Analysis of Construction Monitoring and Control of Tunnels Crossing Broken Faults and Water-rich Geology

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Abstract. In view of the poor geology such as tunnel engineering crossing faults or passing faults, the construction of surrounding rock and support is complicated. During construction, it is necessary to ensure the stability of the surrounding rock and support system, and ensure the timing of the secondary lining construction. For this reason, through the analysis and processing of monitoring data, the law of stratum change is mastered, and the supporting parameters and construction methods are adjusted and revised at the same time, so as to provide the best information for the tunnel surrounding rock and supporting lining construction.

Keywords: Broken Faults, Tunnel Construction, Monitoring and Control.

1. Project Overview

1.1 Project Overview Analysis
Xili Railway Station–Shigu Station of Shenzhen Metro Line 13 are located between Xili Railway Station and Baoshi Road Station in Nanshan District, Shenzhen. After this section of the line left Xili Railway Station, it went northward through Vanke Cloud City Project Department, Dashi 1st Road, and finally entered Shigu Station. The line mainly passes through urban roads and Vanke Cloud City planning plots. The section line structure is a single-layer three-span box structure and a single-hole single-line horseshoe-shaped tunnel. The length of the left line of the section is about 300 meters, the starting end of the left line (about 230 meters) is parallel to the stop line and the turn-back line, and 70 meters after the left line is the left line parallel to the stop line. The right line is about 300 meters long and laid separately. The strata crossing the section are strongly weathered granite (soily), strongly weathered granite (mass), moderately weathered granite, lightly weathered granite, strongly weathered fault breccia, and developed boulders. According to regional geological data, the underground section of the site passes through a structural fault. The strata that the cave body passes through are all rock layers. The rock masses around the fault are broken, joints and fissures are extremely developed, with good connectivity, and it is a water-rich zone of groundwater. When the tunnel is under construction, water inrush and water inrush are prone to occur.

1.2 Difficulties and Construction Methods
Tunnel engineering crossing faults or passing through faults and other bad geology will cause tunnel tunnel collapse, mud and water inrush, coal and gas outburst problems [1]. Moreover, the construction tunnel is located in a water-rich area, and measures must be taken to protect the groundwater from flowing by itself, prevent ground surface settlement, protect the underground ecological environment,
and unify the benefits of environmental protection, society and economy. The mileage of the left line (69.987 meters) is parallel to the left line and a wiring line, which is constructed by the mining method, and the lining structure is a single-hole double-line horseshoe-shaped structure. The right line tunnel is constructed by the mining method, and the structure is a single-hole single-line horseshoe-shaped tunnel (see the table 1).

| Table 1. Tunnel Construction Method |
|-------------------------------------|
| Section type | length | Surrounding rock grade | Section size (width * height) | Construction method |
| A-1          | 58     | III                  | 6.1*6.5                      | Step method        |
| A-2          | 201.485| IV/V                | 6.5*6.9                      | Circular step method |
| A-3          | 40     | V                    | 6.5*6.9                      | Circular step method |
| B            | 73.94  | III/IV/V             | 15.1*10.3                    | CRD method         |

1.3 Construction Monitoring Purpose
During the construction of a tunnel crossing a water-rich fault, the geological conditions are complex and changeable, and the interaction between the surrounding rock and the support will cause safety accidents such as deformation, fracture, collapse, and collapse; therefore, the deformation and pressure of the surrounding rock must be monitored and verified Construction effect of supporting lining. Through the analysis and processing of monitoring data, and mastering the law of stratum stability changes, the supporting parameters and construction methods can be adjusted and revised to ensure the ultimate safety and stability of surrounding rock and supporting lining [3].

2. Key Points of Monitoring and Control of Tunnel Construction

2.1 Layout of Monitoring Points

![Monitoring Point Layout Plan](image)

Figure 1. Monitoring Point Layout Plan

In the case project, the fault fracture zone of the tunnel was constructed by the three-bench micro bench method, and the full-section curtain grouting support was used for the advance pre-support [5]. On the A section of the main fault zone and the B section of the fault-affected zone, the bolt axial force, the initial supporting surrounding rock pressure, the initial supporting concrete stress, the secondary lining contact pressure, and the secondary lining concrete stress were monitored and measured respectively. The measurement points were arranged at intervals of 11 meters along the longitudinal direction of the fault zone, and the initial support vault subsidence, horizontal convergence and secondary lining convergence were measured (see the figure 1).
2.2 Main Monitoring and Control Projects

Table 2. Main Items of Monitoring and Control

| Serial number | Monitoring items         | Test methods and instruments       | Test accuracy |
|---------------|--------------------------|-----------------------------------|---------------|
| 1             | Vault sinking            | Leveling method, level, steel ruler | 0.09mm        |
| 2             | Horizontal convergence   | Tunnel clearance change definition | 0.09mm        |
| 3             | Axial force of anchor rod| Mechanical force measuring anchor  |               |
| 4             | Surrounding rock pressure| Pressure cell                      |               |
| 5             | Contact force pressure of secondary masonry | Concrete strain gauge |               |
| 6             | Secondary lining concrete stress | Concrete strain gauge |               |

2.3 Monitoring Control Frequency and Deformation Rate

Table 3. Monitoring Control Frequency and Deformation Rate (Note: d is the width of tunnel excavation)

| Serial number | Monitoring frequency | Deformation displacement speed (mm/d) |
|---------------|----------------------|--------------------------------------|
| 1             | 3 Times/d            | 6                                    |
| 2             | 2 Times/d            | 1~6                                  |
| 3             | 2 Times/3~4d         | 0.6~1.1                              |
| 4             | 2 Times/4d≥          | 0.3~0.6                              |
| 5             | 1 Times/6d           | <0.3                                 |

3. Analysis and Results of Tunnel Construction Monitoring and Control

3.1 Displacement Monitoring Analysis

The purpose of displacement monitoring is the most intuitive reflection of the changes in the stress form of surrounding rock and support, which can provide reliable and direct information for the stability of underground caverns, and is easy to measure [2].

Displacement measurement items include initial support level convergence, vault subsidence, and secondary lining convergence measurement. The initial support displacement is measured at a distance of 11 meters, and the measurement period is from after sprayed concrete to before the secondary lining [9].

Monitoring data of section displacement (see the table 4 and figure 2).

Table 4. Monitoring Data of Section A and B Section Displacement

| Section | Monitoring items         | Maximum deformation rate/mm | Cumulative deformation/mm |
|---------|--------------------------|----------------------------|--------------------------|
| A       | Vault sinking            | 1.5                        | 13.82                    |
|         | Convergence of the upper survey line level | 1.185                   | 7.1                      |
|         | Convergence of the lower line level | 1.332                    | 9.35                     |
| B       | Vault sinking            | 1.5                        | 9.42                     |
|         | Convergence of the upper survey line level | 0.912                    | 6.85                     |
|         | Convergence of the lower line level | 1.24                     | 7.221                    |
Displacement monitoring results show that from the analysis of table 4 and figure 2, it can be seen that the distance between the second lining convergence measurement section before and after the fault zone is also 11 meters, which is close to the injection length of a lining trolley. The monitoring period is from the second lining to convergence and stability. The initial support displacement value loses the displacement before the shotcrete and the displacement after the secondary lining. The measured clearance displacement is the largest at the vault. The greater convergence during invert excavation indicates that the excavation procedures after the measurement points are buried have a greater impact on the displacement. When the invert is closed, the displacement accounts for more than 75% of the measured displacement, and the measured secondary lining convergence is less than 3.8mm.

3.2 Anchor Bolt Axial Force Monitoring Analysis
The purpose of anchor bolt axial force monitoring is to understand the force state and axial force of the bolt, judge the development trend of surrounding rock deformation, roughly judge the boundary of the strength decrease area of the surrounding rock, evaluate the supporting effect of the bolt, and determine the parameters of the bolt rationality [11].

Axial force monitoring of the anchor rod, 5 measuring anchor rods are set for each measurement section, the anchor rod is 3.5 meters long, and each has 4 measuring points (see the figure 3 and 4).
From the analysis of the monitoring results, it can be seen from figure 3 and 4 that the measured anchor rod is mainly subjected to tensile force. The maximum tensile force reaches 15.6kN. The maximum tensile force of the anchor rod occurs at 2.1-2.7 meters (section A) and 1.4-2.1 meters (section B). The surrounding rock deformation is within a reasonable limit, the supporting effect is good, and the bolt design parameters are reasonable.

3.3 Analysis of Supporting Pressure
Support pressure purpose. Supporting pressure includes the initial support surrounding rock pressure and the secondary lining contact pressure. Support pressure measurement, understand the forces and working conditions of the initial support and the secondary lining, check the rationality of the design of the initial support and the secondary lining, judge the reliability and safety of the support structure, and also provides reliable information for judging the stability of the tunnel [10].

The results of support pressure analysis show that the design is reasonable, safe and reliable (see the figure 5 and 6).

Figure 4. B-Section Anchor Axial Force Monitoring Design

Figure 5. The Pressure Diagram of the Surrounding Rock at the Initial Stage of the Arch of A Section
3.4 Support Stress Analysis
Support stress purpose. The supporting stress includes the initial supporting concrete stress and the secondary lining concrete stress. The support should be tested by force measurement to understand the deformation characteristics and stress state of the support structure, grasp the magnitude of the stress on the support structure, judge its stability and safety, and check the rationality of the support structure design [9].

The support stress analysis result can be seen from figure 7, the support stress is less than 0.7MPa, the support state is stable, and the support structure design is reasonable. The supporting stress did not exceed the ultimate strength of the material. The initial supporting stress fluctuated greatly during the excavation of the lower step and the invert, and gradually stabilized after the second lining was constructed [6].

4. Monitoring Data Analysis and Processing
4.1 Analysis of the Influence of Construction Steps on Initial Support Compressive Stress and Displacement
The initial support pressure and stress measurement points are buried before the shotcrete, and the displacement measurement points are buried after the shotcrete. The measurement results show that the middle and lower steps and the excavation of the inverted arch have a certain impact on the initial

Figure 6. Time Curve Diagram of Contact Pressure of Secondary Lining of Section B

Figure 7. The Stress Diagram of the Initial Supporting Concrete of the Left Arch of the A Section Design
support pressure, stress and displacement, that is, the pressure, stress and displacement time curve has large fluctuations in the initial stage, and the invert is closed. And after the second lining is applied, it gradually stabilizes.

The excavation process after burying the measuring points disturbed the upper steel frame and shotcrete, causing fluctuations in supporting pressure and stress. Give full play to the role of the initial support steel frame and shotcrete to reduce the influence of the excavation disturbance at the lower part of the tunnel on the upper initial support. The construction parameters such as the length and height of the steps and the width of the lower horse mouth excavation can be appropriately adjusted to ensure the lower opening. The excavation is safe and the tunnel is stable [12]. During the construction of the secondary lining, the pressure and stress of each measuring point accounted for more than 80% of the final measured value. This shows that the initial support force is fast, the initial deformation is large, and the stability time is short. The second step should be strengthened. The pressure, stress and displacement before the secondary lining are monitored, and the invert is implemented in time.

4.2 Displacement along the Longitudinal Direction of the Tunnel

This section is located in the fault fracture zone, the surrounding rock is broken, the stability is poor, and the deformation is large. In order to ensure the stability of the tunnel, the secondary lining was not constructed in accordance with the 0.2mm/d requirement during the construction process. Therefore, in the displacement measurement, not only the displacement of the initial support was measured, but also the displacement of the secondary lining was measured. Long-term monitoring was also carried out (see the figure 8,9 and table 5) [4].

**Table 5. Average of Measured Displacements**

| Section                | Vault sinking | Arch foot level convergence | Wall waist level convergence | Secondary lining convergence |
|------------------------|---------------|------------------------------|------------------------------|------------------------------|
| Main fault zone        | 9.15          | 5.277                        | 5.816                        | 3.330                        |
| Fault affected zone    | 8.24          | 4.765                        | 5.163                        | 2.200                        |

**Figure 8. Initial Support Displacement Diagram**
The result analysis can be seen from Figure 8, the final value of the initial support displacement is distributed along the longitudinal direction of the tunnel. The maximum wall waist level converges to 7.652 mm, the maximum arch toe level converges to 9.352 mm, and the maximum vault sinking is 13.9 mm. It can be seen from Figure 9 that the final measurement of the displacement of the secondary lining is distributed along the longitudinal direction of the tunnel. It can be seen from table 5 and figure 8 that the displacement value of the fault zone is significantly larger than that of the adjacent section, and the displacement value of the main fault zone is significantly larger than the fault-affected zone. Therefore, different support parameters of different sections are used in the design.

5. Analysis and Prediction of Final Value by Fitting Curve Method

5.1 Purpose and Significance
The ability to predict the final value of each measurement item (including displacement, pressure, stress, etc.) as early as possible will be of great significance for guiding design and construction. The method of fitting the curve is simple and easy to implement, as long as the curve form is suitable, it is sufficient to meet the engineering needs [8].

5.2 Data Analysis of Fitting Curve Method
As shown in table 6, the fitting effects of the measured data are all good, and the correlation coefficients are all above 0.90.

| Section | Monitoring items | Maximum deformation rate/mm | Cumulative deformation/mm | Regression curve | Correlation coefficient R² |
|---------|------------------|-----------------------------|--------------------------|-----------------|---------------------------|
| A       | Vault sinking    | 1.5                         | 13.82                    | $U=13.254ecp(-3.254/t)$ | 0.92                      |
|         | Convergence of the upper survey line level | 1.185                     | 7.1                      | $U=7.421ecp(-3.145/t)$ | 0.934                     |
|         | Convergence of the lower line level   | 1.332                     | 9.35                     | $U=15.685ecp(-11.245/t)$ | 0.984                     |
| B       | Vault sinking    | 1.5                         | 9.42                     | $U=11.254ecp(-3.214/t)$ | 0.9                      |
### 5.3 Analysis of the Relative Development Trend of Supporting Pressure and Stress Monitoring Items

The tunnel construction effect is the result of multiple factors. After the tunnel was excavated, the initial ground stress was continuously released and deformed. After the initial support and the secondary lining are constructed, the initial support and the secondary lining interact with the surrounding rock, and the support pressure, stress and displacement are constantly changing during the interaction. Many factors in the construction process will have an impact on the size and development of these measurement items [7]. The relationship between the relative development trend of multi-measurement items of section A is obtained by dimensionless support pressure and stress (see the figure 10). It can be seen that the initial support pressure and stress develop faster, and the secondary lining pressure and stress develop slowly. In the initial support measurement project, the support pressure is faster than the support stress.

![Figure 10. The Relative Development Trend Chart of Supporting Pressure and Stress](image)

The analysis results show that the initial support force is fast and the stabilization time is short, and the secondary lining force is slower and the stabilization time is long. The development of concrete stress lags behind the support pressure, and the increase of the support pressure leads to the increase of the stress. During construction, the support stiffness and setting time should be adjusted in time according to the characteristics of the support.

### 6. Summary Discussion

Tunnels in the fault fracture zone are more deformed than ordinary tunnels in surrounding rock sections, with a larger initial deformation rate, longer deformation time, and greater surrounding rock pressure. The construction of the secondary lining does not need to be restricted by the specification. If the specification value is applied, the construction time of the secondary lining will be delayed, making the deformation difficult to control and even causing a collapse. It is very uneconomical to take measures to increase the stiffness of the initial support to reduce the deformation. It is feasible and safe for the large deformation tunnel to construct the secondary lining earlier to bear part of the load caused by the insufficient initial support.

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