Unloading-creep test and long-term strength study of different initial conditions of limestone

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Abstract. The high-slope limestone on the right bank of the Wudongde Hydropower Station dam site was considered as a research object to conduct a triaxial unloading-creep test, and then to analyze in detail the limestone's creep characteristics under different test conditions so as to investigate the limestone's unloading-creep mechanical properties under different unloading rates and initial stress levels. The results show that the faster the unloading rate, the greater the limestone's axial and lateral creep rate when under the same stress state. Furthermore, the lateral creep rate is greater than the axial creep rate, indicating an apparent lateral expansion. When the unloading rate is constant, the stress difference has a significant impact on the limestone. The specific manifestation is that the greater the deviator stress, the more pronounced the limestone creep phenomenon, and the rock sample is prone to damage. The steady-state rate intersection method is employed to determine the limestone's long-term strength, and the λ parameter is introduced to reduce the influence of the axial and lateral strain increments on the long-term strength determination during the unloading process.

1. Introduction

The hard and brittle rock mass of high slopes is often in a high ground stress state and remains stable under natural conditions. The original balance of the rock mass will be broken during engineering excavation, resulting in unloading deformation and failure. Although some progress has been made on the mechanical properties of rock mass under unloading conditions, due to the long rheological test cycle, high accuracy, and environmental requirements, it is still in the theoretical stage, and it is challenging to conform to actual engineering fully. Studying the mechanical unloading properties of engineering slopes' hard and brittle rock masses and improving the accuracy of judging the long-term strength of unloading rock masses has become a vital engineering construction research topic in China.

Scholars worldwide have conducted numerous studies on the rheological characteristics of rock unloading by setting different stress paths and test environments to simulate the unloading-rheological process of rock mass in engineering construction. Griggs conducted creep tests on soft rocks such as limestone, shale, and sandstone as early as the 1930s [1]. The test results revealed that obvious creep deformation would occur when the external load of sandstone and siltstone reaches 12.5% to 80% of the failure load. A 30-year flexural creep test on granite was conducted by It, H. [2], and the results
revealed that the granite exhibited a viscous flow without yield stress. Fujii, Y. [3] conducted a comparative analysis of a rock's axial and lateral creep deformation characteristics and concluded that lateral deformation could be used as an essential indicator for judging rock damage. Boukharov [4] studied the creep of hard and brittle rocks at three different creep stages using an indoor triaxial creep test. Maranin [5-6] employed triaxial compression tests to study the creep behavior of granite; Kinoshita, N. [7] investigated the uniaxial creep properties of granite at different temperatures and discovered that temperature accelerated the creep failure. The long-term strength threshold of hard and brittle rocks was confirmed by Damjanac [8]. Li, J. L. [9] performed a triaxial unloading-creep test on sandstone in 2010, obtaining a typical three-stage full-process test curve of sandstone creep, and studied the non-linear mechanical characteristics of sandstone unloading-creep.

Gascbarbier, M. [10] conducted triaxial creep tests on clay rock with different loading methods and temperatures and found that its strain rate and strain size increase with the increase of deviatoric stress and temperature. Nicolas [11] used triaxial unloading-rheological tests to study the rheological properties of limestone with initial fractures. They described the different deformation characteristics of limestone at the upper and lower confining pressure of 55 MPa, respectively, and combined the rheological rate to explain the various stages of limestone. There has also been some research progress on determining the long-term strength of rocks. Pushkarev, V. [12] proposed a theoretical method for determining the long-term strength of soft rocks in the 1970s. Efimov, V. [13] studied the determination of the long-term strength of rocks under constant loading rate conditions. Damjanac, B. [14] determined that the long-term strength of hard and brittle rocks should account for 0.4–0.6 of the uniaxial compressive strength through laboratory tests.

Scholars at home and abroad have made significant advances in studying the unloading-rheological properties of rock masses, but there is a dearth of research on the unloading-creep properties of hard and brittle rocks, particularly the mechanism analysis of rock flow under various experimental conditions set by the simulation engineering. Furthermore, further exploration into the method for determining the long-term strength of hard and brittle rocks under unloaded conditions is required. As a result, this study uses the high-slope limestone on the right bank of the Wudongde Hydropower Station as the research object and conducts constant axial pressure staged unloading-confining pressure triaxial unloading-creep tests at different unloading rates and stress levels. The unloading-creep mechanical properties of limestone under different unloading rates and initial stress levels and its long-term strength prediction are discussed to provide a reliable reference for similar projects' slope construction and long-term stability.

2. Introduction to test conditions

2.1. Rock sample collection and preparation

The limestone used in the test came from the high slope on the right bank of the Wudongde Hydropower Station. The rock quality has undergone shallow metamorphism, and the overall structure is compact. It is a hard and brittle rock, with calcite limestone as the main component. The rocks are made up of light-gray blocky structures. The main minerals in the mirror analysis generally contain a small amount of quartz, and the chemical analysis typically has a small amount of acid-insoluble substances, mainly SiO₂, Al₂O₃, and Fe₂O₃.

The on-site rock block has a diameter of 50 mm, a height of 100 mm, and an end flatness of ≤±0.5 mm. The research samples were selected from six aspects in rock properties: appearance, quality, height, diameter, density, and longitudinal wave velocity that are similar to those samples, to minimize the influence of the discreteness of the sample on the test results. Figure 1 depicts a part of the completed sample.
2.2. Triaxial unloading-creep test scheme
The initial confining pressure of the test is set to 9 MPa because the initial horizontal ground stress of the local surrounding rock is 8.8–10.4 MPa, and the average ground stress level is about 9.2 MPa. The peak strength of the limestone was determined using the conventional triaxial test with a confining pressure of 9 MPa before the triaxial unloading-creep test was carried out. As a result, the test's initial stress level is set to 9 MPa, and the axial compression is 70% and 80% of the peak strength of the conventional triaxial compression test, which is 89.8 and 99.2 MPa, respectively.

The axial pressure $\sigma_1$ is kept constant throughout the test, while the confining pressure $\sigma_3$ is gradually removed to perform the triaxial unloading-creep test, that is, the initial condition is a constant axial force $\sigma_1$, and the confining pressure $\sigma_3$ is gradually removed to make the deflection stress $(\sigma_1-\sigma_3)$ increases step by step. To simulate different excavation speeds and the on-site geostress environment of the project, different unloading rates, and initial stress levels were set for experiments. The unloading rate is set to 0.01 and 0.15 MPa/s, respectively, 0.1 times and 1.5 times the conventional loading rate (0.1 MPa/s). Table 1 lists the three-axis unloading-creep test scheme.

| Table 1. Triaxial unloading-creep test scheme |
|-----------------------------------------------|
| **Unloading conditions** | Graded | **unloading rate** | $\sigma_1$/MPa | $\sigma_3$/MPa | $\sigma_1-\sigma_3$/MPa |
|---------------------------|--------|--------------------|----------------|----------------|--------------------------|
|                           | 1      |                    | 9              | 9              | 80.8                     |
|                           | 2      | 0.01 MPa/s         | 89.8           | 7              | 82.8                     |
|                           | 3      |                    |                | 5              | 84.8                     |
|                           | 4      |                    | 3              | 86.8           |                          |
|                           | 1      |                    | 9              | 80.8           |                          |
|                           | 2      | 0.15 MPa/s         | 89.8           | 7              | 82.8                     |
|                           | 3      |                    |                | 5              | 84.8                     |
|                           | 4      |                    | 3              | 86.8           |                          |
|                           | 1      |                    | 9              | 90.2           |                          |
|                           | 2      | 0.01 MPa/s         | 99.2           | 7              | 92.2                     |
|                           | 3      |                    |                | 5              | 94.2                     |
|                           | 4      |                    | 3              | 96.2           |                          |
|                           | 1      |                    | 9              | 90.2           |                          |
|                           | 2      | 0.15 MPa/s         | 99.2           | 7              | 92.2                     |
|                           | 3      |                    |                | 5              | 94.2                     |
|                           | 4      |                    | 3              | 96.2           |                          |

Figure 1. Part of limestone
The test steps are as follows: (1) Load $\sigma_1 = \sigma_3$ to 9 MPa at 0.1 MPa/s depending on the hydrostatic pressure conditions; (2) Wait for the sample's deformation to stabilize, and continue to increase $\sigma_1$ to the initial stress value set at the actual loading rate; (3) Set $\sigma_1$ constant, and gradually unload the confining pressure according to the test plan's unloading rate. After the sample's creep deformation is stabilized under each unloading level, continue to the next unloading of the confining pressure until the unloading-creep failure occurs.

3. Analysis of test results

3.1. Creep curve analysis

Figure 2 illustrates the triaxial unloading-creep curve of the limestone, and Table 2 lists the statistical test data according to the creep curve. Figure 3 depicts the schematic diagram of the instantaneous strain increment and the creep strain increment from Table 2.

![Figure 2](image1.png)  
(a) $\sigma_1 = 89.8$ MPa  
(b) $\sigma_1 = 99.2$ MPa

**Figure 2.** Creep curve at an unloading rate of 0.01 MPa/s

![Figure 3](image2.png)

**Figure 3.** Instantaneous/creep strain increment

As can be seen, Figure 2 reveals that the creep process of limestone in the unloading-creep test can be roughly divided into three stages: (1) deceleration creep stage; (2) stable creep stage; (3) non-linear
accelerated creep stage. As Figure 2 shows, the sample is in the elastic deformation stage before reaching the different initial stress states. When the confining pressure is 9 MPa, the creep phenomenon of the specimens with different initial stress levels is more apparent, and the lateral creep strain increment is much larger than the axial creep strain increment at this time. When the confining pressure is unloaded to 7 MPa, the limestone of the axial creep deformation is not visible. The creep deformation of the rock sample gradually stabilizes with time, and the creep curve gradually becomes horizontal. At this stage, the lateral strain is greater than the axial strain. When the confining pressure is unloaded to 5 MPa, the specimen with lower deviator stress \((\sigma_1 = 89.8 \text{ MPa})\) exhibits attenuated creep and steady-state creep in the axial and lateral deformations. As the confining pressure drops, the new cracks appear and gradually expand. Since the new cracks are not connected to each other, the limestone exhibits a phenomenon of steady-state creep. At this unloading level, the specimen with the higher deviator stress \((\sigma_1 = 99.2 \text{ MPa})\) exhibits an accelerated creep stage. Also, at this stage, the axial creep strain increases by 487.25με, and the lateral creep strain increases by 1438.04με, expressed as a visible lateral expansion phenomenon. Because the crack growth stage develops faster under high deviator stress levels, the rock is damaged, and the bearing capacity is weakened, so the specimens with lower deviator stress \((\sigma_1 = 89.8 \text{ MPa})\) only show the accelerated creep stage when the confining pressure is unloaded to 3 MPa, and the creep amount at failure is much smaller than the value under the higher deviator stress level. The unloading effect causes the sample's plastic deformation to increase and the cracks in the limestone to propagate more quickly, resulting in the limestone's failure and the macroscopically non-linear accelerated creep failure.

Table 2. Triaxial unloading-creep test data of different stress levels and unloading rates of limestone

| Stress level /MPa | Creep strain increment/με | Instantaneous strain increment/με | Average creep rate /10^-6·h^-1 | Creep time /h |
|------------------|--------------------------|----------------------------------|-------------------------------|--------------|
| \(\sigma_1\)     | \(\sigma_3\) | \(\sigma_1+\sigma_3\) | \(\Delta\varepsilon_1\) | \(\Delta\varepsilon_3\) | \(\Delta\varepsilon_3\) | Axial | Lateral |
| 89.8             | 9                   | 80.8                           | 118.42                        | -694.67       | \(\varepsilon\) | 3.44 | 20.19 | 34.4 |
| 89.8             | 7                   | 82.8                           | 42.39                         | -457.35       | 112.18 | -287.38 | 0.82 | 8.90 | 51.39 |
| 89.8             | 5                   | 84.8                           | 286.68                        | -841.91       | 133.36 | -329.76 | 6.85 | 20.13 | 41.83 |
| 89.8             | 3                   | 86.8                           | 475.95                        | -1105.68      | 294.87 | -642.32 | 153.53 | 356.67 | 3.1 |
| 99.2             | 9                   | 90.2                           | 142.73                        | -706.49       | \(\varepsilon\) | 4.48 | 22.19 | 31.84 |
| 99.2             | 7                   | 92.2                           | 34.89                         | -391.17       | 127.93 | -323.47 | 0.64 | 7.20 | 54.3 |
| 99.2             | 5                   | 94.2                           | 487.25                        | -1438.0       | 284.02 | -381.56 | 203.02 | 599.18 | 2.4 |
| 0.01             |                     |                                | 2349.61                       | -4797.35      |                     |        |        |        |
| 89.8             | 9                   | 80.8                           | 122.45                        | -641.57       | \(\varepsilon\) | 4.99 | 26.15 | 24.53 |
| 89.8             | 7                   | 82.8                           | 48.07                         | -404.86       | 126.71 | -324.61 | 1.01 | 8.51 | 47.57 |
| 89.8             | 5                   | 84.8                           | 327.57                        | -817.71       | 150.64 | -372.48 | 8.01 | 19.99 | 40.91 |
| 89.8             | 3                   | 86.8                           | 611.54                        | -1241.93      | 333.07 | -725.54 | 430.66 | 874.60 | 1.42 |
| 0.15             |                     |                                | 2654.01                       | -5418.87      |                     |        |        |        |
| 99.2             | 9                   | 90.2                           | 137.43                        | -641.29       | \(\varepsilon\) | 4.47 | 20.88 | 30.72 |
| 99.2             | 7                   | 92.2                           | 55.18                         | -371.72       | 140.38 | -354.95 | 1.14 | 7.67 | 48.48 |
| 99.2             | 5                   | 94.2                           | 419.29                        | -1656.32      | 311.66 | -418.7 | 147.12 | 581.16 | 2.85 |

Table 2 shows that the limestone's axial and the lateral strains gradually increase with time, with the lateral strain clearly greater than the axial strain. Based on the average creep rate in the axial and lateral directions, it can be concluded that the limestone's average lateral creep rate is higher than the axial creep rate under different deviatoric stresses. The accelerated creep stage accounts for only about 3% of the total duration, indicating that the limestone exhibits a clear failure trend in a short period after applying a higher stress level. From a macroscopic point of view, the strain increases instantly.
after the last stage is unloaded. For example, when unloading at 89.8 MPa, the strain at instant failure will be $7146.96 \mu \varepsilon$. The total creep variable is only $4023.05 \mu \varepsilon$ in the limestone's entire triaxial unloading-creep test process. The increment of failure strain is 1.78 times the total creep variable, and the final failure speed is faster. This should be prioritized in engineering.

3.2. Analysis of the influence of unloading rate on unloading-creep characteristics

3.2.1. The effect of unloading rate on creep strain

The initial confining pressure of the rock sample is 9 MPa, and the axial stress is maintained at 89.8 and 99.2 MPa, respectively. Figure 4 shows the axial and lateral creep increment changes of the confining pressure at different unloading rates.

When the axial creep strain increment at different unloading rates are compared, it can be seen that at $\sigma_1 = 89.8$ MPa, the overall axial strain of the rock sample with an unloading rate of 0.15 MPa/s is greater than the axial strain of 0.01 MPa/s. The greater the unloading rate is in the state of constant axial pressure unloading confining pressure, the more pronounced the axial deformation of the specimen is, and the macroscopic manifestation is axial compression. The overall axial creep at an unloading rate of 0.15 MPa/s is smaller than that at an unloading rate of 0.01 MPa/s at $\sigma_1 = 99.2$ MPa. When comparing the lateral creep strain increments at different unloading rates, it can be seen that when $\sigma_1 = 89.8$ MPa, the lateral creep strain of the rock sample increases more at a lower unloading rate (0.01 MPa/s) after the confining pressure is gradually unloaded from 9 to 5 MPa. It enters the accelerated creep stage after the confining pressure continues to be unloaded to 3 MPa, and the rock sample with a lower unloading rate (0.01 MPa/s) has a minor increase in the lateral creep strain. At $\sigma_1 = 99.2$ MPa, the lateral creep increases with the unloading rate.

In summary, the creep strain is slightly affected by the unloading rate, and it is related to the degree of unloading, that is, the deviatoric stress level. With increasing deviator stress, the creep strain increments under different unloading rates first decrease and then increase. They all decrease when the confining pressure is unloaded from 9 to 7 MPa, primarily because the axial pressure is loaded from 0 MPa to preload before the confining pressure is stable at 9 MPa, causing the internal fissures of the rock mass to develop more visibly, resulting in more significant creep deformation in the creep stage when the confining pressure is 9 MPa.

![Axial creep strain increment](image1)
![Lateral creep strain increment](image2)

Figure 4. Change graph of creep strain increment under different unloading rates

3.2.2. The effect of unloading rate on creep rate

Take samples with unloading rates of 0.01 and 0.15 MPa/s, $\sigma_1 = 89.8$ MPa as examples to study the influence of the unloading rate on the creep rate of limestone, as shown in Figure 5(a)–(b).
Figure 5 reveals that the creep change trend is essentially the same when the two different unloading rates are subjected to the same confining pressure. When there is no accelerated creep, the creep rate gradually decreases before stabilizing. The creep rate is a U-shaped curve when the accelerated creep occurs, corresponding to the three stages of rock creep-attenuation creep stage, steady-state creep stage, and non-linear accelerated creep stage. In general, the sample's attenuation and accelerated creep phases lasted for a short duration, while the steady-state creep phase lasted longer. The lateral creep rate of the sample is significantly greater than the axial creep rate under different unloading rates, indicating that the lateral creep deformation develops more rapidly than the axial deformation, resulting in significant lateral expansion. During the rock sample's accelerated creep stage, the axial and lateral creep rates increase rapidly and non-linearly.

When comparing two different unloading rates, it is clear that when both are unloaded at the same stress level, their creep rates appear to change suddenly. The unloading rates are 0.15 MPa/s axial strain and lateral strain, respectively. These values are far greater than the axial and lateral strain rates of 0.01 MPa/s, with a short fracture duration.

3.3. Influence of stress level on unloading-creep characteristics

Figure 6. Deviatoric stress-strain curve of limestone under different stress levels

As Fig. 6 shows, the influence of the axial pressure on the creep deformation varies with the size of the confining pressure, and the creep of the specimen at high confining pressure is roughly the same.
under different axial pressures. In Table 2, for example, when the confining pressure is 9 MPa, the axial and lateral creep under different axial pressures are nearly identical, and the high confining pressure weakens the axial pressure's influence. As the unloading of the confining pressure decreases, the lateral restraint is slowly released, the axial pressure effect gradually appears, and the axial and lateral strains show an increasing trend. As shown in the figure, the unloading speed is 0.01 MPa/s, and the confining pressure is 5 MPa. The axial and lateral strains of the rock sample under the axial compression of 99.2 MPa are about twice the axial and lateral strains of 89.8 MPa axial compression, respectively.

The rock sample is more prone to failure as the deviator stress increases under higher axial pressure. Taking 0.01 MPa/s unloading rate as an example, when the sample is unloaded to 3 MPa under the confining pressure at 89.8 MPa axial pressure, the sample gets destroyed. When the confining pressure is unloaded to 5 MPa at 99.2 MPa axial pressure, the sample gets finally broken, and the amount of strain at the time of the failure is also more considerable.

As can be seen, the size of the deviator stress has a significant impact on the rock sample's creep characteristics. The main insight is that the greater the deviator stress, the more pronounced the rock sample's axial and lateral creep deformation; at the same time, the rock sample will be more easily destroyed.

4. Judgment and analysis of long-term strength of limestone

The long-term strength of the rock mass is the critical stress that the rock mass can withstand for an extended period without internal damage. The degree of damage caused by the long-term stress to the inside of the rock mass is used to determine the rock mass' long-term strength [15-16]. Among other methods, the isochronous stress-strain curve, steady rheological rate intersection, volume expansion methods are currently employed to evaluate the long-term strength of rock masses.

The isochronous stress-strain curve method is a convenient and straightforward way to judge the long-term strength of a rock mass. As a result, the long-term strength of limestone unloading-creep is evaluated using the isochronous stress-strain curve method. The time-axial strain curves for different initial stress levels have been drawn based on the limestone unloading-creep tests results. Figures 7 and 8 show an example of the limestone's unloading-creep curve with 0.01 MPa/s unloading rate and 89.8 MPa initial stress.

![Figure 7. Limestone unloading-Creep Time-axial strain curve](image1)

![Figure 8. Limestone unloading-creep long-term strength](image2)

It can be seen from Figures 7 and 8 that the characteristics of the axial creep curve drawn by this method are consistent with the characteristics of the rock's accelerated creep failure stage. The isochronous stress-strain curve demonstrates this. When T has an obvious inflection point in the isochronous curve at 5 o'clock, it can be seen that the axial strain growth rate at the inflection point and the axial strain increment begins to decrease with time, so the corresponding sample strength at the inflection point can be regarded as the rock's Long-term strength. Therefore, the sample's long-
term rheological strength obtained by the isochronous stress-strain curve method under this condition is 83.8 MPa. However, subjective factors can easily affect this method, and its creep characteristics in hard rocks, such as limestone, are less evident than in soft rocks. Therefore, the isochronous-stress-strain method is more suitable for determining the long-term creep strength of soft rocks but not for calculating the long-term strength of hard rock.

Jiang Yuzhou concluded that the mechanical characteristics of the stable creep stage of the rock are the basis for evaluating the possibility of a rock failure after studying the long-term rheological strength of high arch dam rocks [17]. Zhang Longyun [18] utilized this information to analyze the creep characteristics of hard rock at various stages and proposed a method for determining the stable creep rate intersection point. In view of this, this study employs the stable creep rate intersection method to solve the long-term strength of limestone, introduces a parameter $\lambda$ to reduce the impact of the unloading stage on the creep rate, and improves the stability of the creep rate intersection method.

As an example, consider the deformation in the axial direction: suppose the instantaneous axial strain during the specimen removal of the confining pressure is $\varepsilon_0$, and the total axial strain of the entire creep process is $\varepsilon_1$, then the formula for calculating the parameter $\lambda$ is given as:

$$\lambda = \frac{\varepsilon_0 - \varepsilon_1}{\varepsilon_1}$$

Consider the 0.01 MPa/s sample and the 89.8 MPa stress as an example. The entire test stage's total axial and lateral creep strain amounts are $0.0023 \times 10^{-2}$ and $-0.0191 \times 10^{-2}$, respectively. The axial and lateral strains generated during unloading are $1023.44 \times 10^{-6}$ and $-3099.61 \times 10^{-6}$, respectively. As a result, the rock's axial and lateral strains in the unloading process respectively account for 0.022 and 0.063 of the total creep strain. Suppose the axial velocity is $v$ and the lateral velocity is $v_1$; the corrected axial and lateral velocities are $0.978v$ and $0.937v_1$, respectively.

As shown in Table 3, the $\lambda$ value of limestone under different test conditions.

| Unloading rate /MPa·s$^{-1}$ | Axial Stress level /MPa | Lateral Stress level /MPa |
|-------------------------------|-------------------------|--------------------------|
|                               | 89.8                    | 99.2                     |
| 0.01                          | 0.978                   | 0.98                     |
| 0.15                          | 0.992                   | 0.994                    |

As shown in Figure 9, consider the samples under 0.01 MPa/s unloading rate and the initial stresses of 89.8 MPa and 99.2 MPa as examples to draw the improved steady-state creep rate intersection diagram.

The axial and lateral creep rates of the specimen are relatively low at a lower stress level. The axial creep and lateral creep rates begin to increase as the deviator stress gradually increases. However, after a long period of creep, the lateral creep rate rapidly increases, approaching and exceeding the axial creep rate. The lateral creep strain begins to exceed the axial creep strain at this moment and continues to do so until the test is completed. Figure 9 shows the intersection of the axial strain rate and lateral strain rate curves, and the stress level value corresponding to this intersection is the long-term strength value of the sample. As a result, at an unloading rate of 0.01 MPa/s, the long-term strength of the rock with initial stress of 89.8 MPa is 81.4 MPa, and the long-term strength of the rock with initial stress of 99.2 MPa is 90.4 MPa.
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Figure 9. Determination of long-term strength by the steady rheological rate intersection method after introducing λ.

5. Conclusion
(1) Limestone shows a certain degree of deformation in both axial and lateral directions under test conditions where the constant axial pressure gradually unloads the confining pressure. The lateral creep deformation is more visible, and lateral expansion eventually destroys the sample. Under the failure confining pressure, it went through three typical stages of rock creep-attenuation creep, steady-state creep, and non-linear accelerated creep stages.
(2) Under different unloading rates, the lateral creep rate of the specimen is greater than the axial creep rate. With the increase of the unloading rate, the lateral creep rate also increases significantly and shows a significant lateral expansion phenomenon.
(3) The deviator stress size has a significant impact on the sample's creep characteristics. The central realization is that the greater the deviator stress is, the more pronounced the axial and lateral creep deformation of the rock sample is and the easier it is to destroy the rock sample.
(4) In the stable creep rate intersection method, the stress level corresponding to the intersection of the axial and the lateral creep rates at a given moment is the long-term rock strength. The λ parameter is introduced based on this method to reduce the influence of the unloading process on the long-term strength and ensure the results are more reliable.

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