Study on the Creep Characteristics of Gentle Dip Red Bed Mudstone of the Surrounding Rock Tunnel

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Abstract. Red bed soft rock exhibits poor physical and mechanical properties and certain creep characteristics, which cause continuous deformation of tunnels and underground engineering structures during operation. The rock mass at the bottom of a railway tunnel in Sichuan Province is mudstone of the Penglaizhen Formation of the Upper Jurassic. It has a thin to medium-thick layered structure. Moreover, the rock formation is nearly horizontal. In this paper, the shear creep test and deep learning are employed to study the creep characteristics of gentle dip red bed mudstone. The results indicate that the red bed mudstone in the tunnel site exhibits medium-low creep characteristics. When the stress level is relatively low, the rate of the creep deformation gradually reduces with time, and when it reaches a certain time, the deformation no longer increases, and the final deformation tends to a stable value. Conversely, when the stress level is relatively high, although the rate of the creep deformation gradually reduces as the time increases, it remains unchanged when it reduces to a certain value. At the initial stage of creep, the deformation of each grade is evident; at the middle stage, the deformation is slow; and at the later stage, the deformation remains unchanged, that is, it enters the stable creep stage after a rapid decay in creep rate. The long-term strength of red bed mudstone in the tunnel site is low, which easily causes continuous deformation of the surrounding rock of tunnels under the action of high ground stress. According to the long-term deformation monitoring data at the bottom of the tunnel, combined with 20 groups of red bed mudstone creep parameter samples and the upper arch deformation data of the tunnel numerical model, the deep learning inverse analysis model of the creep parameter of rock mass is established based on the deep learning algorithm. Finally, we obtain the creep parameter of the red bed mudstone via inverse analysis. The research results provide a basis for engineering structure design and long-term deformation prediction of red bed mudstone strata in this area.

Keywords: Gentle Dip Red Bed Mudstone, Creep Characteristics, Deep learning, Creep Parameter

1. Introduction

The red bed soft rock is widely distributed in Southwest China. Its lithology is mainly red bed mudstone, sandy mudstone, argillaceous siltstone, sandstone, and other soft rocks, which are interbedded or interbedded. It is found that the red bed soft rock is easy to soften, expand, disintegrate, and creep, with poor engineering performance [1]. Zhang analyzed the shear creep characteristics of red bed mudstone under different normal stresses in both the natural and saturated states and proposed the value selection suggestion of long-term shear strength [2]. Xu analyzed the creep characteristics of red bed mudstone using the uniaxial compression creep test and established three new nonlinear creep
constitutive equations [3]. Fan conducted shear creep test on purple mudstone of the Badong Formation and studied the applicability of its creep characteristics and various creep constitutive models [4]. Ju proposed an improved Burgers constitutive model considering water content for the creep characteristics of red bed mudstone [5]. Wu and Liu proposed an improved nonlinear creep constitutive model based on the actual creep characteristics of rock mass [6-7]. The tunnel and underground engineering structures often suffer from large deformation during the operation period due to the creep characteristics of the red bed soft rock. Zhong established the layered deformation mechanism model of the foundation of red bed soft rock and systematically analyzed the short-term, medium-term, and long-term deformation mechanism and characteristics of the foundation [8]. Wang and Yang conducted physical and mechanical analyses of the surrounding rock for the red bed soft rock tunnel under construction and proposed construction control measures [9-10]. For the selection of the creep parameter of rock mass, He obtained the creep parameter of red bed soft rock using the triaxial creep test and built a Particle Swarm Optimization and Support Vector Machine model to predict the displacement change of the surrounding rock [11]. Zhang et al. established the displacement back analysis method based on deep learning and further determined the creep parameter that is in line with the actual situation [12-13].

In this paper, we used the creep problem of the red bed mudstone at the bottom of a railway tunnel in Sichuan Province as the basis and employed the shear creep test to analyze the creep characteristics of the red bed mudstone. Moreover, we obtained the average creep parameter based on the Burgers constitutive model. Finally, we used the upper arch deformation data that was actually monitored combined with the deep learning inverse analysis and obtained the creep parameter that is in line with the actual upper arch deformation.

2. Materials and Methods

2.1. Research background

The rock mass at the bottom of a railway tunnel in Sichuan Province is mudstone of the Penglaizhen Formation of the Upper Jurassic. It has a thin to medium-thick layered structure, and the rock stratum is nearly horizontal. The tunnel section and deformation monitoring points are presented in Figure 1. Tunnel inverted arch occurred in the upper deformation during the operation. After more than five years of deformation monitoring, we calculated and drew the deformation time history curve of the tunnel inverted arch (Figure 2) and found that the deformation of the tunnel inverted arch is the largest in the middle and gradually reduces at both ends while the sidewall remains unchanged. The deformation in the middle part of the tunnel inverted arch basically increases linearly, and the time effect is significant, with significant time effect and creep characteristics. Therefore, we sampled the rock mass at the bottom of the tunnel for the shear creep test.
2.2. Shear creep test

The rock samples (Figure 3) for the shear creep test of the red bed mudstone were all obtained from the upper arch section of the tunnel, and the sampling depth was between 8 and 10.7 m, with 6 rock samples in total. The test specimen (5.0 × 5.0 × 5.0 cm), presented in Figure 4, was obtained from a rock sample that was cut and underwent fine grinding.

![Fig.3. Collected rock samples on-site](image1)

![Fig.4. Test specimen](image2)

The shear creep test uses the method of graded loading. Table 1 presents the preload value of the test specimen. During loading, the normal load is initially applied on the target value at a speed of 0.05 MPa/s and then maintained; subsequently, the horizontal load is applied. The horizontal load adopts the method of incremental loading in a step-by-step manner. The loading rate is 10 KN/min, with each level of loading continuing for about 48 h, and the deformation rate under each load is less than 0.0004 mm/h. Then, carry on the next stage of loading, repeat the above process until the specimen fails.

**Table 1. Test specimen preload value**

| Specimen No. | Predetermined normal load /kN | Predetermined shear load /kN |
|--------------|-------------------------------|-----------------------------|
| 1            | 10                            | 4, 5.5, 7, 8.5, 10…         |
| 2            | 12.5                          | 5, 6.5, 8, 9.5, 11…         |
| 3            | 15                            | 6, 7.5, 9, 10.5, 12…        |
| 4            | 8                             | 4, 5, 6.5, 8, 9.5…          |
| 5            | 14                            | 6, 7.5, 9, 10.5, 12…        |
| 6            | 20                            | 8, 10, 12, 14, 16…          |

During the creep test, under the action of the horizontal shear force, when the shear stress is greater than a certain value, the test specimen cracks horizontally. As time accumulates, the crack spreads and forms new small cracks, which eventually causes destruction. The test process is presented in Figures 5 and 6.

![Fig.5. Test specimen cracking](image3)

![Fig.6. Failure of test specimen](image4)
3. Analysis of Creep Characteristics of Red Bed Mudstone

3.1. Analysis of the shear creep test results

According to the test result data, we calculated and sorted out the shear strain corresponding to the different creep times of the specimen under different horizontal shear stresses, with the shear strain designated as the ordinate and time as the abscissa. We drew the creep curve of the red bed mudstone under different normal stresses of six groups of test specimens, as presented in Figure 7.

![Creep Curve](image)

**Fig. 7.** Creep curve of the red bed mudstone of (a) 1# test specimen; (b) 2# test specimen; (c) 3# test specimen; (d) 4# test specimen; (e) 5# test specimen; and (f) 6# test specimen.

From Figure 7, it can be seen that the red bed mudstone at the bottom of the tunnel exhibits medium-low creep characteristics. In the shear creep test, the specimen has direct elastic response at the time of loading, and then, the creep deformation gradually increases with time. When the stress level is relatively low, the rate of creep deformation gradually reduces as time increases. After a certain period of time, the deformation no longer increases, and the final deformation tends to a stable value. Conversely, when the stress level is relatively high, although the rate of creep deformation gradually reduces as time increases, when it decays to a certain value, it remains unchanged. In the early stage of the creep, the graded deformation of the sample is evident; in the middle stage, the deformation is slow; and in the later stage, the deformation remains unchanged, that is, it enters the stable creep stage after undergoing a rapid creep rate decay.

The test specimens all failed at the last stage of loading. This indicates that the creep of the specimens entered the accelerated creep stage. During this stage, a relatively large strain was generated in the specimen, and small cracks formed along the seam. This caused the specimen to experience shear failure along the structural plane.

3.2. Long-term creep strength
In this paper, we employed the stress–strain isochronous curve method to determine the long-term creep strength of the sample. According to the test results, we drew the isochronous cluster curves of the test specimen, as presented in Figure 6.

![Isochronous cluster curves](image)

**Fig. 8.** Isochronous cluster curve of the red bed mudstone of (a) 1# test specimen; (b) 2# test specimen; (c) 3# test specimen; (d) 4# test specimen; (e) 5# test specimen; and (f) 6# test specimen.

In the isochronous curve method, the stress corresponding to the asymptotic line formed by the inflection points of the linear and nonlinear sections of each isochron is considered as the long-term strength of the rock. In addition, the inflection points of the isochron mark the transformation of the rock from the viscoelastic stage to the plastic stage [14]. Therefore, through the observation and analysis of the inflection points of the isochronous curve clusters of each group of specimens (Figure 8), the long-term strength of the specimens is determined in the shear creep test, as presented in Table 2.

| Specimen No. | Normal stress (MPa) | Long-term strength (MPa) | Shear strength (MPa) | Long-term strength/shear strength |
|--------------|---------------------|--------------------------|----------------------|----------------------------------|
| 1            | 4                   | 2.9                      | 3.9                  | 0.72                             |
| 2            | 5                   | 3.6                      | 4.9                  | 0.73                             |
| 3            | 6                   | 3.9                      | 5.1                  | 0.76                             |
| 4            | 3.2                 | 2.4                      | 3.6                  | 0.67                             |
| 5            | 5.6                 | 4.0                      | 5.5                  | 0.73                             |
| 6            | 8                   | 5.6                      | 7.9                  | 0.71                             |

From Table 2, it can be seen that the long-term strength of the red bed mudstone at the bottom of the tunnel is between 67% and 76% of the shear strength, with an average value of 72%. Approximately 72% of the shear strength can be used as the long-term strength of the red bed mudstone, which is basically consistent with the research results of other scholars who determined that the value is approximately 70%.

### 3.3. Creep model
The creep curve of the red bed mudstone specimen includes three stages: the instantaneous elastic deformation under loading, the deceleration creep under load, and the stable creep. The creep curve characteristics are in good agreement with the Burgers model, which exhibits the properties of instantaneous elastic deformation, deceleration creep, and constant speed creep. The Burgers model is a viscoelastic body composed of Maxwell and Kelvin elements in series. It has four adjustable parameters: \( E_m \), \( \eta_m \), \( E_k \), and \( \eta_k \). Therefore, the Burgers model (Figure 9) well describes the creep curve before the accelerated creep stage of the red bed mudstone in the tunnel site.

![Burgers creep model](image)

**Fig. 9.** Burgers creep model

Burgers creep parameter equation is as follows:

\[
\varepsilon(t) = \frac{\tau}{E_m} + \frac{\tau}{\eta_m} t + \frac{\tau}{E_k} \left(1 - e^{-\frac{E_k}{\eta_k} t}\right)
\]  

(1)

By fitting the creep curve of the red bed mudstone in the tunnel site with the least-squares method and calculating the Burgers creep parameter using Equation (1), the creep parameter of the test piece is obtained. Subsequently, the average creep parameter of the test specimen is also obtained (Table 3).

| NO. | \( E_m \) (GPa) | \( E_k \) (GPa) | \( \eta_m \) (GPa·h) | \( \eta_k \) (GPa·h) |
|-----|-----------------|-----------------|----------------------|----------------------|
| 1   | 0.244           | 2.38            | 1120                 | 13.7                 |

4. **Inverse Analysis of the Creep Parameter Based on Deep Learning**

This paper used the generalized regression neural network (GRNN) to conduct inverse analysis of the creep parameter of the red bed mudstone. The specific process is presented in Figure 10. Compared with other deep learning methods, the GRNN artificially sets fewer parameters, and the network learning all relies on data samples. Moreover, it does not require a thorough understanding of the inherent nature of the research object; it only needs to give input and output data [14-15].

![Deep learning process](image)

**Fig. 10.** Deep learning reverse analysis process of the creep parameter

Based on the average value of the creep parameter of the red bed mudstone, we randomly selected 20 groups of creep parameter samples (Table 4) and used these as the creep parameters of the tunnel numerical model rock mass. The upper arch deformation data of the tunnel model, which correspond to each group of the creep parameter, was obtained using the numerical model creep calculation. Then, we drew the upper arch deformation time history curve (Figure 11).

| NO. | \( E_m \) (GPa) | \( E_k \) (GPa) | \( \eta_m \) (GPa·h) | \( \eta_k \) (GPa·h) |
|-----|-----------------|-----------------|----------------------|----------------------|
The deep learning inverse analysis model is based on 20 sets of red bed mudstone creep parameter samples. Their corresponding numerical model arch deformation samples, of which 20 sets of creep parameter samples, were used as input terminals and their corresponding numerical model arch deformation samples are used as output terminals. The upper arch deformation data of the tunnel model is input into the deep learning inverse analysis model, and the red bed mudstone creep parameter based on the actual upper arch deformation data are output, as presented in Table 5.

| Table.5. Creep parameter of the red bed mudstone based on the actual upper arch deformation data |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| E\textsubscript{m} (GPa) | E\textsubscript{k} (GPa) | η\textsubscript{m} (GPa·h) | η\textsubscript{k} (GPa·h) |
| 0.55 | 3.06 | 1720 | 50.5 |

We bring the red bed mudstone creep parameter obtained via deep learning inverse analysis into the tunnel numerical model and obtain the upper arch deformation data of the tunnel inverted arch through creep calculation. Subsequently, we compare it with the actual upper arch deformation data of the tunnel inverted arch (Figure 12). It can be seen from Figure 12 that the error in the later stage is greater than that in the earlier stage of the two groups of deformation data. This may be because the smoothing factor to be set in GRNN is not the optimal value. The accuracy of deep learning can be improved by adjusting the smoothing factor. In this paper, we used the relatively optimal smoothing factor obtained from numerous tests. Thus, some errors may exist, but the overall fitting degree of the two groups is high. It indicates that the creep parameter obtained from the deep learning inverse analysis is in agreement with the engineering reality and that the method of determining the creep parameter is correct and reasonable. At the same time, the creep parameter obtained using this method can be utilized to predict the long-term upper arch deformation of the tunnel inverted arch using numerical calculation.

5. Conclusions
This paper is based on the upper arch deformation of the tunnel inverted arch caused by the creep of the red bed mudstone at the bottom of a railway tunnel in Sichuan Province. We conducted the shear
creep test on the red bed mudstone and analyzed its creep characteristics in the tunnel site. Moreover, we obtained the creep parameters in accordance with the actual upper arch deformation of the tunnel inverted arch through deep learning inverse analysis. The main conclusions drawn from this study are as follows:

- The red bed mudstone in the tunnel site exhibits medium-low creep characteristics, and its creep is comprised mainly of three stages: instantaneous elastic deformation stage, deceleration creep stage, and stable creep stage.
- The long-term strength of the red bed mudstone at the bottom of the tunnel is low, with a maximum value of only 5.6 MPa, which is between 67% and 76% of the shear strength. About 72% of the shear strength can be used as the long-term strength of the red bed mudstone.
- By using the methods of deep learning and displacement back analysis, we obtained the creep parameter of the red bed mudstone in accordance with the actual upper arch deformation of the tunnel inverted arch, which can provide reference for similar projects.

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