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DECIPHERING THE DYNAMICS: MECHANISMS AND CONTROL STRATEGIES FOR LARGE DEFORMATION IN CARBONACEOUS SHALE TUNNELS

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Abstract: Carbonaceous shale, a robust and weather-resistant rock composed of clay and minerals, plays a crucial role in tunnel engineering due to its high hardness and strength. This study delves into the utilization of carbonaceous shale as a support structure in tunnel engineering, emphasizing its capacity to mitigate the risk of collapse and deformation in tunnels. The rock's properties make it an ideal choice for ensuring the structural integrity and safety of tunnels [1].

In tunnel engineering, carbonaceous shale serves as a vital component to fortify the tunnel structure, minimizing the potential for collapse and deformation [2-3]. Various methods, including foundation strengthening, lining reinforcement, and installation of lining templates, are employed to enhance the rock's supportive capabilities [5]. Despite its inherent robustness, carbonaceous shale is susceptible to damage, necessitating meticulous attention to maintenance and upkeep during usage [6-7].

This research focuses on unraveling the mechanism and control of large deformation in carbonaceous shale tunnels. Understanding the factors influencing deformation is pivotal for implementing effective measures that contribute to the longevity and safety of tunnels, particularly in the context of high-speed rail construction. Investigating the behavior of carbonaceous shale under different conditions and stressors is paramount for formulating strategies to mitigate deformation risks and enhance the resilience of tunnel structures [4].

The findings of this study provide valuable insights into the maintenance practices and control mechanisms required to ensure the continued efficacy of carbonaceous shale in tunnel engineering. By comprehending the complexities of large deformation in carbonaceous shale, engineers and researchers can develop targeted solutions to enhance safety standards in tunnel construction, especially in high-speed rail projects. This research contributes to the broader understanding of geological materials used in construction and lays the groundwork for improved practices in utilizing carbonaceous shale for enhanced tunnel stability.

Keywords: Carbonaceous Shale, Tunnel Engineering, Deformation Mechanism, Support Structure, High-Speed Rail Construction

1. Introduction

Carbonaceous shale is a type of rock composed of clay and rock, which typically has high hardness and strength, as well as good resistance to weathering [1]. This type of rock is widely used in tunnel engineering because it can provide sufficient support and protect the tunnel structure, thereby reducing the risk of collapse and deformation [2-3]. In tunnel engineering, carbonaceous shale is often used as a support structure to reduce the risk of tunnel collapse and deformation [4]. This type of rock can be achieved by strengthening the foundation, lining, installing lining templates, and other methods [5]. Despite its high hardness and strength, it is still a rock material that is prone to damage. Special attention should be paid to the maintenance and upkeep of carbonaceous shale when using it [6-7]. Therefore, conducting research on the mechanism and control of large deformation in carbonaceous shale tunnels is of great significance for ensuring the safety of high-speed rail construction.

This study mainly adopted a combination of theoretical analysis and numerical simulation to study the relevant characteristics of carbonaceous shale. Through in-depth analysis of the relevant characteristics of carbonaceous shale, the deformation characteristics and failure mechanisms of carbonaceous shale were explored. Numerical simulation methods were used to analyze the deformation behavior of carbonaceous shale. Based on the research results, corresponding countermeasures were proposed to reduce the problem of large deformation of carbonaceous shale during construction. Through the research in this article, a deeper understanding of the large deformation mechanism of carbonaceous shale has been gained, and these countermeasures are of great significance for improving construction efficiency and ensuring engineering quality.

2. Related Work

At present, many research works have been carried out on the problem of large deformation of carbonaceous shale tunnels. Among them, the most representative research results include: Yang K conducted triaxial compression experiments on carbonaceous shale and combined it with acoustic emission technology to study its mechanical properties and damage evolution [8]. Zhou Jian used a discrete particle model to numerically simulate the dynamic and static stiffness coefficients of rock texture surfaces, providing new theoretical support for understanding and predicting the deformation of rock structural planes, helping to optimize the tunnel construction process and reduce the risk of large tunnel deformation caused by changes in geological conditions [9]. Zhang Guangze pointed out the definition of double exponential in-situ stress and the classification criteria for large deformation caused by rock bursts. This study helped to more accurately predict and prevent rock burst phenomena in tunnels, ensuring the safety of tunnel construction [10]. Chang Gang studied the deformation effect of rock excavation around deep hard rock composite tunnels [11].

Although many achievements have been made so far, there are still some problems that need to be solved. Although triaxial compression testing and acoustic emission technology can achieve good results, the influence of environmental factors on the performance of carbonaceous shale has not been fully considered. In addition, the lack of sufficient experimental validation of the model and its difficulty in being universally applicable in different geological environments are urgent issues that need to be addressed. How to effectively monitor and predict the large deformation of carbonaceous shale tunnels is still a topic worthy of in-depth research. Based on the summary of previous research results, this article took the Yaxi Expressway Tunnel as an example to illustrate how to simulate and conduct on-site monitoring experiments in the engineering practice of large deformation tunnels to study the problem of large deformation in tunnels.

3. Reasons for Large Deformation of Carbonaceous Shale Tunnels

3.1 Physical and Chemical Properties of Carbonaceous Shale

Carbonaceous shale is a rock composed of various minerals, among which the most common are quartz, feldspar, mica, etc. There are certain interactions and chemical bonds between these minerals, which make carbonaceous shale have a certain water sensitivity [12]. The degree of expansion and rupture depends on factors such as mineral type, mineral particle size, and water sensitivity. In some cases, carbonaceous shale undergoes a "hydration" reaction, where small pores and cracks appear on the surface [13]. Research and testing on the mechanical properties of carbonaceous shale should be strengthened to better understand its deformation behavior and its impact on the stability of support materials in tunnel engineering.

3.2 Ground Stress Theory

Ground stress is the main factor affecting the large deformation of tunnel surrounding rock. According to the principles of rock mechanics, the stress state of the surrounding rock can be divided into three stages, including stress release stage, stress stability stage, and stress loading stage. On this basis, this article establishes a mechanical model for large deformation of surrounding rock, and establishes the basic relationship of damage constitutive law through effective stress [14-15]:

$$[\sigma]=(1-D)[\sigma^{*}]=(1-D)[C][\varepsilon] \quad (1)$$

Among them, [C] is the material monotype matrix; D is the damage variable; [σ] is the stress matrix; [σ^*] is the effective stress matrix; [ε] is the strain matrix. Due to the extremely uneven internal structure of rock materials and the varying strength of internal microelements, this paper simulates damage evolution by calculating the strength distribution of each microelement.

$$P(F)=\frac{m}{F_0}\left(\frac{F}{F_0}\right)^{m-1}\exp\left[-\left(\frac{F}{F_0}\right)^{m}\right] \quad (2)$$

Among them, F is the distribution variable of the random distribution of microelement strength, and m and F_0 are distribution parameters.

3.3 Numerical Simulation

In order to construct and analyze a three-dimensional model of a carbonaceous shale tunnel, this paper uses the Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) finite difference software for numerical simulation, which is an effective method [16]. Firstly, the accurate geometric shape and size of the carbonaceous shale tunnel in the software are designed to ensure the detailed and accurate 3D model. Afterwards, this article sets the material properties of carbonaceous shale. The properties of different materials are shown in Table 1:

Table 1: Material properties

Rock type	Modulus of elasticity (GPa)	Poisson's ratio	Shear strength (MPa)
Carbonaceous shale	5	0.25	40
Sandstone	20	0.25	30
Limestone	30	0.2	30
Granite	45	0.3	60
Shale	3	0.4	20

From Table 1, it can be seen that the elastic modulus of carbonaceous shale is 5GPa; Poisson's ratio is 0.25, and the shear strength is set to 40 MPa to reflect its physical characteristics. In addition, based on actual geological survey data, initial geostress conditions are set, with a vertical stress of 30 MPa and a horizontal stress of 25 MPa. Fixed boundary conditions are set at the bottom and sides of the model to simulate constraints in the geological environment. Subsequently, the gradual excavation process of the tunnel is simulated and the changes in stress and deformation at each step are observed. Stability by extracting key data such as displacement and deformation is evaluated. Finally, the simulation results are compared with theoretical analysis and on-site data to verify the accuracy of the model. Based on the analysis results, the model parameters are adjusted and suggestions for reinforcement and support are proposed. This entire process requires the participation of professional geological engineers or experts in relevant software to ensure the accuracy and reliability of the analysis.

4. Large Deformation Mechanism

This article takes a coal shale tunnel on the Yaxi Expressway as the research object. The coal shale tunnel on the Yaxi Expressway is a double hole four lane tunnel, with a total length of 1186m on the left and right lines and a maximum burial depth of about 856m. The entrance is located on the ridge, with steep terrain and a large slope of the mountain. The maximum burial depth of the tunnel is about 704m, which is a typical high stress tunnel. The tunnel body in the carbonaceous shale section is cylindrical, and there are multiple joint cracks with a direction of about 90 ° developed locally in the tunnel body. The joint surface is rough; the joints are dense, and the cracks are developed [17]. The surrounding rock has the characteristic of alternating soft and hard rocks. Carbonaceous shale is mainly distributed near the tunnel entrance, and its lithology includes carbonaceous shale, carbonaceous dolomite, sandy shale, etc. Figure 1 shows the excavation plan using the full cross-section method, with a cycle of 5cm, starting from the excavation perspective window and ending at 180cm.

During the on-site testing phase, this article divides three excavators into multiple groups for excavation and support construction. The first is to carry out shallow support construction (such as shotcrete, anchor rods, etc.); next is to carry out deep support construction (such as anchor rods, steel arches, etc.); finally, initial support construction (such as steel arches and shotcrete) is carried out. In order to obtain a true reflection of the stress and deformation of the surrounding rock, this article tests two sets of data on site: the first set is displacement measurement of the tunnel surrounding rock before and after excavation; the second group is to measure the displacement of the tunnel surrounding rock during the construction process. On site testing mainly includes installing displacement sensors around the tunnel perimeter; both sides of the tunnel are monitored through multi-point displacement sensors; the settlement of the tunnel arch is measured. The purpose of on-site testing is to obtain accurate data and identify potential issues that may arise in the project.

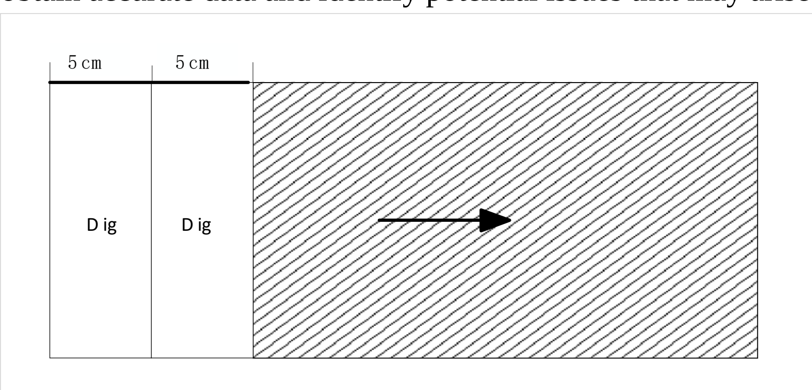

Figure 1: Full section excavation plan

4.1 Geological Conditions

In order to conduct a more comprehensive data analysis, this article combines the relevant information obtained by engineers and construction managers as shown in Table 2:

Table 2: Geological condition information

Index	Describe	Impact Analysis	Recommended actions
Tunnel location	Yaxi high-speed double-hole four-lane tunnel	Increased construction difficulty	Detailed topographic mapping prior to construction
Length and burial depth	High burial depth	High altitude stress environment	Ground stress monitoring, adopting appropriate supporting structures
Ground stress conditions	The earth stress burial depth is about 704m	Surrounding rock deformation and stability issues	Strengthen initial support and adjust construction plans in a timely manner
Rock mass structure	Local joint fissures develop, trending at about 90°	Surrounding rock stability is poor and construction risks increase	Strengthen monitoring and treatment of crack areas during construction
Main lithology distribution	Carbonaceous shale, carbonaceous dolomite, sandy shale, etc.	Affect surrounding rock stability	Take special reinforcement measures, such as anchors, shotcrete, etc.

4.2 Stress Situation

Due to the characteristics of softening and swelling when encountering water in carbonaceous shale, it is difficult for the initial support deformation to fully recover to the initial state after the initial support is completed, that is, to reach a "dead support" state. The initial support deformation shows a long duration of deformation, with significant deformation occurring in a short period of time and a large amount of deformation. The initial support deformation has a long duration, asymmetric deformation, and the deformation amount is significantly affected by construction. During the construction process, some sections of the support system are severely damaged due to the unreasonable support system, and the initial support deformation and failure form is mainly arch sinking. In this case, the stability of the initial support is affected and accidents such as collapse are prone to occur. During the construction process, attention should be paid to timely adjusting the support structure, strengthening the support strength, and also strengthening construction quality management and monitoring. The main purpose of engineering construction is to fully exert the strength of the initial support structure, make it have sufficient stiffness and rigidity, and ensure that the support structure would not experience phenomena such as falling or collapsing during the construction process. If these conditions are not met, the initial support would not be able to play its due role. Therefore, it is necessary to pay attention to the monitoring of initial support deformation and timely discover the development trend and degree of deformation. The monitoring process is shown in Figure 2.

Through the above monitoring process, data collection and analysis are conducted on the large deformation mechanism of carbonaceous shale tunnels.

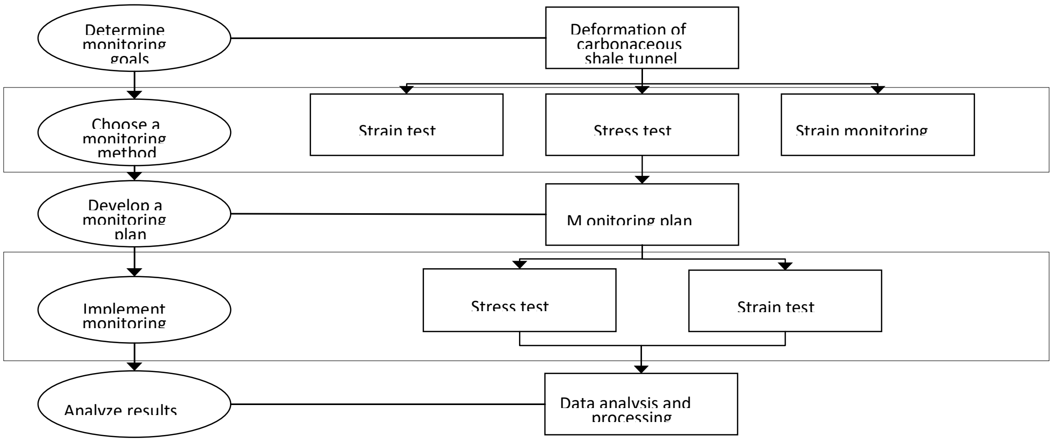

Figure 2: Monitoring process

4.3 Construction Technology

This article collects three different construction techniques. Among them, A is the traditional sequential construction method, which mainly performs excavation and support work in steps. B is the new Austrian tunneling method, which involves synchronous excavation and support, and the use of shotcrete and anchor rods. C is a mechanized shield tunneling method that uses tunnel excavators for continuous excavation. D is the double-sided wall heading method, which is constructed through "long anchor rods+short footage". The collected evaluation data related to construction technology are shown in Table 3:

Table 3: Comparison of construction processes

Construction information	A	B	C	D
Construction period (months)	12	9	10	11
Estimated cost	High	Middle	High	Middle
Security risk	Middle	Low	Low	Low
Quality control	High	Middle	High	High
Environmental impact	Middle	Low	Low	Low
Expected outcome	Stable structure and long cycle	Fast, cost-optimized	High efficiency	Control surface subsidence, suitable for soft strata or urban areas

From Table 3, it can be seen that the A process is suitable for the construction method of short tunnels or sections with significant changes in geological conditions. Due to the long construction period, it is usually selected when time allows and cost control is relatively strict. The B process is suitable for various geological conditions, especially when the geological conditions are unstable or complex. It allows for flexible adjustment of support measures during the construction process, resulting in higher safety, but also requires higher skills from the construction team. The C process is suitable for longer tunnels, especially when geological conditions are stable. It can achieve high-speed construction and reduce the impact on the surrounding environment. However, the initial cost is relatively high, especially the investment in tunnel boring machines. Surface subsidence and surrounding environmental protection are the main concerns, and this article chooses process D.

4.4 Groundwater Impact

For the degree of groundwater impact during excavation and support processes, this article defines 1%-2% as minor impact, 2%-5% as moderate impact, and 5%-10% as severe impact. The collected groundwater impact data is shown in Figure 3:

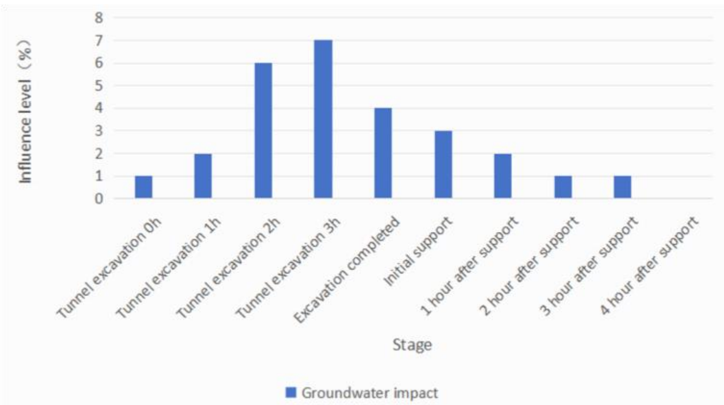

Figure 3: Groundwater impact

From Figure 3, it can be seen that the impact on groundwater is relatively high in the early stage and gradually increased, reaching the highest level of severity. During the support stage, the impact gradually decreases, reaching zero within 4 hours of support. This indicates that during the excavation and support process of the foundation pit, the influence of groundwater on the foundation pit gradually increases. However, during the support stage, the influence gradually decreases. This also means that during the excavation and support process of the foundation pit, attention should be paid to controlling the water level and quantity of groundwater to avoid posing a threat to the stability of the foundation pit.

4.5 Surrounding Rock Characteristics

The surrounding rock of the carbonaceous shale tunnel is composed of carbonaceous shale, carbonaceous dolomite, sandy shale, etc. The rock types are gray black, brownish black, and gray white mudstone cemented or semi cemented, block shaped soft rocks. After excavation, the surrounding rock of the tunnel is cylindrical, with many joints and cracks locally. The tunnel body forms many "V" shaped structures locally, as shown in Figure 4. Due to the weak nature of carbonaceous shale, the surrounding rock undergoes strong deformation and failure after tunnel excavation. The crown sinks significantly, followed by the foot of the arch. During the construction process of carbonaceous shale tunnels, the deformation of surrounding rock is a very important aspect. It not only affects the construction and progress of the tunnel, but also affects the quality and safety of the entire project. Therefore, monitoring the deformation of tunnel surrounding rock is very necessary.

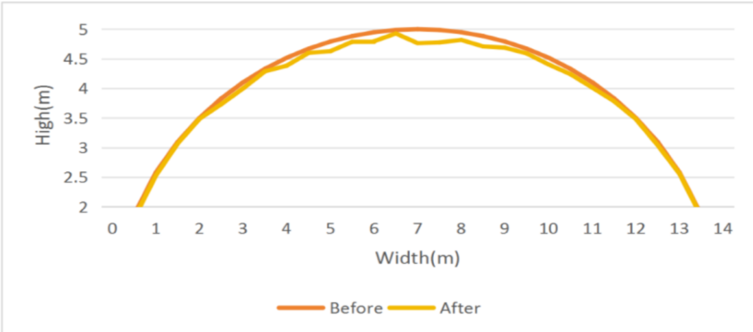

Figure 4: Cave data

4.6 Deformation Data

In addition, the data collected in this article for excavation and support at different time periods are shown in Figure 5:

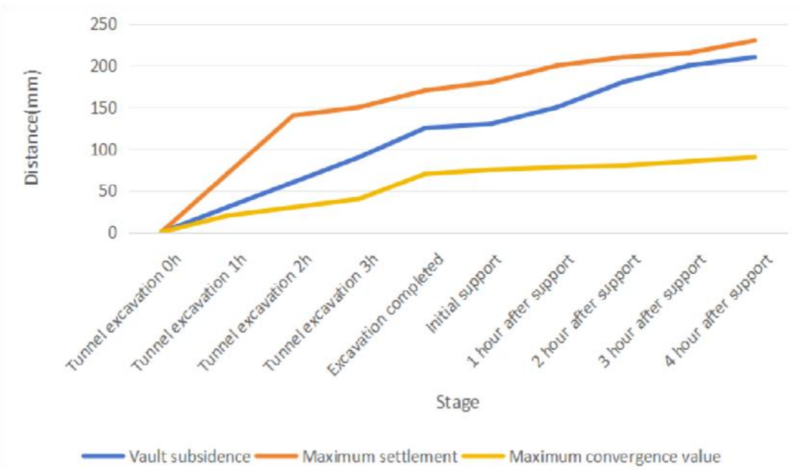

Figure 5: Excavation and support data

The excavation data in Figure 5 shows that during the tunnel excavation process, the surrounding rock undergoes strong deformation, with an arch crown sinking of about 125 mm and a maximum settlement of about 170 mm; the peripheral convergence deformation is obvious, with a maximum convergence value of 70 mm. The initial support deformation is large, with some sections having arch crown sinking of over 200 mm and a maximum settlement of 230 mm; the maximum convergence deformation during the support stage is between 75-90mm, with a maximum convergence value of 90mm, exhibiting rapid deformation in a short period of time. After the initial support installation, the growth rate of deformation decreases, indicating that the deformation of the surrounding rock gradually tends to a stable state.

5. Large Deformation Control Measures

In this article, a combination support system of "anchoring+grouting" should be adopted in the coal shale tunnel, and the construction process should be adjusted appropriately according to the grade of surrounding rock and construction progress. Based on the geological conditions of the surrounding rock and excavation depth of the tunnel, it is determined to use the double-sided wall heading method for construction. When using this method, the principle of "long anchor rods+short footage" is mainly used for support, and the construction process is adjusted appropriately according to the surrounding rock conditions and construction progress. The surrounding rock strength of this tunnel is relatively low. In order to improve the stability and bearing capacity of the initial support, small pipe grouting reinforcement should be used for the initial support. It is recommended to control the burial depth of the small conduit within 3 meters during grouting, and set up a concrete ring around the initial support. At the same time, considering the special structure of the surrounding rock of the carbonaceous shale tunnel, it is recommended to control the distance between the initial supports within 2 meters. Due to the obvious time-dependent deformation characteristics of carbonaceous shale tunnels, it is recommended to adjust construction techniques, advance support, excavation methods and other construction measures in a timely manner according to changes in surrounding rock during the construction process. Especially when there is soft rock near the coal shale tunnel face, the construction time can be appropriately advanced to alleviate the pressure on the soft rock. In addition, it is necessary to strictly control the magnitude of the arch crown settlement and horizontal convergence, as well as the rate of velocity change.

6. Conclusions

This article conducted research on geological conditions, construction techniques, groundwater impact, and surrounding rock characteristics, and explored in depth the situation after excavation of carbonaceous shale tunnels. Through the analysis of impact data at different stages, measures for controlling large deformations were proposed. By refining the support and adjusting the construction time, the soft rock pressure was relieved. Future research needs to further explore the detailed relationship between these stages and the large deformation of tunnel surrounding rock, and attempt to optimize existing mechanical models to improve their prediction accuracy and practicality.

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