Study on the supporting time of the secondary lining of the highway tunnel with weak surrounding rock

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Abstract. Based on the Dongxiu tunnel project of Liyu highway under construction in Guangxi province of China, this paper attempts to study the supporting time of the secondary lining of the highway tunnel with weak surrounding rocks. Firstly, the measurement data of typical section of the tunnel is fitted and used to reveal the evolution law of the settlement of the tunnel vault and peripheral convergence of the sidewall. Then the three-dimensional simulation is carried out to verify the rationality of the evolution law. After that, the supporting time of the secondary lining is determined relying on the results of field monitoring and numerical simulation. The results show that, both the settlement of the tunnel vault and the peripheral convergence for the Dongxiu tunnel can be characterized by exponential function, and it is reasonable to construct the secondary lining at 24th-25th day after excavation. The results can not only guide the subsequent construction on site but also provide reference for the determination of supporting time of the secondary lining of similar tunnel projects.

1. Introduction

With the continuing development of the highway tunnel engineering, the construction technology of the highway tunnel is becoming more and more mature, especially for the tunnel with the weak surrounding rock. Among these construction technologies, the New Austrian Tunnelling Method (NATM) is most commonly used[1-3]. This method emphasizes the combination of rock support and monitoring measurement. The core of NATM is to protect the surrounding rock and make the best use of its self-supporting capability. How does it make full use of the self-supporting capability of the surrounding rock while preventing its continuous deterioration? The determination of reasonable supporting time of the secondary lining is particularly critical.

Many researches have been carried out for this problem in the past decades. Sulem et al. put forward the convergence restriction method which pointed out that the supporting time of the secondary lining can be back deduced by analysing the final deformation of the surrounding rock in 1987[4]. Xie et al. considered the creep damage theory and obtain the reasonable supporting time of the secondary lining on the basis of the creep property of weak rock[5]. Liu et al. proposed that the ultimate displacement in theory, intraday displacement and accumulative displacement obtained from in-situ monitoring could be used as the index to determine the supporting time of the secondary lining of the tunnel with large deformation[6]. Wang et al. determined the rheological parameter of surrounding rock by the analysing the theoretical deformation formula of primary lining and the fitting formula of the measured data.
Combined with the related specifications, it can be used to determine the supporting time of the secondary lining[7]. Wu et al conducted deep works on the determination of the supporting time of the secondary lining in the tunnel with large span through in-situ monitoring, similitude model tests, numerical simulation and theoretic analysis, and the principle of minimum support resistance was proposed to determine the optimal supporting time accordingly[8]. The specifications for design of highway tunnels pointed out that it is suitable to conduct the secondary concrete lining when the deformation ratio of the surrounding rock is less than 0.2 mm/day from a series of engineering practice experience[9]. The determination of the reasonable supporting time of the secondary lining has always been a key point in the tunnel project.

Based on the Dongxiu tunnel project of Liyu highway engineering under construction in Guangxi province of China, the supporting time of secondary lining is studied and optimized in this paper by in-situ monitoring and numerical simulation analysis. Firstly, the measurement data of typical section of the tunnel was described by the statistical analysis, so as to reveal the temporal evolution law of the deformation of surrounding rock induced by excavation activity. Meanwhile, the three-dimensional simulation was carried out. Finally, the supporting time of the secondary lining for the tunnel is determined through the combination of the in-situ monitoring and numerical simulation results. This research can provide reference for determining the supporting time of the secondary lining of tunnel under the similar engineering conditions.

2. Temporal law of the measured deformation of surrounding rock

2.1. Engineering background

Dongxiu Tunnel (see Fig.1) is a two-way four-lane tunnel with a net height of 5.0m and a net width of 11.0m, located in the Xinyu town of Mengshan, Guangxi Province. According to regional geological data, the quaternary residual slope at the entrance and exit of the tunnel is thick. The classification of surrounding rock near the tunnel exit is divided into Ⅴ-level, and the surrounding rock of tunnel body is divided into Ⅲ~Ⅳ level. Due to the poor stability of rock mass in structural fracture zone and bedrock fracture zone, the surrounding rock classification is reduced accordingly. The surrounding rock is mainly composed of semi-hard or soft clastic rock, and the bedrock is weathered and broken seriously. Some tunnels have unfavorable interlayers such as structural fracture zone and bedrock fracture zone, which is bad for the stability of the tunnel and easy to cause local instability of surrounding rock during construction, such as fall-block, collapse and water inrush disaster (see Fig.2).

2.2. Excavation and support methods

The tunnel is excavated by using the upper and lower two-step method as shown in Fig.3, and the designed single-time excavation footage along the tunnel axis is 2m. After the initial support of the upper section, the lower half section is excavated. Smooth blasting or pre-split blasting is adopted to minimize the disturbance and damage to the surrounding rock. For each excavation step, shotcrete, anchor rod and steel arch are applied successively. Under the condition that the initial support is stable, the bolt and reinforcement outcropping should be cleaned, and the shotcrete should be added to make
the surface flat and smooth, then the waterproof plate is laid. Finally, the C30 concrete is molded in the whole section.

Figure 3. The excavation diagram of Dongxiu tunnel.

2.3. Regression analysis of monitoring data
In the excavation process of tunnel engineering, in-situ monitoring on the rock deformation has become an important means for investigating the dynamic state of surrounding rock and structure, optimizing support parameters and ensuring construction safety\cite{10-12}. To study the stability of Dongxiu tunnel during construction and verify the feasibility of construction scheme, the monitoring sections in the tunnel section from chainage ZK34+310 to ZK34+380 which has typical weak rock mass are chosen to reveal the settlement of the tunnel vault and peripheral convergence of the sidewall.

2.3.1 Analysis to settlement of the tunnel vault. Via statistical analysis, the regression analysis curve of the accumulated settlement of the vault on the section ZK34+330 of the tunnel is shown in Fig.4. The BoxLucasII function (see Eq.1) in the index function category is found to be the most appropriate one to describe the temporal evolution law of the cumulative settlement value of tunnel arch over time through screening and analysis. As shown in Figure 4, in the early stage after the excavation, the subsidence rate of tunnel vault increases continuously and fluctuates greatly. This is due to mechanical excavation and blasting on the surrounding rock has a large disturbance and initial support to constrain the deformation of surrounding rock has hysteresis. When the upper bench is excavated, the settlement velocity of the vault is relatively large, which is about 0.2-0.5 mm/d. The settlement velocity gradually slows down after the excavation of this part. As the distance between the monitoring section to the tunnel face sections become farther and farther, the growth rate of the accumulated settlement curve first increases sharply, and then gradually slows down until it tends to be stable. According to the fitting formula, when X tends to infinity, that is, when the excavation date is infinite, the cumulative maximum of the vault settlement is about 7.04mm. After 23 days of the excavation of ZK34+330 section, the settlement rate of vault is less than 0.2 mm/d, which meets the requirements of secondary lining in the specification. At this time, the settlement of vault is 5.72mm, and the distance between the tunnel face and the monitoring section is about 46m. Similarly, the analysis results of the vault settlement of the whole three monitoring in the concerned tunnel section from chainage ZK34+310 to ZK34+380 are shown in Table 1.

Figure 4. The temporal evolution curve of the accumulated settlement of the vault on section ZK34+330 of the tunnel.
\[ y = a \cdot (1 - e^{-bx}) \]  

(1)

Table 1. Analysis results of the settlement of the tunnel vault on the monitoring sections.

| Monitoring Section | Accumulated peripheral convergence/mm | Maximum cumulative peripheral convergence/mm | Distance from the monitoring section to the tunnel face/m | Supporting timing of secondary lining/d |
|-------------------|--------------------------------------|---------------------------------------------|--------------------------------------------------------|---------------------------------------|
| ZK34+330          | 6.14                                 | 7.63                                        | 48                                                     | 23                                    |
| ZK34+350          | 6.55                                 | 8.01                                        | 50                                                     | 25                                    |
| ZK34+370          | 6.37                                 | 7.42                                        | 48                                                     | 24                                    |

2.3.2 Analysis to peripheral convergence of the tunnel sidewall. The regression analysis curve of the accumulated peripheral convergence on section ZK34+330 of the tunnel is shown in Fig.5, and the temporal evolution law of the accumulated peripheral convergence around tunnel over time can also be described by the BoxLucas1 function. It can be seen that the peripheral convergence rate increases rapidly and fluctuates greatly in the early stage of excavation, which is the same as the growth of vault subsidence rate. It is also due to excavation and blasting disturbance and the initial support has not yet been applied timely. As the distance between the tunnel face and the measurement section becomes farther and farther, the growth rate of cumulative curve of peripheral convergence first increased sharply, and then slowed down gradually until it tended to be stable. According to the fitting formula, when X approaches infinity, that is, when the excavation date is infinite, the cumulative maximum of peripheral convergence is about 7.63mm. After 24 days of the excavation of ZK34+330 section, peripheral convergence rate began to be less than 0.2mm/d, in line with the secondary lining construction requirements in the specification. At this time, the peripheral convergence accumulated to 6.14mm, and the distance between the tunnel face and the section was 48m. Similarly, the construction time of the secondary lining of ZK34+350 and ZK34+370 sections can be obtained. The analysis results of the peripheral convergence around the three sections are shown in Table 2.

Figure 5. The temporal evolution curve of the accumulated peripheral convergence of the tunnel sidewall on section ZK34+330 of the tunnel.

Table 2 Analysis result of the peripheral convergence of sidewall at the monitoring sections

| Monitoring Section | Accumulated peripheral convergence/mm | Maximum cumulative peripheral convergence/mm | Distance from the monitoring section to the tunnel face/m | Construction timing of the secondary lining/d |
|-------------------|--------------------------------------|---------------------------------------------|--------------------------------------------------------|---------------------------------------|
| ZK34+330          | 6.14                                 | 7.63                                        | 48                                                     | 23                                    |
| ZK34+350          | 6.55                                 | 8.01                                        | 50                                                     | 25                                    |
| ZK34+370          | 6.37                                 | 7.42                                        | 48                                                     | 24                                    |
From above temporal evolution law of both settlement of the tunnel vault and the peripheral convergence of sidewall, it can be seen that, the supporting time of the secondary lining for the concerned tunnel can be determined as 23th-25th days after excavation.

3. Numerical simulation of the supporting time optimization

3.1. Establishment of the numerical model
Numerical simulation is an important means of geotechnical engineering research, which is often used in the prediction and stability analysis of tunnel surrounding rock excavation response. To verify the evolution law of vault settlement and peripheral convergence obtained above, the FLAC3D software[13] is used to carry out the simulation of excavation and support of the Dongxiu tunnel. The grid model and excavation diagram are shown in Fig.6. The Mohr-Coulomb model built in software is chosen to describe the mechanical properties of surrounding rock. The shell element, entity unit and cable element are used to simulate the initial support, the secondary lining and the anchor respectively [14]. The parameters used in the simulation are shown in Table 3. Before the numerical excavation, the initial stress should keep balance, which makes the initial stress state of the model fit with the actual initial stress state of the tunnel.

![Figure 6. The 3D numerical model the concerned tunnel section.](image)

### Table 3 The parameters used in the numerical simulation

|                          | Unit weight /KN·m⁻³ | Elastic modulus /GPa | Poisson's ratio | Cohesion /MPa | Angle of internal friction/° |
|--------------------------|---------------------|----------------------|-----------------|---------------|----------------------------|
| Surrounding rock (III-grade) | 26.9                | 10                   | 0.28            | 1.2           | 45                         |
| Concrete (C25)           | 22.0                | 26                   | 0.2             | —             | —                          |
| Concrete (C30)           | 25                  | 30                   | 0.2             | —             | —                          |
| Bolt (Q345)              | 78.5                | 206                  | —               | —             | —                          |
| Mesh reinforcement       | 78.5                | 210                  | —               | —             | —                          |
| Steel arch               | 78.5                | 210                  | —               | —             | —                          |

3.2. Evolution law of the settlement of the tunnel vault
Fig.7 shows the simulation results of vault settlement (the contour of displacement in the vertical direction) corresponding to different excavation steps. With the increase of excavation steps (the tunnel face is moving forward), the displacement of the tunnel vault increases continuously. The accumulated...
settlement curve of the vault obtained from the simulation result of the tunnel excavation is shown in Fig.8. In the early stage of excavation, the settlement rate is relatively high. With the strengthening of the interaction between the initial support and surrounding rock, the settlement of the vault gradually slows down.

![Figure 7](image_url)

(a) 5th excavation step  (b) 10th excavation step  (c) 15th excavation step  (d) 25th excavation step

Figure 7. The simulation results of settlement of the vault (the contour of displacement in the vertical direction/mm) corresponding to the different excavation step.

![Figure 8](image_url)

Figure 8. The accumulated settlement curve of the vault obtained from the simulation results of the tunnel excavation.

3.3. Evolution law of the peripheral convergence of the sidewall

The simulation results of peripheral convergence (the contour of displacement in the horizontal direction) corresponding to different excavation steps is shown in Fig.9, and the accumulated peripheral convergence obtained from the simulation results of the tunnel excavation is shown in Fig.10. It can be seen that, at the beginning of excavation, for the surrounding rock is disturbed and not constrained by the initial support, the peripheral convergence rate increases rapidly. Although the surrounding rock is III-level, the rock mass is mainly weakly weathered argillaceous siltstone. The local fractures are more developed, and the cumulative deformation is increasing. Subsequently, due to the finish of the initial supports, the peripheral convergence rate of the tunnel slows down. At 25th excavation step, the distance between the tunnel face and the monitoring section is 50m, and the peak value of the peripheral convergence is 4.03mm and keeps stable, which means the construction of the secondary lining can be carried out.
4. Conclusion
Taking the Dongxiu tunnel under construction as the engineering background, this paper introduces the principle of interaction between tunnel surrounding rock and lining. Through the collation and regression analysis of the monitoring data of typical sections with weak surrounding rock, the temporal evolution law of vault settlement and peripheral convergence of tunnel sidewall are revealed respectively, and the optimal supporting time of secondary lining is then primarily determined. The FLAC$^3$D is used to simulate the excavation and support process of monitoring section of Dongxiu tunnel. The rationality of the evolution law of vault settlement and peripheral convergence is verified, and the accuracy of the selection of supporting time of secondary lining is verified. The main research conclusions are as follows:

(1) Regression analysis and numerical simulation results show that the vault settlement and the peripheral convergence rate increase rapidly at first, and then gradually slow down until stable. On the whole, the deformation and the growth ratio of the surrounding rock during the excavation of the upper bench of the tunnel are larger than the excavation of the lower bench.

(2) It is more suitable for the construction of the secondary concrete lining of the tunnel when the tunnel excavating face has passed about 48-50 m (namely, during the 23$^{th}$-25$^{th}$ days after the excavation). This research results can provide reference for the optimization of lining timing of surrounding rock support in similar projects.

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