Collapse mechanism and treatment technology of large-span soft rock highway tunnel

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ABSTRACT: Tunnel collapse seriously affects the security of the constructers and delays the engineering schedule. Based on the Liangwangshan Tunnel project located in western China, the collapse mechanism of large-span soft rock tunnel under loose load was revealed by theoretical calculation, field measurement and numerical simulation. The low strength-stress ratio of the unconsolidated fragment rock mass leads to a very high loose pressure. The measured stresses of the arch have exceeded its strength, which indicates that the arch is less secure. The FEM results show that I18 steel arch is incapable of resisting ground pressure in this project. Besides, a segmented and graded treatment technique was proposed to deal with tunnel collapse, and the tunnel deformation was successfully controlled. The monitoring data showed that the tunnel was stable after treatment, which shows that the segmented and graded treatment technique was successful and effective.

Keywords: large-span tunnel, soft rock tunnel, in-situ monitoring, collapse mechanism.

1 INTRODUCTION

Large deformation and collapse of weak tunnel has attracted widespread attention from the engineering community (Xu & Xia 2021, Ling 2012), and the suppression of the tunnel collapse problem has become urgent. For the collapse mechanism, comprehensive studies (Ding et al. 2011, Song 2011, Xu et al. 2021a, Yan 2012) have shown that the factors influencing tunnel collapse are mainly: tectonic fracture zone, indirect action of groundwater, water surge and mud, tunnel bias and construction method, and geological conditions of surrounding rock. As the research progressed, scholars began to focus on theoretical derivation to analyze the tunnel collapse process (Wang 2010, Wang & Tan 2012, Wang 2013, Xu et al. 2022). Some scholars use statistical analysis (Wang & Zhu 2008, Wang et al., 2016) to conclude that the main influencing factors of tunnel collapse are: geological conditions, tunnel burial depth, tunnel section form and size, underground water, blasting disturbance, improper construction measures and design.

Scholars have achieved valuable results on tunnel collapse management measures. He et al. (2010) carried out researches on treatment measures such as surface drainage, small conduit grouting, surface trap, monitoring and measurements based on a shallow buried bias tunnel project. Xie (2011) introduced a treatment of tunnel collapse based on Sifangshan tunnel project, the radial grouting consolidation combined with I-beam and other initial support treatment measures were employed for the collapse area. The backfill technology based on arch theory was adopted by Zhu et al. (2019) for treating the collapse cavity, which showed a good effect. Li & Jin (2014) systematically introduced a series of comprehensive technical treatment measures such as cavity treatment, cavity drainage treatment, cavity wall treatment and overfill pre-grazing.

The collapse mechanism based on field data before tunnel collapse is less in present studies. Besides, many studies focus on the collapsed section of the tunnel, without considering the slightly cracked and severely deformed sections of the initial support near the collapsed section. It is the purpose of this paper to reveal the collapse mechanism of a large-span tunnel and propose a treatment technology base on the Liangwangshan tunnel in western China. The in-situ monitoring was carried out in the tunnel near the mileage of the collapsed section. Numerical simulation and theoretical analysis were combined to analyze the collapse mechanism of large-span soft rock road tunnel under high ground stress, and segmental and graded treatment techniques were proposed to control the tunnel deformation. The research results can provide reference for tunnel construction under similar engineering geological conditions.

2 TUNNEL LEFT LINE COLLAPSE DESTABILIZATION MECHANISM

2.1 Project profile

Liangwangshan tunnel of Fuzhou-Yichang expressway is located in Kunming, western China. The tunnel is designed as a separated six-lane tunnel. The average depth of the tunnel is 250m, and the surrounding rock is mainly composed of siltstone, sandstone and dolomitic limestone. The overall integrity of the surrounding rock is poor and the structural plane is relatively developed. The engineering geology of surrounding rock is mainly classified as IV ~ V. The original design of the initial support is I18 type steel frame with a longitudinal spacing of 0.8m, and spraying concrete lining with thickness of 24 cm. The initial support at ZK33+093 generated obvious deformation and cracking after excavation on July 22, 2022. Few hours later, the arch of section ZK33+093~+106 was destabilized and collapsed, the longitudinal length of the collapsed section was 13 m, as shown in Figure 1.

(a) Section ZK33+096~106 (b) Section ZK33+079

Figure 1. Collapse of Liangwangshan tunnel at different sections.

2.2 Ground pressure

The tunnel span is about 17.1 m at section K33+100, the excavation reveals very weak rock mass at this section. According to the "*Highway Tunnel Design Code*" promulgated by Chinese government, the equivalent height of loosen arch and the corresponding vertical load of the tunnel are:

$$h_1 = 0.45 \times 2^{S-1}\omega \tag{1}$$

$$q = \gamma h_1 \quad (2)$$

Where: S is the perimeter rock level; ω is the width influence coefficient, ω = 1+i (B-5); B is the tunnel span (m); i is the rate of increase or decrease of perimeter rock pressure for every 1m increase or decrease of B, based on the perimeter rock vertical pressure at B = 5m, when B< 5m, take i = 0.2; B > 5m and i = 0.1. q is the vertical mean pressure (kN/m^2).

2.3 Calculation model and parameters

The tunnel support is composed of steel frame and shotcrete concrete, which is simulated by beam element in the FE simulation. The calculation parameters of each part of the support structure are shown in Table 1. The load-structure calculation model was established, and the steel frame and shotcrete in the initial support and temporary support were equated to beam units using the equivalent stiffness method. The SF4a initial support has a modulus equivalent of elasticity of 27.8 GPa, with inertia moment of 1.16×10^{-3} cm^4 and weight of 25.8 kN/m^3. The equivalent elastic modulus of SF5a initial support is 29.7 GPa, with inertia moment of 2.1×10^{-3} cm^4 and weight of 26.4 kN/m^3.

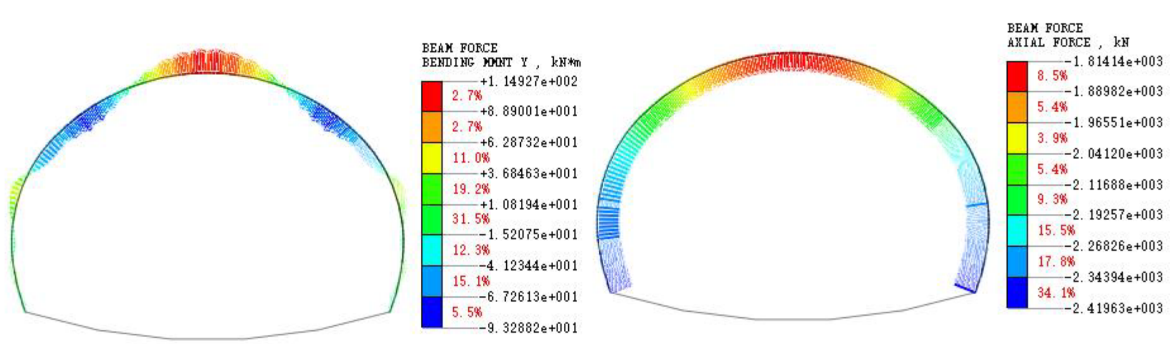
Table 1. Calculation parameters of support structure.

Material properties	Compressive strength/MPa	Tensile strength/MPa	Modulus of elasticity/GPa	Poisson's ratio
C25 shotcrete	15	1.5	25	0.2
Steel arch	235	235	200	0.25

2.4 Stability of tunnel support in very weak (grade V) rock masses

Figure 2 presents the calculated bending moment and axial force of the tunnel initial support excavated in very weak (grade V) rock masses. It indicated that most of the compressive stresses of shotcrete are less than the yield strength, but the stresses at the top of the steel frame vault and the left and right arch shoulders exceed the yield strength, and destabilization damage occurs, while the buckling damage of the steel frame further causes cracking and crumbling of the shotcrete.

The calculation shows that the shotcrete compressive stress is less than the yield strength, but the stress at the top of the steel frame arch and the left and right arch shoulders exceeds its yield strength and destabilization damage occurs, while the steel frame buckling damage further causes cracking and crumbling of shotcrete. Figure 3 compares the calculated tunnel deformation by FE method and the photo of tunnel collapse. The FE simulation result basically coincides with the field conditions. It indicates that the SF4a type initial support cannot meet the safety and stability of the tunnel cavity in very weak (grade V) rock masses.



(a) Bending moment (b) Axial force

Figure 2. Internal forces of tunnel support (SF4a type)

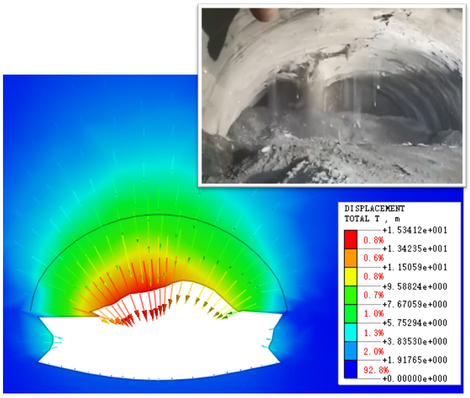


Figure 3. Comparison of the calculated tunnel deformation by FE method and the photo of tunnel collapse.

3 FIELD MONITORING AND DATA ANALYSIS

In order to find out the collapse mechanism of the tunnel at section K33+106, in-situ monitoring was carried out at section K33+084 just around the collapse section. The main monitoring items include the surrounding rock pressure behind the initial support, the stress of the steel arch of the initial support, and the contact pressure between the second liner and the initial support. The monitoring points were arranged at the top of arch, arch shoulders, waist and foot. The installation and burial of field monitoring instruments are shown in Figure 4.

Figure 5(a) shows the change of the surrounding rock pressure behind the initial support at K33+084 cross section. It can be seen that the surrounding rock pressure at the arch top and shoulder exceeded 400 kPa on 20 August and is increasing daily. According to this, it can be judged that the surrounding rock pressure has reached the level of V-level loose load of surrounding rock. Figure 5(b) shows the change of the contact pressure between the second liner and the initial support. It can be seen that the contact pressure data at each measuring point is small, no more than 0.2MPa. Therefore, the safety of the tunnel is relatively high after laying the second lining.

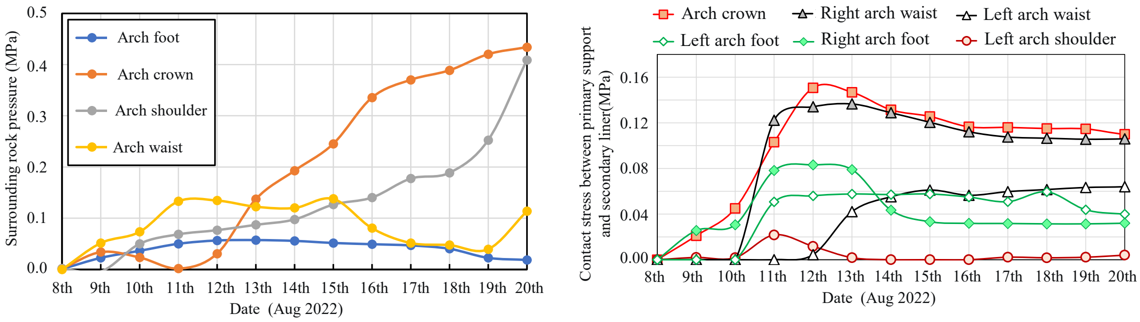
4 SEGMENTAL TREATMENT TECHNOLOGY FOR TUNNEL COLLAPSE

The initial support arches at sections ZK33+065~+070 are slightly cracked, therefore, temporary steel arch guard and radial grouting are adopted to strengthen the design measures of secondary lining. At ZK33+070~+093, initial support deformation and penetration limit is serious, has basically failed. This section is mainly backfilled by backpressure of the cave body, and arch replacement should be carried out with the aid of advance support. In this section, the backfill of cave body is mainly adopted, and the arch is replaced with the aid of advance support. At ZK33+093~+106, the tunnel has collapsed and needs to be excavated and supported again. During the support, the lining structure was changed to SF5a lining, and the reserved deformation of the initial support was 30cm.

At section ZK33+065~+070, the cave slag was first used to backfill to the upper step, and the protective arch was installed from the small mileage to the large mileage to close into a ring. Before the secondary lining construction, the temporary protective arch is removed and the loose surrounding rock is radially grouted. Radial grouting was performed on the section of arch wall immediately after the initial support construction was completed. At section ZK33+070~+093, before the steel arch removal, the overrunning double-layer small conduit was laid in the previous cycle. After the removal of steel arch, undercutting was carried out with the gun head of excavator. After positioning and installing the steel arch, a 4m long Φ89×5mm locking anchor pipe was installed and welded firmly with L-bar to the steel arch. Concrete pads were added at the gap between the steel arch and the initial sprayed concrete to wedge the steel arch. At section ZK33+093~+106, 25cm thick C25 shotcrete was used to temporarily close the palm face. Before the construction of pipe shed, two bays of guiding frame were constructed on the completed primary support surface near the palm face, and then Φ50 small conduit was inserted between the pipe shed after the construction of pipe shed was completed. The micro-step method was adopted, and the elevation arch was excavated separately, and the remaining unexcavated part was excavated manually with mechanical excavation to reduce the disturbance to the bottom rock layer.

Figure 6 presents the settlement curve of the arch after the above sections were treated. It can be seen that after 20 days of construction, although some section deformation does not converge temporarily, the surrounding rock deformation is small on the whole. This indicates that the segmental graded treatment technique is successful and effective.

Figure 4. Installation and embedding of monitoring instruments.



(a) Behind the initial support (b) Between the second liner and the initial support

Figure 5. Variation of surrounding rock pressure at different positions of K33+084 section.

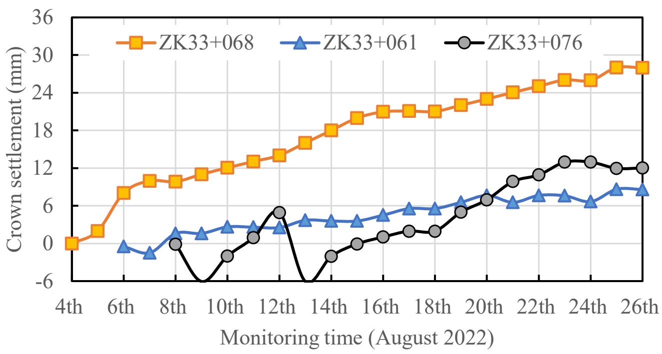


Figure 6. Settlement of the arch at the tunnel left line after the collapse section is treated.

5 CONCLUSION

Taking Liangwangshan Tunnel of Fu-Yi Expressway in China as the engineering background, the collapse mechanism of large-span soft rock highway tunnel under loose load was analyzed by means of theoretical calculations, numerical simulations, and field monitoring. The results show that: (1) The surrounding rock in tunnel collapse section is loose and broken, the loose pressure is large, and the strength stress ratio of surrounding rock is low. (2) The surrounding rock pressure detected on site has reached the loose load of V-class surrounding rock. Under the action of large loose pressure (mainly the vertical pressure), the stress of I18 steel arch near the vault has exceeded its yield strength, and buckling failure occurs, which leads to tunnel collapse. (3) The section ZK33+065~+070, ZK33+070~+093 and ZK33+093~+106 were treated by using the field segmental and graded treatment technology, and the roadway deformation was successfully controlled. The monitoring data show that the tunnel is generally stable after treatment of the collapse section in the left line of the tunnel, and there is no cracking, spalling and other phenomena of the initial supporting shotcrete. The above indicates that the segmental and graded treatment technology is successful and effective.

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REFERENCES

Ding, Y., Li, T.F., Li, Y.J. & Fan, D.B. 2011. Collapse mechanism of a speedway tunnel and its numerical simulation. *Journal of Chengdu University of Technology (Science & Technology Edition)* 38 (2), pp. 236-240.

He, C.T., Wang, X.L. & Xiao, P.F. 2010. Comprehensive treatment technology for tunnel collapse in shallow buried partial pressure section. *Railway Engineering* (11), pp. 54-56.

Li, Y.J. & Jin, J.W. 2014. A brief discussion of complex geological zone tunnel collapse and roofing treatment technology. *Highway* 59 (08), pp. 310-312.

Ling, Y. 2012. Research on collapse mechanism of soft rock tunnel and the influence of aftershocks to the tunnel stability of Guanggan expressway. Ph.D. thesis. Chengdu University of Technology, Chengdu.

Song, B. 2011. Research on tunnel collapse mechanism and treatment measures in Da Shan expressway. Ph.D. thesis. Chengdu University of Technology, Chengdu.

Wang, C.B. & Zhu, H.H. 2008. Tunnel collapse mechanism and numerical analysis of its influencing factors. *Chinese Journal of Geotechnical Engineering* 30 (3), pp. 450-456.

Wang, D.X. 2013. Research on collapse in deep tunnel by upper bound analysis under hoek-brown criterion and pre-warning standard. Ph.D. thesis. Central South University, Changsha.

Wang, Y.C. 2010. Mechanism and control measures of collapse of mountain tunnel. Ph.D. thesis. Zhejiang University, Hangzhou.

Wang, Y.C., Li, Y.B., Qiao, W. & Li, Y.L. 2016. Study on the quantitative evaluation of influencing factors of tunnel collapse based on analytic hierarchy process. *Bulletin of Science and Technology* 32 (05), pp. 180-186.

Wang, Y.L. & Tan, Z.S. 2012. Structural instability analysis and prevention measures of structural collapse in Muzhailing slate tunnel. *Rock and Soil Mechanics* 33 (S2), pp. 263-268.

Xu, C. & Xia, C. (2021). A new large strain approach for predicting tunnel deformation in strain-softening rock mass based on the Generalized Zhang-Zhu strength criterion. *International Journal of Rock Mechanics and Mining Sciences*, 143, pp. 104786.

Xu, C., Xia, C. & Han, C. (2021a). Modified ground response curve (GRC) in strain-softening rock mass based on the generalized Zhang-Zhu strength criterion considering over-excavation. *Underground Space*, 6(5), pp. 585-602.

Xu, C., Xia, C. C. & Han, C. L. (2022). Elastoplastic Solutions for Deep Tunnel Excavation in Weak Rocks with High Geostress Considering Different Stress Release Measures. *International Journal of Applied Mechanics*, 14(08), pp. 2250077.

Xie, E.L. 2011. Analysis of the causes and measures for the collapse of the Sifang mountain tunnel. *Journal of China & Foreign Highway* 31 (06), pp. 217-220.

Yan, L.Q. 2012. Study on treatment measures and formation mechanism of the collapse disaster in Gaoling tunnel. Ph.D. thesis. Chang'an University, Xi'an.

Zhu, F.P., Chen, L.Y. &Yao, Y.H. 2019. Analysis of the causes of collapse and management of an extra-long tunnel. *Architecture Technology* 50 (S2), pp. 39-42.