Experimental study on creep characteristics of anchorage rock with cracks under cable pulling condition

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Abstract. The creep characteristics of anchorage rock mass with cracks are the basis for the stability control of anchorage rock and current research hotspots. Relying on the Muzhailing soft rock tunnel project, the anchorage segment is taken as the research object, numerical simulation as the main method is used to systematically study the instantaneous and creep mechanical properties of rock with different crack combinations under the condition of cable pulling, the results show that: 1) Under instantaneous pulling conditions, the effective anchorage range is funnel-shaped, and the maximum value of the maximum shear stress(MSS) appears at the front end of the anchorage rock, while under long-term pulling conditions, the effective anchorage range is uniform along the cable axis distribution, the maximum value of the MSS appears at the end of the cable; 2) Cracks with specific combinations can expand the anchorage range along the axial direction and slow down the shear failure at the front end of the anchorage rock, which is especially obvious for the anchorage rock under instantaneous pulling conditions 3) The optimal number of cracks and the specific area can be obtained by the "virtual intersection method". For the instantaneous MSS and the creep MSS, there is an obvious 45° crack angle effect. The research results are intended to provide a reference for further probing the creep mechanism of anchorage rock with complex crack combinations.

1. Introduction

In recent years, with the development of rock engineering to deeper underground space, geological disasters, especially creep disasters caused by the "three highs and one disturbance" have increased, and engineering accidents caused by this have been common. A large number of data indicate that\cite{1-3}, most of the anchorage engineering failures often occur in the late stage when the engineering structure is put into use, and at the same time, the creep effect of the surrounding rock is less considered in the design of underground engineering support. With the continuous deepening of people's understanding of rock as an anisotropic complex geological medium, the importance of the creep characteristics of anchorage rock with complex crack combination is becoming more and more obvious. Therefore, under the conditions of cable pulling, research on the creep characteristics of anchorage rocks with cracks is a prerequisite for disaster prevention in anchoring engineering\cite{14-18}.

Since the concept of creep was proposed, a large number of scholars have conducted extensive research on the creep properties of rocks, and have also achieved abundant results. Since the 21st century, with the development of information technology and the continuous improvement of experimental equipment, the research on the creep characteristics of cracked rock has increased significantly\cite{9-14}. In recent years,
with the emergence of anchor cables represented by NPR anchor cables that can adapt to rock large deformations, the creep characteristics of anchorage solids under the condition of anchor cable pulling have gradually become a new research focus [15-18]. Although the above research results are abundant, the research is mostly focused on cracked rocks without anchor cables and anchorage rock without cracks. There is little research on the creep of cracked anchorage rock. At the same time, there is also a lack of understanding of the instantaneous mechanical properties of cracked anchorage rock. Based on the comparison of instantaneous and creep mechanical properties of anchorage rock, this paper carried out numerical experiments on the creep properties of anchorage rock with different crack combinations under the cable instantaneous pulling and long-term pulling conditions, aiming to enrich the research results in this field, providing a reference for understanding the creep mechanism of anchorage rock with cracks.

2. Experimental design
This paper relies on the Muzhailing soft rock tunnel project. The tunnel has a large burial depth and relatively developed rock joints and cracks. It adopts NPR end anchor cable support method with alternating length. The pre-tensioning force of anchor cable is 300 KN which is used as the pulling force of anchor cable in numerical test. The row spacing between anchor cables is 1000 mm × 1200 mm, wherein the length of anchor section is 1500 mm, and this is taken as the research object. The geometric characteristics of the crack in the anchor section are divided into the number of cracks, the crack specific area and the crack angle. The number of cracks is 0, 1, 2, 3, and the anchorage segment is divided equally, the crack specific area is expressed as the ratio of the crack area to the anchorage rock cross-sectional area, respectively 0.03, 0.13, 0.33, 0.53, the inclination of the crack is the angle between the crack and the vertical direction, respectively 0°, 30°, 45°, 60°. Using flac3d software to establish the numerical model shown in Figure 1, the anchorage depth of anchor cable is 1500 mm, the model size is 1000 mm × 1200 mm × 3000 mm.

3. Parameters acquisition
In order to obtain the basic mechanical parameters of the rock, uniaxial compressive strength tests were carried out on the rock samples taken from Muzhailing tunnel. These samples contain beddings and no cracks, and the angles of these beddings are 0°, 30°, 45° and 60°, respectively. The test results are shown in Figure 2, and the basic mechanical parameters of the rock are shown in Table 1.
Figure 2. Uniaxial compression failure pattern of the samples.

Table 1. Basic mechanical parameters of rock.

| Bedding angle | $K$/GPa | $G$/GPa | $c$/MPa | $f$/° | Compressive strength/MPa | Density/kg·m$^{-3}$ |
|---------------|---------|---------|---------|------|--------------------------|---------------------|
| 0°            | 19.09   | 7.64    | -       | -    | 85.94                    | 2300                |
| 30°           | 23.48   | 9.40    | -       | -    | 62.54                    | 2300                |
| 45°           | 19.28   | 7.71    | -       | -    | 40.99                    | 2300                |
| 60°           | 26.25   | 10.50   | -       | -    | 45.63                    | 2300                |
| 90°           | 30.52   | 12.21   | -       | -    | 72.22                    | 2300                |
| Mean value    | 23.72   | 9.50    | 12      | 45   | 61.46                    | 2300                |

Note: $K$ and $G$ are bulk modulus and shear modulus of the sample, respectively. $c$ and $f$ come from references [19] in which the rock samples are the same as that in this paper.

The Moore Coulomb criterion is used for the instantaneous constitutive model of the numerical experiment, and the Burgers creep model is used for the creep constitutive model, as shown in Figure 3.

Figure 3. Burgers model$^{[20]}$.

The creep equation of the Burgers model is$^{[20]}$:

$$
\varepsilon(t) = \frac{\sigma}{E_2} + \frac{\sigma}{\eta_2} t + \frac{\sigma}{E_1} \left(1 - e^{-\frac{t}{\eta_1}}\right)
$$

(1)

where $\sigma$ is the normal stress; $E_2, \eta_2$ are the elastic modulus and viscosity coefficient of the Maxwell body; and $E_1, \eta_1$ are the elastic modulus and viscosity coefficient of the Kelvin body.

The parameters of the Burgers creep equation are fitted by using the monitoring data of points A and C on section K222+001 and section k222+003 of the Muzhailing tunnel, as shown in Figure 4. The fitted results are shown in Figure 5 and Figure 6, and the fitted values of the parameters are shown in Table 2.
Figure 4. Location of monitoring points.

Figure 5. Fitted results of Section K222+001. Figure 6. Fitted results of Section K222+003.

Table 2. Parameters of Burgers equation.

| Parameters | $E_1$/GPa | $E_2$/GPa | $\eta_1$/GPa | $\eta_2$/GPa |
|------------|-----------|-----------|--------------|--------------|
| Mean fitted value | 44.2 | 127.4 | $1.2\times10^3$ | $5.0\times10^5$ |

4. Result analysis

4.1 Instantaneous and creep displacement analysis

When the 300kN pretension is applied, the instantaneous displacement field (IDF) inside the anchorage rock changes with the number of cracks as shown in Figure 7. It can be seen from the figure that under the condition of anchor cable pulling, the maximum instantaneous displacement appears at the front end of the rock, and the displacement field gradually attenuates from the funnel shape to the deep part, indicating that the effective anchorage range is concentrated at the front end into a funnel shape, and the anchorage effect gradually weakened towards the rear end. With the appearance of crack and the increase in number of cracks, the displacement field forms a new funnel shape after crossing the crack, just like the formation of a new anchorage displacement field after the crack. The reason is that the appearance of crack and the increase in number of cracks make the stress of the anchor cable at the crack area increase compared with that without crack, and the anchorage range expands at the back end and the displacement field increases accordingly, indicating that the increase of the number of cracks can expand the anchorage range of the anchor cable.
Figure 7. Variation of IDF with the number of cracks.
Figure 8 shows the creep displacement field (CDF) of the anchorage rock. The creep duration is 48 hours, and the displacement at the intersection of rock and the anchor cable is recorded. It can be seen from the figure that the maximum value of the creep displacement also appears at the front end of the rock. The difference is that the maximum creep displacement develops along the anchor cable deeper than the instantaneous situation. Moreover, the funnel-shaped range of the CDF expands deeper than the IDF, indicating that the anchorage range of the rock will develop deeper with time under long-term pulling loads.

Figure 8. Variation of CDF with number of cracks.
Figure 9 shows the change of the IDF of anchorage rock with the crack specific area. It can be seen from the figure that with the increase of the crack specific area, a new funnel-shaped displacement field formed behind the crack gradually increases, indicating that the increase of the crack specific area can expand the anchorage range of the anchor cable in the axial direction.
Figure 9. Variation of IDF with crack specific area.
Figure 10 is the change of the CDF with the crack specific area. It can be seen from the figure that as the crack specific area increases, the new funnel-shaped displacement field formed behind the crack gradually increases, indicating that under the condition of long-term anchor cable pulling, the increase of the crack specific area can expand the anchorage range of the anchor cable in the axial direction.

Figure 10. Variation of CDF with crack specific area.
Figure 11 is the change of the IDF of rock with crack angle. It can be seen from the figure that with the appearance of the crack angle, the asymmetric distribution of the displacement field of the anchorage section begins to appear, and as the angle gradually increases, the asymmetry becomes more and more obvious near the crack. The asymmetry is less and less obvious when it goes deep behind the crack.

Figure 11. Variation of IDF with crack angle.
In Figure 12, the asymmetry of CDF expands with the increase of crack angle, and the change is more obvious than that of IDF.
According to the above numerical test results, (a), (b) and (c) in Figure 13 respectively show the changes of instantaneous displacement and creep displacement at the front end of the anchorage rock with the number, area and angle of cracks. The figure shows that in any case, the creep displacement is much larger than the instantaneous displacement, which is also consistent with the large deformation characteristics of Muzhailing soft rock. As the number and the specific area of cracks increase, both the instantaneous displacement and creep displacement increase linearly; as the angle of the crack increases, both the instantaneous displacement and creep displacement decrease nonlinearly. For the instantaneous displacement, before 45°, the deceleration rate is slower, and after 45°, the deceleration rate increases sharply. It can be seen that for instantaneous displacement, the crack angle has an obvious 45° effect; for creep displacement, as the angle increases, the decreasing speed gradually increases.
Figure 13. Variation of instantaneous displacement and creep displacement at the front end of the anchorage rock with the number, area and angle of cracks.

4.2 Instantaneous and creep MSS analysis

Due to the pulling process of the anchor cable, the rock mass around the anchor cable is mainly subjected to shearing. After the anchor cable is pulled out, shear failure occurs between the rock mass and the binder and the anchor cable. Therefore, the stress discussed in this paper is the maximum shear stress. Figure 14 shows the variation of the instantaneous MSS field of the anchor with the number of cracks. From the figure, the maximum instantaneous MSS occurs in a small part of the area where the front end of the rock closely surrounds the anchor cable. Compared with the displacement field, the maximum shear stress field is mainly concentrated in a cone-shaped distribution around the anchor cable, and the attenuation in the axial direction of the anchor cable is slower than in the lateral direction of the anchor cable. With the appearance of cracks, a new cone-shaped maximum shear stress distribution field appears behind the cracks, indicating that the occurrence of cracks and the increase in number can effectively expand the anchorage range of the anchor cable in the axial direction. At the same time, the cracks play a certain role in sharing the stress concentration area at the front end of the rock, reduce the concentrated stress and avoid premature tensile shear failure at the front end of the rock.

Figure 14. Variation of instantaneous MSS field with the number of cracks.

Figure 15 shows the change of the creep MSS field of the anchorage rock with the number of cracks. It
can be seen from the figure that after a certain creep time, the MSS field of the rock is basically uniformly distributed along the axial direction of the anchor cable and tightly wound. Around the anchor cable, the maximum value of the MSS appears at the end of the anchor cable, which is the opposite of the instantaneous situation, indicating that during the creep process, the concentrated stress is gradually released from the front end point to the end in the axial direction until it is evenly distributed around the anchor cable and reaches the maximum value at the end of the anchor cable. Moreover, the MSS curve at the front end of the rock shows a decay trend, and with the appearance and the increase in the number of cracks, the MSS field expands slightly in the lateral direction of the anchor cable, and there is no obvious change in the axial direction.

**Figure 15.** Variation of creep MSS field with the number of cracks.

Figure 16 shows the change of the instantaneous MSS of the rock with the crack specific area. It can be seen from the figure that as the crack specific area increases, the new cone-shaped MSS field formed behind the crack gradually increases. It shows that the increase of the crack specific area can also expand the anchorage range of the anchor cable in the axial direction and reduce the concentrated stress at the front end of the rock, but the effect is not obvious.
Figure 16. Variation of instantaneous MSS field with crack specific area.

Figure 17 is the change of the creep MSS field of the rock with the crack specific area. It can be seen from the figure that the increase of the crack specific area slightly expands the distribution range of the MSS field along the lateral direction of the anchor cable. Along the axial direction, the MSS field is hardly affected.

Figure 17. Variation of creep MSS field with crack specific area.

Figure 18 is the variation of the instantaneous MSS field of the rock with crack angle. It can be seen from the figure that with the increase of the crack angle, the instantaneous MSS field appears obviously asymmetrically distributed along the lateral direction of the anchor cable, and as the angle increases further, this asymmetry becomes more and more obvious. This rule is also applicable to the variation of the creep MSS field of the rock shown in Figure 19. The asymmetry of the two is reflected in the lateral direction of the anchor cable.
Figure 18. Variation of instantaneous MSS field with crack angle.

Figure 19. Variation of creep MSS field with crack angle.

The shear stress distribution of the cable interface is shown in Figure 20. Before $x_0$, the shear stress increases linearly with the depth; after $x_0$, the shear stress decreases exponentially with the distribution function of $\tau_0(x)$, and the maximum shear stress is $\tau_{0\text{max}}$. Therefore, the tensile force $P$ of the cable can be expressed as follows:

$$P = \pi d \int_0^{x_0} \tau_0(x) \, dx = \tau_0(x) \Big|^{x_0}_{0} + \int_0^{x_0} \tau_0(x) \, dx = A_0$$

(2)

Where $d$ is the diameter of cable.

When there is a crack in the effective anchorage range, the shear stress of cable interface at the crack is 0, and the shear stress of cable interface on both sides of crack redistributes, as shown in Figure 21. In this case, the tensile force $P$ of the cable can be expressed as follows:

$$P = \pi d \int_0^{x_1} \tau_1(x) \, dx + \int_{x_1}^{x_{12}} \tau_2(x) \, dx = \tau_1(x) \Big|^{x_1}_{0} + \int_0^{x_1} \tau_1(x) \, dx + \tau_2(x) \Big|^{x_{12}}_{x_1} + \int_{x_1}^{x_{12}} \tau_2(x) \, dx = A_1 + A_2$$

(3)

If the cable tension $P$ remains constant, then

$$A_0 = A_1 + A_2, \quad A_0 > A_1, A_0 > A_2$$

(4)

$$\tau_{0\text{max}} > \tau_{1\text{max}}, \quad x_{12} > x_{10}$$

(5)

That is, the maximum shear stress of the cable interface is less than that without cracks, and the effective anchorage depth is greater than that without cracks, this can be used to infer the situation with multiple cracks. This paper only discusses the theoretical distribution of shear stress at the cable interface without considering the time effect, and further studies are needed in the case of creep.
Figure 20 Theoretical distribution of shear stress at cable interface\(^{(21)}\). Figure 21 Theoretical distribution of shear stress at cable interface with crack.

According to the above numerical test data, (a), (b) and (c) in Figure 22 respectively show the changes of the maximum instantaneous MSS and creep MSS with the number, area and angle of cracks. It can be seen from the figure that in any case, the maximum instantaneous MSS of the rock is greater than the maximum creep MSS, because the creep process allows the stress to be effectively released through deformation and slows the damage of the rock material. With the increase of the number and the specific area of the cracks, the maximum instantaneous MSS tends to increase slowly and then decrease sharply, while the maximum creep MSS increases approximately linearly. In the same coordinate system, it is difficult to have an intersection point, however, considering that the damage caused by creep stress is greater than the instantaneous stress, after the creep effect is amplified, the two have a virtual intersection point, and the abscissa corresponding to the intersection point is the optimal number of cracks and the crack specific area.

As the crack angle increases, the maximum instantaneous MSS fluctuates slightly before 45°, and the maximum creep MSS decreases slowly before 45°, and both decrease rapidly after 45°, indicating that the instantaneous MSS and creep MSS of the anchorage rock have obvious 45° crack angle effects.

In actual anchorage engineering, grouting is a common method to improve the stability of rock mass with cracks. According to the conclusions in this paper, proper control of the grouting amount and strength of the slurry to reserve a certain amount of cracks is beneficial to improve the long-term stability of the anchorage rock.
Figure 22 Variation of the maximum instantaneous and creep MSS of the anchorage rock with the number, area and angle of cracks.

5 Conclusion
Based on the Muzhailing soft rock tunnel project, this paper takes the anchorage segment as the research object, systematically studies the instantaneous mechanical properties and creep mechanical properties of anchorage rock with different crack combinations under the condition of anchor cable pulling, the main results are as follows:

(1) Under the condition of instantaneous cable pulling, the anchorage rock displacement field and MSS are funnel-shaped along the axis of the cable, and the maximum displacement and MSS appear at the front end of the rock; under long-term cable pulling, the anchorage rock displacement field is funnel-shaped, the maximum value appears at the end of rock, the MSS field is evenly distributed along the anchor cable axis, and the maximum value appears at the end of the anchor cable.

(2) The increase in the number and the specific area of cracks can expand the effective anchorage range of the anchor cable, reduce the concentrated stress and avoid premature shear failure at the front end of the anchorage rock to a certain extent. For the instantaneous displacement of the front end of the anchorage rock and the maximum instantaneous MSS, there is an obvious 45° crack angle effect, but for the creep displacement and the maximum creep MSS, the effect is not obvious.

(3) The existence of certain crack geometric characteristics is beneficial to the distribution of the MSS of the anchorage rock. Among them, the optimal number and specific area of cracks can be obtained by the virtual intersection method described in this paper. After the crack angle is greater than 45°, the maximum instantaneous displacement and creep displacement, the maximum instantaneous MSS, and the maximum creep MSS all have a clear decreasing trend.

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