Study on Stress Characteristics of Multi-arch Tunnel Lining under Weak Surrounding Rock Conditions Based on Field Measurement

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Abstract. Considering the complexity of stresses on multi-arch tunnel structures under conditions of shallow depth, unsymmetrical pressure and weak surrounding rocks and the actual geological exploration of the Xiaojian Mountain Multi-arch Tunnel, the cross-sections in strongly-weathered section were selected for embedment of monitoring and measurement equipment to monitor in real time the stress of support structures during tunnel construction. In addition, the finite difference software FLAC3D was adopted to study the surrounding rock deformation during the excavation of the multi-arch tunnel. As a result, the stress state and deformation characteristics of the support structures under unsymmetrical pressure and construction disturbance were obtained. Based on the analysis of monitoring data, it can be concluded that under conditions of shallow depth and unsymmetrical pressure, reduction of stress imbalance on the support structures is of utmost importance to the structural stability of a multi-arch tunnel and that the method of cross-validation between monitoring & measurement and numerical simulation enables more accurate analysis of stability of tunnel structure and better guidance for construction.

1. Introduction

The rapid economic development of China has driven the continuous extension of its expressways into mountainous areas [1]. However, in mountainous areas, the selection of tunnel form is not only constrained by the geological and topographic conditions, but also restricted by the plane, longitudinal and transverse indicators of the route and the combination design of the three aspects [2-3]. Compared with a separated tunnel, a multi-arch tunnel has more complex structure, and during construction, it has greater the excavation section and is more frequently disturbed by surrounding rock [4-5]. Moreover, the stability of the surrounding rock-support system is complex and changeable, especially the center diaphragm which is subjected to very complex stresses, including tensile, compressive, bending and shear stresses and the stability of which has a bearing on the overall stability of a multi-arch tunnel[6-8]. In recent years, scholars at home and abroad have conducted a lot of studies on the surrounding rock deformation and stress distribution, stress on support structure, and other aspects of multi-arch tunnels by means of numerical simulation, theoretical analysis, field monitoring, etc. and also made many
achievements. Nevertheless, due to varied landforms and geological conditions at different tunnel sites, the findings of studies in individual cases are not universal, in particular under conditions of shallow depth, unsymmetrical pressure and weak surrounding rock where the multi-arch tunnels are likely to encounter a range of problems including surrounding rock collapse and lining diseases during construction [9].

In the study, in view of the specific engineering conditions of the Xiaojian Mountain Tunnel, typical cross-sections were selected to monitor the lining structures of the two-lane multi-arch tunnel throughout the construction, and the development and distribution rules of internal forces of primary support and secondary lining structures were analyzed to provide a basis for optimization of support system.

2. Project Overview
The Xiaojian Mountain Tunnel is located in Yuhua Community, Chenggong District, Kunming City. It is designed to pass through the Xiaojian Mountain. It connects the Expressway from Huangtupo Village to Majinpu (Huangma Expressway) in the small mileage direction and Kunmingnan Railway Station in the large mileage direction, with route strike of 281°. The maximum buried depth of the tunnel is about 41 m. According to the design of a multi-arch tunnel, end-wall tunnel portals are adopted.

As Xiaojian Mountain Tunnel is a double-arch tunnel under conditions of full unsymmetrical pressure, ultra-shallow depth and different surrounding rock, its construction is difficult and of high safety risk. Structures with ultra-shallow depth and under unsymmetrical pressures are prone to diseases including compressional deformation and cracking of primary support and secondary lining during construction. Additionally, the construction procedures of a double-arch tunnel are complex and the excavation may cause frequent disturbance to the rock mass. Its construction is difficult and of high safety risk.

3. Test of Lining Structure

3.1. Test items and test point arrangement
Field tests on the deformation and stress of lining structure of the Xiaojian Mountain Tunnel include monitoring of the steel arch for primary support and the stress of secondary lining concrete, which was conducted from May 2020 to December 5, 2020. In light of the geological exploration data of the Xiaojian Mountain Tunnel, the cross-section of the strongly-weathered section K0+836 was selected as the typical cross-section for monitoring.

(1) Internal force test of primary support structure
The cross-section for monitoring and measurement was set according to the geological conditions of surrounding rock of the tunnel. Refer to Figure 1 for the arrangement of measuring points on the cross-section for monitoring. The internal forces of steel supports were measured with steel rebar meters. For each monitored cross-section, the monitoring was done by a total of 17 steel rebar meters arranged along the vault, two hances, two side walls and invert of the tunnel. During welding, water was sprayed for cooling. After the embedment had been completed and the temperature stabilized, the data were read by digital readouts.
(2) Internal force test of secondary lining structure
For each monitored cross-section, the measurement was done by concrete strain meters embedded in shotcrete at 20 positions along the vault, two hances, two side walls and invert of the tunnel. After initial shotcreting of the surrounding rock, a strain meter was fixed on the initially shotcreted surface, and then shotcreting was done again to cover the strain meter completely and keep it in the center of shotcreted layer. After initial setting of shotcrete, measurement was done with a digital readout. Concrete strain meters were buried in secondary lining and fixed with iron wires. After pouring of concrete with forms, measurement was done with a digital readout.

3.2. Analysis of internal force test results of primary support
Figure 3 presents the stress-time curves of steel arches in typical cross-sections of left and right tubes of the Xiaojian Mountain Tunnel. The specified compressive stress was positive, while the tensile stress was negative. The stress diagrams of primary supports for the multi-arch tunnel under weak surrounding rock conditions were developed according to the field monitoring data.
Figure 3. Stress-time curve of steel arch in cross-section of K0+836

Figure 4 is the axial force diagram of steel supports for this cross-section, which shows that the axial forces of steel supports at the shallowly-buried side of the tunnel are greater than those at the deeply-buried side. This is due to the fact that the buried depths of the left and right tubes are different. The stress passed to the center diaphragm after tunneling at the deeply-buried side is greater than that at the shallowly-buried side. Besides, the stresses passed to the center diaphragm via lining from the left and right tubes are also different. To balance the pushing force at the deeply-buried side of the tunnel, the acting forces of primary supports and surrounding rock at the shallowly-buried side of the tunnel were increased. Therefore, in the process of providing rockbolt-and-shotcrete primary support, the steel supports shall also be densified properly to make sure that the primary supports at the shallowly-buried side of the tunnel will not suffer yield failure under unsymmetrical pressure.

As shown in Figure 5, the stress on the left side wall of the tunnel is greater than that on the right side wall. Moreover, the stresses on the right vault of the tunnel and on the left part next to the top of the center diaphragm reach 25.98 MPa and 26.76 MPa respectively, exceeding the ultimate compressive strength of C25 concrete. This indicates that the unsymmetrical pressures have significant effects on the individual points of primary supports for the tunnel. Since only several points of shotcrete reach the ultimate strength, there is no much influence on the overall stability of primary supports. Besides, the tunnel is on a slope, and the combined actions of the gravity of overlying surrounding rock itself and the unbalanced pushing force lead to large deformation of surrounding rock and high stress within the vault during the provision of primary support for the tunnel, which shall be taken into account during construction.
3.3. Analysis of internal force test results of secondary lining

Figure 6 gives the stress-time curves of secondary lining concrete. The specified compressive stress was positive, while the tensile stress was negative. The stress state diagram of secondary lining concrete in left and right tubes in the cross-section of K0+836 was developed through analysis of the secondary lining stress-time curves.

It can be seen from Figure 7 that the secondary lining concrete from the top of the center diaphragm to the vault at the shallowly-buried side of the tunnel bears more stress, with the maximum value of 5.75 MPa, which has reached the shear strength of C30 concrete. This indicates that the lining structure within this range is affected by the unsymmetrical pressure transferred via the lining structure at the deeply-buried side of the tunnel.

4. Numerical Simulation of Strongly-weathered Basalt Section

4.1. Model building

The midpoint at the bottom of the center diaphragm is regarded as the origin of coordinates for the calculation model. The longitudinal direction of tunnel is regarded as the Y-axis, which is positive in the inward direction. The transverse direction is treated as the X-axis, which is positive in the rightward direction. The vertical direction is treated as the Z-axis, which is positive in the upward direction. Considering the limitation of model size and the necessity to include the actual typical cross-section for monitoring, the longitudinal length of the model is set to 90 m. In light of the influence scope of tunnel the excavation and the conclusions of elastic mechanics, the vertical and transverse lengths of the calculation model are set to be three times the tunnel span from the outer contour of the tunnel respectively. Due to the shallow depth of the tunnel, the top of the model is the actual terrain. Refer to Table 1 for the values of calculation parameters.
4.2. Analysis of simulation results

To analyze in a more accurate manner the distribution characteristics of vertical displacement of surrounding rock in construction stages of the multi-arch tunnel under weak surrounding rock conditions, the curves of change in vertical displacement of surrounding rock with construction stages at monitoring points in left and right tubes are drawn as shown in Figure 9 and Figure 10.
5. Conclusion

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