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Case study on the mechanics of NPR anchor cable compensation for large deformation tunnel in soft rock in the Transverse Mountain area, China

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Abstract: A study was conducted to analyze the deformation mechanism of strongly weathered quartz schist in the Daliangshan Tunnel, located in the western Transverse Mountain area. A large deformation problem was experienced during the tunnel construction. To mitigate this problem, a support system was designed incorporating negative Poisson ratio (NPR) anchor cables with negative Poisson ratio effect. Physical model experiments, field experiments, and numerical simulation experiments were conducted to investigate the compensation mechanical behavior of NPR anchor cables. The large deformations of soft rocks in the Daliangshan Tunnel are caused by a high ground stress, a high degree of joint fracture development, and a high degree of surrounding rock fragmentation. A compensation mechanics support system combining long and short NPR anchor cables was suggested to provide sufficient counter-support force (approximately 350 kN) for the surrounding rock inside the tunnel. Comparing the NPR anchor cable support system with the original support system used in the Daliangshan tunnel showed that an NPR anchor cable support system, combining cables of 6.3 m and 10.3 m in length, effectively prevented convergence of surrounding rock deformation, and the integrated settlement convergence value remained below 300 mm. This study provides an effective scientific basis for resolving large deformation problems in deeply buried soft rocks in western transverse mountain areas.

Key words: soft rock; large deformation; NPR anchor cable; physical model; numerical simulation; compensation mechanics

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1 Introduction

The national economy of any country is heavily reliant on transportation, which is essential to economic growth. As the economy of China continues to grow rapidly, the need for road construction and development is growing rapidly, particularly in the western mountainous regions. This construction is essential for narrowing the gap between residents and stabilizing the country's borders. However, these regions are characterized by numerous fracture zones, poor rock integrity, complex geological conditions, and large deformation of soft rocks with higher ground stress. Owing to these field conditions, some tunnel constructions have experienced deformations exceeding 1 m. Therefore, controlling large deformations of surrounding rocks in these areas has become a top priority while constructing highway tunnels [1].

Several studies have been conducted on tunnels with soft rock large deformation. Deformation mechanism aspects: LI et al [2] studied the creep characteristics of rock by conducting shear experiments under different seepage pressures, providing a scientific basis for the support of seepage tunnels. LI et al [3] optimized the parameters of anchor cable based on the longitudinal wave velocity of rock mass in soft rock tunnel. PENG et al [4] studied the deformation characteristics of soft and weak interlayer surrounding the rock of tunnels, and analyzed its mechanical response mechanism. TANG et al [5, 6] investigated the short- and long-term effects of the water on sandstone, which led to patterning effects on sandstone. YIN et al [7, 8] examined the shear mechanical response of granite after water quenching cycle under conventional triaxial compression and sandstone under thermal loading with the same normal stiffness boundary conditions, which provided a scientific basis for the research on the support of high-temperature water-bearing tunnels. REN et al [9] studied the rock burst characteristics and precursors under static and dynamic triggering conditions from the perspective of multifractal theory, and they made contributions to the research of deeply buried rock burst tunnels. Numerical simulation and physical modeling experimental aspects: TANG et al [10, 11] performed numerical simulations to study the deformation characteristics of tunnel bottom drums and the cracking behavior of non-homogeneous brittle solids under thermal shock, contributing to the optimization of bottom drums in tunnels. ZHU et al [12] used numerical simulation techniques to study the fatigue failure characteristics of water-bearing sandstone under cyclic load, providing the scientific basis for the stability of rock mass under the condition of water-bearing sandstone background. LI et al [13] used the similar method to study the behavior of arch roof support in deep tunnels and concluded that the high preload anchor cable can compensate for the mechanical support of surrounding rock. SUN et al [14] investigated the movement law of the surrounding rock mass after tunnel excavation by establishing a similar physical model.

Previous studies have made significant contributions to the understanding of movement laws of tunnel surrounding rock. However, they did not focus on the mechanism and control method for large deformation areas of soft rock. The present study aims at investigating the compensation mechanics in NPR anchor cable active support using the engineering geological background of Daliangshan. The study involves evaluation of different support schemes and experimental and mechanical analysis of NPR anchor cable mechanics considering the Dalangshan tunnel. Physical model experiments, field monitoring and numerical simulation experiments are used to evaluate the NPR anchor cable support system in Dalangshan tunnel. The results provide a scientific basis for dealing with large deformation tunnels in soft rock not only in Sichuan-Tibet region but also other regions.

2 Geological overview of Daliangshan tunnel project

2.1 Engineering geology background

The Daliangshan tunnel is a crucial control section for the construction of the Yunnan Linqing Expressway, situated within Yunxian County, Lincang City, Yunnan Province, China. It has a total length of 10210 m and a maximum burial depth of 1199.53 m. It is located in the western transverse mountain region, which characterized by high and middle mountain tectonic denudation geomorphology. Additionally, due to the collision and extrusion between Asia-Europe plate, Pacific plate and Indian Ocean plate (Himalayan Fracture Zone), a "three high" zone with elevated ground stress levels, extensive joint development and fissures with significant fragmentation of surrounding rock, has developed in this region.

The surrounding rocks of the Daliangshan tunnel mainly belong to the strongly weathered quartz schist. It is powdery and the color alternates between gray-white and black. The rock mass contains a large amount of clay filling that is primarily thin-layered, fractured and loose. It has poor mechanical properties and softens to mud when it comes in contact with water. Overall, the surrounding rock has poor mechanical properties, having a greater impact on the stability of the surrounding rocks. There are 17 large fracture zones in the whole section of the tunnel, with a dip angle of about 83°, resulting in complex geological environment and characteristics, as shown in Figure 1.

2.2 Analysis of large deformation of original support system for the tunnel

The original support scheme of the Daliangshan tunnel adopts the principle of NATM method support, which is essentially a low-stress compensation support method. After tunnel excavation, the surrounding rock is supported in time to give full play to the self-supporting capacity of the tunnel surrounding rock. Whereas, for deeply buried tunnels, low stress compensation does not allow for stress recovery in the surrounding rock, and it does not allow for timely compensation of stresses. After tunnel excavation, the minimum principal stress σ_3 of the surrounding rock decreases to zero, and the maximum principal stress σ_1 would produce a stress concentration and increase to twice the original maximum principal stress, which ultimately leads to the damage of the surrounding rock of the tunnel.

Figure 1 shows the soft rock deformation area of the Daliangshan tunnel, which has three large fracture zones and severe rock fragmentation. During tunnel construction, there were frequent occurrences of vault sinking, intrusion extrusion, uneven convergence of falling blocks on both sides of the tunnel, and serious damage to the tunnel profile. Even after installing ordinary anchor cable support, the maximum convergence rate remained at 20−50 mm/d with local twisting and deformation of I-beams. Following the addition of initial arch processing support in section K20+320-K20+131 near the right-side road centerline elevation, arch filling caused cracking and bulging up to 60 cm. In section ZK20+012-ZK20+083, longitudinal cracks and concrete crush damage appeared on both sides of arch waist of the second lining concrete, as well as at its top. Furthermore, the ring main reinforcement showed V-shaped twist. Despite several attempts to replace support systems in the Daliangshan tunnel, initial support cracking and falling blocks, as well as steel frame distortion, occurred due to varying forms of deformation and damage, resulting in a large cumulative deformation around the tunnel's surrounding rocks. There was evident dominant part and direction of deformed sections with high magnitude and durations, causing side wall convergence up to meter-long deformations, while the support deformation exhibited a hysteresis effect. This is consistent with characteristics associated with large deformations of soft surrounding rock extrusions.

Figure 2 illustrates the self-advancing anchor cable support system used in the tunnel. Settlement

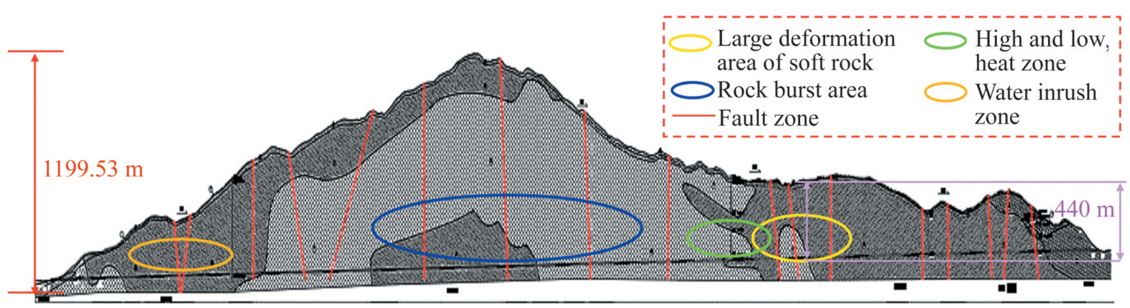

Figure 1 Progress map of the Daliangshan tunnel

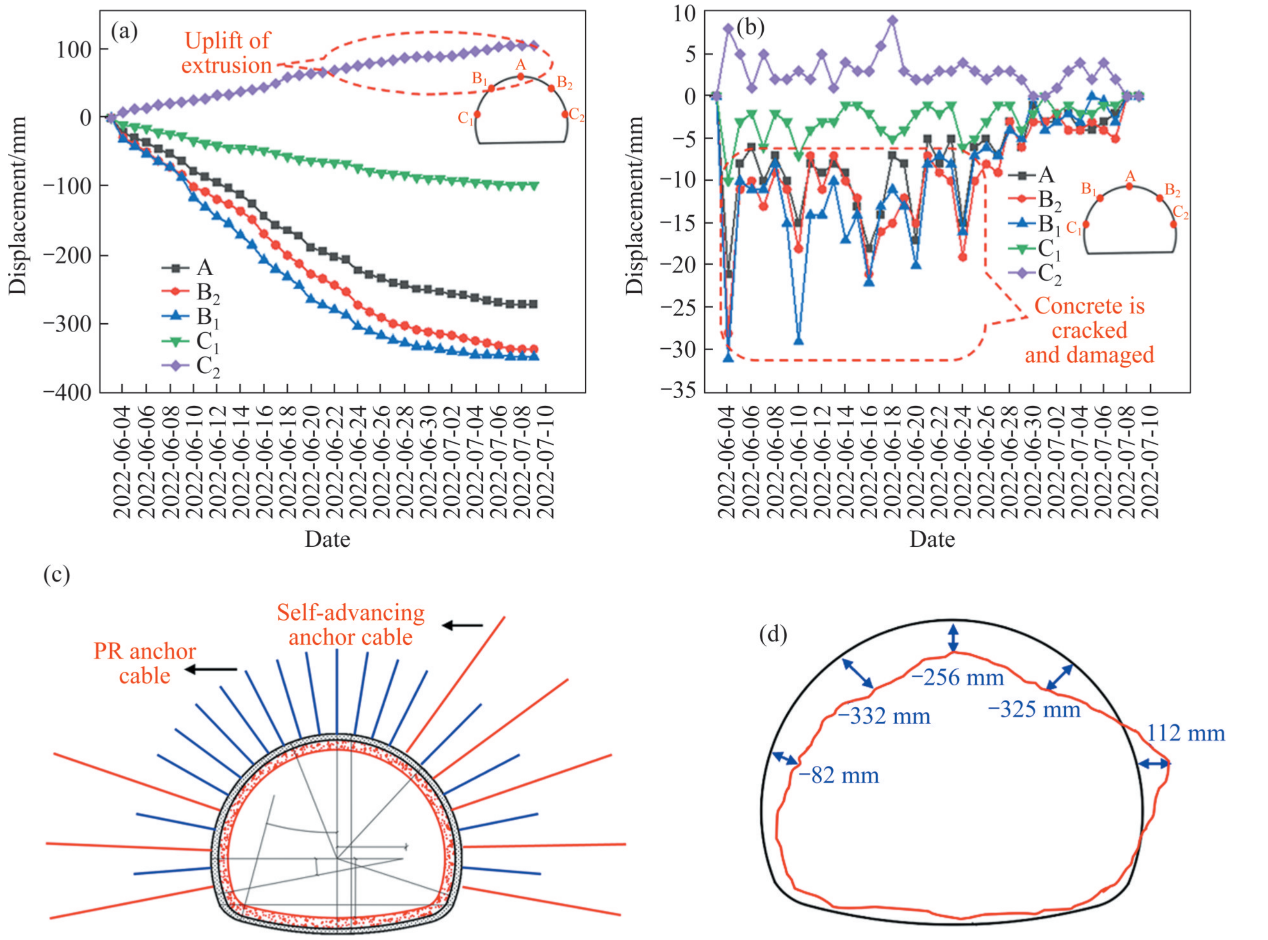

Figure 2 Self-advancing anchor cable support scheme: (a) Accumulated displacement; (b) Daily settlement; (c) Self-advancing anchor cable support scheme; (d) Tunnel deformed asymmetrically

of the surrounding rock was observed on both sides of the spanners, with a maximum displacement of up to 332 mm. Asymmetrical development was observed on both sides of the arch, with subsidence (82 mm) on the left and intrusive extrusion (112 mm) on the right. Consequently, despite replacing the self-advancing anchor cable support, significant asymmetric deformation still occurred in the Daliangshan tunnel. This indicates that self-advancing anchor cable support alone cannot effectively restrain the surrounding rock deformation.

3 Mechanical mechanism of NPR anchor cable excavation compensation

NPR anchor cable is a support structure with negative Poisson ratio effect. When a traditional material is subjected to an impact load, the material compresses under the impact force and flows from the impact part to the four sides in a direction perpendicular to the impact. However, the negative Poisson material is compressed in the impact direction and contracted on the side, and the material flows towards the impact site. This phenomenon increases the local density of the material, resulting in a more effective resistance to indentation. Studies show that under the same initial density conditions, materials with negative Poisson ratio exhibit higher yield strength than the traditional materials.

NPR anchor cables are composed of constant resistors, strands, trays, and locks [15, 16]. The working of the NPR anchor cable can be divided into three stages: elastic deformation support phase, structural sliding constant resistance support phase, and ultimate deformation support phase. In the elastic deformation support stage, the tension in the rock mass is less than the designed constant resistance value of the NPR anchor cable, thus

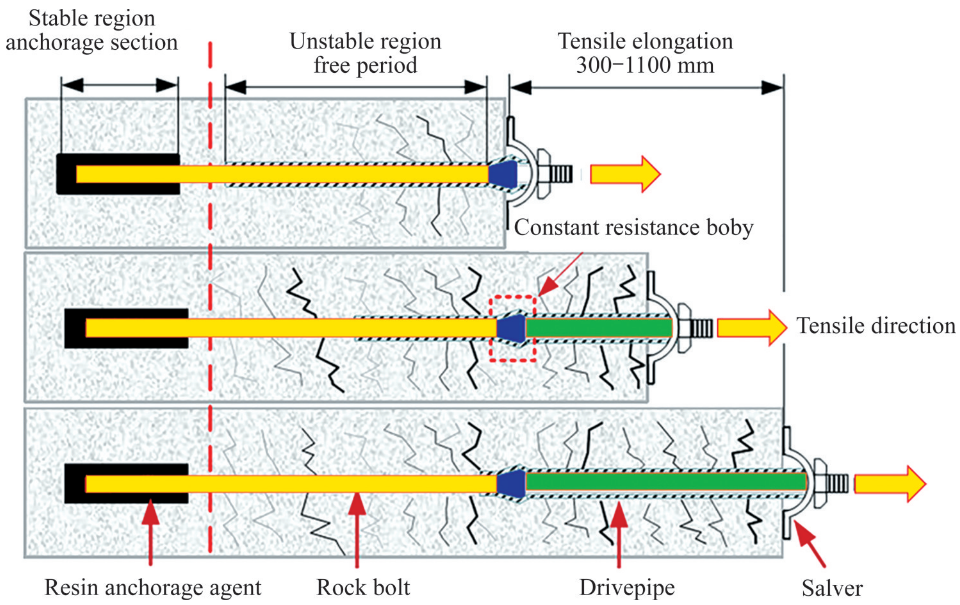

Figure 3 Composition and supporting principle of NPR anchor cable [18]

causing elastic deformation in the cable. In the structural sliding constant resistance support stage, the damage to surrounding rocks is significant and force acting on the anchor cable exceeds its designed range of constant resistance values. This triggers the sliding of a rod within a sleeve, thus absorbing energy generated by damage through stretching and sliding. This prevents failure or fracture of the anchor rod due to large deformations in engineering rock masses. Finally, during the extreme deformation support stage, large deformations occur in surrounding rocks around roadways, reaching new equilibrium states under mechanical compensation from NPR anchor cables [17, 18], as shown in Figure 3.

The compensation mechanics of NPR anchor cables rely on their exceptional mechanical properties. The dynamics of a single NPR anchor cable was investigated using a static tension system, including the Hopkinson dynamic loading apparatus and ODE45 iterative program. The experimental results are presented in Figure 4 [19].

The static tensile test results showed that the NPR anchor cable exhibited favorable stretching characteristics. After surpassing a stretching length of approximately 100 mm, the cable entered a constant resistance phase, where its overall stretching length could reach up to 790 mm. During this period, the average value of constant resistance remained stable at around 350 kN. Additionally, results from Hopkinson kinetic experiment revealed that when subjected to dynamic impact, the NPR anchor cable experienced an initial peak force within 1 ms, with a peak value of roughly 538.9 kN. The force soon recovered to zero after just 10 ms due to a frictional slide between the constant resistance body and casing, which induced structural deformation in the anchor rod. These findings suggested that the NPR anchor cable has excellent adaptability to dynamic impacts.

Since the NPR anchor cable primarily relies on the frictional resistance between the constant resistance body and the constant resistance casing to resist the external force, it was important to study the time history curves of the dimensionless velocity and acceleration of the system under the variation of the sliding friction coefficient μ_d, as shown in Figures 4(c) and (d). It can be seen that the time profile of the system acceleration exhibited intense periodic oscillations after entering the viscous slip phase, and the oscillation amplitude decreased with the increase in the dynamic friction coefficient. The amplitude of the viscous slip motion reached 0.2 when μ_d=0.35. The amplitude of the viscous slip motion reached 0.09 when μ_d=0.45, whereas the amplitude became 0.04 when μ_d=0.55. At μ_d=0.65 and 0.75, the amplitude was further reduced to a negligible level, with an average reduction of about 55.0%. It can be seen in Figure 4(d) that when μ_d<0.6, the first response

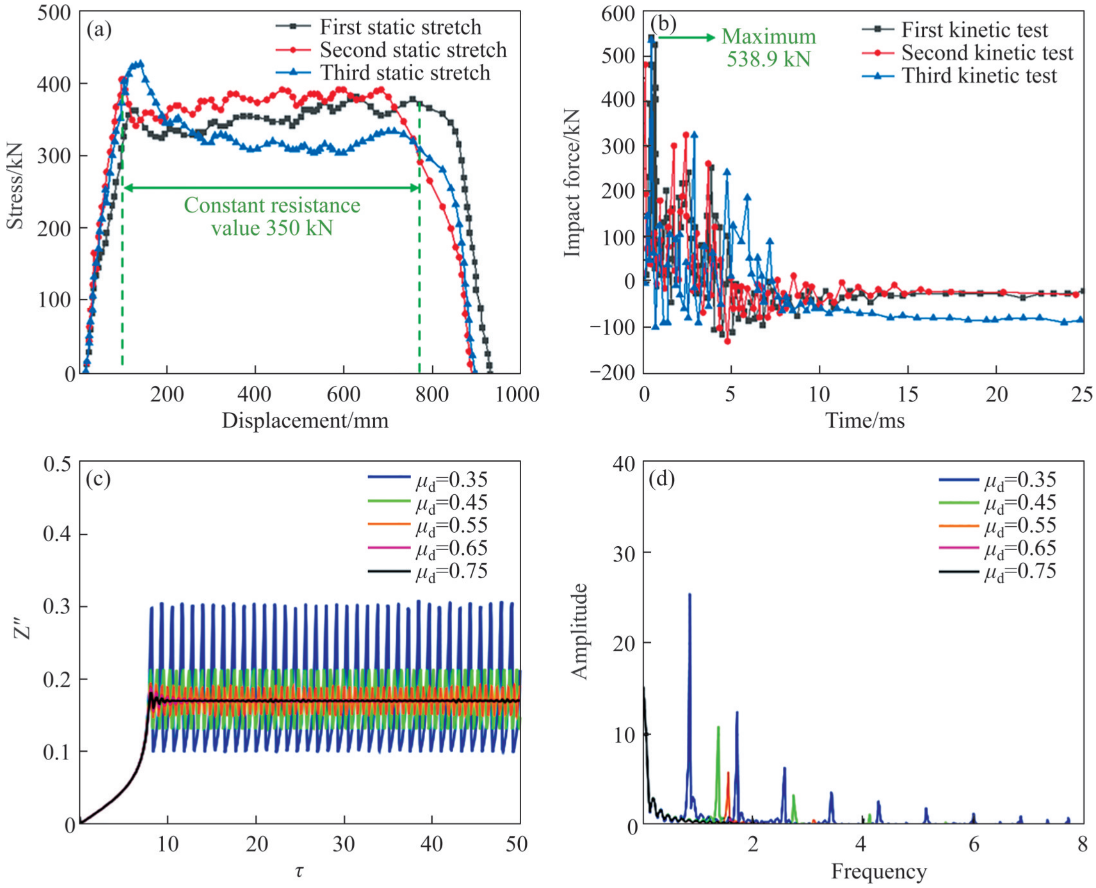

Figure 4 Experimental analysis of NPR anchor cable mechanics: (a) Static tensile test; (b) Dynamic impact test; (c) Influence of friction coefficient between constant resistance body and constant resistance casing on acceleration (Z'': Dimensionless acceleration; τ: Dimensionless time) [19]; (d) Effect of friction coefficient between constant resistance body and constant resistance casing on spectral response of acceleration (Frequency and Amplitude: Dimensionless) [19]

frequency of the acceleration, i. e., the combined force, shifted to the right as μ_d increased, corresponding to values of 0.86, 1.38, and 1.56, respectively. The response curve of acceleration when $\mu_d \geqslant 0.65$ was approximately horizontal and the oscillation gradually disappeared, so the low-frequency signal predominated instead.

4 Experimental study of physical model under NPR anchor cable support

This study further involved investigations of the deformation law of surrounding rock near K20+009, which was buried at a depth of 440 m. A physical model with a scaling ratio of 1: 50 was designed based on mechanical parameters and relevant theories. A proportional scheme was also followed for the design of NPR anchor cable. Initially, static tensile experiments were conducted on the actual NPR anchor cable using the static tensile test equipment to obtain its constant resistance value. Small indoor tensile machines were then used to conduct similar experiments on 3D-printed NPR anchor cables until an appropriate specimen was selected for testing in the physical model experiments. These tests were carried out using a hydraulically loaded experimental system with model sizes of 1600 mm×40 mm×1600 mm to monitor the changes in surrounding rock during the tunnel excavation with NPR anchor cable support. The physical model was monitored using both digital speckle (DIC) monitoring system and stress−strain data acquisition instrument measurement (Figure 5).

The burial depth of the tunnel in the soft rock large deformation area was found to be approximately 440 m based on geological exploration. The vertical stress and horizontal stress were about 10.6 MPa and 14.4 MPa, respectively. Using the stress similarity ratio, it was concluded

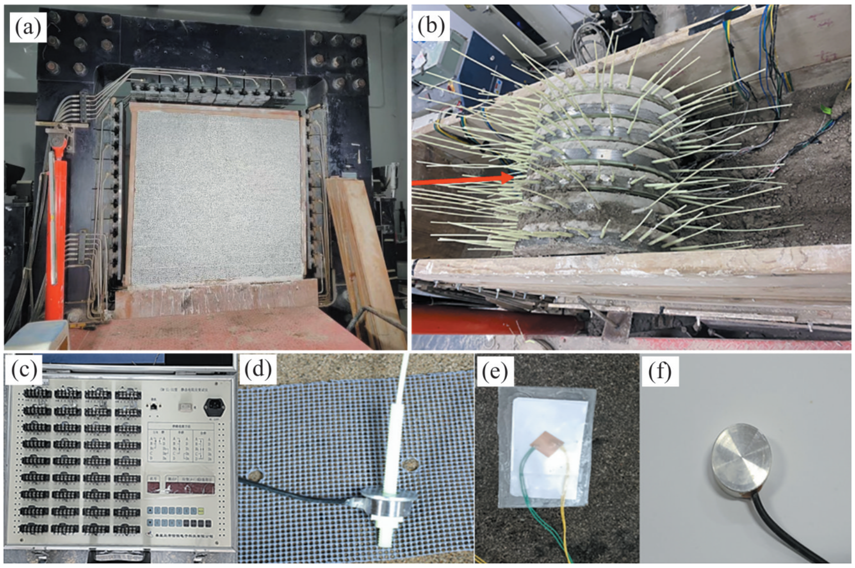

Figure 5 Test monitoring equipment and scheme design: (a) Three-dimensional loading tester; (b) Tunnel and NPR anchor cable; (c) Stress and strain sampling instrument; (d) Axial force meter; (e) Strain gage; (f) Pressure cell

that the vertical stress of the physical model closely matched the actual buried ground stress at 0.2 MPa. At a simulated buried depth of 660 m, the stress was approximately 0.3 MPa, whereas the stresses were 0.4 MPa and 0.5 MPa at simulated depths of 880 m and 1100 m, respectively. Therefore, this proved that the compensating mechanical behavior of NPR anchor cables can be applied to support soft rock large deformation tunnels over extended distances (kilometer level). Figure 6 shows the pressurization process with all pressures being vertical pressures.

4.1 DIC monitoring and analysis

Figure 7 shows that the surrounding rock near section K20+009 experienced significant asymmetrical displacement due to its stress

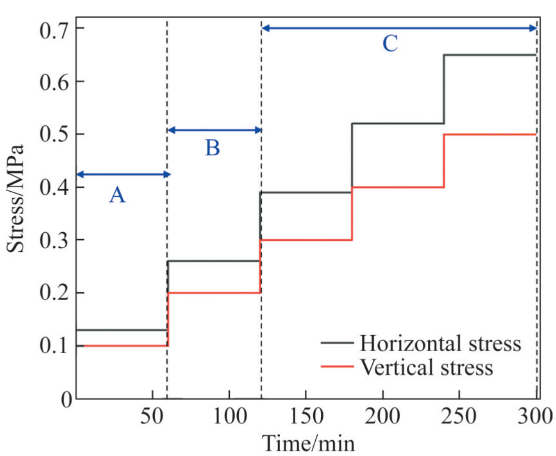

Figure 6 Stress loading path (A−Proto-rock stress stage; B−Actual depth stress phase; C−Overload stage)

asymmetry. Settlement and collapse dominated on the left side of the tunnel, while extrusion and uplift dominated on the right side. The vertical displacement distribution under actual tunnel burial conditions with NPR anchor cable support was simulated at 0.2 MPa, while the rock movement under overload conditions of K20+009 section with NPR anchor cable support was simulated at 0.3−0.5 MPa. As the excavation and overload pressures increased, there was a corresponding increase in the vertical displacement of the surrounding rock of the tunnel. However, the maximum displacement of the tunnel after full excavation was about 3.6 mm, indicating that NPR anchor cables had strong restraint effects on the surrounding rock.

Following the completion of the top-step excavation, there was an overall settlement displacement of approximately 1.6 mm on the left side of the tunnel. The right side experienced relatively small displacement. During the excavation of the middle step, there was a small-scale large settlement of about 1.9 mm in both the left arch roof and shoulder. As the excavation progressed to the next step, the settlement range on the left side expanded further. At this stage, bulge displacement at the right arch shoulder was about 0.2 mm due to the asymmetric extrusion of rock on the left side. Vertical pressure increased as overloading and pressurization increased, causing

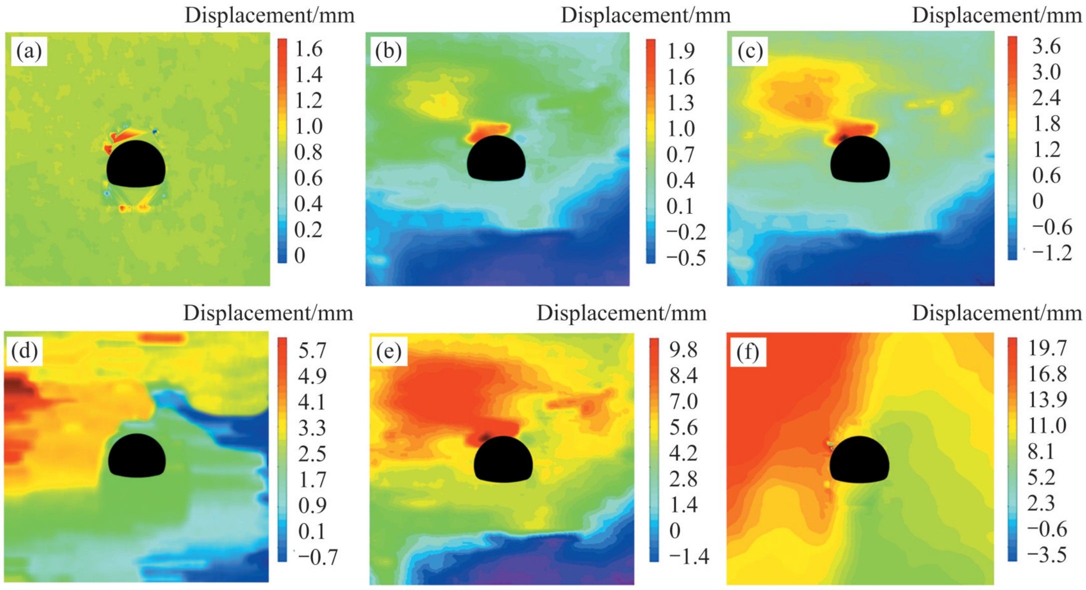

Figure 7 Contour diagram of vertical displacement obtained using DIC: (a) Upper step excavation (0.2 MPa); (b) Middle step excavation (0.2 MPa); (c) Lower step excavation (0.2 MPa); (d) Overload pressurization 0.3 MPa; (e) Overload pressurization 0.4 MPa; (f) Overload pressurization 0.5 MPa

both left and right displacement settlements and uplifts to continue expanding until they reached a joint position. However, due to compensating mechanical support from NPR anchor cables, overall tunnel collapse was minimal, allowing for retention as a whole unit.

4.2 Stress−strain monitoring and analysis

The DIC monitoring technique was used to examine the collapse of the model surface and analyze the deformation mechanism of the rock surrounding the tunnel from its surface. Strain gauges, earth pressure boxes, and anchor cable axial force gauges were utilized to monitor displacement and force within both the surrounding rock and steel arch to gain a more comprehensive understanding of the deformation state inside the tunnel. The resulting monitoring curves were depicted in Figure 8.

For linearly elastic materials, the relationship between strain and displacement can be expressed in terms of Hooke's law, where the displacement is obtained by multiplying the data monitored by strain gauges by the initial length. Figure 8(a) shows that both the strain monitoring and digital image correlation (DIC) monitoring results were similar. The tunnel had obvious asymmetric deformation, and the maximum settlement of the tunnel after full excavation is basically maintained at about 4 mm with excellent supporting effect. The overall surrounding rock primarily experienced settlement, while the right arch waist deformation was extrusion projection with deformation of approximately 2.6 mm. From Figure 8(b), it can be seen that the overall force on the tunnel envelope shows an increasing trend with increasing excavation steps and pressure values. A larger force of about 7.9 kPa was observed on the left side compared to the force of 7.5 kPa on the right side. It can be observed from Figure 8(c) that during the initial tunnel excavation stages, stress variations in steel arches were minimal, and they predominantly experienced tension. However, with complete excavation of the tunnel and increasing vertical stress levels, the forces transformed from tension to pressure. Finally, Figure 8(d) depicts the stress curve of the NPR anchor cable exhibiting an oscillating upward trend throughout its length. Even when subjected to pressures up to 0.5 MPa, NPR anchor cables did not fail, confirming their excellent stress compensation effect in supporting deeply buried soft rock large deformation tunnels.

4.3 Pressure monitoring and analysis of surrounding rock of the tunnel

To study the evolution mechanism of surrounding rock around the tunnel with NPR anchor cable support, stress monitoring points were

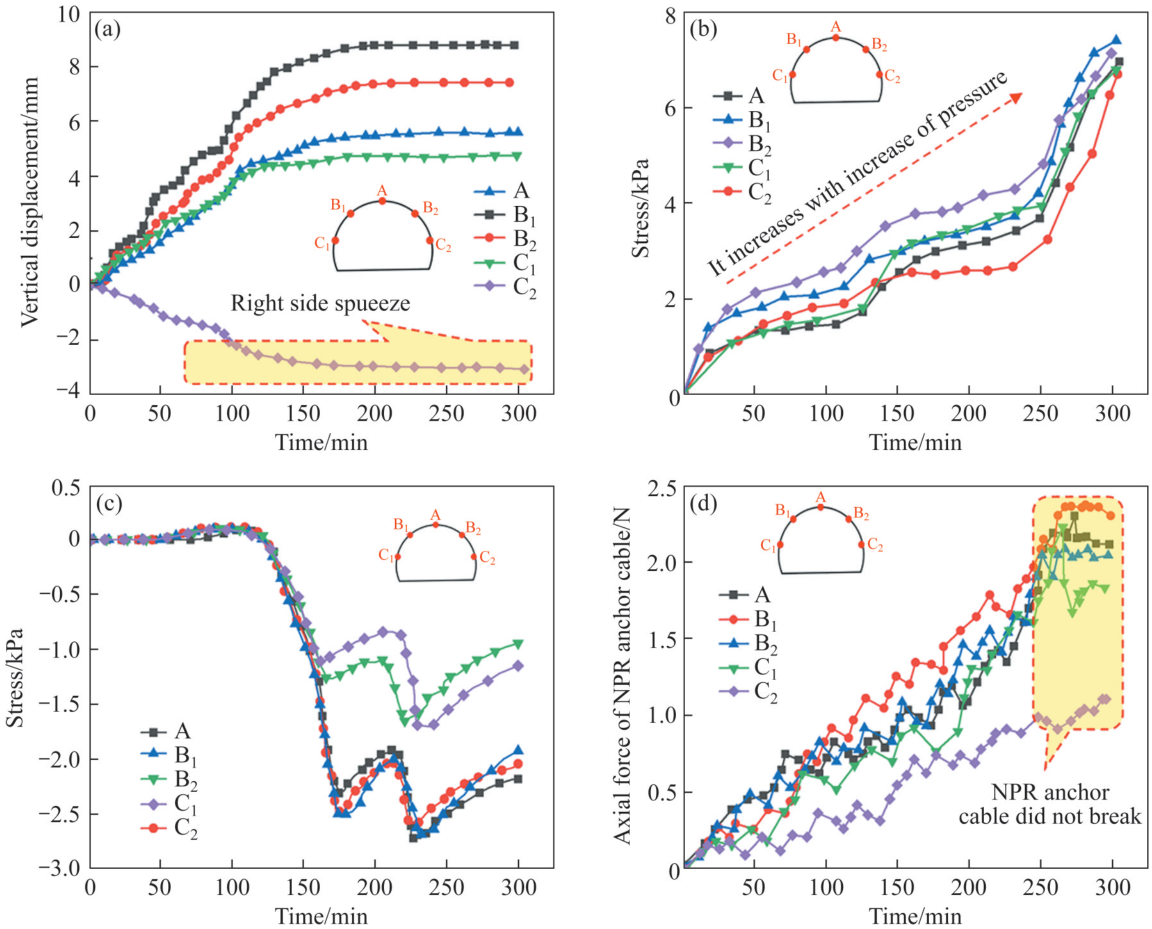

Figure 8 Strain−displacement monitoring diagram: (a) Monitoring of strain; (b) Surrounding rock stress monitoring; (c) Stress monitoring of steel arches; (d) NPR anchor cable axial force monitoring

set up in four layers (eight for each layer) around the tunnel. Stress data were recorded in two stages: complete excavation and maximum overload. This allowed for analysis of the compensation mechanical support effect of NPR anchor cable, as shown in Figure 9. Since the stress variation during upper and middle step excavation was minimal, only the numerical distribution of stress under full excavation and final overload is presented in Figure 9.

The figure shows that the stress value decreased as the monitoring profile increased. After overloading and pressurization, the inner ring experienced a greater increase in stress growth than the outer ring. The left side of the tunnel had a higher stress value than the right side; however, there was a larger growth rate on the right side. Stress concentration occurred mainly in the vault and spandrel of the tunnel face. The overall stress value of surrounding rock with the NPR anchor cable support was low, indicating an effective control effect of loose circle. Therefore, it can be concluded that NPR anchor cable had significant compensation mechanical control effects on tunnel stresses.

4.4 Temperature field monitoring and analysis

Friction is caused by the movement between rock masses, which leads to an increase in internal temperature. The temperature field is determined by shear damage within the rock (which causes a temperature rise) and tensile rupture (which results in lower temperatures). Physical model experiments following the tunnel excavation often reveal frictional tension and shear damage to the surrounding rock. Therefore, studying variations in the temperature field can help to understand the overburden movement characteristics of the tunnel envelope and the infrared radiation mechanism of rocks.

Figures 10(a), (b) and (c) illustrate the variation in temperature during the tunnel

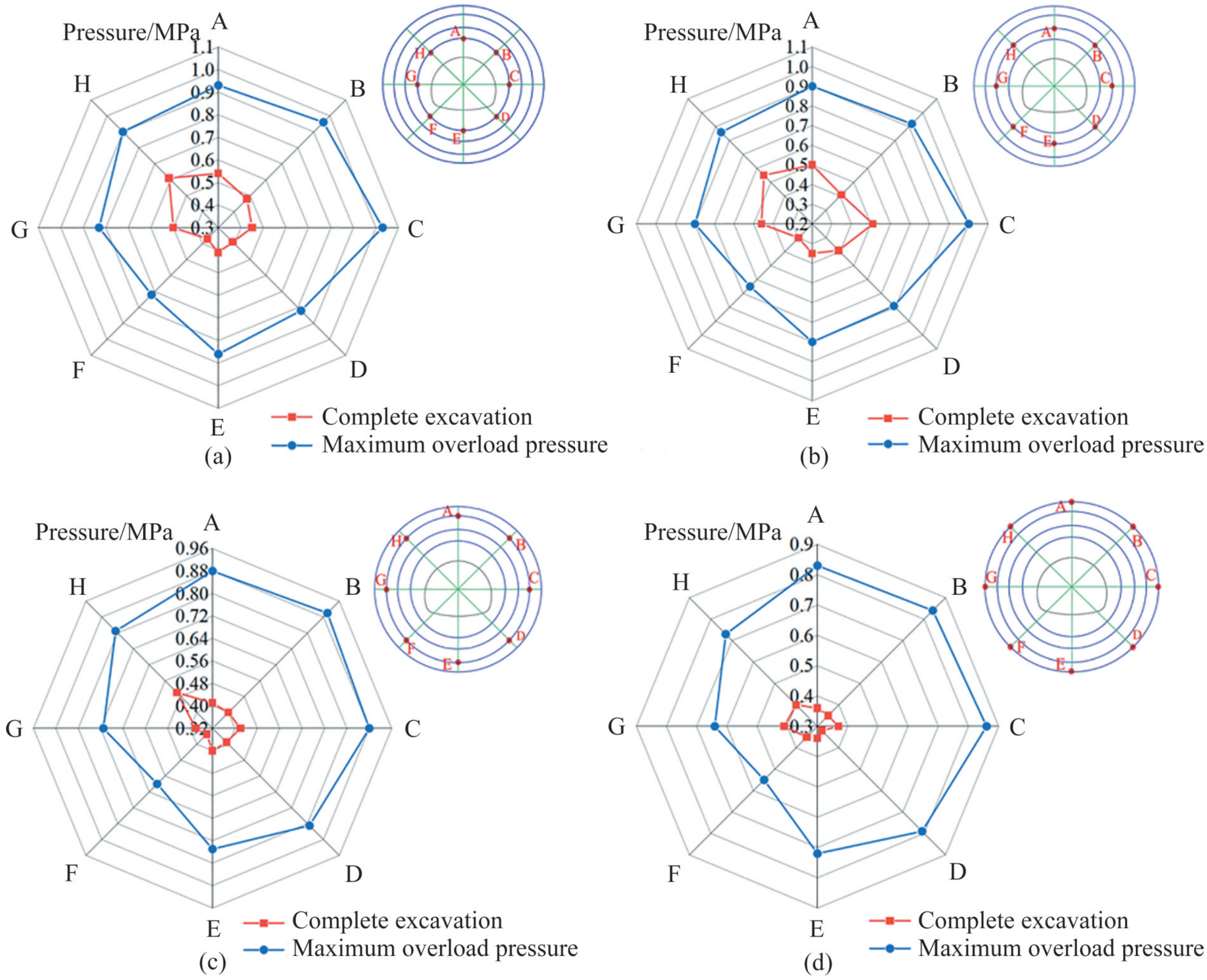

Figure 9 Tunnel surrounding rock stress monitoring: (a) The first layer stress monitoring; (b) The second layer stress monitoring; (c) The third layer stress monitoring; (d) The fourth layer stress monitoring

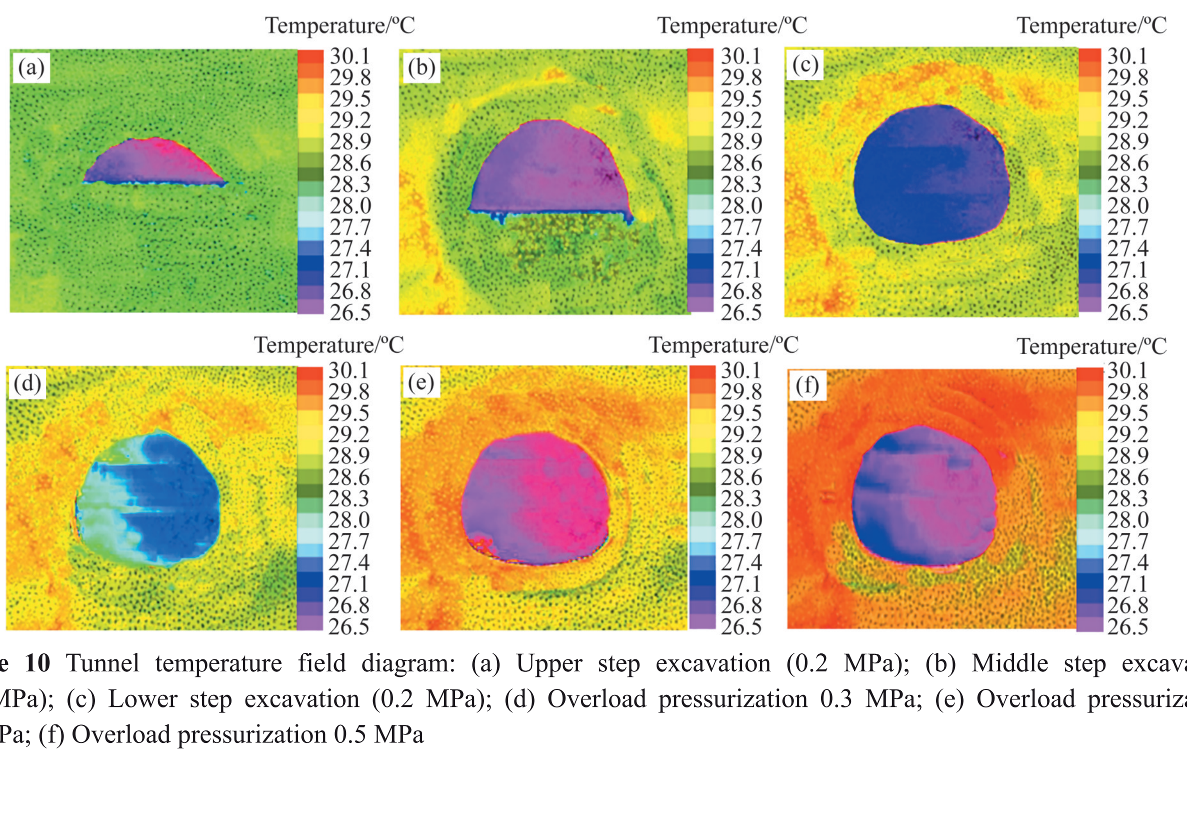

Figure 10 Tunnel temperature field diagram: (a) Upper step excavation (0.2 MPa); (b) Middle step excavation (0.2 MPa); (c) Lower step excavation (0.2 MPa); (d) Overload pressurization 0.3 MPa; (e) Overload pressurization 0.4 MPa; (f) Overload pressurization 0.5 MPa

excavation process. The temperature of the surrounding rock remained stable at approximately 28.6 ℃ after the upper step was excavated. However, there was minimal temperature change at the left and right arch shoulders following excavation of the middle step. Some areas at the top of the tunnel arch experienced an increase in temperature to 29.5 ℃ , indicating that shear deformation occurred in the surrounding rock. Following the completion of excavation for lower step, movement trend of surrounding rock expanded further, with temperatures near upper step reaching about 29.8 ℃. Despite certain shear changes caused by tunnel excavation that resulted in a rise in temperature, the majority of regions were transformed into low-temperature zones, which proves that NPR anchor cable is effective in controlling deformation of surrounding rock, thereby minimizing collapse degree around tunnels.

The overload pressurization can be seen in Figures 10(d), (e) and (f). As the overload pressurization increased, shear damage occurred in the surrounding rock of the tunnel to a greater extent. Additionally, the temperature rose from 29.8 ℃ to 30.1 ℃. The lower step of the tunnel experienced a temperature shift that was dominated by tensile damage with a lower temperature, whereas both middle and upper steps were dominated by higher-temperature shear damage.

5 Field analysis of NPR anchor cable support

The compensating mechanical behavior of NPR anchor cable was implemented in the Daliangshan Tunnel for field analysis. The left tunnel ZK19+927 was monitored as a test section (tensile test), with data including monitoring of NPR anchor cable axial force and surrounding rock settlement. The mechanical mechanism of the tunnel support structure was clarified by analyzing this data. This analysis demonstrated the remarkable mechanical characteristics of the NPR anchor cable for excavation compensation of large-deformation tunnels in soft rock and transverse mountain areas. Figure 11 shows the design scheme of this support system.

Figure 11(a) illustrates that the section support of Daliangshan tunnel was upheld by a combination of long and short NPR anchor cables, with diameter of 21.8 mm and length of 10300 mm and 6300 mm, respectively. Figure 11(b) depicts the supporting system using the NPR anchor cable, which included W steel belt, flexible netting, and resin anchor

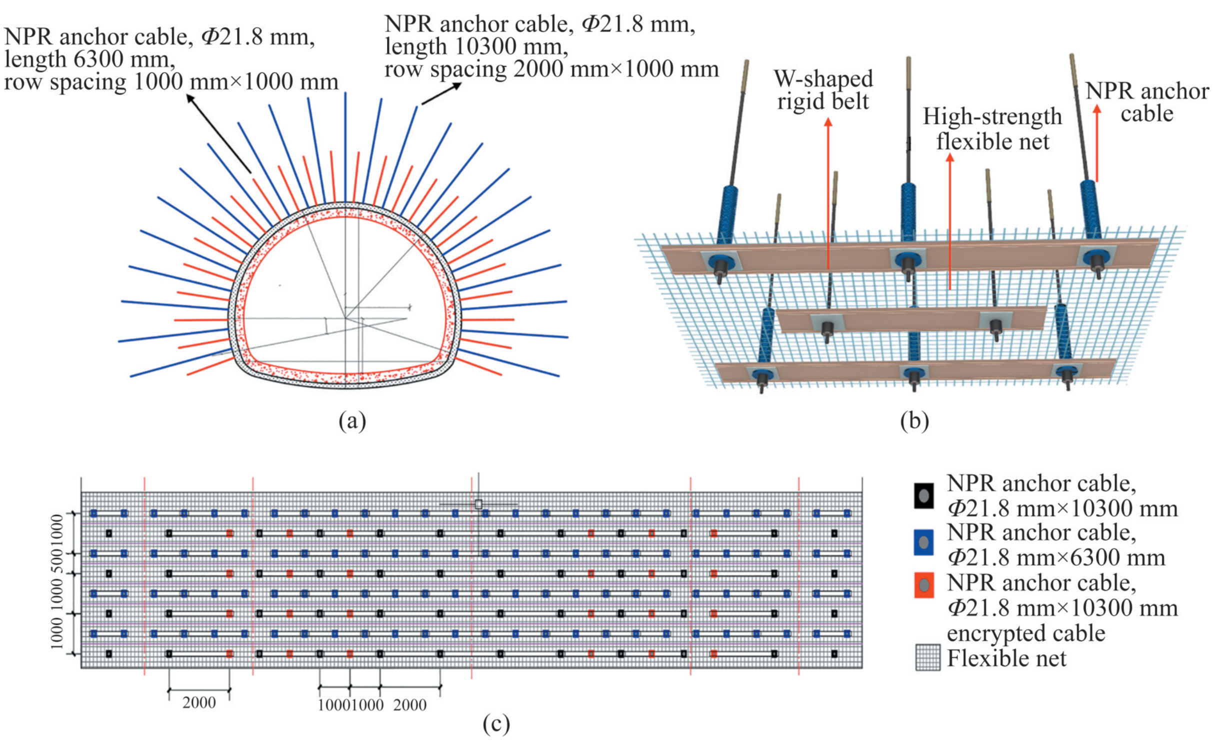

Figure 11 Design of NPR anchor cable in Daliangshan Tunnel: (a) NPR anchor cable support design; (b) NPR anchor cable support system; (c) Tunnel annular arrangement of the NPR anchor cable (unit: mm)

agent, and it maintained a constant resistance value around 350 kN. The annular layout diagram for the NPR anchor cable in Daliangshan tunnel is shown in Figure 11(c). Long and short NPR anchor cables were used as normal support, while encrypted NPR anchor cables served as backup to control the deformation of surrounding rock in more broken areas of the tunnel.

Figure 12(a) displays the axial force monitoring data of the NPR anchor cable after installation. The YL-DSG anchor cable force gauge was installed at the end of the NPR anchor cable. It can be observed that the axial force of the NPR anchor cable stabilized at approximately 340 kN, which satisfied the design requirements. The axial force change of NPR can be divided into three phases: (A) elastic deformation; (B) elasto-plastic deformation with constant resistor slip; and (C) stable phase. In the elastic phase, a linear growth trend was observed in the axial force. The elastic-plastic deformation phase exhibited an oscillation period while maintaining a constant resistance value during its stable phase (approximately 340 kN). Figure 12(b) depicts displacement settlement monitoring curve where the maximum settlement displacement occurred around tunnel surrounding rock. The displacement reached up to 170 mm with the settlement displacement varying in the trend of arch shoulder>arch top>arch waist. The minimum settlement displacement was recorded in the around arch waist at about 40 mm on average, thus proving the effectiveness of NPR anchor cables in controlling the deformation of surrounding rock in the Daliangshan Tunnel through compensating mechanics. It can also be seen from Figure 12(c) that the mechanical properties of NPR anchor cable were about 3 times that of ordinary anchor cables, further proving that the compensatory mechanical behaviors of NPR anchor cable are effective for large-deformation tunnels in soft rock.

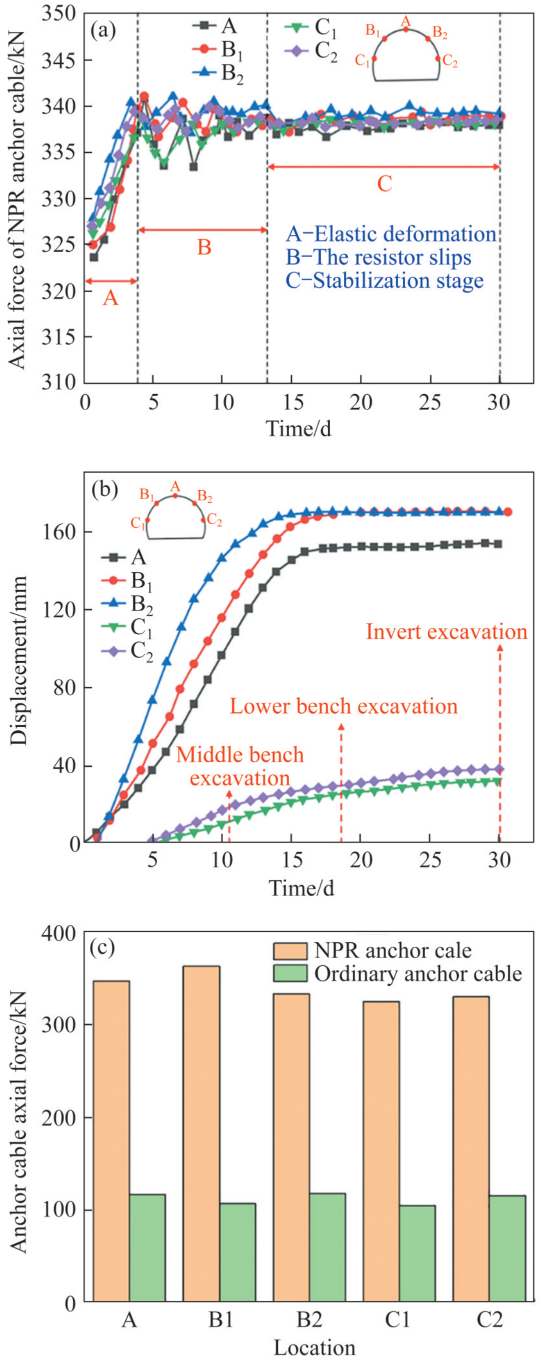

Figure 12 Schematic diagram of NPR anchor cable field experiment monitoring: (a) NPR anchor cable axial force monitoring; (b) Displacement settlement monitoring; (c) Comparison of anchor cable axial forces

6 Numerical simulation experimental study on NPR anchor cable support

Based on physical model experiments and field monitoring data, it can be concluded that NPR anchor cables have an exceptional compensating mechanical effect on soft rock large deformation tunnels. To further verify this behavior, a numerical simulation model was developed using FLAC^{3D} software [20]. The size of the model were 50 m×25 m×50 m. The model was created according to the field support scheme, with the goal of confirming changes in the state of tunnel surrounding rock with NPR anchor cable support. The Mohr Coulomb constitutive relation was used in the model. Figure 13 illustrates the schematic diagram of the

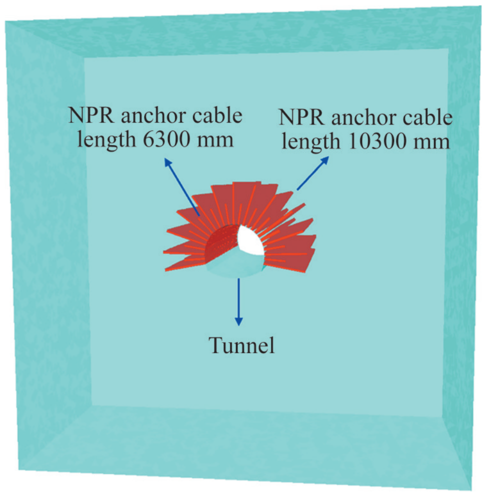

Figure 13 Schematic diagram of numerical simulation model

numerical model of the tunnel with NPR anchor cables.

Figure 14 displays the displacement and pressure contours of the surrounding rock with NPR anchor cable support in x and z directions. It can be observed that the maximum horizontal displacement of the tunnel was approximately 0.046 m, with tension on one side and pressure on the other side. It can further be inferred from Figure 14(b) that the maximum settlement value of the tunnel envelope was 0.19 m, which aligned with field monitoring results. The force contour diagram revealed that the horizontal stress in the surrounding rock of the tunnel was primarily compressive stress, as seen in Figure 14(c). The force near the vault was measured to be −0.0014 MPa, while at arch foot location the force reached its highest point at about −1.3 MPa. Furthermore, both sides of the tunnel experienced a maximum force of −2.6 MPa, as shown in Figure 14(d). Whereas, upper and lower parts experienced smaller forces measured about −0.012 MPa, which proves that NPR anchor cable has a strong control effect on the surrounding rocks.

Figure 15 shows that the displacements of both the anchor cable and liner were relatively small under the control condition of NPR. The maximum displacement in the x direction was approximately 0.04 m, while the maximum settlement displacement in the z direction was 0.17 m. Additionally, a maximum tensile stress of 0.24 MPa was experienced by the NPR anchor cable. The

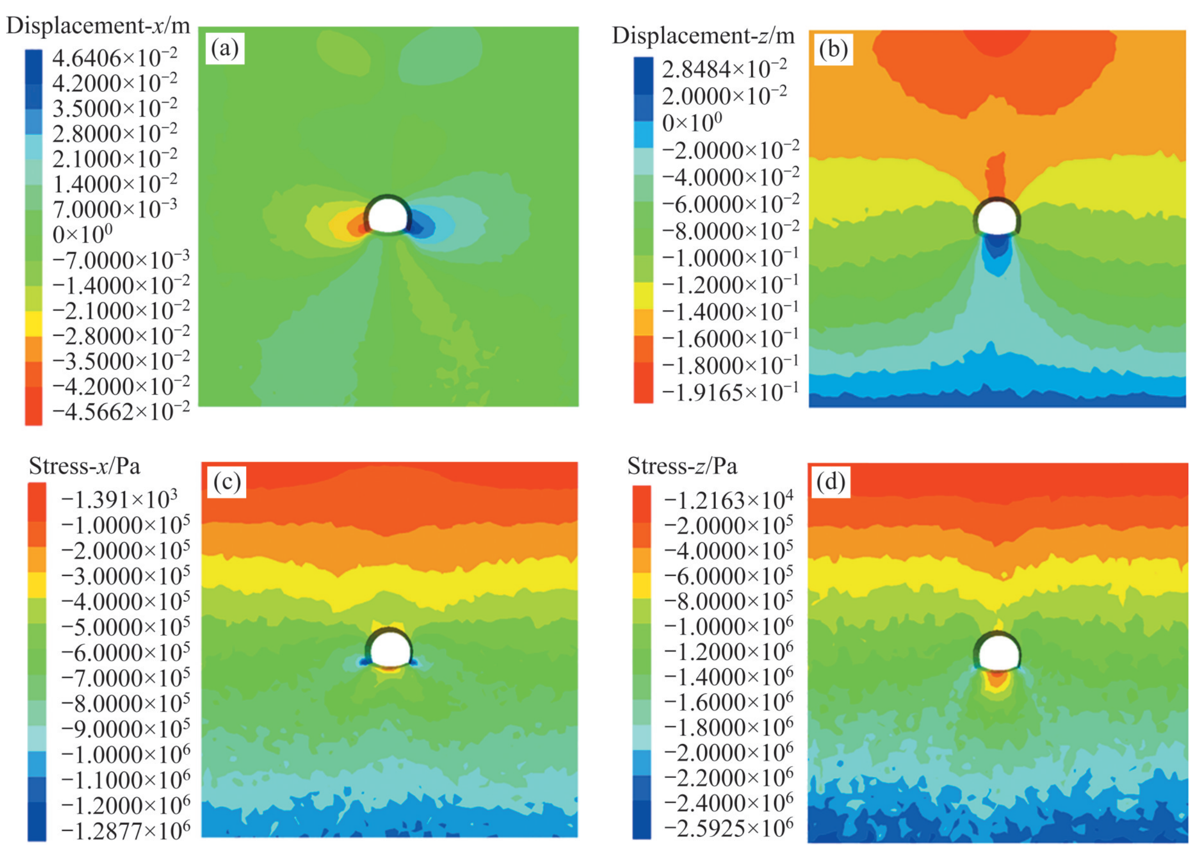

Figure 14 Tunnel surrounding rock numerical simulation experiment results: (a) Displacement-x; (b) Displacement-z; (c) Stress-x; (d) Stress-z

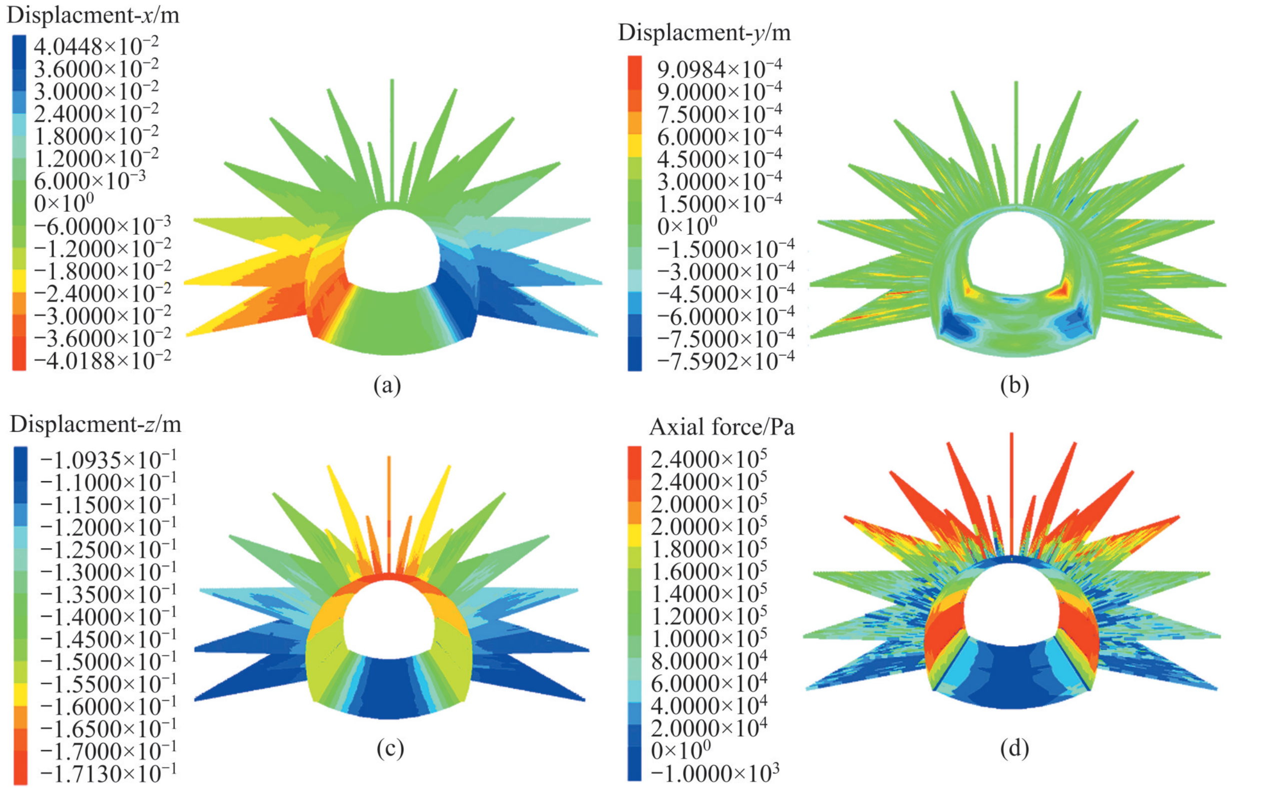

Figure 15 NPR anchor cable and lining numerical simulation results: (a) Displacement-x; (b) Displacement-y; (c) Displacement-z; (d) Axial force

lower step of the tunnel and elevation arch experienced compressive stresses, whereas upper middle step experienced primarily tensile stresses. Based on this analysis, it can be concluded that NPR anchor cable effectively compensates for large deformation areas in soft rock.

7 Conclusions

The present study compared the deformation effect of the surrounding rock of soft rock tunnels with large deformation under the condition of the original support and NPR support using field monitoring, physical model experiments, and numerical simulation. The following conclusions were drawn from the results:

1) The maximum settlement displacement of surrounding rock under NPR cable support was about 3.6 mm after full excavation. No pull-off failure of NPR anchor cable was observed during the experiment, which proves that NPR anchor cable has good mechanical compensation effect on the soft rock tunnel with large deformation and long span (ranging in kilometers).

2) From the field monitoring data, it was observed that the tunnel support method combining long and short NPR anchor cables was effective in controlling the surrounding rock in the tunnel with large deformation of soft rock in the transverse mountain area. Furthermore, the deformation of the surrounding rock in the tunnel was controlled below 300 mm by using the high preload effect (350 kN) of the NPR anchor cables.

3) The physical model and field monitoring data were verified using numerical simulation. The maximum settlement of the tunnel surrounding rock with NPR anchor cable support was 190 mm, which was consistent with the actual monitoring. This further proves the extraordinary mechanical support characteristics of NPR anchor cable for large-deformation tunnels in soft rock and western transverse mountain area. The study provides a scientific basis for the support of other large-deformation tunnels in soft rock.

Contributors

LI Yong provided the concept and edited the draft of the manuscript. ZHENG Jing and HUO Shu-sen conducted the literature review. HE Man-chao and TAO Zhi-gang provided funding support. WANG Feng-nian gave guidance to the manuscript.

Conflict of interest

LI Yong, ZHENG Jing, HUO Shu-sen, WANG Feng-nian, HE Man-chao and TAO Zhi-gang declare that they have no conflict of interest.

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中文导读

横断山区软岩大变形隧道NPR锚索补偿力学案例研究

摘要：针对西部横断山区大亮山隧道强风化石英片岩大变形问题，分析了强风化石英片岩的变形机理，利用负泊松比效应的NPR锚索补偿力学行为进行支护设计，并进行了物理模型实验、现场实验和数值模拟实验。结果表明，地应力高、节理裂隙发育程度高和围岩破碎程度高是大亮山隧道软岩大变形的主要原因，采用长、短NPR锚索组合的补偿力学支护体系，可使隧道内部的围岩保持足够的反支护力(350 kN左右)。通过对比NPR锚索支护体系与大亮山隧道原支护体系，得出大亮山隧道采用6.3 m和10.3 m相结合的NPR锚索支护体系可有效地防止围岩的变形收敛，综合沉降收敛值在300 mm以下。该研究为西部横断山区深埋软岩大变形隧道的支护提供了有效的科学依据。

关键词：软岩；大变形；NPR锚索；物理模型；数值模拟；补偿力学