Experimental Study on Influence of Unloading Rate on Creep Characteristics of Marble under High Stress

Huajun He¹ and Huahui Jin*¹

¹Zhejiang Guangchuan Engineering Consulting Co, Hangzhou 310020, China

Abstract. In the engineering of high stress area, the measures to control the stability of surrounding rock by reducing excavation footage and excavation speed are to adjust the unloading rate of surrounding rock caused by excavation. In this study, unloading creep tests of marble under high stress conditions were carried out to study the effect of unloading rate. Research results showed that the axial and lateral instantaneous strain and creep strain of the sample increased with the increase of unloading rate; the lateral creep characteristic of marble under unloading condition was stronger than that of axial creep characteristic, and it was more obvious with the increase of unloading rate; the failure of specimens under unloading creep condition was mainly caused by the rapid increase of lateral strain, and the brittleness of rock was increasing with the increase of unloading rate. The Burgers model was used to describe the creep curves of specimens, and the variation of the parameters with the unloading rate was analyzed. The fitting results showed that the instantaneous elastic modulus $E_1$, $E'_1$ and the viscosity coefficients $\eta_1$, $\eta'_1$ all decreased with the increase of the unloading rate, which can be described by linear relationship within the unloading rate range of this experiment. Compared with the time of whole creep tests, the time for each specimen to enter the steady-state creep was similar, it was considered that the effect of unloading rate on $\eta_1/E_1$ and $\eta'_1/E'_1$ can be ignored.

1 Introduction

Compared to the soft rock material, it is generally considered that the hard rock material has relatively weak viscosity1,2. With the continuous construction of some large-scale projects, more and more practice shows that in the process of excavation or unloading of valley trenching under high ground stress, in addition to the common surface rock mass failure (such as rockburst) in a short time due to the rapid release of elastic strain energy, the deformation and failure of hard rock generally have to go through a more obvious time-dependent process. The above phenomenon are strongly manifested in hard rock projects such as granite in the Three Gorges Hydropower Project1, marble in the Jinping Hydropower Station2, sandy slate in the river reaches of the Yalong River3, granite in the reservoir area of the Laxiwa Hydropower Project in the upper reaches of the Yellow River4. In view of this, many scholars have been conducted studies on the creep characteristics of hard rock under unloading by using experiments and related theories. Such as Yan7 carried out unloading creep tests with lateral stress unloading gradually on the marble of the Jinping Hydropower Station diversion tunnel, and pointed out that there were significant differences between the axial and lateral deformation. Zhu8 carried out triaxial unloading creep tests on the green sandstone of the Jinping II Hydropower Station, and established the rock damage evolution equation and variable parameter nonlinear Burgers model. Yang9 prepared fractured specimens from Chongqing sandstone, carried out triaxial unloading creep tests and proposed a damage creep model to establish the relationship between intact rock and fractured rock mass.

Based on the analysis of current studies, the differences of creep properties of hard rock have been investigated from different unloading values10, different loading-unloading paths11, different initial confining pressure and other conditions, while the researches on creep characteristics of hard rock under different unloading rates are relatively less. Moreover, the relevant research results of conventional unloading tests of hard rock show that the unloading rate has a significant impact on mechanical properties. In fact, the essence of the measures to control the stability of the surrounding rock by reducing the excavation footprint and lowering the excavation speed in practical projects in high stress areas is to adjust the unloading rate of the surrounding rock caused by excavation11.

In this study, the unloading creep tests of hard marble under high initial confining pressure were carried out, the effects of different unloading rates on the deformation, strength and failure mode of the materials were investigated, and a creep model considering the effects of different unloading rates was established. The results can provide references for the unloading creep characteristics of hard rock and the evaluation of the time-dependent stability of hard rock projects in high stress areas.

* Corresponding author: 691436049@qq.com
2 Testing procedure

The Specimens made from marble had a columnar shape with a diameter of 50 mm and a height of 100 mm, which were accordance with the standard recommended by the International Society for Rock Mechanics. The specimens were taken from the same rock mass with dry densities of 2.62-2.81 g/cm³ and the peak strength $\sigma_c$ of about 128.5 MPa at the confining pressure $\sigma_3=0.6$ MPa. In order to ensure the failure of specimens during tests, the initial axial compression $\sigma_1$ and initial high confining pressure $\sigma_3$ were set to 130 MPa and 40 MPa, respectively. In the test process, the axial compression $\sigma_1$ was constant and the confining pressure $\sigma_3$ was unloaded gradually, the unloading value $\Delta \sigma_3$ was constant (15 MPa) and the unloading rate $\Delta \sigma_3$ was 0.10 MPa/s, 0.3 MPa/s, 0.6 MPa/s and 0.9 MPa/s, respectively. Firstly, the confining pressure $\sigma_3$ was loaded at a rate of 0.05 MPa/s, and the axial compression $\sigma_1$ was loaded at a rate of 0.5 kN/s up to 40 MPa. Secondly, $\sigma_1$ was loaded at a rate of 0.5 kN/s up to 130 MPa. Thirdly, the $\sigma_1$ and $\sigma_3$ were kept constant until the creep deformation of specimens stabilized (the observed displacement increment must be less than 0.001 mm/h and the time must not be less than 50 h). Finally, the $\sigma_1$ was kept constant, while the $\sigma_3$ was unloaded with the set unloading rate $\Delta \sigma_3$ to the set value. After the deformation of specimens under each level of confining pressure reached stability, then the next level of unloading was carried out until the tests ended when specimens were destroyed.

3 Results

The creep curves of specimens obtained in creep tests under different unloading rates are plotted in Fig. 1. The ranges of axial and lateral instantaneous strain of the four specimens loaded to the initial stress state ($\sigma_1=130$MPa, $\sigma_3=40$MPa) were 0.415%-0.421% and 0.074%-0.080%, and the ranges of axial and lateral creep strains were 0.082%-0.092% and 0.022%-0.036%, respectively, which indicated that the dispersion of specimens was well controlled.

Table 1 summaries the instantaneous strain and creep strain of specimens under different unloading rates. It can be observed that with the increase of unloading rate, the instantaneous strain and creep strain of all axial and lateral increased, but the increase of lateral was larger than that of axial. Taking the instantaneous strain and creep strain of specimens at the unloading rate $\Delta \sigma_3=0.1$ MPa/s as an example, when the stress level $\sigma_3=25$ MPa, for $\Delta \sigma_3=0.3$, 0.6 and 0.9 MPa/s, the percent increase of axial instantaneous strain for specimens were -0.5%, 4.7% and 6.4%, while that of lateral instantaneous strain were 9.4%, 17.1% and 30.6%, respectively; the percent increase of axial creep strain for specimens were 6.1%, 28.9% and 44.2%, while that of lateral creep strain were 28.9%, 25.2% and 44.2%, respectively. When $\sigma_3=10$ MPa, for $\Delta \sigma_3=0.3$, 0.6 and 0.9 MPa/s, the percent increase of axial instantaneous strain for specimens were 3.1%, 5.5% and 5.7%, while that of lateral instantaneous strain were 24.8%, 49.6% and 55.5%, respectively; the percent increase of axial creep strain for specimens were 10.5%,
20.9% and 25.8%, while that of lateral creep strain were 12.1%, 21.1% and 46.1%, respectively.

Table 1. Instantaneous strain and creep strain of specimens under different unloading rates (σ1=130 MPa)

| σ3 / MPa | v_Δσ3 / (MPa/s) | axial | lateral |
|----------|-----------------|-------|---------|
|          | v0 % | Δv % | v0 % | Δv % | v0 % | Δv % |
| 25       | 0.5008 | 0.1253 | -0.1149 | 0.0468 | 0.5008 |
|          | 0.4980 | 0.1330 | -0.1257 | 0.0554 | 0.4980 |
|          | 0.5245 | 0.1615 | -0.1346 | 0.0585 | 0.5245 |
|          | 0.5326 | 0.1554 | -0.1501 | 0.0674 | 0.5326 |
| 10       | 0.6433 | 0.1368 | -0.1874 | 0.0772 | 0.6433 |
|          | 0.6633 | 0.1511 | -0.2337 | 0.0866 | 0.6633 |
|          | 0.6788 | 0.1654 | -0.2803 | 0.0935 | 0.6788 |
|          | 0.6801 | 0.1721 | -0.2913 | 0.1128 | 0.6801 |

It also can be indicated from the above data that the increase of stress differences (σ1-σ3) affected the increase of lateral instantaneous strain and creep strain with v_Δσ3.

The variation curves of the ratio of lateral strain (ε3) to axial strain (ε1) (μ = ε3 / ε1) with v_Δσ3 of specimens at the initial moment and the end time of creep at different stress levels are shown in Fig. 2. The curves showed an upward trend in all four states, that is, μ increased with v_Δσ3. It was obvious that the increasing slope of the two curves at σ3=25 MPa was slower than that at σ3=10 MPa, which indicated that the increasing trend of μ with v_Δσ3 was stronger at σ3=10 MPa. When v_Δσ3 was constant, μ would increase with the creep time, and the increase of μ would occur at the moment of unloading the next level of the confining pressure. A larger number of experimental results show that the axial and lateral creep deformation of marble under unloading conditions are significantly different, and the lateral creep characteristics are more obvious than the axial characteristics. This point was not only verified by the test results in this study, but also more obvious with the increase of unloading rates.

Fig. 2. Relationship between μ and v_Δσ3

The failure of all four specimens occurred during the third stage of unloading, and the images of failure are shown in Fig. 3. All specimens showed the failure characteristic of macroscopic shear surface, while the angle of the rupture surface increased with the unloading rate. For v_Δσ3=0.1, 0.3, 0.6 and 0.9 MPa/s, the angle of the rupture surface were about 60°, 62°, 67° and 71°, respectively. By combining the data in Table 1 and Fig. 2, it can be concluded that the failure of specimens under unloading creep conditions was mainly due to the rapid increase of lateral strain. Moreover, the brittleness of specimens was increasing as the unloading rate increased.

(a) 0.1 MPa/s (b) 0.3 MPa/s (c) 0.6 MPa/s (d) 0.9 MPa/s

Fig. 3. Failure of specimens under different unloading rates

4 A modified Burgers model

4.1. The Burgers model and parameter inversion

Since specimens were all failed during the unloading process, the creep curves of each specimen were fitted with the conventional element model, which aimed to investigate the effect of unloading rates on the parameters of the element model.

After dealing with the specimen creep curves by Chen method, it was found that the Burgers model had a good fitting effect on each curve. The Burgers model is shown in Fig. 4, which can be described under three-dimensional stress state as

\[ \sigma = \frac{S_1}{2G_1} + \frac{S_2}{2G_2} \left[ 1 - e^{-\frac{\varepsilon}{\eta}} \right] + \frac{S_3}{2\eta t} \]  \hspace{1cm} (1)

\[ \varepsilon_m = \frac{\sigma_m}{3K} \]  \hspace{1cm} (2)
where $e_{ij}$ is the deviatoric strain; $S_{ij}$ is the deviatoric stress; $K$ is the bulk modulus; $G_1$ and $G_2$ are the shear modulus; $\varepsilon_m$ is the spherical strain; $\sigma_m$ is the spherical stress; $K$, $G_1$, $G_2$, $\eta_1$ and $\eta_2$ are the mode parameters, which are determined by fitting the test results, $E_1$ and $E_2$ in Fig. 4 can be transformed into $K$, $G_1$ and $G_2$ by the equation of elastic mechanics. The creep curves of each specimen were fitted by Eqs. (1) and (2), and the creep parameters under different conditions were obtained as shown in Table 2.

Table 2. Parameters of Burgers model

| Stress levels | $\sigma_1$/MPa | $\sigma_3$/MPa | $\nu_{\text{eff}}$/ (MPa/s) | $E_1$/MPa | $\eta_1$/MPa-h | $E_2$/MPa | $\eta_2$/MPa-h | $E_1'$/MPa | $\eta_1'$/MPa-h | $E_2'$/MPa | $\eta_2'$/MPa-h |
|---------------|----------------|---------------|-----------------------------|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|
| 25            | 0.1            | 23680         | 8081367                     | 13332     | 9931           |           |                |           |                |           |                |
|               | 0.3            | 20088         | 7643015                     | 13930     | 9544           |           |                |           |                |           |                |
|               | 0.6            | 22021         | 7225685                     | 12944     | 9332           |           |                |           |                |           |                |
|               | 0.9            | 21060         | 6119210                     | 12879     | 10354          |           |                |           |                |           |                |
| 10            | 0.1            | 14051         | 4272541                     | 9923      | 10313          |           |                |           |                |           |                |
|               | 0.3            | 13483         | 3951055                     | 9041      | 9861           |           |                |           |                |           |                |
|               | 0.6            | 13437         | 3815453                     | 8994      | 7926           |           |                |           |                |           |                |
|               | 0.9            | 9717          | 3986541                     | 7230      | 9432           |           |                |           |                |           |                |

4.2 The effect of the unloading rate on the parameters

For the Burgers model, the instantaneous elastic modulus $E_1$ and $E'_1$ reflect the instantaneous deformation of specimens; the viscosity coefficients $\eta_1$ and $\eta'_1$ reflect the rate of the steady-state creep stage; $\eta_2/E_2$ and $\eta'_2/E'_2$ reflect the time to reach the steady-state creep stage. Fig. 5 shows the variation curves of $E_1$, $E'_1$, $\eta_1$ and $\eta'_1$ with the unloading rate $v_{\text{eff}}$, from which several conclusions can be drawn as followings:

(1) For $E_1$ and $E'_1$, which basically decreased as $v_{\text{eff}}$ increased, the relationship can be expressed by linear function fitting within the unloading rate ranges of this experiment as

\[
E_1 = -1.88v_{\text{eff}} + 22.61 \quad (3)
\]

When $\sigma_3=25$MPa,

\[
\eta_1 = -2351.5v_{\text{eff}} + 8384.3
\]

When $\sigma_3=10$MPa,

\[
\eta_1 = -1355.6v_{\text{eff}} + 6503.5
\]

(2) For $\eta_1$ and $\eta'_1$, which basically decreased as $v_{\text{eff}}$ increased, the relationship can also be expressed by linear function fitting within the unloading rate ranges of this experiment as

\[
E'_1 = -16.79v_{\text{eff}} + 90.96
\]

(a) the instantaneous elastic modulus $E_1$.
Failure of specimens under unloading creep condition was the rupture surface increased. It can be inferred that the increase of lateral was significant, while the increase of axial 

Experimental restarch of unloading triaxial rheological tests and its nonlinear damage constitutive model of Jinping hydropower station green sandstone. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(10): 2153 – 2159.

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5 Conclusions

The stress of rock is unloading during the excavation of deep buried tunnel, it is necessary to study the creep behavior of rock under unloading condition.In order to analyze the influence of unloading rate on the unloading creep of hard rock, the triaxial unloading creep tests under high stress were carried out on marble in this study, and a modified Burgers model considering the influence of unloading rate was established based on the test results.

The results showed that the unloading rate had a significant effect on the unloading creep characteristics of marble, the conclusions can be generally summarized as:

1. With the increase of unloading rate, all instantaneous strain and creep strain of axial and lateral increased, while the increase of lateral was significant larger than that of axial.

2. With the increase of unloading rate, the angle of the rupture surface increased. It can be inferred that the failure of specimens under unloading creep condition was mainly due to the rapid increase of lateral strain. Moreover, with the increase of unloading rate, the brittleness of rock was increasing.

3. $E_1$, $E_1'$, $\eta_1$ and $\eta_1'$ decreased as $\Delta \sigma$ increased, the relationship of which can be fitted by linear function. The fitting results showed that the decreasing rate of the lateral elastic coefficient $E_1'$ was greater than that of the axial elastic coefficient $E_1$, and the fitting lines of axial and lateral were basically parallel under different stress levels.

4. The difference between the minimum value and the maximum value of $\eta/E_2$ and $\eta'/E_2'$ was small. Compared with the creep time of the whole test (each load stage of 50 h), the time of each specimen entering the steady-state creep stage was similar. Therefore, the effect of $\Delta \sigma$ on $\eta/E_2$ and $\eta'/E_2'$ can be neglected in this study.

5. The further research will be carried out from the numerical calculation of the model established in this paper, so as to realize the engineering application.

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