tunnel is located are beaches and underwater slopes. The coasts on both sides are 4m~6m above sea level. The seabed elevation is -1.0m~ -7.8m, and the depth of sea water is greatly affected by the tide. The south navigation rout is close to Mawan port embankment, with a water depth of about 3.8~9.2m, the lowest sea bottom elevation of -7.8m. The north navigation rout is close to Dachanwan wharf embankment, with a water depth of about -5.6m. The lowest seabed elevation of the middle area is -4.0m. From top to bottom, the stratum is composed of filling, silt, sand, sandy clay, strongly weathered rock (mixed granite), and moderately weathered rock (mixed granite). The buried depth of the tunnel is about 9.96m~21.85m, mainly located in strongly or moderately weathered rock. The design maximum water pressure is 0.5MPa.
For the permeability coefficient \( (k) \), the Single Hole Pumping Test was adopted in the geological investigation stage. According to the type of groundwater and the type of pumping test, the calculation formula of the permeability coefficient of the single hole pumping test is used (MOHURD 2009). The recommended range of permeability coefficient of each rock and soil layers are showed in Table 1.

### Table 1. Recommended range of permeability coefficient of each rock and soil layer.

| Serial number | Stratum                  | Saturation weight \( (kN/m^3) \) | Permeability coefficient \( (m/d) \) | Permeability grade          |
|---------------|--------------------------|-----------------------------------|--------------------------------------|-----------------------------|
| 1             | Filling                  | 18.8                              | 5.0                                  | Moderately permeable        |
| 2             | Silt                     | 16.6                              | 0.001                                | Slightly permeable          |
| 3             | Sand                     | 20.6                              | 20.0                                 | Strongly permeable          |
| 4             | Sandy clay               | 18.2                              | 0.5                                  | Weakly permeable            |
| 5             | Strongly weathered rock  | 22.5                              | 5.0                                  | Moderately permeable        |
| 6             | Moderately weathered rock| 25.0                              | 0.3                                  | Weakly permeable            |

3. **Numerical model**

The outer diameters of segment, shield machine and cutter head are 15m, 15.42m and 15.53m respectively. The grouting clearance (the gap between the segment and surrounding rock) is 265mm. The tail shield of the large diameter shield is equipped with shield tail brush, slurry stop plate, shield tail clearance measuring device. Grouting, grease and other pipelines are arranged in the circumferential direction of the tail shield (Figure 3).

![Figure 3. Shield tail structure of the large diameter shield (unit: mm).](image-url)
According to the geological conditions of Mawan Tunnel, the section near the middle of the sea is selected for numerical calculation. The specific mileage stake is YK3 + 068.48 (Figure 2). There are two kinds of rock stratum interface within the tunnel height. The tunnel is mainly located in the moderately weathered granite stratum, and the strongly weathered granite intrudes into the tunnel vault about 2.8m. The sea water depth is about 6.2m, and the tunnel buried depth is about 26.5m. The water and soil pressure on the vault of the tunnel is about 6.2 * 10 + 26.5 * 19 = 565.5kPa. The shield machine is equipped with 8 grouting holes, which are arranged symmetrically along the vertical direction. The cross section of the grouting hole is a 50 mm square with a 25 mm semicircle on both sides. Because of symmetry, only half of the numerical model of synchronous grouting is selected for calculation. The size of the numerical model is 1:1 to the actual one, and the longitudinal length of the tunnel is 6m (equal to the length of the 3 ring segments) (Figure 4).

According to the surrounding rock boundary and permeability coefficient, the corresponding slurry seepage diffusion and pressure boundary conditions are set on the outer arc surface of the model (the interface between the grouting body and the surrounding rock); The inner arc surface of the model (the interface between the grouting body and the segment) is set as the impermeable boundary; The moving wall boundary is set at the end face of shield tail to simulate the propulsion of shield tail (Figure 4). The propulsion speed of the moving wall is 4.1667e-4 m/s calculated by constructing one ring segment about 80 minutes.

![Figure 4. Calculation section and numerical model](image)

In order to study the influence of different grouting pressures, three cases of grouting pressure are designed: In case 1, the grouting pressure is taken as the corresponding water and soil pressure at each grouting hole + 10kPa; In case 2, the grouting pressure is taken as the corresponding water and soil pressure x (1 + 5%) at each grouting hole; In case 3, the grouting pressure is taken as the corresponding water and soil pressure x (1 + 10%) at each grouting hole.

4. Results analysis

4.1. Synchronous grouting slurry diffusion

Through numerical calculation, the slurry diffusion trajectory (streamline) of Mawan synchronous grouting is obtained (Figure 5): (1) Due to the influence of gravity, the streamline inclines to the bottom along the longitudinal direction; (2) After the shield tail is pulled out, the slurry near the shield tail will flow along the tunnel in a circular direction to fill the shield tail gap; (3) From
Case 1 to Case 3, the grouting pressure increases gradually, and the slurry near the grouting hole changes from laminar diffusion form to whirling turbulent flow form.

4.2. Pressure distribution of synchronous grouting slurry

Figure 6 shows the pressure along the longitudinal distribution in the middle part of the contact surface between synchronous grouting slurry and surrounding rock: (1) Due to the negative pressure generated by the movement of shield tail, the pressure shows a slight upward trend near the tail in a short distance, which is most obvious in Case 1 with the lowest grouting pressure; (2) When the grouting pressure is high, the pressure distribution of slurry from Case 2 to Case 3 changes little, mainly because the boundary pressure condition is constant and the seepage velocity increases.

Figure 7 shows the pressure along the circumferential direction of the contact surface between synchronous grouting slurry and surrounding rock at the shield tail: (1) The data points near the grouting hole are dense, which shows that the pressure at the grouting hole fluctuates greatly. From the local enlarged drawing, it can be seen that the pressure at Case 2 and Case 3 fluctuates obviously; (2) The pressure changes slowly at the vault and bottom and sharply in the middle, which is closely related to the change rate of vertical height.

![Figure 5. Spread out drawing of slurry diffusion trajectory line (unit: m).](image)
4.3. Slurry leakage and buoyancy

The seepage volume of slurry can be calculated by integrating the seepage velocity of the interface between slurry and surrounding rock (Table 2): (1) Although the contact area between the slurry and the strongly weathered rock is smaller than that of the moderately weathered rock, the leakage is larger than that of the moderately weathered rock because of its larger permeability coefficient; (2) From condition 1 to condition 3, with the increase of grouting pressure, the amount of slurry leakage increases.

The buoyancy of each segment can be obtained by integrating the pressure on the interface between the slurry and the segment (Table 3): (1) From the first ring segment to the third ring along the longitudinal direction of the tunnel, the buoyancy of the single ring segment gradually decreases with the solidification of the slurry; (2) From Case 1 to Case 3, the buoyancy of single ring segment decreases with the increase of grouting pressure; (3) During synchronous grouting, due to the heavy slurry (about 15kN/m³), the buoyancy is much greater than that under the action of water pressure only.

| Leakage surface                                      | Leakage of slurry (m³/s) |
|-----------------------------------------------------|--------------------------|
|                                                     | Case 1 | Case 2 | Case 3 |
| Interface between slurry and strongly weathered rock | 7.67E-05 | 2.81E-04 | 3.22E-04 |
| Interface between slurry and moderately weathered rock | 1.33E-05 | 3.47E-05 | 3.88E-05 |

Table 3. Buoyancy of each ring segment.

| Cases | Buoyancy of each segment (kN) | Buoyancy of each segment in operation period |
|-------|--------------------------------|---------------------------------------------|
|       | First ring segment | Second ring segment | Third ring segment |                                    |
| Case 1 | 5306.4 | 5176.8 | 4864.4 |
| Case 2 | 5073.6 | 4972.0 | 4782.4 | 3534.3 |
| Case 3 | 5029.6 | 4932.8 | 4758.6 |

5. Conclusions

Based on a large diameter subsea shield tunnel project, this paper establishes a numerical model of synchronous grouting. The slurry diffusion law, pressure distribution, slurry leakage and buoyancy of segment under different grouting pressure are discussed. The main findings of this paper are as follows:
(1) As the grouting pressure increases (from Case 1 to Case 3), the flow pattern of slurry near the grouting holes changes from laminar diffusion form to whirling turbulent flow form. This shows that the greater the grouting pressure, the faster the slurry flow speed and the more complex the slurry flow pattern.

(2) During synchronous grouting, due to the heavy slurry (about 15kN/m$^3$), the buoyancy is much greater than that under the action of water pressure only. With the increase of synchronous grouting pressure, the leakage of slurry increases, but the buoyancy of segment decreases.

(3) In this paper, the tunnel surrounding rock is approximated as the boundary condition of pressure and leakage. While the mechanical properties of shield synchronous grouting slurry are complex and difficult to observe and measure directly. In future research, it is necessary to further compare and analyse with the actual situation, and then modify the numerical model.

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