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Research on Creep Deformation and Control Mechanism of Weak Surrounding Rock in Super Large Section Tunnel

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Abstract In order to solve the difficulties of creep deformation of surrounding rock in super large section tunnel, taking Letuan tunnel of Binlai expressway, a typical super large cross-section tunnel as research background, the creep mechanical characteristics of surrounding rock are taken into consideration, and the influence of different supporting forms such as bolt reinforcement, rock grouting, high-strength arch and concrete lining on surrounding rock deformation and failure mechanism is comprehensively studied. The creep failure mechanism and high strength control mechanism of surrounding rock are obtained. Research results show that the surrounding rock shows obvious creep mechanical characteristics, the continuous growth of surrounding rock deformation has brought severe challenges to the tunnel support; the surrounding rock of super large cross-section tunnel shows unstable creep deformation failure mechanism with obvious acceleration of creep stage under the condition of no support; the influence mechanism of different support forms on the control effect of surrounding rock creep deformation is systematically studied, and the evaluation indexes of deformation control rate and creep control rate of surrounding rock prove that confined concrete, as a high-strength support type, has significant advantages for surrounding rock creep control. Based on the large-scale mechanical test system of tunnel, the mechanical test of confined concrete arch is carried out, and the bearing mechanism and mechanical characteristics of confined concrete arch are clarified. The field application results show that the confined concrete arch can effectively control the creep deformation. The research results can provide theoretical basis for relevant projects.

Keywords Super large section tunnel ·
Creep failure mechanism · Anchor injection control ·
Initial support system · Confined concrete

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1 Introduction

In recent years, the construction speed of traffic tunnel is faster and faster, the scale is larger and larger, and the geological conditions are more and more complex. Under the influence of high stress, weak broken surrounding rock and fault fracture zone, the deformation rate and deformation amount of tunnel surrounding rock are significantly increased. At the same time, a large number of field

measurements and laboratory tests show that the mechanical properties of loose rock mass in broken zone are significantly affected by time, which means the creep phenomenon is prominent. Especially for traffic tunnel engineering with long service life, if the support design is unreasonable, its creep deformation will lead to large-scale deformation and failure of surrounding rock, and seriously affect the safety of tunnel construction (Sun 2007; He and Guo 2018; Xie 2019; Wang et al. 2013; Gao et al. 2008, 2017; Chen et al. 2009; Meng et al. 2012a, b).

The core content of tunnel support structure design is surrounding rock-support interaction. The main purpose of support design is to formulate corresponding support structure and construction method for different surrounding rock. In other words, different support structures and construction methods are used to control the deformation of different types of surrounding rock. Although great achievements have been made in the construction of underground engineering in the world, the engineering analogy method based on experience is still widely used in the design of supporting structure, which lacks reliable theoretical guidance and makes it difficult to achieve scientific design.

In the field of surrounding rock support theory, the classical pressure theory developed in the early twentieth century holds that the pressure acting on the support structure is the quality of the overlying strata. According to the construction experience of many years in Austria, L.V.Rabcewic, an Austrian engineer, summarized and proposed a new Austrian tunnel construction method (NATM) in the 1960s. This construction method puts forward flexible support and active support method, which has certain guiding significance for soft rock tunnel. Most of the above analysis methods are based on the classical elastic–plastic analysis theory to obtain the influence of surrounding rock elastic–plastic deformation on the support structure, but the effect of surrounding rock creep on the support structure during the operation of the project is hardly considered.

In terms of rheological rock mass stability control, Tian et al. (2020) proposed a design method of buffer layer yielding pressure support parameters for soft rock tunnel engineering based on elastic–plastic theory and considering the time weakening of surrounding rock parameters and the support resistance of buffer layer. Li et al. (2016) developed a

high-strength bolt grouting support technology with a new high-strength combined hollow grouting bolt as the core to solve the problems of weak and broken surrounding rock and frequent failure of supporting components in large-section chamber. Wang et al. (2017, 2018a, b, c; 2019a, b) developed the square confined concrete (SQCC) support system with high-strength bearing characteristics, put forward corresponding design methods, and applied the support system to underground engineering. Xiao et al. (2014, 2017) proposed to adopt high-strength and high preload bolt (cable) support and "zone grouting reinforcement" technology for surrounding rock control of large cross-section tunnel with complex conditions. Chen et al. (2019) proposed an intelligent back analysis method of rock mass creep parameters based on the displacement increment sensitivity analysis for large underground caverns under high in-situ stress. Liu et al. (2018) improved the Traditional Nishihara model and proposed the nonlinear variation parameters creep model of rock. Zhu et al. (2020) proposed the joint support technology for deep soft rock roadway to solve the problems of the large deformation of surrounding rock caused by high stress soft rock rheology.

Some research shows that "only from the above-mentioned viewpoints of rock creep, can we make a convincing and reasonable explanation for engineering practical problems, such as the instability during the construction period of the tunnel, the deformation displacement of surrounding rock and the continuous growth and development of the deformation pressure on the lining structure, and the time effect interaction between lining support and surrounding rock." In fact, from the time course of elastic–plastic deformation, because the elastic–plastic deformation of tunnel surrounding rock occurs and completes immediately, in many cases, the support often fails to catch up with the elastic–plastic deformation of surrounding rock, and the secondary stress release and long-term creep deformation during operation are the key points of supporting. Therefore, it has a wide range of engineering significance to clarify the interaction mechanism of surrounding rock and support, consider the creep deformation of surrounding rock, and get the viscoelastic plastic solution in line with the engineering practice, and provide reference for the support design. Qi (2006) takes Wushaoling railway tunnel project and Xiamen east passage submarine

Table 1 Physical and mechanical parameters of rock mass

Rock grade	Stage of surrounding rock	Uniaxial compression strength /MPa	BQ	Internal friction angle $\varphi/°$
III	Moderately weathered limestone and marl	23.8–45.5	372.5	28~40
IV	Strongly weathered limestone and marl	15.5–34.2	290.6	20~30
V	Strongly weathered limestone and marl	15.5–34.2	242.8	14~30

Table 2 Initial support system of tunnel

Arch type	Arch space (m)	Shotcrete	Anchor bolt
H20×20 Section steel arch	0.60	C25 shotcrete	Φ25 hollow grouting bolt

tunnel project as the research background, and the creep characteristics of soft rock are studied. The optimization design of tunnel support structure considering the creep aging characteristics of rock is also studied. Based on the Nishihara's model, Hou (2008) derived the elastic–plastic–creep deformation equation of the surrounding rock of axisymmetric circular roadway. The iterative algorithm under the condition of continuous change of reaction force of passive support is put forward, which makes a new exploration on the mechanism of surrounding rock support.

Letun tunnel is a typical super large section tunnel in China. Because the main lithology of the tunnel site is strongly weathered limestone and marl, local dissolution cracks are developed and the surrounding rock creep phenomenon is obvious, which brings many technical problems to the tunnel support, while the traditional support engineering lacks scientific design. Therefore, it is necessary to study the reasonable control method and support system design of tunnel surrounding rock creep research.

2 Project Overview

2.1 Engineering Geology

The surrounding rock of tunnel is Ordovician limestone. The weathering zone has well-developed reticular fractures, and karst development areas exist in some areas. Dissolution fissures are mostly seen near the surface, filled with cohesive soil, and the bedding is relatively developed. According to the Chinese code for design of highway tunnel (JTG D70-2004), the surrounding rock is classified on the basis of rock strength and integrity coefficient, considering surrounding rock characteristics, environment and other factors. The classification of tunnel surrounding rock is shown in Table 1.

2.2 Original Support Scheme

During the construction of the original support scheme of the tunnel, the bearing capacity of surrounding rock itself is considered. The initial support structure is determined by engineering analogy. The specific support parameters are shown in Table 2 and the support section shape is shown in Fig. 1.

The supporting lining form is a composite lining structure with bolt and arch and shotcrete as primary support and reinforced concrete as secondary lining. For the weak surrounding rock and fault fracture zone, appropriate supporting measures should be taken, including grid steel arch, section steel arch and rock mass grouting to ensure the stability of surrounding rock and the safety of initial support. According to the concept of new Austrian method, the surrounding rock and supporting structure need to bear the load together. Before the tunnel excavation, the natural rock mass has a certain original rock stress, and after the initial support structure is
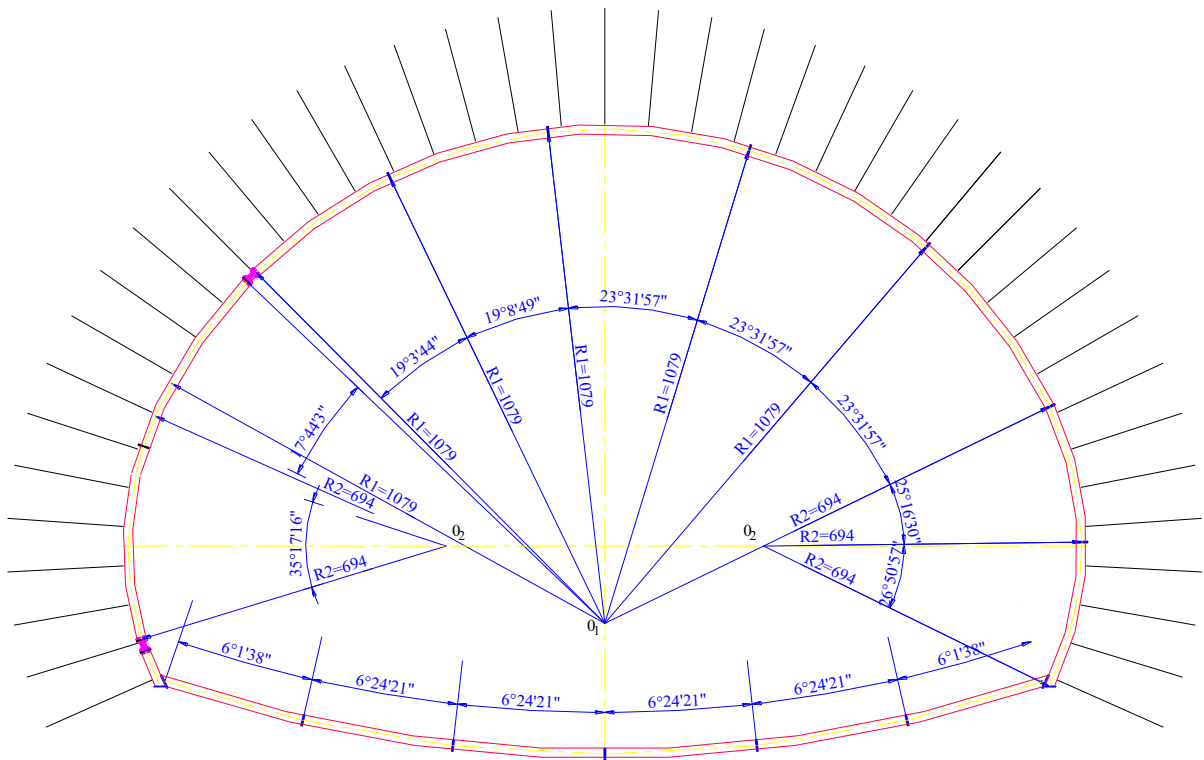
Fig. 1 Tunnel support design

applied, the elastic–plastic deformation of surrounding rock gradually produces deformation pressure, which directly acts on the initial support structure. The initial support structure can improve the stress conditions of surrounding rock mass, give full play to the self-stability ability of surrounding rock, and at the same time, it is close to the surrounding rock to form a composite system with good sealing performance, which can effectively protect the surrounding rock. Therefore, the primary support system is the main body to maintain the stability of surrounding rock and ensure the safety of tunnel construction. However, in the design of tunnel support, structural design and calculation are often only carried out for the secondary lining structure as safety reserve, while for the initial support system, empirical analogy method is adopted, which lacks reliable theoretical guidance and is difficult to achieve scientific design. It will cause great safety risk to the project construction and later operation.

Under the creep action of surrounding rock, the supporting force of supporting structure is a time-dependent value, which is a passive reaction force

increasing with the increase of creep deformation of surrounding rock into the tunnel. Therefore, different support forms have great influence on the stability control of surrounding rock due to the different supporting procedures, support forms, support strength and stiffness. Therefore, based on the engineering geological conditions, the numerical test of tunnel support is conducted, and the creep control mechanism of different support forms is clarified, which provides the basis for relevant engineering design.

3 Numerical Analysis

3.1 Analysis Model

In this paper, using numerical software FLAC 3D, creep constitutive model selection model of component model, its compared with empirical model has the advantages of simple and convenient, physical meaning, visually complex rock creep property, and can meet the deformation of rock from the concept of

Table 3 Mechanical parameters of surrounding rock

Rock strength	Density P (kg/cm^3)	Elastic modulus E/GPa	Possion's ratio υ	Cohesion c/MPa	Internal friction angle $\psi/°$
IV	2683	3.5	0.29	45	29

Table 4 Burgus model parameters

Parameter	E_M/GPa	E_K/GPa	η_M/GPa h	η_K/Gpa h
Value	1.473	0.334	11.355	0.465

elasticity, plasticity and viscous components, therefore, mainly from the creep model of this kind of choice conforms to the characteristics of creep test curve model. Most of the specimens go through transient strain, transition creep and steady-state creep at different stress levels, and finally develop to failure under the last stress level. Burgers model is composed of Maxwell model and Kelvin model in series, which is a kind of composite viscoelastic body. It can better reflect the creep aging characteristics of weak rock mass. Its main characteristics are as follows: it has instantaneous strain, which is determined by the elastic deformation characteristics of Maxwell body; then the creep goes through transition or initial creep stage, and its gradual coefficient is determined by Kelvin body; after going through transition creep stage, it enters into steady-state creep stage, at which the creep rate is constant.

The surrounding rock of the supporting project is mainly marl, and the marl is limestone mixed with mud, belonging to grade IV surrounding rock. As the main content of this paper aims to discuss the control mechanism of different support forms for the creep deformation of surrounding rock, and does not make in-depth discussion on the specific creep law of rock, therefore, according to the engineering analogy principle, combined with the relevant literature research results, the mechanical parameters of surrounding rock near the tunnel are selected in Tables 3 and 4.

In this paper, the supporting components used in the simulation include bolt, arch and concrete arch. Bolt support is simulated by rod element, arch is simulated by beam element, and arch body is simulated by shell element. Shell element can directly set thickness. See Tables 5 and 6 for specific parameters.

3.2 Section Size Analysis

The size of tunnel section is the most significant feature of large cross-section tunnel and traditional

Table 5 Mechanical parameters of arch

Arch type	Elastic modulus E/GPa	Possion's ratio	Sectional area/cm^2
H20 × 20 section steel	206	0.3	64.26
Confined concrete SQCC180 × 10	206	0.2	68

Table 6 Equivalent mechanical parameters of surrounding rock and shotcrete layer

Material	Elastic modulus E_1/MPa	Possion's ratio μ	Cohesion c/MPa	Internal friction angle $\varphi/°$	Tensile strength σ_t/MPa
Shotcrete	2300	0.16	1.50	35.0	1.00

Table 7 Numerical simulation of tunnel sections

Scheme	Variable	Selected values
A. Tunnel section	① Section area	① Take 0.5 times, 0.75 times, 1 time, 1.25 times and 1.5 times of the original size

Table 8 Numerical simulation of tunnel design parameters

Scheme	Variable	Selected values
B. Anchor bolt	① Bolt strength (Φ25)	① Take 1 times, 1.2 times, 1.4 times, 1.6 times, 1.8 times and 2 times of the original scheme1
	② Bolt space	② 0.5 m,0.75 m,1 m,1.25 m,1.5 m
C. Grouting bolt	① Grouting length (3 m)	① 3 m, 3.5 m,4 m,4.5 m,5 m
	② Rock strength	② Take 1 times,1.25 times,1.5 times,1.75 times,2 times of the original scheme1
D. Arch	① Arch strength (H200× 200)	① Take 1 times,1.2 times,1.4 times,1.6 times,1.8 times,2 times of the original scheme1
	② Arch space	② 0.6 m,0.8 m,1 m,1.2 m,1.4 m
E. Concrete lining	① Concrete strength (C30)	① Take 1 times,1.2 times,1.4 times,1.6 times,1.8 times, 2 times of the original scheme1
	② Concrete thickness	② 500 mm,600 mm,700 mm,800 mm,900 mm

cross-section tunnel. This section mainly considers the specific creep deformation and stability analysis of tunnel surrounding rock under different cross-section sizes. In order to clarify the deformation characteristics of tunnel surrounding rock with different cross-section sizes, combined with the engineering parameters, the multiple of original design area of tunnel is taken as variable to establish tunnel analysis model (Table 7). The stress and deformation law of tunnel surrounding rock under different section size conditions is studied, and the basic stress characteristics and laws of large section tunnel surrounding rock are clarified.

3.3 Support Scheme Design

A series of numerical simulation schemes with different supporting parameters are designed for the supporting tunnel by selecting the reinforcement forms such as anchor bolt reinforcement, grouting reinforcement, arch support and secondary lining, as shown in Table 8. Each scheme reduces or enlarges a certain proportion as the analysis parameter based on the original design scheme of the supporting project.
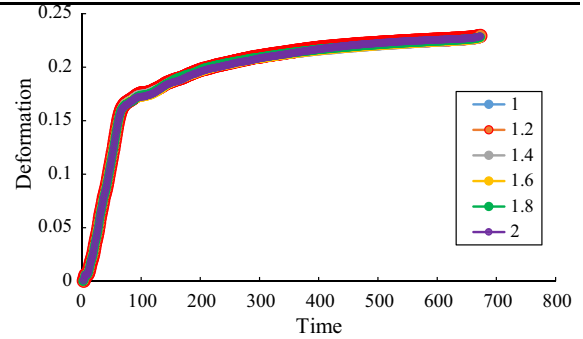
3.4 Result Analysis

According to Fig. 2, the curves of radial displacement at vault with time under different scaling ratios of tunnel original design size under the condition of no support are given, and the positive value indicates that the displacement direction points to the tunnel. It can be seen that at the same time, the larger the tunnel section, the greater the radial displacement, that is, the larger the cross-section of surrounding rock is, the greater the deformation pressure of the supporting structure is, and the greater the support resistance is required. After loading to a certain extent, the deformation of surrounding rock will enter the accelerated creep stage, and then the support cost will increase significantly. The displacement curve of tunnel vault accords with the typical three-stage creep curve, which shows that the creep constitutive model selected in this paper conforms to the general law of rock creep. The stress of tunnel surrounding rock shown in Fig. 3 shows that under the creep condition, the stress distribution law of different span tunnels is small, the stress at arch foot is relatively concentrated, and the stress in the vault and inverted bottom arch of tunnel is small.
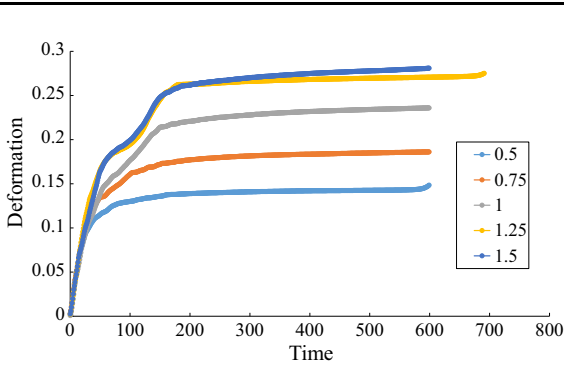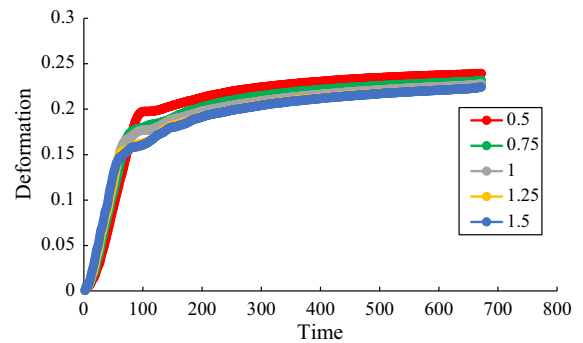
Fig. 2 Tunnel creep curve under the influence of section size

Fig. 4 Creep curve of tunnel under the influence of bolt strength

Analysis of support effect. Figure 4 shows the variation of radial displacement of tunnel vault with time when different strength bolts are applied after excavation. It can be seen that at the same time, the control effect of different strength bolts on radial displacement is not obvious. Figure 5 shows the variation of radial displacement of tunnel vault with time under different bolt spacing. It can be seen that the larger the support spacing, the greater the critical deformation of surrounding rock entering the constant velocity creep stage, that is, the more difficult the surrounding rock control is. However, the deformation of each support scheme tends to be the same. In conclusion, only changing the bolt strength has no obvious effect on the creep control of surrounding rock, but the different bolt spacing has a certain

Fig. 5 Tunnel creep curve under the influence of bolt spacing

(a) 0.5times

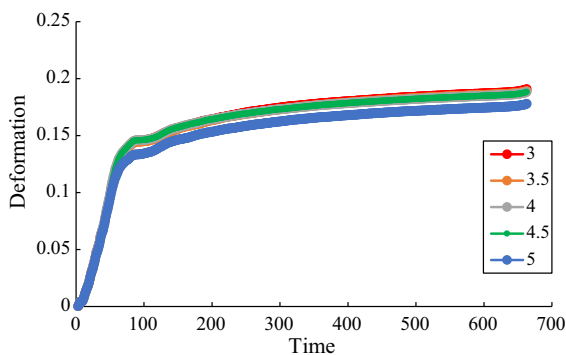**(b)** 1times

(c) 1.25times

(d) 1.5times
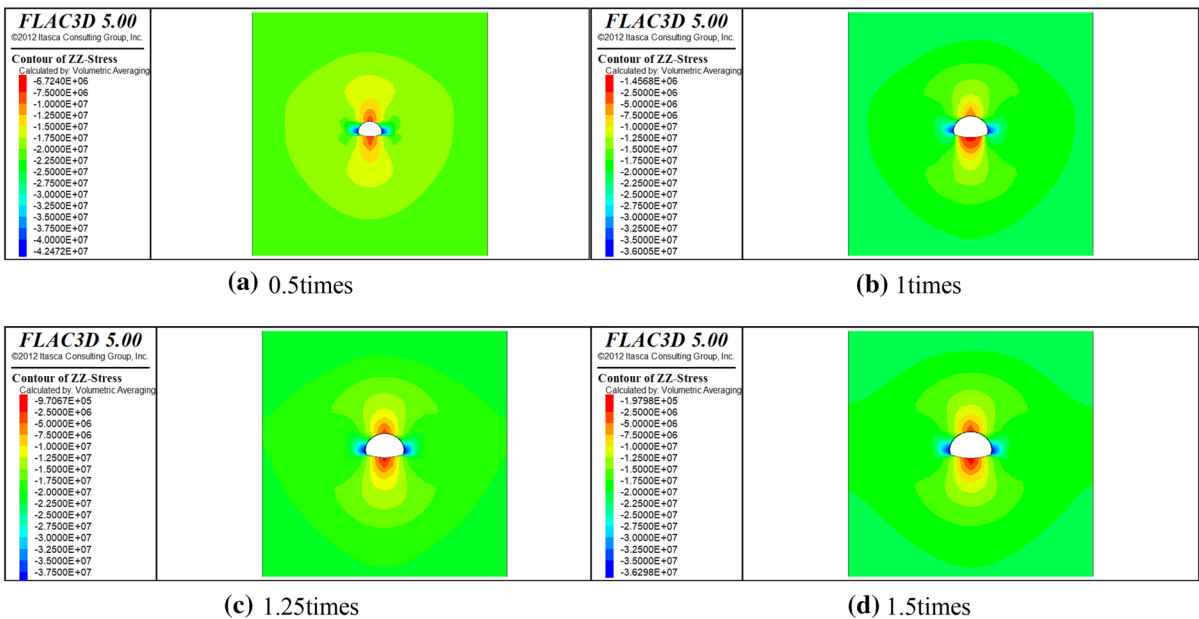
Fig. 3 Stress distribution of tunnel surrounding rock under the influence of different section sizes

impact on the creep deformation. The smaller the distance between bolts is, the *denser* the bolts are arranged, and the better the supporting effect is.
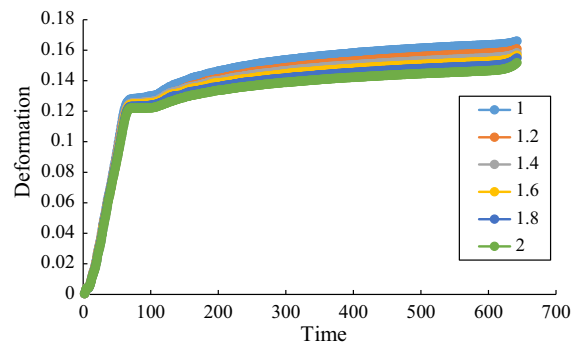
Figure 6 shows the displacement curve of vault after surrounding rock grouting reinforcement after excavation. It can be seen that the influence of surrounding rock grouting on the first stage of creep is very small, but in the constant velocity creep stage, the larger the grouting range, that is, the longer the grouting bolt, the smaller the radial displacement. At the same time, the spacing between curves increases with the increase of grouting range, which indicates that there is a certain critical support strength for improving the strength of surrounding rock by grouting reinforcement. Only when the range is increased to a certain value, the surrounding rock will be controlled. The effect will increase significantly.

Figure 7 shows the variation of radial displacement of tunnel vault with time when different strength arch frames are constructed after excavation, and Fig. 8 shows the variation of radial displacement of tunnel vault with time under different arch spacing. It can be seen that the effect of arch support form on the initial stage of creep is very small, but at the same time, different arch strength and arch spacing have significant influence on the creep rate of constant velocity creep stage. At the same time, the higher the arch strength is, the denser the arch layout is, that is to say, the greater the support resistance per unit range is, the more obvious the control effect of surrounding rock creep is.
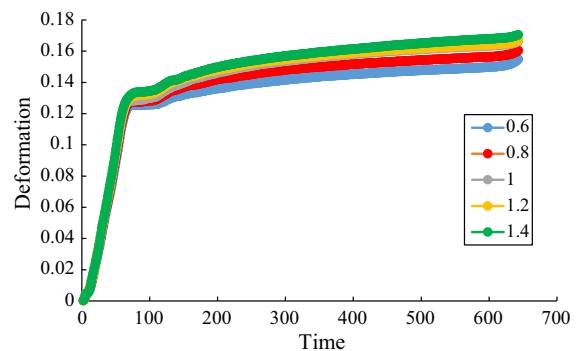
Figure 9 shows the variation of radial displacement of tunnel vault with time when secondary lining
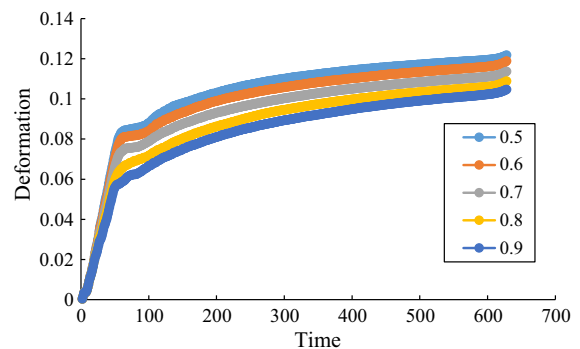

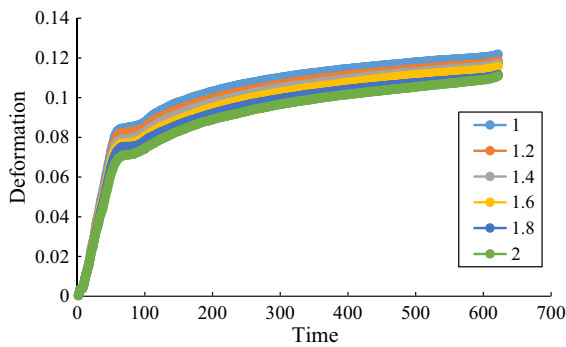Fig. 7 Tunnel creep curve under the influence of arch strength

Fig. 8 Tunnel creep curve under the influence of arch spacing

Fig. 9 Creep curve of tunnel under the influence of secondary lining thickness

with different thickness is applied after initial support, and Fig. 10 shows the variation of radial displacement of tunnel crown with time under different secondary lining strength. It can be seen that the effect of arch support form on the initial stage of creep is very small, but the control effect of arch support is different from that of arch support in constant velocity creep stage, and the control effect

Fig. 6 Creep curve of tunnel under the influence of grouting length

Fig. 10 Creep curve of tunnel under the influence of secondary lining strength

on creep rate is not obvious. At the same time, the higher the secondary lining strength is, the smaller the creep deformation of surrounding rock is.

To sum up, the arch strength has the most significant control effect on creep rate, and changing the thickness of secondary lining has the most obvious control effect on creep deformation. In addition, changing the bolt density and grouting reinforcement can also control the deformation of surrounding rock.

Creep control analysis of surrounding rock. In order to analyze the control effect of surrounding rock under different factors, the evaluation indexes of deformation control rate and creep control rate are established by comprehensively considering creep deformation amount and deformation rate. The index of deformation control rate represents the control degree of deformation of surrounding rock of each scheme compared with the scheme without support (Eq. 1), and the index of creep control rate represents the control degree of deformation rate of surrounding rock of each scheme compared with the scheme without support (Eq. 2). The higher the value, the better the control effect of surrounding rock is.

$$\eta_1 = \frac{\Delta_0 - \Delta_s}{\Delta_0} \times 100\% \tag{1}$$

$$\eta_2 = \frac{v_0 - v_s}{v_0} \times 100\% \tag{2}$$

where Δ_0 is the displacement of vault without support, Δ_s is the displacement of vault with support, v_0 is the displacement rate of vault without support, v_s is the displacement rate of vault with support.

Figure 11 shows the comparison chart of deformation control rate and creep control rate evaluation index under each support scheme. Because the control mechanism of secondary lining and primary support is different, this paper selects different initial support forms for comparative analysis. Because the arch has obvious effect on creep control, this paper selects two times of the strength of conventional arch as the form of high-strength arch. It can be seen that high-strength arch has significant control effect on surrounding rock deformation and creep rate.

4 Indoor Test of Confined Concrete Arch

The analysis results in Fig. 12 show that the high-strength arch support has a significant effect on the creep of surrounding rock, and the control rate of creep rate of surrounding rock can be increased by 25.23% when the strength of high-strength arch is twice of the traditional arch bearing capacity. In recent years, with the rapid development of highway tunnels in China, confined concrete arch has gradually developed into the high-strength arch commonly used in large cross-section highway tunnels. Some studies have shown that the strength of confined concrete arch with the same steel content can reach about 2 times of that of traditional steel arch, which provides technical guarantee for tunnel engineering to effectively control surrounding rock creep without increasing cost Proof.

Therefore, based on the full-scale arch test system of Shandong University, the mechanical properties test of confined concrete arch frame is carried out in this paper, which provides theoretical and experimental basis for creep deformation control and support design of related projects.

4.1 Test Overview

The indoor test is based on the large-scale mechanical test system of arch in Shandong University underground support engineering laboratory, which is mainly composed of reaction structure, loading and control system, monitoring system and accessory components, as shown in Fig. 13.

The reaction structure is a ladle concrete structure with an outer diameter of 10 m, which can realize the large-scale mechanical test of the arch frame of the
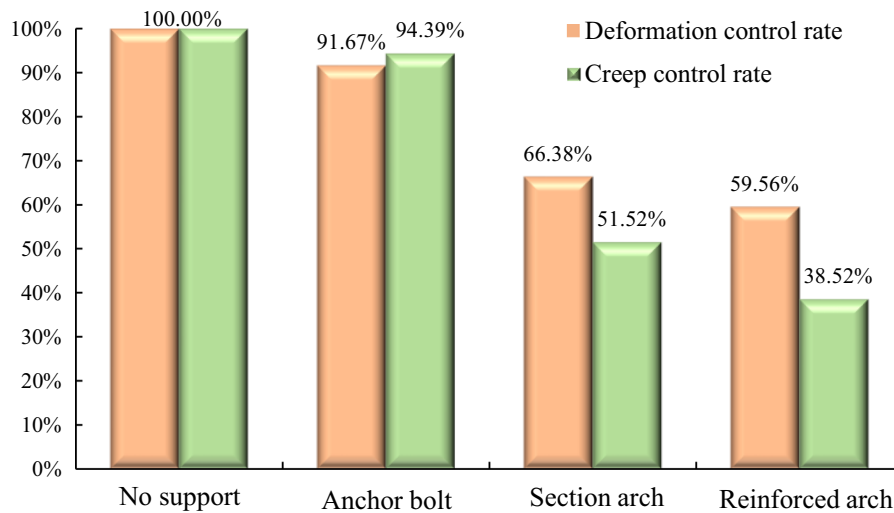
Fig. 11 Comparison of control indexes of various support forms
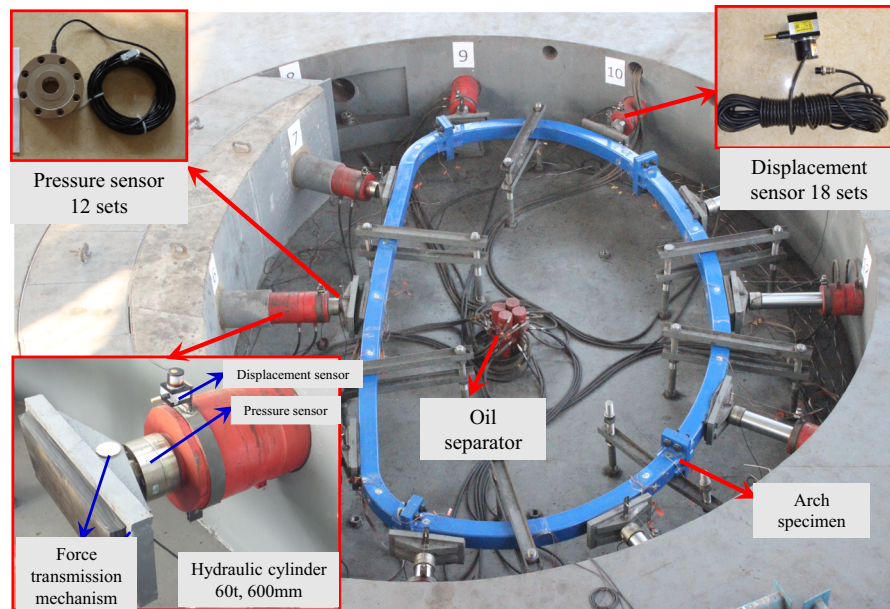
Fig. 12 Test system

traffic tunnel. At the same time, the assembly of the combined module can provide the reaction force for the arch test of different shapes. The loading and control system is composed of hydraulic pump station, 12 groups of hydraulic cylinders, automatic measurement and control system, force transmission and dispersion device, etc. The automatic measurement and control system are composed of data acquisition and processing system, computer control

system and display system. The loading speed and pressure holding time of different stages can be set. High speed sampling can be realized, test data can be displayed in real time, and various test curves can be output and drawn as required. The force transmitting and dispersing device is composed of force transmission hinge, force transmission disperser and force transmission rubber. The force transmission hinge can ensure that the load direction is vertical to the

(a) Before test   **(b)** After test
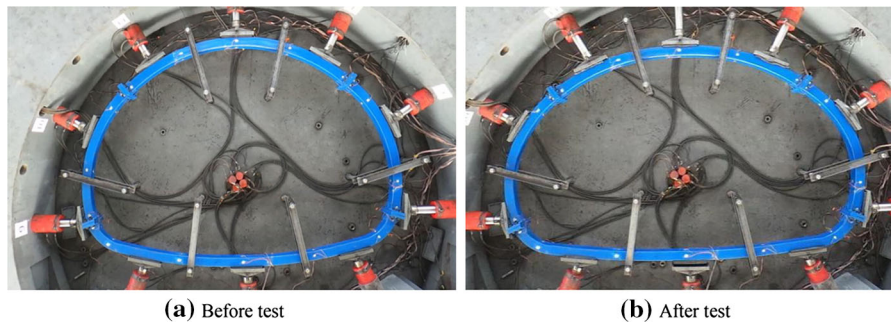
Fig. 13 Arch form before and after test

Table 9 Statistics of three center test arch

Scheme	Specimen number	Specimen type	Load	Concrete
1	SQCC150×8	Confined concrete	Bias load	C40

outline line of the component when the test component is deformed. The force transmission disperser can transfer the oil cylinder thrust to the larger range of the arch frame, reducing the stress concentration. The force transfer rubber further makes the force transfer disperser contact with the surface of the arch frame It is more sufficient to effectively reduce the stress concentration and prevent the arch frame from premature failure due to stress concentration, which will affect the test results.

The test monitoring system consists of radial stress monitoring, radial displacement monitoring, strain monitoring and steel–concrete coupling monitoring instruments. Radial displacement monitoring is to accurately collect and analyse the radial deformation of the arch during the test by installing the displacement sensor at the designated position of the test arch and equipped with data acquisition and processing unit. Radial stress monitoring means that the radial stress of arch is accurately collected and analysed by installing force sensor on each hydraulic cylinder loading head and equipped with data acquisition and processing unit. Strain monitoring is the real-time acquisition of the strain sensor on the surface of the arch frame by using the strain gauge, which can effectively analyse the strain situation of the specified position of the arch. Steel concrete coupling monitoring is to use acoustic emission instrument to

process the acoustic emission signals picked up by the probes at different positions of the arch frame, and analyse the failure of core concrete.

4.2 Test Scheme

In order to master the stress, deformation and failure characteristics of three centre arch under radial pressure, analyse its bearing mechanism and clarify the design basis of arch frame, the indoor test design scheme is as follows (Table 9).

4.3 Test Procedure

At the beginning of the test, the loading cylinder is installed in the specific position, and the appropriate loading radius is adjusted. The radial pressure sensor is installed at the front end of the oil cylinder, and the force transmission hinge and force transmission disperser are installed at the front end of the pressure sensor; the lower baffle beam of the transverse baffle is installed, and the bolts are adjusted to make each baffle beam in the same horizontal plane, providing a platform for the arch frame assembly. On the other hand, the displacement sensor is installed at the designed position, fixed on the welding positioning steel plate by bolts, and the strain sensor is arranged at the designated position according to the

requirements, and each monitoring sensor is connected with the corresponding monitoring acquisition unit through the wire.

After the installation of each part, the hydraulic control system is used to slowly increase the pressure to ensure that all cylinders are in contact with the test arch. First, the preloading is applied with a rate of no more than 3% of the estimated damage load, and then the loading is carried out at a rate of 10kN/min. The pressure is kept for 0.5 min without 30kN until the specimen is damaged.

4.4 Test Results

The three oil cylinders at the bottom are fixed close to the arch, so they can't extend and load actively, but can collect passive reaction force during the loading process; the remaining oil cylinders keep the loading ratio of 3:2; after the test starts, the arch frame deforms slowly and evenly, and the oil cylinder advances more evenly; with the load rising, the arch crown sinks, and the convex speed of left and right sides obviously starts to accelerate, and the arch crown will increase obviously At 1339.9 s, the arch crown deformation is more obvious, the arch bottom is separated from the oil cylinder, and the arch frame becomes flat as a whole; at the end of 1680 s test, the arch deformation is more serious, and the maximum displacement occurs in the vault and two sides. Figure 13 shows the shape comparison of the arch before and after the test.

In the process of continuous increase of arch deformation, some parts of the arch frame appear strength failure phenomenon, as shown in Fig. 14. At the end of the test, the steel tube bulge slightly at the side of the arch frame, and no obvious strength failure is found in other parts of the arch.

Through the observation and summary of the whole test process, it can be seen that:

(1) In the whole test process, except for the three oil cylinders at the bottom of the arch, the load applied by the other three oil cylinders at the top and the upper oil cylinders basically maintained a loading ratio of 3:2 to achieve the expected loading scheme; the pressure stabilizing effect of each group of oil cylinders was good after reaching the predetermined load.

(2) Under this loading scheme, including the bottom cylinder reaction, the overall ultimate bearing capacity of the arch is 1798.9 kN. When the bearing capacity of the arch reaches 1339.9 kN in 910 s, the local buckling occurs, and the deformation is accelerated, and then the load increase rate slows down, but it still rises steadily.

(3) When the arch is finally damaged, the top oil cylinder extends out, that is, the vault of these positions sinks, with the maximum displacement of 365 mm; the arch side displacement is positive, and the two positions are slightly protruding due to the overall flat deformation of the arch, with the maximum deformation of 74 mm.

(4) In the final failure of the arch, only three loading points of the arch crown have a significant decline, and the rest of the load does not show a significant drop phenomenon, which shows that the arch is mainly the top of the more serious damage.
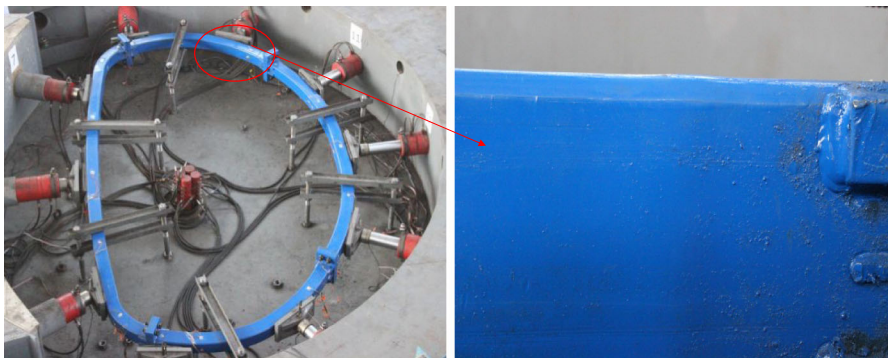

Fig. 14 Local buckling

SQCC150×8 arch has high strength and good ductility, and its ultimate bearing capacity is 2.5 times that of I22B traditional steel arch (Wang et al. 2016; Pan et al. 2017), the steel arch cannot provide long-term and effective support reaction force for surrounding rock, SQCC150×8 can continue to provide high force under large deformation, so it has good bearing capacity in later stage. The test results show that the confined concrete arch can effectively control the creep of surrounding rock of super large cross-section tunnel, and the arch has stable bearing capacity and good ductility, so it should be used as the preferred arch support form for related tunnel engineering.

5 Field Application

Through the above analysis of the arch frame composite structure and various influence factors of the initial support components, it is clear that the confined concrete arch has a good control effect on the surrounding rock creep. In order to further prove the above conclusion, the confined concrete arch is selected for field application test, the support sheme is as shown in Table 10, and the effect of arch support is determined by analysing the deformation amount and deformation rate of tunnel in the process of tunnel excavation and support.

The layout of measuring points is shown in Fig. 15. Each measuring point is measured at least three times. When the reading error of the three times is less than 0.05 mm, the average value is taken as the final value (Fig. 16).

It can be seen from Fig. 16 that the final settlement rate of all sections is within 0.2 mm/day of the basic stability criterion of surrounding rock specified in the specification. In the first 3 days, the settlement of arch crown increased rapidly; in 4–5 days, the increase of vault settlement slowed down slightly, accounting for about 25% of the total amount, indicating that the internal deformation of surrounding rock has been effectively controlled, the loose range has been effectively controlled, and the supporting structure has begun to play a supporting role as the bearing body of surrounding rock pressure; in 5–15 days, the settlement of arch crown increases fastest, accounting for about 70% of the total amount, which indicates that there is a relationship between the stratum and the supporting structure The results show that the initial support and surrounding rock have reached the stress equilibrium state; after 15 days, the settlement of arch crown basically does not increase, and the tunnel structure reaches a new stable state. It can be seen that the high-strength confined concrete support scheme plays a significant role in regulating the settlement rate of arch crown and effectively controls the creep deformation of surrounding rock.
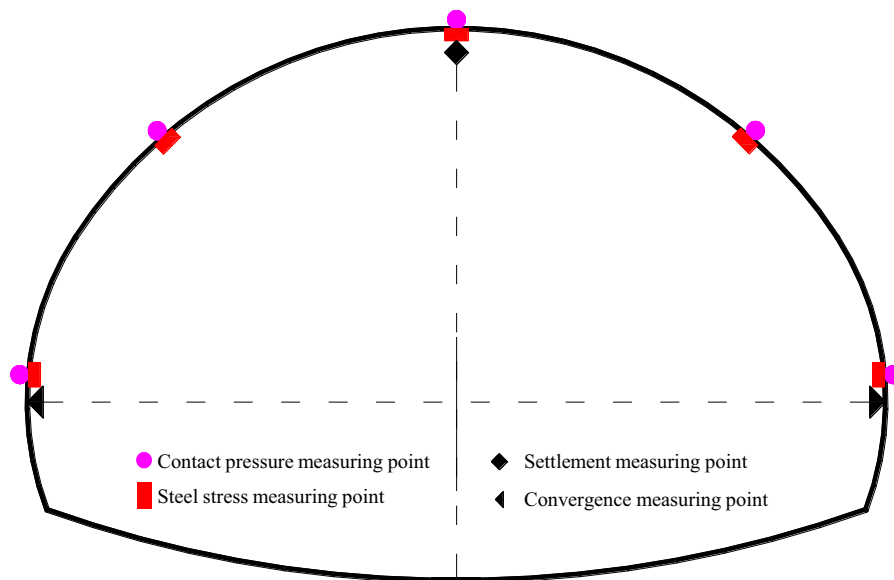
Fig. 15 Testing points

Table 10 Support contrast scheme

Rock strength	Support type	Original support type
IV	SQCC150-8 arch	I22b section steel arch
Other support	Anchor bolt: Φ25 mm hollow grouting anchor, l=400 cm, spacing 100 cm (ring) × 100 cm (longitudinal)	
	Reinforcement mesh: diameter Φ8mm, spacing 20 cm (ring) × 20 cm (longitudinal)	
	Concrete spraying layer: strength C25, thickness 28 cm	

Fig. 16 Monitored vault settlement curves on site

(a) Total settlement curve   **(b)** Settlement rate curve
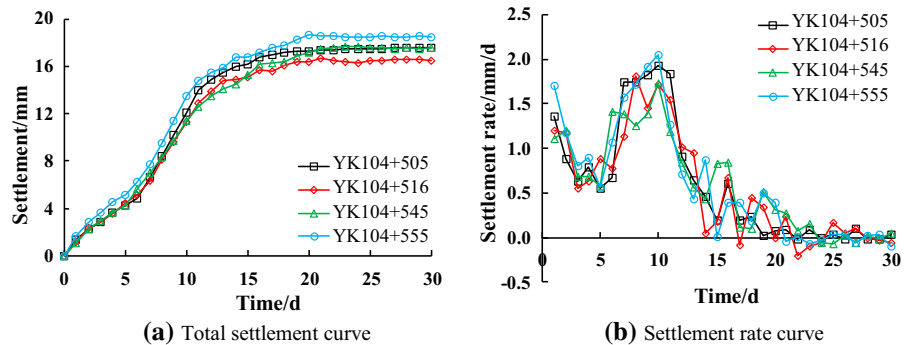
6 Conclusions

Based on Letun tunnel, a typical super large section tunnel of Binlai expressway, this paper analyses the creep mechanical characteristics and supporting forms of surrounding rock by combining indoor test with numerical test, and studies the creep failure mechanism and high-strength control mechanism of surrounding rock by comprehensively considering different supporting forms such as bolt reinforcement, rock grouting, high-strength arch and secondary lining. The results show that:

(1) Relying on the engineering rock has obvious creep mechanical characteristics, the continuous growth of surrounding rock deformation has brought severe challenges to the tunnel support; the surrounding rock of super large cross-section tunnel shows unstable creep deformation failure mechanism with obvious acceleration creep stage under the condition of no support.

(2) As an active support form, bolt support can provide relatively low support strength and has no obvious effect on creep deformation. Only when the grouting range reaches a certain critical value, can the grouting reinforcement form play a significant role. In contrast, arch support and concrete arch body as passive support form have significant effect on creep control, and arch support has significant effect on reducing creep rate.

(3) The indoor test results show that the confined concrete arch has higher economic benefits. The results of indoor and field tests show that the confined concrete arch can effectively control the creep of surrounding rock of super large cross-section tunnel, and the arch has stable bearing capacity and good ductility, so it should be used as the preferred arch support form for related tunnel engineering.

Availability of data and materials Data transparent.

Code availability The code is available.

Declaration

Conflict of interest None.

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