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Research Article

Study on the Stability of a Transition Section from Soft to Hard Surrounding Rock Based on the Solid-Fluid Coupling Effect

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To study the stability of a transition section of a tunnel from soft to hard surrounding rock under seepage conditions, FLAC3D software was used to numerically simulate the transition section of the Laomushan Tunnel from the Shiqian to Yuping (Dalong) Expressways in Guizhou Province, China, and to explore different working conditions. The characterization of the tunnel seepage field, stress field, and displacement field and the analysis of the force of the primary lining support structure describe the influence of the seepage field on the stress field distribution and displacement field changes. The reliability of the calculation results is verified by comparison with displacement measurements collected during field monitoring. The design values of the primary support structure parameters of the transition section from soft to hard surrounding rock of the Laomushan Tunnel basically met the strength requirements. The research results provide references for the design and construction of similar projects.

1. Introduction

With the continuous development of China's economy, the total mileage of highway in China is gradually increasing. To adapt to mountainous terrain, the proportion of highway tunnels is increasing, and engineering geological conditions are becoming increasingly complex. In southern China, the annual precipitation and groundwater resources are abundant. The seepage problem in the process of tunnel construction has an important influence on the stability of the surrounding rock. Therefore, it is of great practical significance to discuss the influence of the seepage field on the stability of the surrounding rock of a tunnel considering the fluid-structure coupling effect.

In recent years, many scholars have performed a considerable amount of research on the stability of tunnel excavation under the condition of abundant water. Snow, based on the assumption of an infinite extension of the fracture surface, proposed a formula describing the relative permeability tensor [1]. An artificial neural network was used to predict the surface subsidence, and field measurement results were in good agreement [2]. Based on solid-fluid coupling theory, Zhang et al. [3] used FLAC3D finite difference software for simulation and on-site monitoring to analyze the stability of a tunnel excavation, obtained the risk prediction function of the tunnel excavation under confining pressure, determined the most dangerous excavation depth of the face, and provided a reference for subsequent work. Li et al. [4] proposed the coupling theoretical model of variable mass seepage and deformation of a saturated broken rock mass; this model can be used to gain a better understanding of the deep flow mechanics of a broken rock mass and the prevention and control of water inrush disaster of a deeply buried tunnel. Li et al. [5] established an evaluation model to calculate and analyze the water inrush problem of a tunnel and compared the results with field observations to demonstrate that this theoretical method can provide an effective way to quantify the disaster risk of underground engineering. Zhao et al. [6] discussed the effect of solid-fluid coupling on the stability of antiburst rock pillars and obtained the safety coefficient of the antiburst rock pillar by constructing an analysis method that links to the solid-fluid coupling strength reduction method for karst cave water inrush, providing a new way to research the stability evaluation of water inrush of an engineering rock mass. Zou et al. [7] studied the influence of the grouting circle thickness, permeability coefficient, and other factors on pore water pressure by establishing a two-field solid-fluid coupling model of the tunnel seepage field and stress field and obtained reasonable grouting circle reinforcement parameters and optimal waterproofing and drainage control formulas. Yue et al. [8] found that the results of solid-fluid coupling analysis considering foundation pit dewatering are closer to the field measurement results through the establishment of a three-dimensional finite element model of solid-fluid coupling. Zheng et al. [9] established a model to analyze the stability of a frozen wall of a tunnel based on the solid-fluid coupling theory, aiming at the improvement in the stability of the frozen wall of the Zhuji intercity rail transit project. The deformation of the frozen wall increased under the solid-fluid coupling effect and became increasingly significant with decreasing thickness. Li et al. [10] analyzed the stress and deformation characteristics of a large-cross-section loess tunnel in the early stage of construction by establishing a three-dimensional finite element model. The results show that the results considering the solid-fluid coupling are closer to the field measured value than those not considering the solid-fluid coupling. Ni et al. [11] used the finite element method to study the coupling mechanism of the grout and the rock mass. The results show that the calculation error is reduced when considering the solid-fluid coupling effect.

Based on the study of the solid-fluid coupling effect and the stability of the surrounding rock during the blasting construction of the transition section from soft surrounding rock to hard surrounding rock of the Laomushan Tunnel, considering the different grades of the surrounding rock, the solid-fluid coupling analysis of the excavation of this tunnel section is carried out by using FLAC3D finite difference software; the distribution characteristics of the seepage field and their influence on the stability of this transition section are discussed. The results provide theoretical guidance for the safety control of blasting excavation of the Laomushan Tunnel.

2. Project Overview

The Laomushan Tunnel of Guizhou from Shiqian to Yuping (Dalong) Expressway is selected as the research object. The Laomushan Tunnel is divided into three levels of surrounding rock: grade V, grade IV, and grade III. The proportion of the length of the surrounding rock class on the left and right lines to the length of the tunnel is as follows: grade V surrounding rock accounts for about 9.8% (215 m), grade IV surrounding rock accounts for about 58.3% (1280 m), and grade III surrounding rock accounts for about 31.9% (700 m). All levels of surrounding rock excavation of the tunnel are constructed by drilling and blasting. The tunnel in the test section is a transitional section between grade III (harder surrounding rock) and surrounding rock grade V (soft rock formation). The engineering geological and hydrogeological evaluation of each surrounding rock section of the tunnel is as follows: the surrounding rock is grade V, the rock mass is relatively complete, and the rock quality is relatively hard. The surrounding rock generally has no self-stabilization ability and loose deformation, and small landslides can occur within a few days to several months and can continue to develop into large landslides, mainly due to plastic flow deformation and extrusion failure. After the tunnel is excavated, the water effluent state is mainly drip and wet; the surrounding rock is grade III, the rock mass is relatively complete, and the rock is relatively hard. The surrounding rock can be stable for several days to one month, and small-to-medium landslides can occur. After the tunnel is excavated, the effluent state is mainly drip and wet. The strata in a cross section and vertical section of the tunnel are shown in Figure 1(a) and Figure 1(b).

Laomushan Tunnel was constructed by the up-and-down step method. The upper step is 5 m high, and the lower step is about 3 m high. The upper and lower steps are, respectively, wedge-shaped cutting blasting and horizontal hole drawing blasting. The No. 2 rock emulsion explosive with a diameter of 33 mm was selected for blasting, the cut hole diameter was 42 mm, and the tunneling cycle size was controlled at 1.8 to 2.3 m. At the same time, air-spaced charge is used to improve the blasting effect, as shown in Figure 2.

3. Numerical Simulation Analysis

3.1. Calculation Model and Parameters. Taking the transition section from soft to hard surrounding rock of the YK76 + 415-YK77 + 451 section as the research object, based on fluid-structure coupling theory (2012) [12, 13], a numerical calculation model of the Laomushan Tunnel is established by FLAC3D software. Mohr-Coulomb's elastic-perfectly-plastic model is used for mechanical analysis. The Laomushan Tunnel is 15.4 m wide and 8.5 m high. After excavation, C25 concrete is initially sprayed to line the tunnel walls, which is simulated with shell units. Considering the influence range of the excavation radius during excavation, the initial model size is $120\,m \times 70\,m \times 40$ m. During the modeling process, each grade of surrounding rock is regarded as a continuous homogeneous medium, and a tetrahedral element model is used for simulation. The grade V surrounding rock changes to grade III surrounding rock along the direction of approximately 34° to the tunnel axis from the x-axis. The area near this surface can be approximated as a transitional section between the simulated soft and hard surrounding rocks. The pore water flow in the rock mass satisfies Darcy's law, and the pore water seepage in the rock mass is regarded as continuous medium seepage. The initial in situ stress only considers the self-weight stress of the rock mass, and the lateral pressure coefficient in the horizontal direction is taken as $\lambda = 1.1$. In the process of seepage calculation, the fluid-solid coupling calculation mode is enabled, the rock-soil unit is set to the isotropic seepage model (MODEL fluid fl-isotropic), and the lining is simulated by the shell element set to the impervious material model (MODEL fluid fl-null). The initial support is made of C25 concrete with a thickness of 80 cm. The bolts are selected as left-handed nonlongitudinal rebars with a diameter of

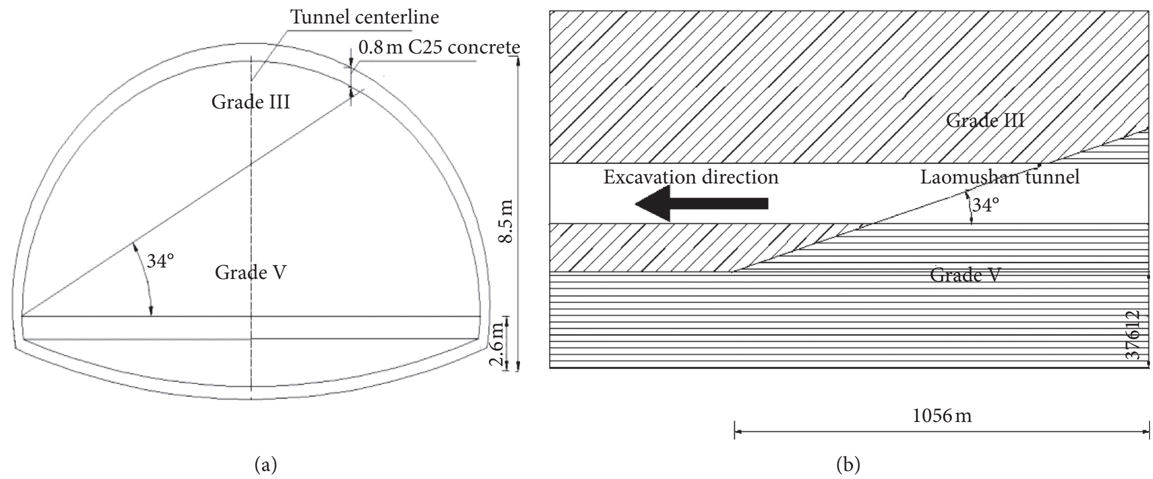


Figure 1: Rock strata crossed by the Laomushan Tunnel: (a) cross section and (b) profile.

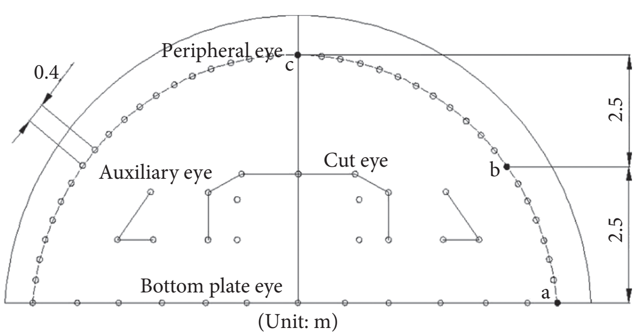


Figure 2: Sectional blasthole layout map.

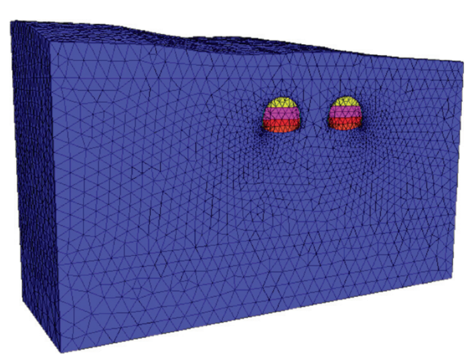


Figure 3: Grid division of the calculation model.

25 mm and a length of 2.5 m. The bolts are symmetrical and radially arranged with a circumferential spacing of l m. The surrounding rock of the tunnel is mainly dolomite. According to the engineering geological survey report and the design code of highway tunnels, the corresponding surrounding rock mechanics are given. The parameters are shown in Table 1. The calculation model is divided into 14,640 units and 62,635 nodes. The calculation grid model is shown in Figure 3.

For mechanical boundary conditions, the upper surface of the tunnel model is selected as the free boundary, and the lower boundary and the four side boundaries are fully constrained. For seepage boundary conditions, the top of the model is fixed, the pore water pressure at the corresponding water grade is fixed, and the boundaries at both sides and the bottom are impermeable. The pore water pressure before excavation is hydrostatic pressure.

Table 1: Index values of the physical and mechanical properties of the surrounding rock at all grades.

Surrounding rock grade	μ	E (GPa)	c (MPa)	φ (°)	κ $(cm \cdot s^{-1})$
III	0.20	8.0	1.2	41.2	3.0×10^{-6}
V	0.45	1.5	0.12	24.1	4.5×10^{-4}
C25	0.20	30.0	6.00	50	Impermeable
Thin layer	0.25	0.2	8.5	30	—
Anchor rod	0.30	200	—	—	—

3.2. Calculation Scheme. The numerical calculation is divided into two working conditions: Working condition 1 does not consider the fluid-solid coupling effect; that is, it ignores the influence of the seepage field during the excavation process. The bulk density of the rock and soil body adopts the saturated bulk density. Timely support during the tunnel excavation process and the influence of tunnel excavation on the stability of surrounding rock under initial stress conditions are analyzed. Working condition 2 considers the influence of the fluid-solid coupling effect on the stability of the surrounding rock and adopts the same supporting scheme as scheme 1 but proceeds to the next step after the fluid-solid coupling is stabilized. According to the geological survey data and water pressure test, the natural porosity ratio is 0.67, the porosity is 0.5, and the permeability is 4.50×10^{-10} $m^2/(Pa \cdot s)$. The software's default Biot coefficient (biot_c) is 1.0, fdens1000, fmod2e9.

3.3. Analysis of the Distribution Characteristics of the Seepage Field. During the excavation of the transition section of the Laomushan Tunnel from soft to hard surrounding rock, the pore water pressure of the face changes with the number of excavation steps, as shown in Figure 4. With the increase of the number of excavation steps, the pressure of the tunnel working face of the vault and waist of the pore water shows a continuous downward trend. Starting from Step 800, the excavation of the lower step leads to a significant decrease in the pore water pressure of each monitoring point (except at the bottom of the arch) of the section, and the arch waist is most affected. Among these locations, as the right arch waist is in the soft rock stratum, the fissures are relatively developed. The tunnel excavation causes the original fissures in the rock stratum to extend due to each step, which makes the pore water pressure of the right arch waist decrease greatly with the increase in excavation steps, from 0.44 MPa. The rock properties of the left arch waist are stronger than those of the right arch waist, and the pore water pressure of the left arch waist thus decreases more slowly than that of the right arch waist with continued excavation.

Due to the excavation of the Laomushan Tunnel, the distribution of the seepage field in the transitional section of soft to hard surrounding rock was disturbed. The contour plot of the changes in pore water pressure due to the tunnel excavation is shown in Figure 5. With the increase in the number of excavation steps, the pore water pressure of the surrounding rock near the tunnel face gradually dissipated, and the tunnel surface pressure showed a downward trend, resulting in continuous changes in the seepage field. The pore water in the excavation section flowed to the void surface under the action of the head pressure, which changed the groundwater seepage path and finally gradually stabilized; the contours of the pore water pressure around the void surface present a closed ring shape, forming a funnel-like seepage area.

3.4. Analysis of the Influence of the Seepage Effect on the Stability of the Surrounding Rock. With the tunnel excavation, the pore water pressure began to drop rapidly, and the seepage path of the groundwater changed. Figure 6 shows the vector distribution of groundwater seepage in the transition section of the Laomushan Tunnel from soft to hard surrounding rock. Figure 6 shows that, with the tunnel excavation, groundwater began to flow along the surrounding rock fractures to the excavation-free face. The seepage in the tunnel face was mainly concentrated on the two sides of the arch waist and the arch foot. The arch waist sidewall was not only an important discharge channel for the groundwater but also the main bearing structure of the multiarch tunnel. The right arch waist and the lower half of the face were located in the soft rock, with a low overall rock mass strength. The occurrence frequency of water leakage in this part of the surrounding rock is high, and the stability is poor. Therefore, during the actual construction of this transition section of the Laomushan Tunnel, it would be suggested that the support is strengthened and that waterproof and drainage measures are taken.

The contour plot of the maximum principal stress distribution in the soft to hard surrounding rock transition section under various working conditions is shown in Figure 7 after the excavation is completed. Figure 7 shows that after the excavation of the tunnel face is completed, the stress at each monitoring point increases sharply. Stress concentration occurs at the right arch of the tunnel face and

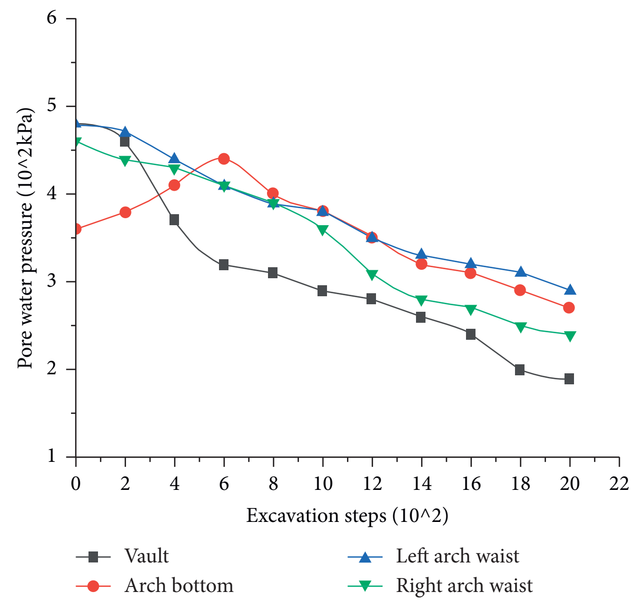


Figure 4: Change curve of pore water pressure.

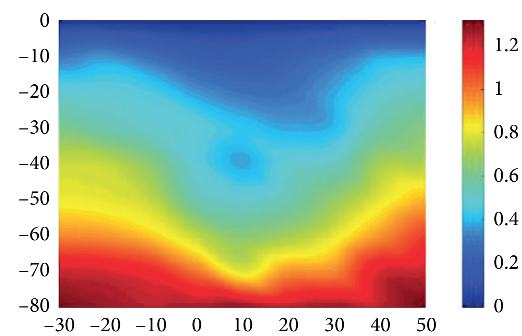


Figure 5: Contour plot of pore water pressure distribution (unit: MPa).

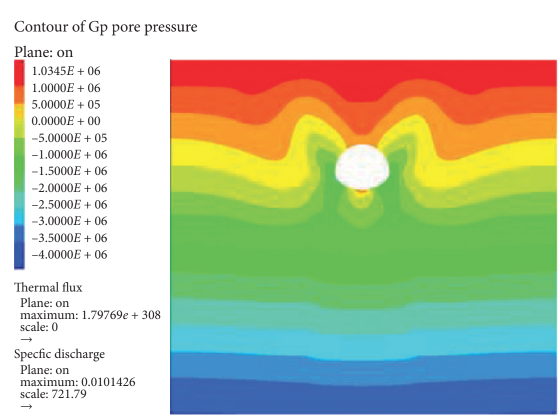
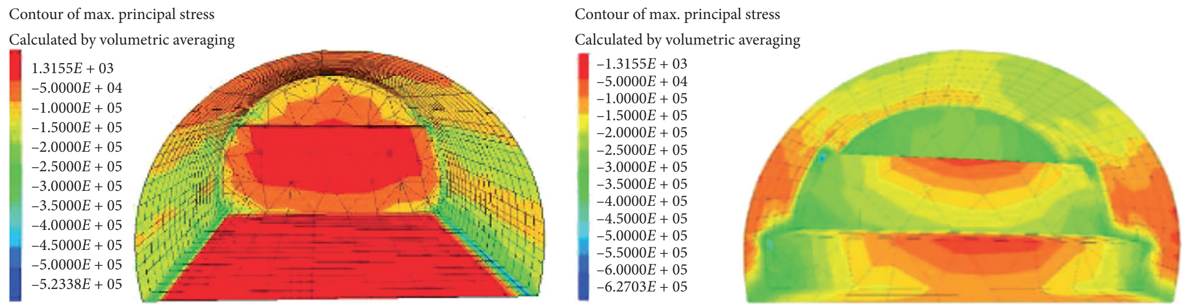


Figure 6: Cloud map of groundwater distribution.



(a) (b)

Figure 7: Stress distribution of the tunnel face: (a) condition 1; (b) condition 2.

the arch feet on both sides of the tunnel. This is due to the destruction of the mechanical balance of the rock mass after the tunnel excavation, and the transition between the soft and hard surrounding rocks formed a certain interface surface. While the radial stress of the tunnel is released, the hoop stress gradually increases. The stress redistributes at the free surface and results in tensile stress at the two arch feet and bottom of the tunnel. In the actual excavation process of the Laomushan Tunnel, drilling and blasting construction destroyed not only the mechanical balance of the rock mass in the transitional section but also the seepage field in the rock mass. The broken rock particles in the weak rock layer with relatively developed fissures are quickly carried away due to the seepage. The formation of new seepage channels changes the seepage path. Considering the fluid-solid coupling effect, the stress concentration at the bottom of the tunnel arch is more obvious. The original 5.23 MPa stress concentration observed under the condition of not considering the seepage field (condition (1) is increased to consider the fluid-solid coupling. The 6.27 MPa stress concentration observed when the fluid-solid coupling is considered (condition (2) shows that the existence of pore water pressure has an adverse effect on tunnel construction. However, the right arch waist and the arch toe on both sides of the tunnel are in the weak surrounding rock, and the fissures are relatively developed. The disturbance on the stress field due to tunnel excavation increases with the decrease in the surrounding rock grade. Therefore, the seepage effect intensifies the impact on the strength of the surrounding rock. The excavation-induced disturbance on the pore water pressure and stress affect each other, and the change trends are basically the same: the combined effect of the two causes the stability of the surrounding rock to be further reduced. The secondary lining should strengthen the support of this part of the tunnel.

Based on the analysis of actual engineering and numerical simulation results considering the fluid-solid coupling effect, the mechanism controlling the stability of the soft to hard surrounding rock transition section is essentially the mutual influence of the changes in the surrounding rock stress and seepage fields at the tunnel surface caused by the tunnel excavation. The removal of the rock mass makes the surrounding rock become unstable.

To further study the influence of the seepage field on the settlement of the surrounding rock during the excavation of the Laomushan Tunnel, Figure 8 shows the calculated contour plot of the tunnel settlement caused by the excavation of each part under the two working conditions; the calculated values of the settlement at the arch bottom are extracted from the model results for comparison with the on-site monitoring results, as shown in Figure 9.

The following conclusions can be drawn from Figures 8 and 9:

(1) Under the two working conditions, the tunnel settlement influence range is relatively large. Regardless of whether the seepage effect is considered, the change trends of the tunnel displacement contour plots are very similar, and the maximum displacement is consistently concentrated at the arch bottom. On the one hand, after the excavation of the tunnel, the weak rock undergoes a large displacement due to the destruction of the original equilibrium state of the surrounding rock; on the other hand, the effect of the inverted arch is ignored in the numerical calculation and is considered only after the tunnel excavation. Initially lining the circumference of the tunnel, the support measures are used to effectively control the development of the displacement around the tunnel. However, the arch bottom is temporarily unsupported, so the maximum tunnel displacement appears at the arch bottom under both conditions.

(2) When the calculation is completed, the maximum settlement of the arch bottom of the tunnel is close to 4.6 mm under condition 1, which does not consider the fluid-solid coupling effect, and the maximum settlement of the arch bottom of the tunnel is 5.5 mm when the fluid-solid coupling effect is considered in condition 2. This is because the tunnel excavation causes the pore water to gradually seep into the tunnel, and the intensified seepage effect reduces the lithology of the surrounding rock. The seepage field and the stress field influence each other and then reach equilibrium with the consolidation and settlement of the surrounding rock. Under the action of seepage, the pore water pressure at the arch bottom of the tunnel is relatively high, which induces a

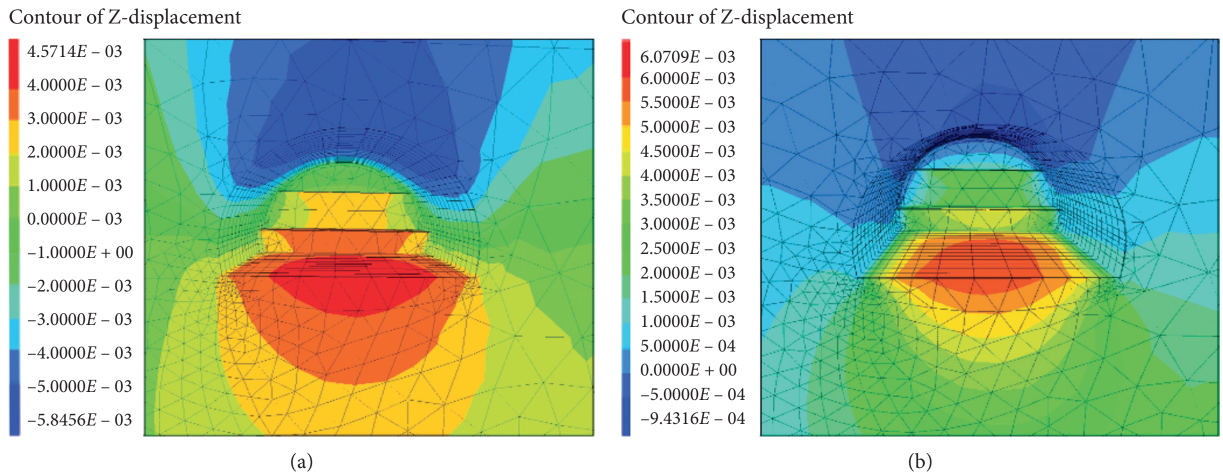


Figure 8: Contour of z-displacement: (a) condition 1; (b) condition 2.

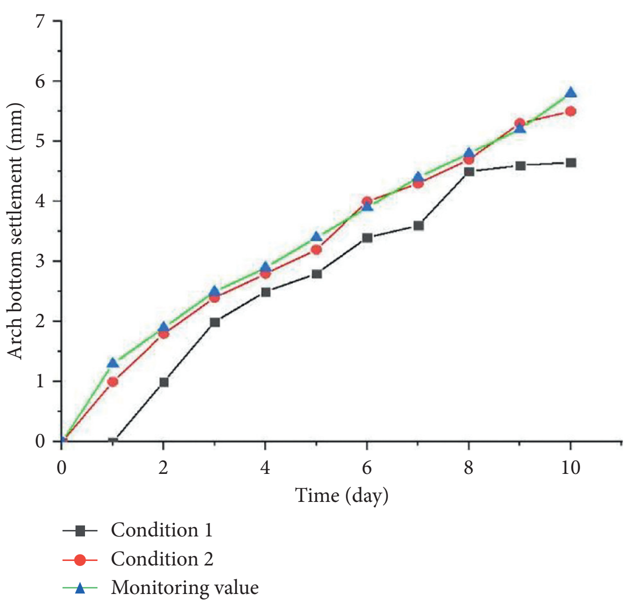


Figure 9: Comparison of calculated and measured values.

floating effect at the arch bottom and further increases the displacement of the arch bottom.

(3) When the calculation is completed, the maximum settlement of the arch bottom of the tunnel is close to 4.6 mm under condition 1 that does not consider the fluid-solid coupling effect, and the maximum settlement of the arch bottom of the tunnel is 5.5 mm when the fluid-solid coupling effect is considered in condition 2. This is because the tunnel excavation causes the pore water to gradually seep into the empty surface, the intensified seepage effect reduces the lithology of the surrounding rock, and the seepage field and the stress field disturb each other and then reach equilibrium, that is, the process of consolidation and settlement of the surrounding rock. Under the action of seepage, the pore water pressure at the arch bottom of the tunnel is relatively large, which has a floating effect on the arch bottom and further increases the displacement of the arch bottom.

4. Stress Analysis of the Support Structure

The transition section of the Laomushan Tunnel from soft to hard surrounding rock was excavated by the method of upper and lower steps, and C25 concrete was used for initial support after excavation. According to the Code for Design of Highway Tunnels, the shear strength, tensile strength, and compressive strength of C25 concrete are 1.8 MPa, 1.3 MPa, and 12.5 MPa, respectively. In this numerical simulation analysis, only the stress state of the initial support of the tunnel is considered. Figures 10(a) and 10(b) show the maximum tensile stress and the maximum shear stress change curves at the vault and the arch waist of the excavation face of the transition section of the tunnel, where the relative distance 0 m is the interface between the soft rock and the hard rock.

Figure 10 indicates that the maximum tensile stress and the maximum shear stress both occur at the right arch waist of the tunnel face in the transition section from soft to hard surrounding rock, with a maximum tensile stress of 1.19 MPa and a maximum shear stress of 0.85 MPa, which are less than the design values of the tensile strength and shear strength of C25 concrete, respectively. The design value of the primary support structure parameters of the Laomushan Tunnel can meet the strength requirements under the solid-fluid coupling effect; the stress concentration phenomenon occurs at the right arch waist of the face of the transition section because the strength of the grade V surrounding rock is low and the stress of the external support structure is high. Therefore, the parameters of the right arch waist and the lower half of the tunnel face near the rock support structure should be higher than those of the surrounding rock of the left arch waist. In addition, to avoid the phenomenon of water seepage caused by the local

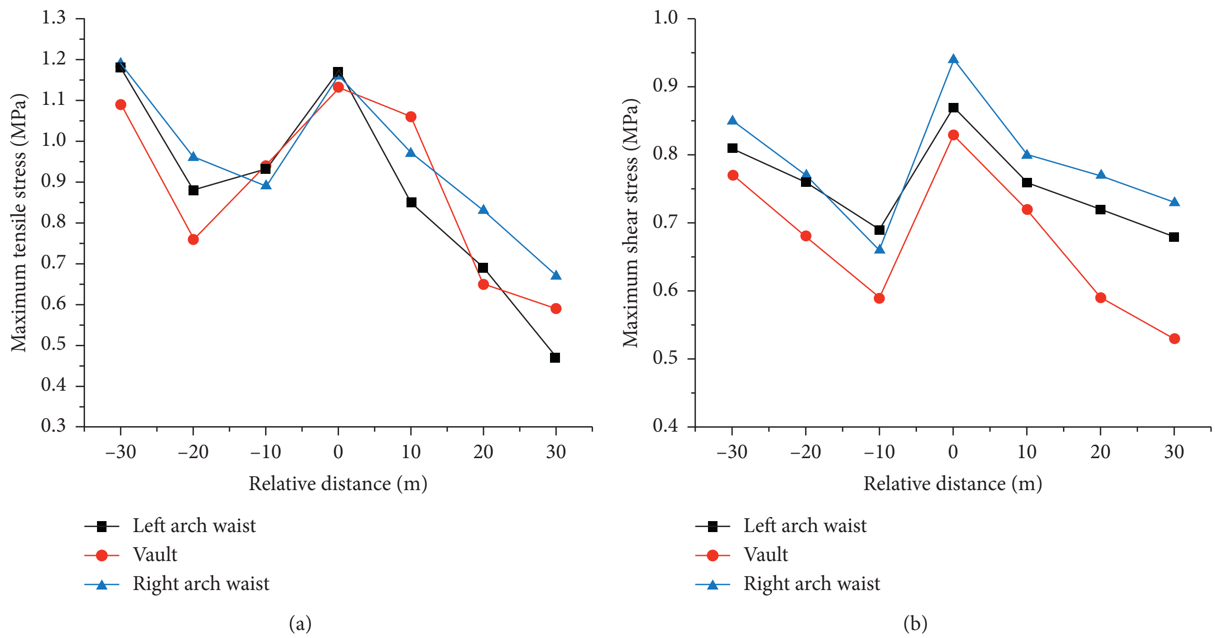


Figure 10: Stress attenuation curve of the lining: (a) maximum tensile stress and (b) maximum shear stress.

cracking of the right arch waist, a secondary lining should be implemented as soon as possible.

5. Conclusion

Through the numerical simulation study of the stability of the excavated transition section from soft to hard surrounding rock under the action of solid-fluid coupling, the following conclusions can be drawn:

(1) With the excavation of this transition section in the Laomushan Tunnel, the distribution of pore water pressure in the tunnel changed. With the increase in excavation steps, the pore water pressure in all parts of the tunnel face decreased and finally formed a funnel-shaped seepage field centered on the free face.

(2) The balance of the mechanical and seepage fields of the soft and hard surrounding rock transition section of the Laomushan Tunnel was destroyed by the drilling and blasting method. Considering the influence of the seepage field, seepage and stress concentration occurred at the arch waist and arch foot on both sides of the tunnel face, and the variation in pore water pressure was basically consistent with those of the stress and strain.

(3) Considering the displacement variation, the seepage effect had a great influence on the displacement of the transition section of the tunnel from soft to hard surrounding rock. Regardless of whether the seepage effect is considered, the maximum displacement was concentrated at the arch bottom. When considering the fluid-solid coupling effect, the settlement of the arch bottom further increased and was closer to the measured value. Therefore, the influence of the seepage field on the stability of transition section of the Laomushan Tunnel cannot be ignored.

(4) Based on the calculation of the fluid-solid coupling effect, the design value of the primary support structure parameters of the Laomushan Tunnel transition section of soft to hard surrounding rock basically met the strength requirements. However, to avoid water seepage caused by cracking of the weak rock layer from the right arch waist to the arch foot, secondary lining support should have been implemented as soon as possible.

Data Availability

The Laomushan Tunnel is 15.4 m wide and 8.5 m high. After excavation, C25 concrete is initially sprayed to line the tunnel walls, which is simulated with shell units. Considering the influence range of the excavation radius during excavation, the initial model size is $120\,m \times 70\,m \times 40$ m. During the modeling process, each grade of surrounding rock is regarded as a continuous homogeneous medium, and a hexahedral element model is used for simulation. The grade V surrounding rock changes to grade III surrounding rock along the direction of approximately 34° to the tunnel axis from the x-axis. The area near this surface can be approximated as a transitional section between the simulated soft and hard surrounding rocks. The pore water flow in the rock mass satisfies Darcy's law, and the pore water seepage in the rock mass is regarded as continuous medium seepage. The initial in situ stress only considers the self-weight stress of the rock mass, and the lateral pressure coefficient in the horizontal direction is taken as $\lambda = 1.1$. In the process of seepage calculation, the fluid-solid coupling calculation mode is enabled, the rock-soil unit is set to the isotropic seepage model (MODEL fluid fl-isotropic), and the lining is simulated by the shell element set to the impervious material model (MODEL fluid fl-null). The surrounding rock of the tunnel is mainly dolomite. According to the engineering geological survey report and the design code of highway tunnels, the corresponding surrounding rock mechanics are given. The natural porosity ratio is 0.67, the porosity is 0.5, and the permeability is $4.50 \times 10^{-10}\ m^2/(Pa \cdot s)$. The software's default Biot coefficient (biot_c) is 1.0, fdens1000, fmod2e9.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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