Optimization of the construction sequence of the expanding excavation around Tunnel

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Abstract. With the background of the construction of the Loushan Tunnel, Flac3D software was used to simulate three different expanding excavation sequence schemes. The simulation results were compared and selected, and it determined that Scheme 3 is the best scheme. In the construction site, tunnel vault settlement and convergence were measured and compared with the simulation results. Conclusions are as follows: ①The final vertical displacement of Scheme 1 was greater than that of Scheme 2 and Scheme 3. In scheme 2, the horizontal displacement of the middle-upper part of the tunnel increased sharply after the excavation of the upper-right part. The maximum bending moment of the supporting structure of Scheme 3 was smaller than that of the other two schemes. In addition, the maximum bending moment in the whole process of expanding excavation transited smoothly, and it fluctuated the most in Scheme 2; ②When the upper-left part is expanded, the vertical displacement and bending moment of the supporting structure of the three schemes all increase greatly. In the actual construction, the most unfavorable factor is that the settlement detection value of the vault increases rapidly after the expanding excavation of the upper-left part; ③The construction sequence adopts Scheme 3, the settlement value & convergence value becomes more and more stable about 7 after excavation, the accumulated settlement value is 17.146mm, and the accumulated convergence value is 14.512mm. The field data is close to the simulated data, no accidents occur in the construction process, and no abnormal phenomena are found in the monitoring and measurement process.

1. Introduction
With the development of city, the traffic pressure is growing, the transformation of existing traffic lines is also becoming mature [1-3]. When the existing tunnels are continuously supplied and used, the demand for tunnel section expansion is increasing day by day [4-6]. At present, due to the high cost, long construction period, and the need to carry out traffic control for a long time, the tunnel section expansion method is often faced with many challenges and difficulties [7, 8].

2. Project profile
Loushan tunnel is located in Loushan Village, Wenling, which is the main traffic artery from Taizhou to Wenling, the traffic flow is large. In order to ensure the traffic, the site construction implements the scheme of one tunnel reconstruction, another tunnel to maintain the traffic. It is required to ensure the safety of the passage tunnel during the construction operation.
The net cross section of the existing tunnel is 10.25×5m² and the minimum distance between the two sections is 29.35m. The net section of the tunnel after the reconstruction and expansion is 17.25×5m², and the minimum distance between the two sections is 25.31m. The maximum burial depth of Loushan Tunnel is 120m, and six parts divided with double straight walls supporting are used for expanding excavation. The three schemes of the construction sequence in tunnel expanding excavation are shown in figure 1. In this paper, Flac3D software is used to simulate the three schemes respectively. The displacement of surrounding rock and bending moment of supporting structure during excavation expansion are mainly investigated. Comprehensively determine the optimal construction sequence of excavation expansion.

![Scheme.1](image1)
![Scheme.2](image2)
![Scheme.3](image3)

**Figure 1. Three tunnel schemes of expanding excavation sequence**

### 3. Numerical simulation of three schemes of the construction sequence in tunnel expanding excavation

#### 3.1 Calculation modeling
The model takes the transverse direction of the tunnel as the X-axis, the axial direction as the Y-axis, the longitudinal direction as Z-axis. The calculation accuracy and efficiency are taken into account comprehensively, and the influence of axial direction is not considered. The unit length of y-direction is 1m. In the x-direction, the calculation model takes 60m from the axis of the tunnel to the negative direction of the X-axis, and 60m from the positive direction of the X-axis. In the Z direction, the calculation model takes 60m from the tunnel axis to the negative direction of the Z axis and 120m from the positive direction of the Z axis. Model the three schemes as shown in Figure 1, the modeling is shown in figure 2 and figure 3. The lower part of the existing tunnel needs to be filled with soil for reinforcement during excavation. After each excavation, I25 I-beam steel and shotcrete are used as the double straight walls supporting and primary branch. These are simulated by shell unit in the model, as shown in figure 4.

![Figure 2. Numerical model](image4)
![Figure 3. Grid details of working face](image5)
![Figure 4. Schematic diagram of double straight wall support](image6)
3.2 Material parameters
Mohr-coulomb model was used for soil material model. During excavation, each part of soil is re-assigned to a null model. The initial branch of double straight walls is the shell unit. The value of each material parameter is shown in table 1.

| Materials  | Density (kg/m³) | Poisson | Elasticity modulus (GPa) | Shear modulus (MPa) | Young modulus (GPa) | Thickness (m) |
|------------|----------------|---------|--------------------------|---------------------|---------------------|---------------|
| Rock       | 2680           | 0.22    | 6.21                     | 22                  | —                   | —             |
| Support    | 3110           | 0.25    | —                        | —                   | 21                  | 0.2           |

4. Analysis of calculation results

4.1 Tunnel deformation analysis
Taking Scheme 1 as an example, Figure 5 shows the vertical displacement change of one expanding excavation cycle. The vault settlement curves of the three schemes during expanding excavation are shown in Figure 6.

It can be got from Figure 6: ①In Scheme 1, when the first two parts of the tunnel are excavated, the settlement of the vault is about -2mm. When the upper-left part is excavated, the settlement of the vault increases sharply. ②In Scheme 2, the vault settlement reached -8.69mm when excavating Step.I (upper-left part), and the vault settlement increased steadily in the subsequent construction. ③In Scheme 3, the expanding excavation of Step.II (upper-left part) causes a large increase in the settlement of the vault, and the vault settlement is greater than the other two schemes after the subsequent construction.

It can be got from Figure 7: ①The maximum horizontal displacement of Scheme 1 and Scheme 3 in the construction process is roughly equal to each other; ②When the maximum horizontal displacement of Scheme 2 is in Step.III and Step.IV, it is much larger than the other two schemes. As shown in Figure 8, after the completion of the Step.II of Scheme 2, the maximum horizontal displacement appears in the middle-upper part of the soil, which is of great risk; ③After the completion of excavation, the position and size of the maximum horizontal displacement are distributed symmetrically according to the axis of the tunnel. Obviously, the excavation of the upper-left part is an important factor causing the instability of the tunnel. Compared with Scheme 1, Scheme 3 can transfer the instability caused by the excavation of the upper-left part more smoothly in the implementation process, while Scheme 2 has greater risks in the construction process.
4.2 Moment analysis of supporting structure

The variation process and maximum value of support bending moment in all six steps of the three schemes are compared, as shown in table 2 and figure 9.

By comparing the supporting moment of the three schemes in the process of excavation expansion and combining with the above analysis results of tunnel deformation, the following conclusions can be drawn: ① In the whole process of excavation expansion, the maximum support bending moment generally appears in the newly excavated working section. And the maximum support bending moment is located near the maximum displacement point of the tunnel after excavation expansion; ② In all three schemes, after the tunnel section is fully expanded, the maximum bending moment value is approximately equal, and all appear in the arch feet on both sides, and the bending moment of the supporting structure is symmetrical and equal; ③ In the process of excavation expansion of three schemes, the maximum bending moment of Scheme.3 is smaller than the other two schemes, and it transits smoothly in the whole process of expanding excavation. The maximum bending moment was fluctuant in Scheme.2. When three schemes in the expanding excavation to the upper-left part and the upper-right part, the supporting moment is at its peak. Therefore, construction monitoring and early warning should be strengthened.

4.3 Summary

Through the comparison of the above simulation results, it is not difficult to find the following rules:

① The results of the three schemes are the same. After the completion of one expanding excavation cycle, the tunnel vault settlement of Scheme.1 and Scheme.2 is basically the same, and the tunnel vault settlement of Scheme.3 is higher. The distribution law of supporting moment is basically the same. However, the maximum horizontal displacement of the middle-upper part in Scheme.2 is much larger than that of the other two schemes at Step.III and Step.IV, where is a greater risk.
In the three schemes, the tunnel vault settlement increases significantly in the upper-left part of the expanding excavation, the supporting bending moment also reaches its peak when the upper-left part and upper-right part are expanded. Therefore, the excavation on the upper-left and the upper-right are key excavation steps, and construction monitoring and early warning should be strengthened.

In the process of a single cycle expanding excavation, Scheme 3 compared with the other two schemes, the maximum value of the tunnel displacement and support bending moment fluctuates less, and the maximum value of the horizontal displacement and support bending moment of the tunnel is smaller than that of the other two schemes. Therefore, Scheme 3 can ensure safety in actual construction.

Table 2. Comparison of supporting moment in the process of excavation expansion of three scheme

| Step | Scheme 1 | Scheme 2 | Scheme 3 | Step | Scheme 1 | Scheme 2 | Scheme 3 |
|------|----------|----------|----------|------|----------|----------|----------|
| I    | ![Diagram](image1) | ![Diagram](image2) | ![Diagram](image3) | IV   | ![Diagram](image4) | ![Diagram](image5) | ![Diagram](image6) |
| II   | ![Diagram](image7) | ![Diagram](image8) | ![Diagram](image9) | V    | ![Diagram](image10) | ![Diagram](image11) | ![Diagram](image12) |
| III  | ![Diagram](image13) | ![Diagram](image14) | ![Diagram](image15) | VI   | ![Diagram](image16) | ![Diagram](image17) | ![Diagram](image18) |

5. Field monitoring
The vault settlement and the haunch convergence were measured at the site. Since the tunnel section is divided, the measurement is conducted in sections when measuring the haunch converges. The schematic diagram of the measurement point placement is shown in figure 10. By superimposing three convergence values of monitoring points 1-2 & 3-4 & 5-6, the convergence value of tunnel haunch can be obtained. No.YK19+880 was selected at the construction site for comparison with the simulation analysis. On March 24, 2018, No.YK19+880 middle-upper part expanding excavation with support were completed, and the first vault settlement measurement was completed at the installation monitoring site on the same day. The upper left section was excavated on March 28, followed by two working days for each step, and one section was expanded on April 6. The arch settlement and haunch convergence curves can be analyzed as shown in figure 11.

- The settlement of the vault and the convergence of the haunch increased rapidly after the excavation in the middle-upper part. The expanding expansion of the middle-upper part of the tunnel led to the damage of the lining structure of the tunnel and the increase of the deformation of the tunnel.
- After the expanding excavation of the upper-left part, the settlement value and convergence value of construction site monitoring increase greatly. Through numerical simulation analysis, it is found that the expanding excavation at the upper-left part will lead to a significant increase in tunnel vault settlement. The monitoring data of field subsidence value is close to the simulation results.
- Haunch convergence data was provided by monitoring point 3-4 before March 28. After that, due to the excavation of the upper-left part, the monitoring data of haunch convergence was
superimposed by monitoring points 1-2 & 3-4. Therefore, the convergence value was increased by double after the upper-left excavation on 29th.

- The settlement value and convergence value become more and more stable about 7 after the completion of expanding excavation, with the cumulative settlement value 17.146mm and the cumulative convergence value 14.512mm. In the numerical simulation study, the maximum settlement occurred at the vault, with a cumulative settlement of 14.490mm and a convergence value of -12.684mm at the haunch. The field data is close to the simulated data, no accidents occur in the construction process, and no abnormal phenomena are found in the monitoring and measurement process.

6. Conclusions

The final vertical displacement of Scheme 1 was greater than that of Scheme 2 & 3. In Scheme 2, the horizontal displacement of the middle-upper part of the tunnel increased sharply after the excavation of the upper-right part. The maximum bending moment of the supporting structure of Scheme 3 was smaller than that of the other two schemes. In addition, the maximum bending moment in the whole process of expanding excavation transited smoothly, and it fluctuated the most in Scheme 2.

When the upper-left part is expanded, the vertical displacement and bending moment of the supporting structure of the three schemes all increase greatly. In the actual construction, the most unfavorable factor is that the settlement detection value of the vault increases rapidly after the expanding excavation of the upper-left part.

The construction sequence adopts Scheme 3, the settlement value & convergence value becomes more and more stable about 7 after excavation, the accumulated settlement value is 17.146mm, and the accumulated convergence value is 14.512mm. The field data is close to the simulated data, no accidents occur in the construction process, and no abnormal phenomena are found in the monitoring and measurement process.

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